Agribusiness and Applied Economics No. 560 March 2005

Impacts of Genetically Modified (GM) Traits on Conventional Technologies

Scott R. Huso
William W. Wilson

Department of Agribusiness and Applied Economics
North Dakota State University
Fargo, ND 58105-5636

Acknowledgments

This research was originally conducted as Scott R. Huso's MS thesis and support was provided by the NDSU Agricultural Experiment Station, and specific grants provided by the USDA/IFAS and the Center of Excellence in Agbiotechnology at NDSU. Comments and suggestions on earlier versions of this report were received from Drs. Stephane Lemarie and Stephan Marette of INRA and from Drs. William Nganje, Robert Hearne and Cole Gustafson. However, errors and omissions remain the responsibilities of the authors.

We would be happy to provide a single copy of this publication free of charge. You can address your inquiry to: Carol Jensen, Department of Agribusiness and Applied Economics, North Dakota State University, P.O. Box 5636, Fargo, ND, 58105-5636, Ph. 701-231-7441, Fax 701-231-7400, e-mail cjensen@ndsuext.nodak.edu . This publication also is available electronically at: http://agecon.lib.umn.edu/.

NOTICE:

Information on other titles in this series may be obtained from: Department of Agribusiness and Applied Economics, North Dakota State University, P.O. Box 5636, Fargo, ND 58105. Telephone: 701-231-7441, Fax: 701-231-7400, or e-mail: cjensen@ndsuext.nodak.edu.

Table of Contents

List of Tables

Table **Page**

List of Figures

List of Figures (Cont'd)

Figure **Page**

Abstract

In hard red spring (HRS) wheat, the two GM traits nearest to commercialization are fusarium resistant wheat (FRW) from Syngenta and Roundup Ready® wheat (RRW). Monsanto announced that it has deferred the commercialization of RRW until issues of market acceptance are alleviated. Monsanto acknowledged that it might reconsider its position if another agbiotechnology firm enters the GM wheat market.

A Cournot quantity competition model was developed to determine the equilibrium quantities of conventional pesticide and agbiotechnology firms. The Cournot model was used because firms that must make production decisions ahead of the selling period, and firms with extensive research and development costs are not able to aggressively set prices. Rather, the conventional and agbiotechnology firms determine Nash equilibrium quantities and then determine a market clearing price for their respective products. The agbiotechnology firm determined a profit maximizing technology fee ($/acre) for its GM trait. The market with conventional wheat only was compared to the market with conventional and GM wheat varieties to determine the price decreases of the conventional pesticide as a result of the GM trait introduction. Changes in farmer surplus, tech firm payoffs, and sector welfare were also analyzed.

Using the actual number of firms with conventional herbicides labeled for use on HRS wheat in North Dakota and marginal production costs ranging from one to three dollars, introduction of RRW would cause a 20-25% price decrease for conventional herbicides. Similarly, four firms produce conventional fungicides labeled for the suppression of FHB in HRS wheat. This value, combined with per acre marginal production costs ranging from one to three dollars, would likely cause a 19-22% price decrease for conventional fungicides, post introduction of GM FRW.

Several implications arise from these results. First, adoption of a new GM wheat variety may not be as high as expected due to likely concurrent price decreases of conventional pesticides. The price decrease leads to a lower production cost of conventional varieties, and some farmers who would likely adopt the GM variety, if there were no price decrease, do not adopt because of the lower cost of conventional production. This price decrease must be included in the determination of potential adoption rates by agbiotechnology firms in their pricing decisions. Second, the release of a GM wheat variety results in an increase in surplus for all types of wheat farmers (GM adopters, conventional pesticide adopters, and no technology adopters). GM adopters benefit because of the release of the GM variety. Conventional pesticide adopters benefit due to the price decreases of the conventional pesticides. Farmers who did not adopt any technology prior to the release of GM wheat may adopt the conventional pesticide because of the lower cost. Third, the release of a GM wheat variety would result in slightly lower payoffs for conventional pesticide producing firms but higher payoffs for agbiotechnology firms. Overall, surplus to farmers and conventional and agbiotechnology firms increases due to the release of a GM wheat variety.

Keywords: genetic modification, fusarium resistance, Roundup Ready®, technology

Impacts of Genetically Modified Traits on Conventional Technologies

Scott R. Huso and William W. Wilson*

Development of GM wheat has not progressed as quickly as other crops. Contributing factors include a combination of complex genetics, market size relative to other crops, exports are of greater relative importance compared to other crops, import country regulations, and competition among exporting countries would be affected by the need for dramatic changes in the marketing systems to comply with identity preservation needs (Wilson et al., 2003). However, several forms of GM wheat are currently being developed. At the forefront in North America are Roundup Ready® (RRW) by Monsanto (which has since been deferred), fusarium resistant (FRW) by Syngenta, and drought tolerance (Wilson et al., 2003). These are input traits because the producer directly realizes the benefits. Introduction of GM traits would likely have the impact of reducing prices of competing conventional technologies.

Wheat competes with weeds for moisture, nutrients, and sunlight. Conventional chemicals are used to kill or stunt weeds and allow the wheat plant to compete and survive, but are limited to specific weeds which may require use of herbicide mixtures. Combinations of hard-to-kill weeds may limit the farmer to target certain weeds and allow others to remain. These factors, combined with the possibility of multiple applications of chemicals, affect farmers' demand for the Ready® technology in wheat. Roundup® herbicide provides superior control of a broad spectrum of weeds, thus reducing the need for several herbicides and widening the farmer's application window. Monsanto, however, realigned its research portfolio and decided to defer commercialization of Roundup Ready® wheat (RRW). Reasons for the deferment include the decline in spring wheat acreage in the United States, a lack of widespread need for superior weed control in the wheat market, and the success of other traits in Monsanto's research portfolio (Monsanto, 2004).

Another input trait that may be highly sought by farmers is fusarium resistance in wheat. Fusarium head blight (FHB) is a fungus disease that can occur on all small grain crops, but is most commonly seen in North Dakota on spring wheat, durum, and barley (McMullen and Stack, 1999). Some conventional varieties are labeled "moderately resistant" to FHB, such as Alsen from North Dakota State University (Ranson and Sorenson, 2003). Although Alsen is a conventional variety, it does not provide total prevention of FHB infestation. Currently, most farmers use a fungicide (e.g., Folicur®-Bayer) to reduce the susceptibility of the plant to the disease. This fungicide is typically applied at the onset of flowering. However, the window of application is small and for this reason fungicides are not 100% effective. Besides yield reduction, FHB causes reduction in quality resulting in price discounts and quality concerns shared by elevators, food processors, as well as consumers. Fusarium resistant technology would eliminate risks related to fungicide application and quality concerns related to this disease.

Although adoption of GM grains has increased significantly over the past seven years, not all farmers benefit equally resulting in a "significant heterogeneity of farmers' economic gains linked to the adoption of GM seed" (Lemarie and Marette, 2003). Differing plant protection problems and greater profits from using conventional chemical pesticides are two of t

---

* Huso is former graduate research assistant and Wilson is professor in the Department of Agribusiness and Applied Economics at North Dakota State University, Fargo

the major reasons that the ceiling of expected adoption and diffusion of GM seeds will be less than 100%. The release of RR soybean in 1996 resulted in a 40% price decrease of two major herbicides, Chlorimuron and Imazethapyr (Gianessi and Carpenter, 2000). This price reduction may have also limited the level of adoption of RR soybeans and the economic benefits associated with the RR technology (Lemarie and Marette, 2003).

Decisions on farmer adoption depend on prospective benefits and costs associated with growing the GM crop variety versus conventional technology. If prices of competing technologies for the GM variety decline, farmers who would otherwise consider planting the GM variety may continue using conventional technologies because of the lower input cost. Such a price decline would also affect the pricing of the new GM technology.

The objective of this paper is to analyze prospective changes in prices of competing technologies of GM wheat varieties (particularly FRW and RRW), if and when the trait is introduced, combined with the determination of conditions under which a farmer would adopt a particular GM wheat trait. The model builds on that used by Lemarie and Marette (2003), which incorporates prices of substitutes in the adoption of a new technology. Stochastic simulation is used to implement random variables into the models representing the uncertain outcomes associated with an unreleased product. Random values associated with the release of GM wheat include yield, quality, input costs, and market acceptance. Simulation results reflect the prospective range of outcomes without the availability of historical data.

Background

This section summarizes the status and development of GM crops and previous literature associated with input pricing models and competition.

GM Traits in the Pipeline

Commercially available GM crops have traits that are input-oriented and these provide direct benefits to farmers in the form of yield increases, cost savings, or ease of production. In corn, permits were granted for the testing of biotech crops with input-oriented traits that are yield increasing, drought and cold tolerant, fusarium resistant, and herbicide tolerant. Testing of biotech corn with output-oriented traits include seed color altered, starch metabolism altered, protein altered, and lysine level increased. In soybean, new traits include yield increasing, fungal resistant, herbicide tolerant, insect resistant, protein altered, oil profile altered, and fatty acid level altered. In cotton, traits being tested include fiber quality altered, fungal resistant, and herbicide resistant (USDA APHIS, n.d.).

Although no GM wheat varieties are currently available, research and development of GM traits is moving forward. Private firms and public institutions are working to develop different GM traits in wheat. Monsanto and Syngenta are leading the way in GM wheat trait development with herbicide tolerant wheat (RRW-Monsanto) and GM fusarium resistant wheat (FRW-Syngenta) (Wilson et al., 2003). In addition, a number of public institutions are working on drought tolerance.

Though RRW has been developed, its commercialization has been deferred. This was due to "portfolio review and dialogue with wheat industry leaders," and that Monsanto has realized that opportunities associated with RRW are "less attractive relative to Monsanto's other commercial priorities" (Monsanto, 2004, para. 2). Monsanto chose to wait until other GM wheat varieties are introduced before continuing commercialization, which is estimated to happen in the next four to eight years (Pratt, 2004). GM FRW is also expected to be near commercialization in the latter part of this decade. Syngenta's anticipated launch of GM FRW was aggressively set for 2007 (Syngenta, 2004). Another, more conservative estimate from Syngenta indicates that GM FRW may be ready for the market in seven years (Pates, 2004). Besides RRW and GM FRW, other GM wheat traits are being developed. Traits that are currently being field tested include those with altered agronomic properties such as drought tolerance, cold tolerance, and yield increases. Other traits include fungal resistance (being tested by ARS, Syngenta, and University of Minnesota), herbicide tolerance (ARS and Monsanto), virus resistance (University of Idaho), and a marker gene (Montana State University). GM traits that constitute product quality alterations include digestibility improvement (Applied Phytologics and Ventria Bioscience), starch metabolism altered (Biogemma), improved bread making characteristics (Montana State), and several others (USDA APHIS, n.d.).

Impacts of GM Crops on Conventional Pesticides

The global market for conventional agrochemical products was valued at $2.8 billion in 2000. The most significant component of the market was herbicides (51%), followed by insecticides (26%) and fungicides (20%). The largest regional market for agrochemicals was North America (31%), followed by East Asia (24%), Western Europe (20%), and Latin America (18%) (McDougall and Phillips, 2003). The herbicide sector grew at an average rate of 2.5% per year over the period of 1980 to 1999, but the value fell by 4.8% during 1999, mainly because of the increase in adoption of herbicide tolerant crops (McDougall and Phillips, 2003). The largest herbicide class, in terms of value, is amino acids. Within amino acids, glyphosate is by far the most significant chemical, with 2000 sales totaling over $3.12 billion. From 1995 to 2000, the sales of most classes of herbicides decreased from 0.3% to 11.6%. Some classes increased in sales at a small value. The amino acid class has seen a sales increase of 14% from 1995 to 2000. This increase in sales is mainly due to the rapid expansion of the overall non-selective herbicide market. Two factors contributing to this market are the increase in adoption of conservation tillage practices and the increase in acreage of crops that have been genetically modified to be tolerant to key members of the amino acid group (McDougall and Phillips, 2003). The economic effects of GM crops have been studied extensively. These effects range from yield, profits, and chemical usage to environmental effects and labor cost savings. Specifically, the impact of the adoption of GM crops on the use of conventional pesticides has been examined for each commercialized GM crop (Carpenter and Gianessi, 2003).

Each of the four commercially available GM crops has had some sort of impact on the agrochemical market. The effect of these GM varieties on pesticide use was examined by Carpenter and Gianessi (2003). Between 1995 and 2000, the percentage of total corn acres treated for four insecticides targeted at the European corn borer (ECB) decreased marginally. However, the use of a newly introduced insecticide, in 1996, increased by 2% over the same time period. Carpenter and Gianessi suggest several possible explanations for the decrease in use of insecticides for ECB. One possible explanation is the introduction of Bt corn varieties and the resulting reduced need for insecticides targeted at the ECB. Another possible reason for the slight decrease in insecticide use from 1995 to 2000 is the relatively light ECB infestations during certain years in the interval. Other reasons include the introduction of new insecticides and a decline in insecticide treatments targeted at pests other than the ECB (Carpenter and Gianessi, 2003).

Cotton is a major pesticide market in the US. The long growing season, higher pest pressure, and high value of the crop require intensive pest management. Cotton growers spend approximately $347 million for insecticides and apply approximately 20 million pounds of active ingredient each year. Cotton growers also spend approximately $320 million for herbicides and apply approximately 30 million pounds of active ingredient each year. The use of insecticides on cotton acres in six major cotton producing states decreased by approximately 3.1 million pounds of active ingredient from 1995 to 2000, a decline of 16%. This decline is believed to be directly linked to the introduction of Bt cotton varieties, but it must also be noted that other factors, such as differences in pest pressure from year to year, may also have caused some decline in insecticide use (Carpenter and Gianessi, 2003).

Two forms of herbicide tolerant cotton became available in the mid-1990s. These are BXN cotton (which is resistant to the broadleaf herbicide bromoxynil) and Roundup Ready® (which is resistant to the non-selective herbicide glyphosate). The percentage of cotton acres treated with the most commonly used herbicides has declined from 1997 to 2000 (Carpenter and Gianessi, 2003). For example, acres treated with trifluralin decreased by 18%, fluometuron decreased by 25%, and MSMA decreased by 17%. Over this same time period, the number of acres treated with glyphosate increased by 43%, and those treated with bromoxynil increased by 5% (Carpenter and Gianessi, 2003).

The case of RR soybeans provides insight to the possible price impacts involved with RR wheat. Adoption of the herbicide tolerant soybeans caused price decreases in conventional herbicides for soybeans since the commercial release of GM soybeans in 1996. However, this is not indicative of all herbicide tolerant varieties. It must be noted that herbicide tolerant corn had minimal effect on the overall pesticide market because of its limited adoption.

Adoption of RR soybeans has been rapid since 1996, reaching a level of 81% of total U.S. soybean acres in 2003. Reasons for farmers' aggressive adoption range from higher yield, to improved weed control without crop injury, to reduced management time spent to supervise production (Gianessi and Carpenter, 2000; Fernandez-Cornejo and Hendricks, 2003). From 1995 to 2000, the percentage of U.S. soybean acres treated for each herbicide class, besides glyphosate, declined (Carpenter and Gianessi, 2003). In some cases, the decline was significant. Imazethapyr use decreased by 32%, trifluralin use decreased by 16%, and chlorimuron use decreased by 6%. The use of glyphosate increased from 20% of acres in 1995 to 62% of acres in 2000 (Carpenter and Gianessi, 2003). Using the 1999 Illinois Agricultural Pest Management Handbook from the University of Illinois, Gianessi and Carpenter (2000) found that the per pound cost of chlorimuron and imazethapyr declined by 40% to 50% in 1997 and 1998 and the price of glyphosate declined by 22% in 1998. Gianessi and Carpenter (2000) then determined: "The result of lower priced Roundup Ready® treatments in comparison with competitive herbicides and the lowering of the price for key herbicides including glyphosate meant that soybean growers spent significantly less on herbicides in 1998 than in 1995," (p. 62). In North Dakota, a similar pattern of herbicide price decrease was noted for key herbicides used on conventional soybeans (Pursuit® and Poast®) as well Roundup® herbicide (Figures 1-3).

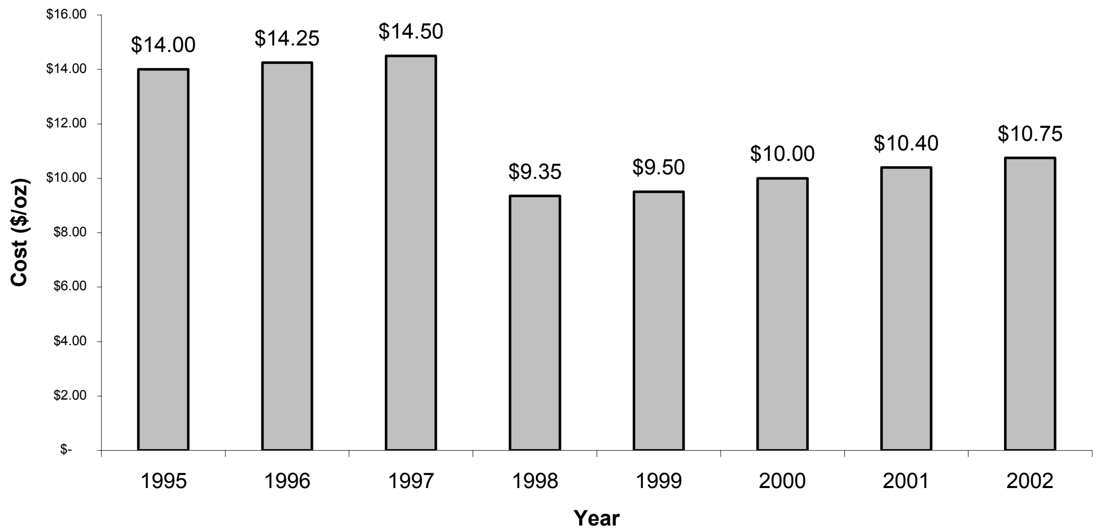

Figure 1. Approximate Retail Price of Pursuit® WGD from 1995-2003 in North Dakota.[1]

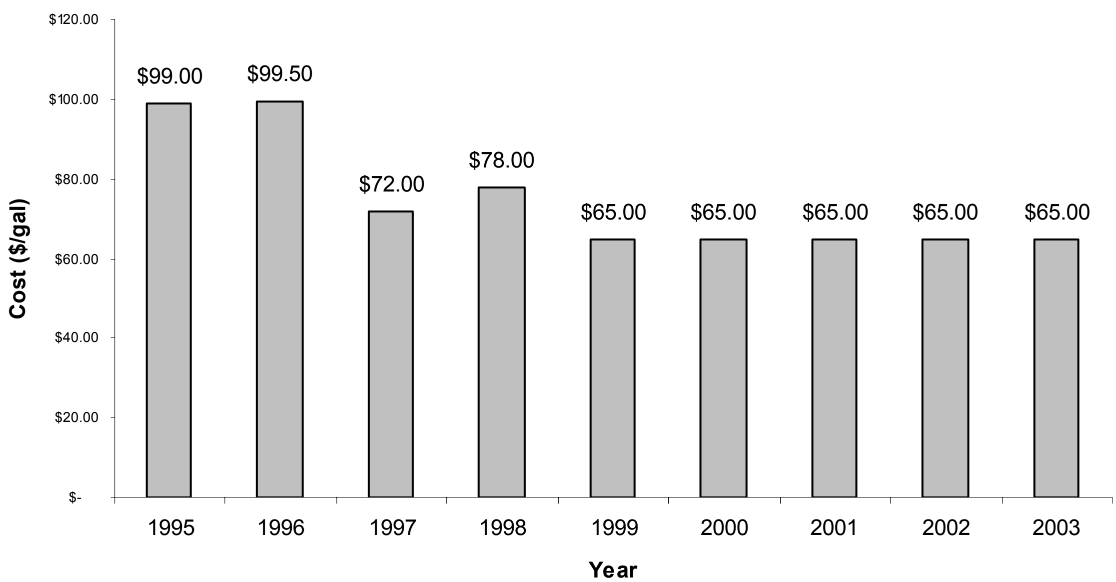

Figure 2. Approximate Retail Price of Poast® from 1995-2003 in North Dakota.[2]

[1] Pursuit® is a member of the imazethapyr herbicide class that controls many broadleaf weeds. Pursuit® is a registered trademark of BASF Corporation.
[2] Poast® is a member of the sethoxydim herbicide class and is used to control annual grasses.

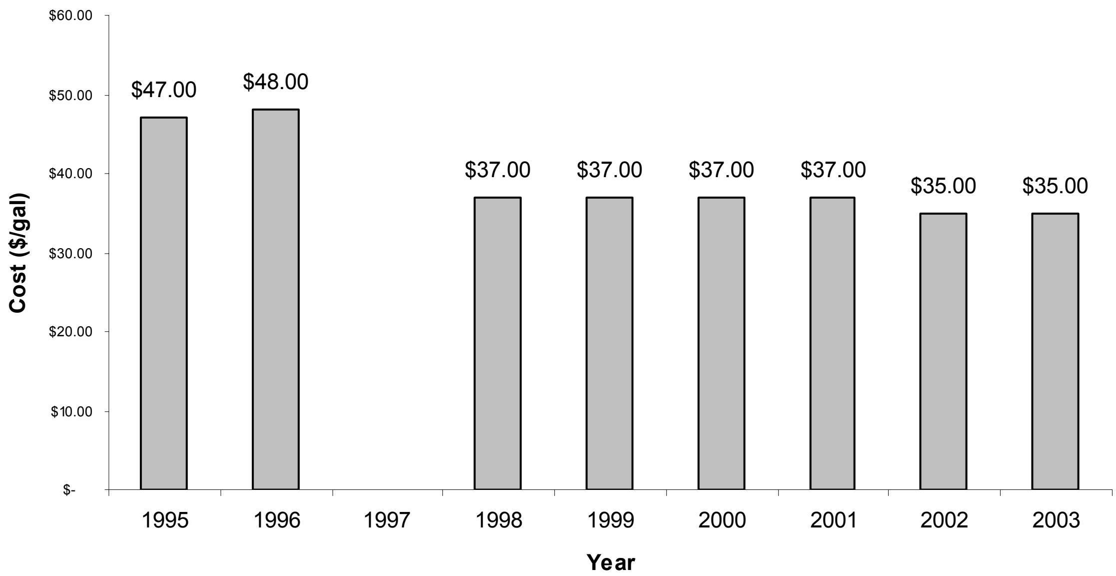

Figure 3. Approximate Retail Price of Roundup® Original from 1995-2003 in North Dakota.[3]

Diffusion of GM seeds is expected to negatively impact pesticide sales. Because of this competition, prices of synthetic pesticides may decrease (which has also been illustrated). Lemarie and Marette (2003) developed the idea that the price decrease of synthetic pesticides may lead to an increase in the surplus for farmers who are still using the conventional pesticides. For RR soybeans, they (2003) suggest that price reductions in conventional herbicides may have limited adoption of RR soybeans and the relative economic benefits derived from such technology. Their model focuses on the relevance of the competition and substitutability between conventional pesticides and GM seeds, and the size and distribution of innovation impacts in regards to new GM technology adoption. They examined two competing products: conventional seed plus conventional pesticides and GM seed plus corresponding pesticides. Market equilibrium was evaluated with and without GM seed and determined that the transfer of surplus from pesticide companies to biotechnology companies is important. They also determined that the transfer of surplus from both biotechnology and chemical firms to farmers, who benefit from market competition and increased product variation, is important.

Factors influencing the farmer's decision to adopt herbicide tolerant soybeans are the level of weed infestation, income, and contractual relations with buyers or suppliers (Nadolnyak and Sheldon, 2001). These factors could be applied to choosing a particular GM trait as well. Then the decision depends also on the price of the technology. The more weed infestation an agricultural producer faces, the more benefits HT soybeans offer (Nadolnyak and Sheldon, 2001). This applies to insects and fungi as well. It is reasonable to assume that as the level of insect infestation increases, the greater the benefits of an insect resistant GM variety, and as the probability of fungal disease increases, the greater the benefits of a disease resistant GM variety. In choosing a GM trait, the farmer determines the significance of each potential pest and decides which to target. Given the potential problems (weeds, insects, diseases, etc.) that are most likely to appear in the field used for production, the farmer chooses which GM variety to plant.

[3] Roundup® is a member of the glyphosate herbicide class and is a non-selective herbicide. Roundup is a registered trademark of Monsanto.

Determining pest infestation levels and desired traits by farmers does not automatically result in adoption of GM traits. The high price of Bt cotton in Argentina was a significant adoption constraint for farmers (Qaim and de Janvry, 2002). In Argentina, Bt cotton was commercially released in 1998. By 2001, Bt cotton covered only about 5% of the national cotton area. This is not because of low demand for GM varieties, because at the same time, adoption of GM soybeans increased to near 100%. However, unlike GM soybeans, which are not patented in Argentina and marketed by different seed companies, Monsanto was granted a national patent over Bt cotton technology and owns the sole provider of Bt seeds. Farmers in Argentina paid $103 U.S. per hectare for Bt cotton seeds, which is more than four times the price of conventional varieties (Qaim and de Janvry, 2002). Qaim and de Janvry (2002) determined that both the farmer and seed producer surplus would increase with a decrease in the price of the seed, thus indicating that the price of the GM seed is significant in adoption decisions of farmers.

Fulton and Giannakas (2001) found that two broad conclusions can be drawn from the literature. First, pricing by seed and chemical companies is strategic; and second, the strategic decisions have important impacts on the distribution of the benefits from research and development. Strategic pricing means that prices are actively determined by firms rather than exogenously. Biotechnology firms routinely conduct market research to determine price elasticity of demand for a certain new technology which influences the technology price. Strategic pricing must closely be linked to sunk costs, because if price is at marginal cost, there is little incentive to undertake research and development expenditures (Fulton and Giannakas, 2001).

Adoption and Diffusion of Genetically Modified Seeds

GM seeds focusing on insect resistance (IR) and herbicide tolerance (HT), along with possible future input-oriented traits such as fungal resistance (FR), are substitutes for conventional seeds and some form of conventional pest control. A farmer could use FR seeds as a direct substitute to the combination of conventional seed varieties and fungicide. Therefore, when disease pressures are high enough, farmers would substitute fungicide applications with the adoption of FR seed varieties. However, if certain disease pressures are not controlled by the FR seed variety, additional fungicide applications may be necessary. In this case, the substitution would occur between the bundle [FR seed + (additional fungicide – if necessary)] and the conventional bundle [conventional seed + fungicide] (Lemarie and Marette, 2003). This substitution pattern is shown in Figure 4.

Seeds that are genetically modified to express the HT trait allow farmers to apply non-selective herbicides (or, burndown herbicides, e.g., glyphosate and glufosinate) through much of the crop's growth cycle. Consequently, conventional post-emergent herbicides can be substituted with burndown herbicides. The HT seed is a complement to the burndown herbicide, and the bundle [HT seed + burndown herbicide] is a substitute to the conventional bundle [conventional seed + post-emergent herbicide] (Lemarie and Marette, 2003). This substitution pattern is shown in Figure 5.

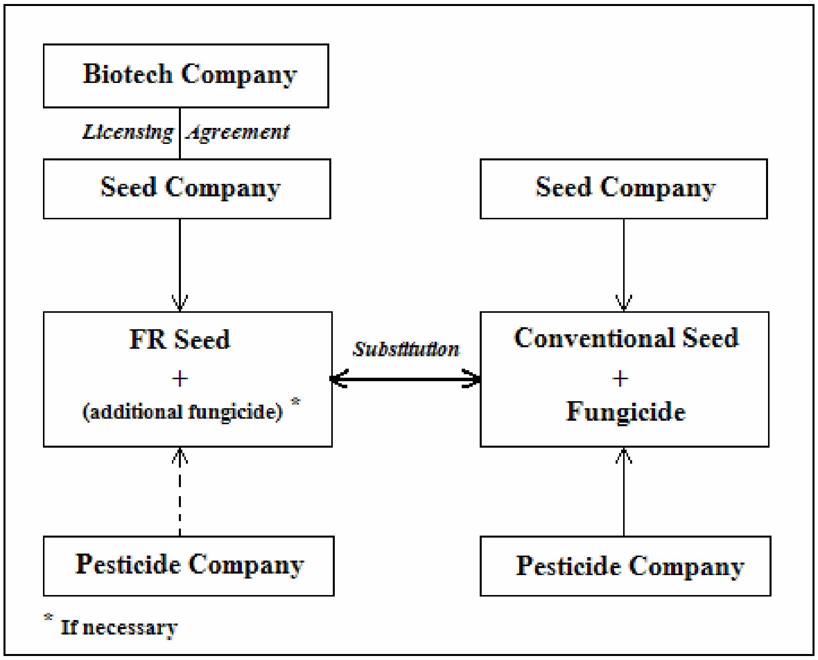

Figure 4. Substitution Pattern of the GM FRW Case.
Source: Lemarie and Marette, 2003, p. 289.

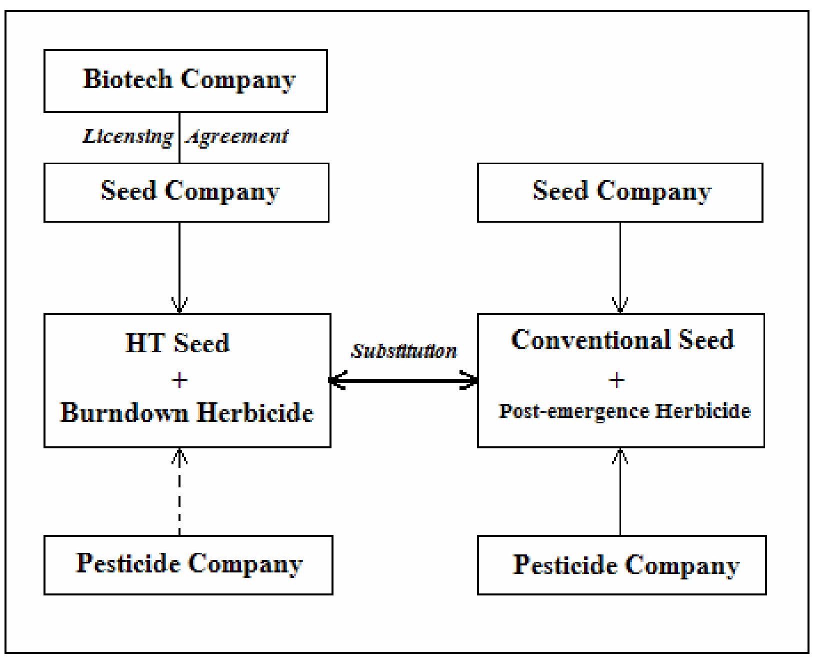

Figure 5. Substitution Pattern in the HT Case.
Source: Lemarie and Marette, 2003, p. 290.

Price Impacts of GM Adoption on Competing Inputs

This section develops a model to analyze the impacts of the introduction of a GM trait on input prices. Variables and relationships are defined to determine the level of impacts and factors that affect the outcome. The theoretical model builds upon that of Lemarie and Marette (2003) which is based on the vertical differentiation model of Mussa and Rosen (1978).

Adoption of GM seeds not only has an effect on output prices, but also affects prices of competing inputs. Lapan and Moschini (2000) analyze how the innovator's pricing is affected when the adoption of the innovation may change the price of some other input used by final producers. They examine innovation adoption under both exogenous and endogenous input prices. Exogenous input prices result in no production inefficiencies because adoption of the technologically superior innovation would be complete. If input prices were endogenous, the monopolist innovator would price the new input such that both new and old inputs would be used, leading to "pure production inefficiency" (Lapan and Moschini, 2000). They use land as the competing input, but Lemarie and Marette (2003) argue that the price of land may not be the best explanation for the endogeneity of diffusion because its adjustment may be slower compared to other input prices. Incomplete adoption is explained by the heterogeneity of farmers and the competition with conventional seed and chemical inputs.

In a market with only a few sellers, pricing and production strategies of any one firm affects industry price and production levels (Besanko et al., 2004). In the Cournot model, the strategic choice of each firm is quantity. Once firms are committed to production, they set whatever price is necessary to clear the market. Because price depends on the production of both firms, the amount that one firm produces depends on how much it expects its competitor to produce, and vice versa. The Cournot model is used in markets where firms make production decisions in advance and are committed to selling all of their output. Because prices adjust more quickly than quantities, each firm sets a price that lets it sell all that it produces. Therefore, each firm expects that if a firm lowers its price, it cannot expect to steal customers from its rivals. Cournot competitors must allow substantial decreases in revenue in order to expand output. The Cournot equilibrium outcome results in positive profits and a price that exceeds marginal and average cost.

Symeonidis (2003) made several propositions that show the attractiveness of the Cournot model when product RandD is extensive. A key proposition made is that profits net of RandD costs are higher under quantity competition than price competition. In an industry with product RandD, there are circumstances where both consumer surplus and firms' profits are higher in the Cournot equilibrium than in the Bertrand equilibrium.

The Model for Price Impacts

For fusarium head blight control, fungicide spray or GM FRW seeds are used. For weed control, conventional post-emergent herbicides or the bundle RRW seed plus burndown herbicides are used. For simplicity, it is assumed that only one synthetic pesticide product is used to solve a plant protection problem, eliminating possible combinations of pesticides. Also, the price of the license fee is the instrument by which technology provides a premium for its innovation.

Alternative technology choices are indexed by i; i=0 referring to the conventional plant protection solution and i=1 referring to the plant protection solution based on the use of GM seed. Technology choice i is supplied by n_i firm(s) which compete(s) on quantity. The marginal production cost of this technology is c_i and the price (which is determined after the level of competition) is p_i (both c_i and p_i are expressed in \$/lb). The conventional input and the GM input are both produced with a constant unit cost ($c_0 = c_1$). This assumption aids in explicitly modeling innovations that take the form of vertically differentiated inputs (e.g., a more productive seed variety). Excluding costs of research and development, production costs of the conventional and GM inputs are assumed to be the same (Lapan and Moschini, 2000).

In the HT case, the farmer pays both the price of the burndown herbicide (p_1) and the price premium of the GM seed (p_L). In the FR case, the farmer pays the GM seed premium (p_L) only. The price premium (p_L) is decided by the agbiotechnology firm, which is assumed to have a monopoly position with respect to the particular GM trait. The use of GM seed on one acre leads to a profit increase of p_L for the biotechnology company.

The technical efficiency (or, production efficiency) for technology choice i is x_i, with $x_1 > x_0$. The farmer's choice between the different plant protection solutions is made on a per acre basis. Farmers are assumed heterogeneous, and each has a willingness-to-pay equal to θx_i for technology choice i, where θ represents individual pesticide demand or the intensity of production problems for each farmer. θ is assumed uniformly distributed between 0 and 1. In the HT case, a farmer with highly intensive weed pressures corresponds to a θ close to 1, while those with less weed pressure correspond to a θ close to 0. In the FR case, a farmer with a wheat crop that is highly susceptible to fusarium head blight corresponds to a θ close to 1, while those with less susceptibility to the disease correspond to a θ close to 0. Use of technology choice i (at the required per acre dosage of each technology choice, a_i) provides an indirect utility of u_i. The indirect utilities are

$$\begin{cases} u_0 = \theta x_0 - a_0 p_0 \\ u_1 = \theta x_1 - a_1 p_1 - p_L \end{cases} . \tag{1}$$

The farmer selects the technology with the highest indirect utility (i.e., adopt GM if $u_1 > u_0$). If the indirect utility for all choices is negative for a given θ, then no product is purchased. The total number of farmers by acreage is denoted by N. In period 1, the biotechnology firm determines the license price; and in period 2, chemical and GM-chemical bundle sellers determine the quantities they produce (Cournot competition). In period 3, farmers determine various quantities of these inputs to purchase.

Market equilibrium with one product: conventional protection only. Market equilibrium is determined with conventional plant protection only and also with introduction of GM products to demonstrate the impacts of the GM traits. Without introduction of GM seeds, only conventional chemical pesticides (i.e., technology choice *0*) exist. A farmer who is indifferent between buying technology choice *0* and buying nothing is identified by the preference parameter $\hat{\theta}$. All farmers with $\theta > \hat{\theta}$ purchase technology choice *0*. As θ is uniformly distributed between 0 and 1, the total demand for conventional herbicides used is[4]

[4] Derivation of the market equilibrium conditions are shown in detail in Appendix A. Computations were done using Mathematica 3.0.

$$Q_0 = Na_0(1-\hat{\theta}) . \tag{2}$$

The preference parameter $\hat{\theta}$ can be determined by assuming $u_0 = 0$:

$$\hat{\theta} = \frac{a_0 p_0}{x_0} , \tag{3}$$

and substituting this expression into the demand function and solving for the inverse demand function yields

$$p_0(Q_0) = \frac{x_0}{Na_0^2}(Na_0 - Q_0) . \tag{4}$$

The profit for seller k is

$$\pi_{0k} = (p_0(Q_0) - c_0)q_{0k} . \tag{5}$$

To determine the profit maximizing quantity for seller k, the following first-order condition must be met:

$$\frac{\partial \pi_{0k}}{\partial q_{0k}} = \frac{x_0}{Na_0^2}\left[Na_0 - 2q_{0k} - \sum_{j=1}^{n_0-1} q_{0j} \right] - c_0 = 0 , \tag{6}$$

with all other n_0-1 sellers being j=1,2,3,…,n_0-1. Solving for q_{0k} yields

$$q_{0k} = \frac{1}{2}\left\{ \left[Na_0 - \frac{Na_0^2 c_0}{x_0} \right] - \sum_{j=1}^{n_0-1} q_{0j} \right\} . \tag{7}$$

Under a symmetric Cournot-Nash equilibrium, all sellers of the conventional technology have the same production quantity of technology choice 0, $q_{0k} = q_{0j}$ for any j. Substituting q_{0k} for q_{0j} yields

$$q_{0k} = \frac{1}{2}\left\{ \left[Na_0 - \frac{Na_0^2 c_0}{x_0} \right] - (n_0 - 1)q_{0k} \right\} , \tag{8}$$

and solving for q_{0k} leads to the equilibrium quantity for each seller:

$$q_0^* = \frac{Na_0(x_0 - a_0 c_0)}{x_0(n_0 + 1)} . \tag{9}$$

Total production equals individual firm production times the number of firms:

$$Q_0^* = q_0^* n_0 . \tag{10}$$

Substitution of Q_0^* into the inverse demand function and solving for the equilibrium price (p_0^*) gives

$$p_0^* = \frac{x_0 + a_0 c_0 n_0}{a_0 (n_0 + 1)}. \tag{11}$$

Using q_0^* and p_0^*, solving for the optimal profit yields

$$\pi_0^* = \frac{N}{x_0}\left[\frac{x_0 - a_0 c_0}{n_0 + 1}\right]^2. \tag{12}$$

The farmers' surplus, s_0^*, in the one product case is

$$s_0^* = N\int_{\hat{\theta}^*}^{1} u_0 \cdot d\theta = N\int_{\hat{\theta}^*}^{1} \theta x_0 - a_0\left(\frac{x_0 + n_0 a_0 c}{a_0 (n_0 + 1)}\right) \text{ or} \tag{13}$$

$$s_0^* = N\left[\left\{\frac{x_0}{2} - \frac{x_0 + n_0 a_0 c_0}{n_0 + 1}\right\} - \left\{\frac{\hat{\theta}^{*2} x_0}{2} - \frac{\hat{\theta}^* (x_0 + n_0 a_0 c_0)}{n_0 + 1}\right\}\right], \tag{14}$$

and is comprised of three main elements. N is the total number of acres for wheat production. The first bracketed term is the indirect utility of a farmer with $\theta = 1$, or the highest need for technology choice *0*. The second bracketed term is the indirect utility of a farmer with $\theta = \hat{\theta}$, or the lowest level of adoption for technology choice *0*. The difference between the two terms is the surplus per acre for farmers who adopt technology choice *0*. Multiplying by N gives total farmer surplus. Sector welfare is defined as

$$W = n_0 \pi_0^* + s_0^*. \tag{15}$$

Market equilibrium with two products: conventional and GM seeds. With two competing plant protection solutions, the farmers' input demand function changes. The price for selecting GM seeds that do not require a complementary pesticide is p_L and the price of a GM-chemical combination is $p_L + p_1$. A farmer who is indifferent (i.e., receives the same utility) between the technology choices *0* and *1* is denoted by $\tilde{\theta}$. Technology choice *1* is used by a farmer with $\theta > \tilde{\theta}$, while technology choice *0* is used by the farmer with θ such that $\hat{\theta} < \theta < \tilde{\theta}$. Because θ is assumed $U[0,1]$, the demand functions for technology choices *0* and *1* are (see footnote 2)

$$Q_0 = Na_0\left(\tilde{\theta} - \hat{\theta}\right) \text{ and} \tag{16}$$

$$Q_1 = Na_1\left(1 - \tilde{\theta}\right). \tag{17}$$

Since $\tilde{\theta}$ denotes a farmer who has equal utility from either product ($u_0 = u_1$),

$$\tilde{\theta} = \frac{a_1 p_1 + p_L - a_0 p_0}{x_1 - x_0}. \tag{18}$$

Demand functions for the two technology choices are

$$Q_0(p_0, p_1, p_L) = Na_0\left(\frac{a_1 p_1 + p_L - a_0 p_0}{x_1 - x_0} - \frac{a_0 p_0}{x_0}\right) \text{ and} \tag{19}$$

$$Q_1(p_0, p_1, p_L) = Na_1\left(1 - \frac{a_1 p_1 + p_L - a_0 p_0}{x_1 - x_0}\right). \tag{20}$$

Equation 19 is the difference between $\tilde{\theta}$ and $\hat{\theta}$, which is the difference in demand per acre for technology choice *0*. Multiplying by the amount applied per acre (a_0) and the total number of acres (*N*) gives total demand for technology choice *0*. Equation 20 is the difference between 1 and $\tilde{\theta}$, representing those farmers with the greatest need for technology choice *1*. Multiplying by a_1 and *N* gives the total demand for technology choice *1*.

Simultaneously solving the two technology choice demand functions for p_0 and p_1, the inverse demand functions are

$$p_0(Q_0, Q_1, p_L) = \frac{x_0}{a_0}\left(1 - \frac{Q_0}{Na_0} - \frac{Q_1}{Na_1}\right) \text{ and} \tag{21}$$

$$p_1(Q_0, Q_1, p_L) = \frac{x_1}{a_1}\left(1 - \frac{Q_0}{Na_0} \cdot \frac{x_0}{x_1} - \frac{Q_1}{Na_1}\right) - p_L. \tag{22}$$

Equation 21 shows that the price for technology choice *0*, p_0, is a function of demand for technology choice *0*, Q_0, demand for technology choice *1*, Q_1, and the license price for technology choice *1*, p_L (because both Q_0 and Q_1 are functions of p_L). The inverse demand function for technology choice *1* shows that the price for technology choice *1*, p_1, is also a function of Q_0, Q_1, and p_L. Since p_1 represents only the price for the complementary herbicide, the license price for the GM trait (p_L) must be subtracted to determine the price of the herbicide only.

Substituting the inverse demand functions in the profit function and maximizing profit for the n_0 and n_1 sellers under a symmetric Cournot-Nash equilibrium leads to the following first-order conditions:

$$\frac{\partial \pi_{0k}}{\partial q_{0k}} = \frac{x_0}{a_0}\left(1 - \frac{(n_0 + 1)q_0}{Na_0} - \frac{n_1 q_1}{Na_1}\right) - c_0 = 0 \text{ and} \tag{23}$$

$$\frac{\partial \pi_{1k}}{\partial q_{1k}} = \frac{x_1}{a_1}\left(1 - \frac{n_0 q_0}{N a_o} \cdot \frac{x_0}{x_1} - \frac{(n_1+1) q_1}{N a_1}\right) - p_L - c_1 = 0 . \quad (24)$$

The first-order conditions are solved to obtain equilibrium quantities for sellers of each technology choice. These quantities can then be used to determine the equilibrium prices:

$$p_0^*(p_L) = \frac{a_0 c_0 x_1 n_0 (n_1+1) + x_0 (x_1 + (a_1 c_1 + a_1 p_L - a_0 c_0 n_0) n_1)}{a_0 (-x_0 n_0 n_1 + x_1 (n_0+1)(n_1+1))} \text{ and} \quad (25)$$

$$p_1^*(p_L) = \frac{x_1 (x_1 + a_0 c_0 n_0 - x_0 n_0 + x_1 n_0) - a_1 (p_L x_1 (n_0+1) - c_1 (x_1 - x_0 n_0 + x_1 n_0) n_1)}{a_1 (-x_0 n_0 n_1 + x_1 (n_0+1)(n_1+1))} . \quad (26)$$

Equation 25 is the equilibrium price of technology choice *0*, and Equation 26 is the equilibrium price of the complementary pesticide needed in technology choice *1*. If two companies supply technology choice *1* ($n_1 = 2$), one firm is the agbiotechnology firm providing the GM trait while selling the complementary pesticide, and the other only sells a competitive complementary pesticide. The firm that sells only the complementary pesticide does not gain profit from the GM trait itself, but only from the sale of the complementary pesticide.

The price of technology choice *0* before and after the introduction of the new technology is compared by Equations 11 and 25, respectively. Factors in Equation 25 that are not in Equation 11 are the technical efficiency of technology choice *1* (x_1), the number of firms producing technology choice *1* (n_1), and the license price for the technology choice *1* (p_L). Differences in technical efficiency between the two technology choices $(x_1 > x_0)$, an increase in the firms producing technology choice *1*, and an increasing license price are reasons that p_0^* will decrease as the market moves from one technology choice to two technology choices.

Equilibrium prices and quantities determine firm profits:

$$\pi_0^*(p_L) = \frac{N (a_0 c_0 x_1 (n_1+1) - x_0 (x_1 + a_1 (c_1 + p_L) n_1))^2}{x_0 (x_0 n_0 n_1 - x_1 (n_0+1)(n_1+1))^2} \text{ and} \quad (27)$$

$$\pi_1^*(p_L) = \frac{N x_1 (x_1 + a_0 c_0 n_0 - x_0 n_0 + x_1 n_0 - a_1 (c_1 + p_L)(n_0+1))^2}{(x_0 n_0 n_1 - x_1 (n_0+1)(n_1+1))^2} . \quad (28)$$

Equilibrium quantities, prices, and profits are a function of the license price, p_L, which is determined by the agbiotechnology firm. The agbiotechnology firm gains profit from both the sale of complementary pesticides to their GM traits, and from the license price received from the sale of GM seeds, p_L. Therefore, the profit function for the agbiotechnology firm is $\pi_B = n_1 q_1^*(p_L) p_L + \pi_1^*(p_L)$. Profit maximization for the agbiotechnology firm with respect to p_L gives the equilibrium license price p_L^* in Equations 29, which depends on the number of firms providing technology choice *0* (n_0), the number of firms providing technology choice *1* (n_1), and the level of technical efficiency of each technology choice (x_0 and x_1):

$$p_L^* = \frac{\left(x_1 + a_0 c_0 n_0 - x_0 n_0 + x_1 n_0 - a_1 c_1 (n_0 + 1)\right)\left(-x_0 n_0 n_1^2 + x_1 (n_0 + 1)\left(-2 + n_1 + n_1^2\right)\right)}{2 a_1 (n_0 + 1)\left(-x_0 n_0 n_1^2 + x_1 (n_0 + 1)\left(-1 + n_1 + n_1^2\right)\right)}. \tag{29}$$

If n_0 increases, competition increases and p_L^* decreases. If n_1 increases, the price of the complementary pesticide decreases, resulting in an increase in p_L^*. If the difference in technical efficiency between the two technology choices decreases, p_L^* will decrease because of the increased competitiveness between the two technology choices.

The farmers' surplus in this case are defined as

$$s_0^* = N \int_{\hat{\theta}^*}^{\tilde{\theta}^*} u_0 \, d\theta \text{ and} \tag{30}$$

$$s_1^* = N \int_{\tilde{\theta}^*}^{1} u_1 \, d\theta. \tag{31}$$

Sector welfare is $W = n_0 \pi_0^* + (n_1 - 1)\pi_1^* + \pi_B^* + s_0^* + s_1^*$. Because two technology choices are available, sector welfare is now represented by including the firms producing technology choice *1*, as well as those farmers who adopt technology choice *1*.

When a complementary pesticide is not required (as in the case of IR and FR), a farmer purchasing technology choice *1* pays only the license price, p_L. Equilibrium quantities, prices, profits and surpluses are also different (see footnote 4). Equilibrium quantities for each technology choice are defined as

$$q_0^* = \frac{N a_0 \left(a_0 c_0 x_1 (n_1 + 1) - x_0 (x_1 + c_1 n_1)\right)}{x_0 \left(x_0 n_0 n_1 - x_1 (n_0 + 1)(n_1 + 1)\right)} \text{ and} \tag{32}$$

$$q_1^* = -\frac{N a_1 \left(-x_1 - a_0 c_0 n_0 + x_0 n_0 - x_1 n_0 + c_1 (n_0 + 1)\right)}{-x_0 n_0 n_1 + x_1 (n_0 + 1)(n_1 + 1)}. \tag{33}$$

Equilibrium prices for each technology choice are

$$p_0^* = \frac{a_0 c_0 x_1 n_0 (n_1 + 1) + x_0 (x_1 + c_1 n_1 - a_0 c_0 n_0 n_1)}{a_0 \left(-x_0 n_0 n_1 + x_1 (n_0 + 1)(n_1 + 1)\right)} \text{ and} \tag{34}$$

$$p_L^* = \frac{x_1^2 (n_0 + 1) - c_1 x_0 n_0 n_1 + x_1 (a_0 c_0 n_0 - x_0 n_0 + c_1 n_1 + c_1 n_0 n_1)}{\left(-x_0 n_0 n_1 + x_1 (n_0 + 1)(n_1 + 1)\right)}. \tag{35}$$

Equations 11 and 34 are the equilibrium price of technology choice *0*, p_0^*, in the market with one technology choice and the market with two technology choices, respectively. Equation 34 indicates that after the introduction of the new technology choice, p_0^* is dependent on the technical efficiencies of each choice, as well as the number of firms producing each technology choice. As the difference between x_1 and x_0 increases $(x_1 > x_0)$, p_0^* in Equation 34 decreases. Also, as n_0 and/or n_1 increase(s), p_0^* decreases because of increased competition.

The price of technology choice *1* is now only the license price, p_L^*. Because the GM trait does not require a complementary pesticide and the assumption of monopoly power, the number of firms supplying technology choice *1* (n_1), is one. Since there are no firms selling complementary pesticides, the equilibrium profits to the sellers of technology choice *0* and technology choice *1* are

$$\pi_0^* = \frac{N\left(a_0 c_0 x_1 (n_1 + 1) - x_0 (x_1 + c_1 n_1)\right)^2}{x_0 \left(x_0 n_0 n_1 - x_1 (n_0 + 1)(n_1 + 1)\right)^2} \text{ and} \tag{36}$$

$$\pi_B^* = \frac{N x_1 n_1 \left(x_1 + a_0 c_0 n_0 - x_0 n_0 + x_1 n_0 - c_1 (n_0 + 1)\right)^2}{\left(x_0 n_0 n_1 - x_1 (n_0 + 1)(n_1 + 1)\right)^2}. \tag{37}$$

Total farmer surplus is defined over the ranges of adoption for each technology choice:

$$s_0^* = N \int_{\hat{\theta}^*}^{\tilde{\theta}^*} u_0 \, d\theta \text{, and} \tag{38}$$

$$s_1^* = N \int_{\tilde{\theta}^*}^{1} u_1 \, d\theta . \tag{39}$$

Finally, sector welfare is defined as

$$W = n_0 \pi_0^* + \pi_B^* + s_0^* + s_1^* . \tag{40}$$

Equation 40 differs from sector welfare in the HT case because of the absence of sellers of complementary pesticides to the GM trait.

Empirical Model Description

The model is applied to hard red spring wheat (HRS) in North Dakota. The prospective release of fusarium resistant wheat (FRW) and Roundup Ready® wheat (RRW) are scenarios used to evaluate the impacts on prices of competing conventional herbicides and fungicides after the release of these GM wheat traits. Players are conventional pesticide producing firms, the agbiotechnology firm, incumbent firms producing the pesticide that complements the GM trait, and farmers who decide which technologies to adopt. The agbiotechnology firm determines the license price (p_L), then all sellers of conventional chemicals and/or GM-chemical bundles determine quantities (Cournot competition), and finally, farmers determine the quantities of the two technology choices to purchase (i.e., adoption).

The model begins with only conventional wheat to determine an equilibrium for comparison between input prices to a market with both conventional and GM wheat. The second scenario includes the release of GM FRW along with availability of the conventional variety. This GM wheat trait would not require a complementary pesticide, so there are no sellers of complementary pesticides to this product. Farmers choose between purchasing a conventional wheat variety and applying a fungicide treatment or a GM FRW variety. The agbiotechnology firm providing the GM FRW trait has a monopoly with respect to that trait and receives profits only from the license price for the GM FRW trait. The third scenario is the market with conventional wheat and RR wheat. RRW requires the application of a glyphosate herbicide. The agbiotechnology firm providing the RR trait has a monopoly on that trait and also sells the complementary herbicide. This firm receives profits from both the license price of the seed, and the sale of the complementary herbicide. Other firms that sell the complementary herbicide do not receive profits from the GM trait, but only from the sale of the herbicide.

Data Sources, Distributions, and Assumptions

Data are used to represent HRSW production in North Dakota in each of the three scenarios. Variables used in the model are described as

N = Number of acres annually planted to HRS in U.S.;

n_0 = Number of firms producing conventional pesticides labeled for use on HRS in ND. For RRW, this is herbicides; for FRW, this is fungicides;

n_1 = Number of firms producing the complementary pesticide to the GM variety. This is only applicable to RRW. Also, one of the firms is the provider of the GM trait. When $n_1 = 1$, no sellers of complementary pesticides (i.e. FRW);

c_0 = Marginal production cost of the conventional pesticide;

c_1 = Marginal production cost of the GM-complementary pesticide solution;

x_0 = Technical or production efficiency of the conventional wheat variety;

x_1 = Technical or production efficiency of the GM wheat variety;

a_0 = Required per acre dosage of the conventional pesticide (assuming no multiple tank mixes are necessary);

a_1 = Required per acre dosage of the complementary pesticide; and

θ = Idiosyncratic pesticide need for each farmer.

Relationships used in the one product scenario are equations 3, 9, 11, 12, 14, and 15; and those used in the conventional plus GM FRW scenario are equations 32, 33, 34, 35, 36, 37, 38, 39, and 40. Finally, relationships in the conventional plus RRW scenario are equations 18, 25, 26, 27, 28, 29, 30, and 31.

Table 1 provides a summary of the data sources. Distributions for yield variables were determined using *Bestfit*, a distribution estimation procedure in *@RISK* (Palisade Corporation, 2000). The idiosyncratic pesticide need for each farmer (θ) is assumed to be uniformly distributed on the interval 0 to 1. This pesticide need can be interpreted as the adoption level for each product and is a function of input prices, application rates, and technical efficiencies of each product. It is unique to each product type and each scenario, therefore, the level of θ for conventional wheat is not the same under both the FRW and the RRW scenarios. Values of the discrete model parameters are summarized in Table 2. Table 3 summarizes the random variable distributions and Table 4 summarizes the base case assumptions. Base case yields are taken from North Dakota Crop Reporting District 3.

Table 1. Data Sources

Model Component	*Data Source*
HRSW Acreage in U.S.	USDA NASS (2004)
Number of herbicide producing firms	Zollinger (2004)
Number of fungicide producing firms	McMullen and Bradley (2004)
Conventional Wheat Yield – ND CRD 3	USDA NASS (2004)
Roundup Ready® Wheat Yield Benefit	Blackshaw and Harker (2002)
Fusarium Resistant Wheat Yield Benefit	Nganje et al. (2001)
Pesticide application rates (Conv and GM)	Zollinger (2004) McMullen and Bradley (2004)

Table 2. Discrete Parameter Values – Base Case

Parameter	*Base Case Value*
U.S. HRSW Acres	N = 15.212 million
Marginal Production Cost	$c_0 = c_1 = 0$
Required per acre dosage	$a_0 = a_1 = 1$
Tech Choice 0 firms	1, 2
Tech Choice 1 firms	1, 2

Table 3. Random Variable Distributions – Base Case

Variable	*Distribution*	*Mean*	*Std. Dev.*	(α_1, α_2)	*(Min, Max)*	*Correlation*
Conventional Yield	Logistic	35.81	4.14	NA	NA	-0.85 with FHB loss
Yield Increase RR Wheat	Uniform	NA	NA	NA	(.11, .14)	Insignificant
Yield Increase FR Wheat/FHB loss	Beta General			(.273, .286)	(.015, .359)	-0.85 with Conv. Yield
Farmer Pesticide Need	Uniform	NA	NA	NA	(0, 1)	NA

Table 4. Base case assumptions

Variable/Parameter	*Value*	*Logic*
N	15.212 million acres	Average HRSW annual planting acreage in U.S.
n_0	1 or 2	Representing monopoly and competition among conventional pesticide firms
n_1	1 or 2	If 1, FRW agbiotech firm; if 2, RRW firm plus competitive herbicide firm
c_0	0	Assumption for simplicity. No marginal cost to produce.
c_1	0	Assumed no additional cost to produce GM seed.
x_0 (yield used as efficiency)	Mean = 35.81 bu/acre St. Dev. = 4.14 bu/acre	Reflective of ND CRD-3 HRSW yield over period 1990-2003
x_1 (yield in scenario 2-FR)	1.5-35.9% benefit over conventional yield	Yield loss due to FHB in ND CRD-3 over period 1993-2000
x_1 (yield in scenario 3-RR)	11-14% benefit over conventional yield	Monsanto field trials across various geographic regions
a_0	1	Assumption for simplicity
a_1	1	Same as above
θ	U[0,1]	Farmers with low WTP for GM=0, high WTP for GM=1

Total HRS acres, marginal cost of production, required per acre dosage, and the number of firms selling conventional or complementary pesticides plus GM technology were assigned values rather than simulated. In the base case, it was assumed that the marginal cost of production of both GM and conventional varieties is zero. A large portion of the total cost associated with a GM trait is fixed due to extensive research and development over many years, and data do not exist on the value of the marginal cost of production and distribution of a GM seed trait. Thus, following Lemarie and Marette (2003), the base case assumes this value to be nil. However, it is recognized that the marginal cost of production is not nil and sensitivities are conducted to illustrate the impact of increasing marginal cost of production.

It is assumed that two firms represent a competitive market. Because of the assumption of no tank mixed pesticides, the use of one or two technology providing firms in the model simplifies the impacts of increased competition in the respective industry and also adds consistency to the analysis. Sensitivities were conducted on the number of firms to more critically detail the impacts of increased competition. Conventional grass and broadleaf control herbicides that are labeled for use in North Dakota are produced by eleven different firms. Nine firms produce a glyphosate herbicide that is labeled for use in North Dakota (i.e., on burndown, HT soybeans, HT corn, pre-harvest for wheat, etc.). Four firms produce fungicides that are labeled for the suppression of FHB in HRS in North Dakota (McMullen and Bradley, 2004). For simplicity in the base case, one producing firm denotes a monopoly with respect to that product, and two producing firm indicates competition among firms. Sensitivities were conducted to evaluate the effects of more competitors on prices, adoption, profits, and welfare.

The analytic model is a set of mathematical relationships that determine the value of outputs (Winston, 2001). Simulations were conducted using @*Risk* to account for randomness in some variables (Palisade Corporation, 2000). Probability distribution functions representing uncertainty are used to define risk. Ten thousand iterations were performed successively until distributions were adequately filled and simulated results were plausible.

Base Case Results

The base case provides results for comparison under different possible conditions or changes in parameters. The three scenarios are described individually followed by a comparison.

Market with only conventional products. In the market with conventional products only, pesticide producing firms decide quantity which ultimately determines prices. Scenario 1 is illustrated for both the conventional market with one (simulation 1) and two competitors (simulation 2) in the conventional pesticide industry. All farmers who are indifferent between purchasing the conventional pesticide and buying nothing are indicated by $\hat{\theta}$; therefore, the demand for the conventional pesticide is determined by those farmers whose need is greater than $\hat{\theta}$. Thus, demand (or, adoption) for the conventional technology is 50% (1 - 0.5) of total HRS acres (Table 5). In simulation 2, competition decreases the price of the conventional technology, p_0, from \$17.91 to \$11.94. The price decrease results in more farmers purchasing the conventional pesticide as indicated by $\hat{\theta}$ dropping to 0.33. Thus, demand is 67% (1 - 0.33), of total HRS acres. Individual firm profit, π_0, in simulation 1 is \$136 million and in simulation 2 is

Table 5. Price Impact Model Results – Conventional and GM FRW

Sim.	*Structure*	P_0	P_L	*Conv. Adopt*	*FRW Adopt*	π_0	π_B	s_0	s_1	W
		--- \$ per acre ---				--- \$ million ---				
#1	$n_0 = 1$ $n_1 = 0$	17.91		50%		136		68		204
#2	$n_0 = 2$ $n_1 = 0$	11.94		67%		61		121		242
#3	$n_0 = 1$ $n_1 = 1$	11.46	15.06	32%	36%	56	83	28	104	271
#4	$n_0 = 2$ $n_1 = 1$	8.44	12.35	47%	30%	30	57	61	103	281

\$61 million (simulation 2 includes two firms so total firm profits is \$122 million). Farmer surplus, s_0, is \$68 million in simulation 1 and \$121 in simulation 2. Sector welfare, *W*, of \$204 million in simulation 1 increased to \$242 million in simulation 2.

The production efficiency of GM FRW is analogous to the yield loss prevention quality of the new GM variety. In CRD 3 (northeastern North Dakota), the average HRS yield loss due to FHB over the period 1993-2000 is 18.3%, and we assume the genetically modified FR wheat would provide 100% prevention of the potential losses due to FHB. Simulations 3 and 4 correspond to market equilibrium with conventional wheat (being provided by one or two firms) and GM FRW (being provided by a single firm owning the trait patent). The total price of the GM plant protection solution is p_L (\$/acre). In the market with two products, FRW is adopted by the farmers with the highest θ value or those with $\tilde{\theta} < \theta < 1$. The conventional technology is adopted by farmers with a θ value such that $\hat{\theta} < \theta < \tilde{\theta}$. Farmers who decide to use neither form of technology have a θ value of $0 < \theta < \hat{\theta}$. In simulation 3, GM FRW was adopted by 36% of the farmers $(1 - 0.64 = 0.36)$. The conventional protection solution was adopted by 32% of the farmers, and 32% of the farmers purchased no plant protection. In simulation 4, the adoption of FRW was 30%, conventional technology adoption was 47%, and 23% of the farmers purchased no plant protection.

The agbiotechnology firm sets a license price, p_L, for FRW of \$15.06/acre. The availability of FRW results in a price decrease of 36% for the conventional fungicide, p_0, from \$17.91 to \$11.46. Also, introduction of GM FRW transfers a majority of firm payoffs from the conventional to the agbiotechnology firm. From simulation 1 to 3, payoffs for the conventional firm decrease from \$136 million to \$56 million (a decrease of 59%) while the payoff to the agbiotech firm was \$83 million in simulation 3. Much of farmer surplus shifted to those farmers who adopt the GM FRW. From simulation 1 to 3, conventional farmer surplus decreases from \$68 million to \$28 million, while the introduction of GM FRW resulted in a farmer surplus of \$104 million to those farmers who adopted the GM FRW technology in simulation 3. Farmer surplus increases because of more product choices. Sector welfare increased by 32.8% from simulations 1 to3.

Comparing simulations 2 and 4 (when $n_0 = 2$), the agbiotechnology firm sets a p_L of \$12.35/acre and the price of the conventional fungicide decreases by 30%, from \$11.94 to \$8.44. This lower price allows farmers with a low willingness-to-pay (or low θ) to purchase the conventional fungicide. For this reason, comparing simulations 3 and 4, adoption of FRW decreased while adoption of the conventional fungicide increased. Introduction of the GM FRW results in a shift of the firm payoffs and farmer surpluses. From simulation 2 to 4, payoffs to the conventional firm decreased from \$61 million to \$30 million, while the agbiotech firm gained a payoff of \$57 million after introduction of the GM FRW. Surplus for conventional farmers decreased from \$121 million to \$61 million from simulation 2 to 4, while the surplus to those farmers that adopted the GM FRW technology was \$103 million in simulation 4.

Market with conventional and GM Roundup Ready® wheat. The prospective release of Roundup Ready® wheat (RRW) is met by the need for a complementary non-selective herbicide (i.e., glyphosate). In this scenario, one agbiotechnology firm provides the Roundup Ready® trait, and also sells a complementary herbicide. When $n_1 = 2$, one firm is the agbiotechnology firm and the other sells a competing complementary glyphosate. Production efficiency for RRW is assumed to be the potential yield benefit of RRW over conventional wheat based on various field trials, an 11-14% increase over conventional varieties. Simulations 1 and 2 are shown along with simulations 5 and 6 to illustrate key changes (Table 6).

Table 6. Price Impact Model Results – Conventional and RRW

Sim.	Structure	p_0	p_1	p_L	Conv Adopt	RRW Adopt	π_0	π_1	π_B	s_0	s_1	W
		------$ acre-------					-------------------- $ million ----------------------					
#1	$n_0 = 1$ $n_1 = 0$	17.90			50%		136			68		204
#2	$n_0 = 2$ $n_1 = 0$	11.94			67%		61			121		242
#5	$n_0 = 1$ $n_1 = 2$	11.73	6.95	7.72	33%	34%	58	18	59	29	98	263
#6	$n_0 = 2$ $n_1 = 2$	8.24	6.24	5.09	36%	31%	29	15	39	57	107	276

Introduction of RRW causes a 34.5% decrease in p_0 from simulation 1 to 5, from \$17.90/lb to \$11.73/lb. The agbiotechnology firm sets an equilibrium license price, p_L, of \$7.72/acre in simulation 5. From this, 34% of the farmers adopt the RRW-complementary herbicide bundle. Those farmers who adopt the conventional plant protection technology (such that $\hat{\theta} < \theta < \tilde{\theta}$) are 33% of the total. Finally, 33% of the farmers adopt no plant protection solution. There is a shift in firm payoffs and farmer surplus post introduction of the GM trait. From simulation 1 to 5, the conventional herbicide firm payoff decreased from \$136 million to \$58 million, while the payoff to a glyphosate producing firm was \$18 million and the payoff to the RRW agbiotech firm was \$59 million post introduction of RRW. Surplus for conventional farmers decreased from \$68 million to \$29 million from simulation 1 to 5, while the surplus to the farmers that adopted RRW was \$98 million in simulation 5. Due to the introduction of RRW, sector welfare increased by 29% from simulation 1 to simulation 5, from \$204 million to \$263 million.

Comparing simulations 2 and 6 (when $n_0 = 2$), the agbiotechnology firm set p_L at \$5.09. The price of the conventional herbicide, p_0, decreases by 31% in this case, from \$11.94/lb in simulation 2 to \$8.94/lb in simulation 6. Farmers benefit from competition and product diversity. Farmer surplus increases from simulation 2 to 6, but it is mostly shifted from conventional farmers to those farmers that adopt RRW. Conventional farmer surplus decreases from \$121 million to \$58 million, while surplus to those farmers who adopt RRW was \$107 million post introduction of RRW. The payoff to the conventional herbicide producing firm decreases from \$61 million to \$29 million, while the glyphosate producing firm has a payoff of \$15 million and the RRW agbiotech firm has a payoff of \$39 million in simulation 6. Sector welfare increases by 14%, from \$242 million to \$276 million.

Table 7 summarizes the results of the base case for each scenario in which there is competition in the conventional pesticide production industry (i.e., simulations 2, 4, and 6).

Table 7. Base Case Summary Results

Market Configuration	*Conventional Only*	*Conventional + GM FRW*	*Conventional + RRW*
Conventional Pesticide Price	\$11.93/lb	\$8.44/lb	\$8.24/lb
Complementary Pesticide Price	NA	NA	\$6.24/lb
License Price/Tech Fee	NA	\$12.35/acre	\$5.09/acre
No Product Adoption	33%	23%	23%
Conventional Adoption	67%	47%	46%
GM Adoption	NA	30%	31%

Variations of Surplus

The release of a GM trait combined with price decreases of conventional technologies result in some farmers adopting a new technology while others continue using the conventional technology. Such interactions allow for farmers with a low level of willingness-to-pay for the GM technology to accrue surplus because of the price decreases of the competing conventional pesticide associated with the release of the GM trait. The variations in surplus measure, developed by Lemarie and Marette (2003), was used to compare farmer surplus as the market shifts from conventional wheat to a market with conventional wheat and GM wheat.

Farmers with the highest willingness-to-pay for the GM trait (i.e., farmers with the highest θ) shift from adopting the conventional pesticide to adopting the GM solution. Some farmers continue adopting the conventional protection. Some farmers that did not adopt any plant protection when only conventional protection was available may purchase the conventional pesticide in the new market because of their low need or willingness-to-pay. The variations of farmer surplus and also changes in firm profits and sector welfare in both market configurations are illustrated in Table 8.

Table 8. Variations of Surplus (\$ million)

Initial Simulation	*Final Simulation*	$\Delta S_{\phi\to 0}$	$\Delta S_{0\to 0}$	$\Delta S_{0\to 1}$	ΔS	$n_0 * \Delta\pi_0$	$\Delta\pi_1 + \Delta\pi_B$	ΔW
#1	#3	8.84	12.76	41.60	63.20	-80.31	83.20	66.09
#2	#4	2.46	19.70	20.34	42.50	-60.60	56.50	38.40
#1	#5	8.10	15.02	36.43	59.55	-77.72	76.92	58.75
#2	#6	2.72	20.26	20.70	43.68	-63.40	53.39	33.67

The variations of surplus show the changes in surplus for one group of farmers as the market moves from conventional to either conventional plus GM FRW or conventional plus RRW. For example, moving from simulation 1 to 3, $\Delta S_{\phi\to 0}$ is the change in surplus of those farmers who purchase no plant protection solution in simulation 1 then purchase technology choice *0* (conventional fungicide) in simulation 3. In simulation 1, 50% of farmers adopt no protection solution and 50% adopt the conventional protection solution. In simulation 3, 36% of farmers with the highest θ adopt GM FRW, 32% adopt the conventional fungicide, and 32% adopt no protection solution. This indicates that 18% of farmers moved from purchasing no protection in simulation 1 to purchasing the conventional protection in simulation 3 (50%-32%). Introducing GM FRW, the surplus for the 18% of total farmers that switched from nothing to conventional fungicide protection increased by $8.84 million.

The surplus to farmers who purchased conventional protection technology in both simulations 1 and 3 ($\Delta S_{0\to 0}$) increases by $13 million. Conventional adoption in simulation 1 was 50% and in simulation 3 was 32%. Adoption of the GM FRW was 36% in simulation 3. Thus, farmers with the highest willingness-to-pay for the new technology become adopters in simulation 3. This leaves 14% of farmers purchasing conventional fungicide in both simulations. Therefore, the increase in surplus to those 14% of farmers is a direct result of the price decrease of the conventional fungicide.

The surplus to farmers who purchase the conventional fungicide in simulation 1 and then adopt the GM FRW in simulation 3 ($\Delta S_{0\to 1}$) increases by $42 million. Adoption of the conventional fungicide in simulation 1 was 50% and adoption of the GM FRW was 36% in simulation 3. Those 36% of total farmers with the highest willingness-to-pay for the GM FRW variety are the ones who moved from conventional to GM FRW. So, the change in farmer surplus for those 36% of total farmers was an increase of $42 million.

The total variation in surplus from simulation 1 to 3 increased by $63 million. Because of the price decrease of the conventional fungicide, the total change in payoff for the conventional fungicide producing firms ($n_0 * \Delta\pi_0$) was a decrease of $80 million from simulation 1 to 3. The total change in payoffs for the fungicide producing firm and the GM FRW agbiotech firm ($\Delta\pi_1 + \Delta\pi_B$) increased by $83 million. Thus, sector welfare increased by $66 million from simulation 1 to 3. Interpretation of the remaining simulations in Table 8 is identical.

The variation of surplus solidifies the notion that adopters of a new GM wheat trait are not the only group to gain surplus. In fact, from simulation 2 to 4, and from simulation 2 to 6, the increase in surplus for farmers who purchase conventional protection in both simulations and the increase in surplus for the farmers who move from conventional to GM technology are similar. From simulation 2 to 4, $\Delta S_{0\to 0}$= $20 million and $\Delta S_{0\to 1}$= $20 million. From simulation 2 to 6, $\Delta S_{0\to 0}$= $20 million and $\Delta S_{0\to 1}$= $21 million. This indicates that farmers who continue to use conventional protection post introduction of a GM wheat variety benefit almost equally as those who adopt the new GM variety.

Sensitivities

Market with only Conventional Products

The price of the technology depends on the number of firms in the conventional pesticide production industry. The number of conventional herbicide producing firms and fungicide producing firms in the U.S. are 11 and 4, respectively. These impacts are shown on both price and adoption levels for herbicides (see Figures 6 and 7)[5] and fungicides (see Figures 8 and 9). The results are intuitive in that as the number of firms increases, the price of the conventional pesticide decreases due to the increase in competition. As a result of lower prices for the technology, adoption rates increase as the number of firms increases.

Market with Conventional and GM Fusarium Resistant Wheat

Number of GM FRW agbiotech firms. In the base case, it was assumed that only one agbiotech firm produced the GM FRW technology because of patent protection and the lack of need for complementary pesticides. A technological innovation is typically granted a patent for a number of years, preventing competition in the production of the innovation and allowing monopoly pricing by the innovator. When the patent expires, entry is permitted which creates competition. Sensitivities were performed to illustrate the effects of an expiring patent resulting in increased competition among agbiotech firms in the production of GM FRW.

As the number of GM FRW agbiotech firms increases from 1 to 6, the price of the GM FRW technology decreases from $12.35/acre to $4.96/acre while the price of the conventional fungicide decreases from $8.44/lb to $3.45/lb (Figure10). With patent protection for one firm, adoption of the conventional variety was 47% while adoption of the GM FRW variety was 30% (Figure11). If the patent expires and three firms produce the GM FRW technology, adoption of the conventional variety is 29% and adoption of the GM FRW variety is 56%. This change in adoption levels is the result of the price decrease and an indirect result of the patent expiration. Figure 12 shows that increased competition in the production of GM FRW technology yields a large surplus increase for producers purchasing that technology, while firms' revenues gradually decline.

Production efficiency of GM FRW. The base case assumption was that GM FRW completely prevents the possibility of FHB infestation. Although GM FRW is being tested in field trials, results of the production efficiency from those tests have not been released. Conventional varieties do provide some protection against FHB, but not 100%. For those reasons, sensitivities were conducted on the level of FHB control of a GM FRW variety, ranging from 10% to 100% of the total estimated yield benefit using a scalar on production efficiency of the GM FRW variety. For example, if the variety provided 50% control of FHB, the variety would provide the producer with 50% of the GM FRW yield benefit.

As the efficiency of the GM FRW variety changes from 10% to 100%, the license price (or, tech fee) for GM FRW technology increases from $9.32/acre to $12.35/acre. Over the same interval, the price of the conventional fungicide decreases from just under $9/lb to just over $8/lb (Figure 13). Figure 14 illustrates that as the yield benefit of the GM FRW trait increases from

[5] All figures referenced in this section are contained in Appendix B at the end of this report.

10% to 100%, the adoption level of the GM FRW variety increases from 26% to 30% and the adoption level of the conventional protection decreases from 50% to 47%. Figure 15 shows that the increase in efficiency results in large payoff increase for the agbiotech firm producing the GM FRW technology. Farmers purchasing the GM FRW technology also have a small increase in surplus.

Marginal cost of GM FRW technology production. It was assumed that the marginal cost of production of the GM FRW variety was zero for two reasons. First, a large portion of the total cost associated with a GM trait is fixed due to extensive research and development over many years. Second, data do not exist on the value of the marginal cost of production and distribution of a GM seed trait. Marginal cost is not nil and sensitivities were conducted to illustrate the impact of increasing marginal cost of production. The marginal production cost remains at nil throughout the sensitivities. The marginal cost of GM FRW technology production was varied from \$1 to \$7 to demonstrate its effects on prices, adoption, and farmer and firm surplus.

The increase in marginal production cost increases the license price. As the marginal cost of GM FRW production increases from \$1 to \$7, the license price increases from \$23.95/acre to \$25.48/acre, and the price of the conventional technology increases from \$22.92/lb to \$24.39/lb (Figure 16). Figure 17 shows that as the marginal production cost of the GM FRW technology increases, adoption of GM FRW declines from 28% to 18%, while adoption of the conventional technology increases from 48% to 55%. The change in adoption is a direct result of the increase in the license price of GM FRW variety. Figure 18 illustrates that as the marginal production cost of the GM FRW technology increases, profits for the agbiotech firm as well as surplus for the farmers purchasing the GM FRW decrease while profits for the conventional fungicide producing firm and the farmers purchasing the conventional technology increase. This result coincides with the changes in prices and adoption levels.

Market with Conventional and Roundup Ready® Wheat

Number of RRW agbiotech firms. In the base case, it was assumed that one firm produced the RRW technology and the complementary non-selective glyphosate herbicide, while another firm produced only a competitive generic glyphosate herbicide. An increase in n_I in the conventional plus RRW scenario represents an increase in competition in the production of the glyphosate herbicide.

Monsanto has experienced this sequence of events in that it held patents on both Roundup® herbicide and Roundup Ready® trait technology. As the patent on the Roundup® herbicide expired, agrochemical firms entered the glyphosate herbicide market to compete with Roundup®. For this reason, Monsanto decreased the price of its Roundup® herbicide (Burchett, 2004), but captures more rents by increasing the tech fee on its Roundup Ready® varieties because farmers' willingness-to-pay for the RR trait + glyphosate bundle did not change. This scenario is represented below.

As the number of glyphosate producing firms increases from 2 to 9, the price of glyphosate herbicide decreases from \$6.24/lb to \$1.80/lb and the price of conventional herbicides decreases from \$8.24/lb to \$7.13/lb. Because of the decrease in the price of the glyphosate, the agbiotechnology increases the license price from \$5.08/acre to \$8.00/acre to capture the remaining willingness-to-pay of producers for the RRW + glyphosate herbicide bundle (Figure 19). Figure 20 illustrates that as competition in glyphosate production increases from 2 firms to 9 firms, adoption of the RRW technology increases from 31% to 40% and adoption of the conventional protection decreases from 46% to 40%. This result coincides with Figure 21 in that the surplus to the farmers purchasing the conventional technology decreases while the surplus to the farmers purchasing the RRW technology increases as competition increases. The increased competition results in lower payoffs for both glyphosate and conventional herbicide producing firms, while the agbiotech firm that produces the RRW technology gains profit from the increase in the license price (Figure 22).

Production efficiency of RRW. This sensitivity uses a multiplier on the yield benefit of RRW to simulate a particular variety providing partial or total yield benefit. This sensitivity was conducted to include 10% to 100% of the total RRW yield benefit. As the level of efficiency gained from RRW increases from 10% to 100% of the total RRW yield benefit, the license price of the RRW variety increases from $5.23/acre to $6.24/acre and the price of the glyphosate herbicide increases from $3.57/lb to $5.08/lb, while the price of the conventional herbicide decreases from $8.49/lb to $8.24/lb (Figure23). Figure 24 illustrates that as RRW efficiency increases from 10% to 100%, adoption of RRW increases from 29% to 31%, while adoption of the conventional technology decreases from 47% to 46%. Both types of farmers (conventional purchasing and RRW purchasing) do not experience much change in surplus due to the increase in efficiency of the RRW variety (Figure 25). Figure 26 shows that the glyphosate producing firm's payoff and the agbiotech firm's payoff increase as production efficiency increases. Payoffs to the conventional producing firm decreases slightly over the same interval.

Marginal production cost of glyphosate herbicide. In the base case, the assumption of no marginal production cost of the glyphosate herbicide was used because the value is unknown and for purposes of simplicity and the GM FRW scenario, sensitivities were performed. As the marginal production cost of glyphosate increases from $1 to $7, the price for glyphosate also increases from $6.86/lb to $10.58/lb (Figure 27). This increase in the price of glyphosate causes the license price (tech fee) of the RRW trait technology to decrease from $4.77/acre to $2.92/acre because of the increasing cost of the bundle (RRW trait + glyphosate). As the price of glyphosate increases, so does the price of the conventional herbicide. As a direct result of the increase in the price of the RRW bundle and an indirect result of the increase of marginal production costs, adoption of RRW decreases from 29% to 17% and adoption of conventional technology increases from 47% to 55% (Figure 28). Coinciding with this result, surplus to farmers purchasing the conventional technology increases while surplus to farmers purchasing the RRW technology decreases with an increase in marginal production cost (Figure 29). Also, payoffs to firms involved in the production of the RRW bundle decrease while profits to conventional technology producing firms increase (Figure 30).

Effect of On-Farm Cost Savings. Using a GM wheat variety, farmers realize a certain level of on-farm cost savings. A survey of hard red spring wheat growers in the United States and Canada conducted by Kalaitzandonakes, Suntornpithug, and Phillips (2004) found that farmers in the United States estimate a RRW variety would provide approximately $9.70/acre in direct cost savings over a conventional variety. This cost saving is attributable to reduced labor cost, application cost, management cost, etc. The base case assumed that on-farm cost savings were nil. Including on-farm cost savings in the utility to the farmers has the impact of increasing their willingness-to-pay for the GM trait.

A cost savings parameter was incorporated into the indirect utility function for growers of the RRW variety to determine the impacts on the base case scenario. The indirect utility function for the grower was transformed to include the cost savings parameter such that: $u_1 = \theta x_1 - a_1 p_1 - p_L + cs$, where cs is the on-farm cost savings. This was used to derive the Cournot-Nash equilibrium quantities, which were used to determine equilibrium prices, profits, and surpluses. This sensitivity was compared to simulation 6 in the base case, which represents competition in the conventional herbicide producing industry in the market with conventional and RRW technologies. Results are shown in Table 9.

Table 9. Incorporating Farmer Cost Savings to RRW Scenario

Sim.	*Structure*	p_0	p_1	p_L	*Conv Adopt*	*RRW Adopt*	π_0	π_1	π_B	s_0	s_1	*W*
		------$ acre-------					----------------- $million --------------------					
#6	$n_0 = 2$ $n_1 = 2$	8.24	6.24	5.09	46%	31%	29	14.15	39	58	107	276
CS	$n_0 = 2$ $n_1 = 0$	11.16	15.36	8.63	31%	38%	26	44	93	2	10	202

With non-nil on-farm cost savings, results suggest the agbiotechnology firm and the complementary herbicide producing firm raise prices and accrue an increase in adoption levels because of the increase in willingness-to-pay of the farmer. Adoption of RRW in simulation 6 was 31%, while adoption when cost savings are considered is 38%. The price of the conventional herbicide also increases, which results in lower adoption for the conventional technology. Adoption of the conventional variety was 46% in simulation 6 and 31% in the cost savings simulation. The increase in adoption level of the RRW technology and increase in prices for both the conventional and the RRW technologies result in the agbiotech firm and complementary herbicide producing firm gaining a portion of the surplus from the farmers. As on-farm cost savings move from zero to $9.70, payoffs for the glyphosate producing firm increase from $15 million to $44 million and for the RRW agbiotech firm increase from $39million to $93 million. Over the same interval, surplus of the farmers who purchase the conventional technology decreases from $58 million to $2 million and total surplus to the farmers who adopt the RRW variety decreases from $107 million to $10 million. Finally, as a result of the inclusion of on-farm cost savings, sector welfare decreases from $276 million to $202 million.

These results indicate that as farmers place a higher value on their on-farm cost savings due to RRW trait, the agbiotech firm would increase the price of the royalty (or, tech fee) and the complement. This increase in price of the RRW bundle [RRW trait + complementary glyphosate] allows the agbiotech firm to capture the majority of the rents away from the farmer.

<u>Impacts of Uncertainty</u>. Price levels in each scenario were determined using simulation methods in *@Risk*, which determined a distribution of these values based on the input parameters and random variables. The reported values in each simulation represent the mean value. Figures 31-33 illustrate the cumulative probability distribution of the technology prices from simulations 1, 3, and 5, respectively. The cumulative probability distribution captures the notion of non-discrete results of performed simulations. For example, Figure 31 illustrates that with 50%

certainty the price of the conventional technology is below $17.90/lb and with 95% certainty the price of the conventional technology is below $24.00/lb. The interpretation of Figures 32 and 33 is similar.

Summary

In hard red spring (HRS) wheat, the two GM traits nearest to commercialization are fusarium resistant wheat (FRW) from Syngenta and Roundup Ready® wheat (RRW). Monsanto announced that it has deferred the commercialization of RRW until issues of market acceptance are alleviated. Monsanto acknowledged that it might reconsider its position if another agbiotechnology firm enters the GM wheat market.

Typically, adoption estimates of GM crops examine the cost-benefit of the GM variety compared to the conventional variety. However, release of a GM variety would impact prices of competing pesticides used on the conventional varieties, making the conventional variety less costly than prior to the GM variety. The release of RR soybean in 1996 resulted in a 40-50% decline in price of two leading conventional soybean herbicides in 1997 and 1998. Considering such price decreases results in lower than expected adoption rates for the GM variety. This causes an increase in surplus for those farmers who adopt the GM variety, as well as those who plant the conventional variety. This also poses major strategic questions for agbiotechnology and conventional pesticide firms in their estimates of adoption rates, prices, and profits.

A Cournot quantity competition model was developed to determine the equilibrium quantities of conventional pesticide and agbiotechnology firms. The Cournot model was used because firms that must make production decisions ahead of the selling period, and firms with extensive research and development costs are not able to aggressively set prices. Rather, the conventional and agbiotechnology firms determine Nash equilibrium quantities and then determine a market clearing price for their respective products. The agbiotechnology firm determined a profit maximizing technology fee ($/acre) for its GM trait. The market with conventional wheat only was compared to the market with conventional and GM wheat varieties to determine the price decreases of the conventional pesticide as a result of the GM trait introduction. Changes in farmer surplus, tech firm payoffs, and sector welfare were also analyzed.

This study provides contributions in that it develops a model to predict price changes of current technologies due to the introduction of a new competing technology. The price impact model is applied to a contemporary problem in GM trait development of HRS wheat. Other prospective GM traits in wheat are under development and will face similar price impact issues. The price impact model can also be applied to different GM traits and crops, as well as any problem involving the release of new technology and its effects on the pricing of an incumbent competing technology.

Under the stylized assumption, the results suggest the release of a RR HRS wheat variety would result in a price decrease of 31-35% for conventional herbicides. This price decrease allows farmers with a low willingness-to-pay for the GM variety to realize cost savings in the production of conventional HRS wheat. The surplus of farmers continuing to produce a conventional variety post-introduction of RR HRS wheat, increased by $13-20 million. Assuming market equilibrium quantities of the conventional and RR wheat technologies, adoption rates were determined as 23% for no product adoption, 47% for conventional varieties, and 30% for RR wheat adoption.

Likewise, the release of GM FRW would result in a price decrease of 30-36% for conventional fungicides. Again, this price decrease allows farmers with a low willingness-to-pay for the GM FRW variety to benefit from lower fungicide prices. The surplus to farmers who continued to produce conventional varieties, post-introduction of a GM fusarium resistant HRS wheat variety, increased by $15-20 million. Assuming competition in the conventional fungicide sector and market equilibrium quantities of the conventional and GM technologies, adoption rates were determined to be 23% for no product adoption, 46% for conventional varieties, and 31% for GM FR wheat adoption. Introduction of either the RR or GM FR wheat traits improved welfare for both growers who adopt the new GM variety and those using the conventional variety (due to the price decline), as well as the agbiotechnology firm.

Using the actual number of firms with conventional herbicides labeled for use on HRS wheat in North Dakota (11) and marginal production costs ranging from one to three dollars, introduction of RRW would cause a 20-25% price decrease for conventional herbicides. Similarly, four firms produce conventional fungicides labeled for the suppression of FHB in HRS wheat. This value, combined with per acre marginal production costs ranging from one to three dollars, would more likely cause a 19-22% price decrease for conventional fungicides, post introduction of GM FRW.

As the number of generic glyphosate-producing firms increase, the price of the glyphosate would decrease and the agbiotechnology firm would increase the technology fee for the RRW trait. Because RRW involves a bundle of the trait and the glyphosate herbicide, the decrease in price of the glyphosate allows the agbiotechnology firm to capture remaining willingness-to-pay for the bundle through the technology fee. This results in lower payoffs to conventional herbicide and glyphosate-producing firms, whereas the agbiotechnology firm experiences an increase in payoffs. This is akin to recent announcements by Monsanto that the cost of its RR soybean system will not change; however, it also announced that the price of its Roundup® Original Max herbicide has been lowered by 25-30% (Burchett, 2004). Since the cost of the RR soybean system is unchanged and the cost of the Roundup® Original Max herbicide has decreased, it can be inferred that the technology fee for the RR trait has increased.

Several implications arise from these results. First, adoption of a new GM wheat variety may not be as high as expected due to likely concurrent price decreases of conventional pesticides. The price decrease leads to a lower production cost of conventional varieties, and some farmers who would likely adopt the GM variety, if there were no price decrease, do not adopt because of the lower cost of conventional production. This price decrease must be included in the determination of potential adoption rates by agbiotechnology firms in their pricing decisions. Second, the release of a GM wheat variety results in an increase in surplus for all types of wheat farmers (GM adopters, conventional pesticide adopters, and no technology adopters). GM adopters benefit because of the release of the GM variety. Conventional pesticide adopters benefit due to the price decreases of the conventional pesticides. Farmers who did not adopt any technology prior to the release of GM wheat may adopt the conventional pesticide because of the lower cost. Third, the release of a GM wheat variety would result in slightly lower payoffs for conventional pesticide producing firms but higher payoffs for agbiotechnology firms. Overall, surplus to farmers and conventional and agbiotechnology firms increases due to the release of a GM wheat variety.

The results of this study provide important policy contributions, in that all producers of hard red spring wheat benefit from the introduction of a GM wheat variety because of price decreases of the conventional pesticides. Thus, agbiotechnology firms are not the only entities to benefit from GM wheat introduction. This is an important issue to convey when addressing market acceptance concerns.

References

Besanko, D., Dranove, D., Shanley, M., and Schaefer, S. (2004). *Economics of Strategy* (3rd ed.). Hoboken, NJ: John Wiley and Sons, Inc.

Blackshaw, R. E., and Harker, K. N. (2002). Selective weed control with glyphosate in glyphosate-resistant wheat (triticum aestivum). *Weed Technology, 16,* 885-892.

Burchett, A. (2004, October). Monsanto slashes Roundup® Original price. *Farm Journal, 128,* Special Features Page.

Carpenter, J., and Gianessi, L. (2003). Trends in pesticide use since the introduction of genetically engineered crops. In N. Kalaitzandonakes (Ed.), *The Economic and Environmental Impacts of Agbiotech* (pp. 43-62). New York: Kluwer.

Fernandez-Cornejo, J., and Hendricks, C. (2003, July 27-30). *Off-farm Work and the Economic Impact of Adopting Herbicide-Tolerant Soybeans*. Paper presented at the meeting of the American Agricultural Economics Association, Montreal, Canada.

Fulton, M., and Giannakas, K. (2001). Agricultural biotechnology and industry structure. *AgBioForum*, *4*(2), 137-151.

Gianessi, L. P., and Carpenter, J. E. (2000, April). *Agricultural Biotechnology: Benefits of Transgenic Soybeans*. Washington, DC: National Center for Food and Agricultural Policy.

Kalaitzandonakes, N., Suntornpithug, P., and Phillips, P. W.B. (2004, July 8-11). *Roundup Ready® WheatIn Canada and the US: A Survey and Analysis ff Potential Farmer Adoption*. Paper presented at the meeting of the 8th ICABR International Conference on Agbiotechnology: International Trade and Domestic Production, Ravello, Italy.

Lapan, H. E., and Moschini, G. (2000). Incomplete adoption of a superior innovation. *Economica, 67,* 525-542.

Lemarie, S., and Marette, S. (2003). Substitution and complementarities in the biotechnology and pesticide markets: A theoretical framework. In N. Kalaitzandonakes (Ed.), *The Economic and Environmental Impacts of Agbiotech* (pp. 287-306). New York: Kluwer.

McDougall, J., and Phillips, M. (2003). The impact of agricultural biotechnology on the conventional agrochemical market. In N. Kalaitzandonakes (Ed.), *The Economic and Environmental Impacts of Agbiotech* (pp. 19-41). New York: Kluwer.

McMullen, M. P., and Bradley, C. A. (2004, January). *2004 Field Crop Fungicide Guide* (PP-622). Fargo: North Dakota State University Extension Service.

McMullen, M. P., and Stack, R. W. (1999, December). *Fusarium Head Blight (Scab) of Small Grains* (Small Grains Publication PP804). Fargo: North Dakota State University Extension Service.

Monsanto. (2004, May 10). *Monsanto to Realign Research Portfolio, Development of Roundup Ready® Wheat Deferred*. Retrieved June 4, 2004, from http://www.monsanto.com/monsanto/layout/media/04/05-10-04.asp

Mussa, M., and Rosen, S. (1978). Monopoly and product quality. *Journal of Economic Theory, 18,* 301-317.

Nadolnyak, D. A., and Sheldon, I. M. (2001, August 5-8). *Simulating the Effects of Adoption of Genetically Modified Soybeans in the U.S.* Paper presented at the annual meeting of the American Agricultural Economics Association, Chicago.

Nganje, W. E., Johnson, D. D., Wilson, W. W., Leistritz, F. L., Bangsund, D. A., and Tiapo, N. M. (2001, October). *Economic Impacts of Fusarium Head Blight in Wheat and Barley: 1998-2000* (Agribusiness and Applied Economics Report No. 464). Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Palisade Corporation. (2000). *@Risk* 4.0 – Student Version. Software. New York.

Pates, M. (2004, May 17). Area farmers to launch pro-biotech effort. *Agweek,* pp. 26-27.

Pratt, S. (2004, May 13). Monsanto shelves GM wheat. *The Western Producer,* p. 1.

Qaim, M., and de Janvry, A. (2002, July 28-31). *Bt Cotton in Argentina: Analyzing Adoption and Farmers' Willingness to Pay*. Paper presented at the annual meeting of the American Agricultural Economics Association, Long Beach, CA.

Symeonidis, G. (2003). Comparing Bertrand and Cournot equilibria in a differentiated duopoly with product R and D. *International Journal of Industrial Organization, 21,* 39-55.

Syngenta. (2004). *Tomorrow's Products by Syngenta*. Retrieved March 24, 2004, from http://www.syngenta.com/en/products_services/tomprod.aspx

United States Department of Agriculture Animal and Plant Health Inspection Service. (n.d.). *Information System for Biotech (ISB)*. Retrieved June 3, 2004, from http://www.nbiap.vt.edu

United States Department of Agriculture National Agricultural Statistics Service. (2004). *Quick Stats:* A*gricultural Statistics Data Base*. Retrieved October 18, 2004, from http://www.nass.usda.gov/QuickStats

Wilson, W. W., Janzen, E. L., Dahl, B. L., and Wachenheim, C. J. (2003, January). *Issues in Development and Adoption of Genetically Modified (GM) Wheats* (Agribusiness and Applied Economics Report No. 509). Fargo: North Dakota State University, Department of Agribusiness and Applied Economics.

Winston, W. L. (2001). *Simulation modeling using @RISK: Updated for Version 4.* Pacific Grove, CA: Duxbury.

Zollinger, R. K. (2004, January). *2004 North Dakota Weed Control Guide* (W-253). Fargo: North Dakota State University Extension Service.

Appendix A: Resolution of Cournot-Nash Equilibria

The complete mathematical derivation of the equilibrium are derived in this appendix.

Market Equilibrium with One Product

A farmer indifferent between buying the conventional product and buying nothing is identified by the preference parameter $\hat{\theta}$. This implies that $u_0 = \hat{\theta}x_0 - a_0 p_0 = 0$, and therefore:

$$\hat{\theta} = \frac{a_0 p_0}{x_0} \tag{A.1}$$

The demand function, $Q_0(p_0) = Na_0(1-\hat{\theta})$, can be rewritten as:

$$Q_0 = Na_0\left(1 - \frac{a_0 p_0}{x_0}\right) \tag{A.2}$$

and the inverse demand function can then be given by:

$$p_0(Q_0) = \frac{x_0}{Na_0^2}(Na_0 - Q_0) \tag{A.3}$$

The profit function for seller *k*, $\pi_{0k} = (p_0(Q_0) - c_0)q_{0k}$, is written as:

$$\pi_{0k} = \left(\frac{x_0}{Na_0^2}(Na_0 - Q_0) - c_0\right)q_{0k} \tag{A.4}$$

Q_0 can be expressed as:

$$Q_0 = q_{0k} + \sum_{j=1}^{n_0-1} q_{0j} \tag{A.5}$$

with q_{0k} being the quantity of seller *k* and q_{0j} being the quantity of seller *j*, for all $j = 1,2,3,...,(n_0 - 1)$. The profit function is rewritten:

$$\pi_{0k} = \left(\frac{x_0}{Na_0^2}\left(Na_0 - q_{0k} - \sum_{j=1}^{n_0-1} q_{0j}\right) - c_0\right)q_{0k} \tag{A.6}$$

To determine the profit maximizing level of q_{0k}, the first-order condition is:

$$\frac{\partial \pi_{0k}}{\partial q_{0k}} = \frac{x_0}{Na_0^2}\left(Na_0 - 2q_{0k} - \sum_{j=1}^{n_0-1} q_{0j} \right) - c_0 = 0 \tag{A.7}$$

Solving for q_{0k} then gives:

$$q_{0k}^* = \frac{1}{2}\left[\left(Na_0 - \frac{Na_0^2 c_0}{x_0}\right) - \sum_{j=1}^{n_0-1} q_{0j}\right] \tag{A.8}$$

and under a symmetric Cournot-Nash equilibrium, all sellers adopt the same strategy. So here, $q_{ok} = q_{0j}$ for any *j* and then q_{0k}^* becomes:

$$q_{0k}^* = \frac{1}{2}\left[\left(Na_0 - \frac{Na_0^2 c_0}{x_0}\right) - (n_0 - 1)q_{0k}^*\right] \tag{A.9}$$

Since all sellers adopt the same strategy, simplifying this expression will yield the equilibrium quantity for each seller:

$$q_0^* = \frac{Na_0(x_0 - a_0 c_0)}{x_0(n_0 + 1)} \tag{A.10}$$

The optimal market equilibrium total quantity is then $Q_0 = q_0^* n_0$ or:

$$Q_0^* = \frac{Na_0(x_0 - a_0 c_0)n_0}{x_0(n_0 + 1)} \tag{A.11}$$

This total quantity can then be substituted into the inverse demand function:

$$p_0(Q_0) = \frac{x_0}{Na_0^2}\left(Na_0 - \frac{Na_0(x_0 - a_0 c_0)n_0}{x_0(n_0 + 1)}\right) \tag{A.12}$$

and simplifying this expression gives the equilibrium market price:

$$p_0^*(Q_0) = \frac{x_0 + a_0 c_0 n_0}{a_0(n_0 + 1)} \tag{A.13}$$

With $p_0^*(Q_0)$ and q_0^*, the optimal firm profit can be written as:

$$\pi_0^* = \left(\frac{x_0 + n_0 a_0 c_0}{a_0(n_0 + 1)} - c_0 \right) \cdot \frac{Na_0(x_0 - a_0 c_0)}{x_0(n_0 + 1)} \tag{A.14}$$

Simplifying this expression gives:

$$\pi_0^* = \frac{N}{x_0}\left(\frac{x_0 - a_0 c_0}{n_0 + 1}\right)^2 \tag{A.15}$$

The farmers' surplus from indirect utility is:

$$s_0^* = N\int_{\hat{\theta}^*}^{1} u_0 \cdot d\theta = N\int_{\hat{\theta}^*}^{1} \theta x_0 - a_0 p_0 \cdot d\theta \tag{A.16}$$

Substitution p_0^* for p_0 gives:

$$s_0^* = N\int_{\hat{\theta}^*}^{1} \theta x_0 - a_0\left(\frac{x_0 + n_0 a_0 c_0}{a_0(n_0 + 1)}\right) \cdot d\theta \tag{A.17}$$

Integrating the expression gives:

$$s_0^* = N\left(\frac{\theta^2 x_0}{2} - \frac{\theta(x_0 + n_0 a_0 c_0)}{n_0 + 1}\Bigg|_{\hat{\theta}^*}^{1}\right), \tag{A.18}$$

$$s_0^* = N\left(\frac{x_0}{2} - \frac{(x_0 + n_0 a_0 c_0)}{n_0 + 1} - \frac{\hat{\theta}^{*2} x_0}{2} + \frac{\hat{\theta}^*(x_0 + n_0 a_0 c_0)}{n_0 + 1}\right) \tag{A.19}$$

Total welfare of the sellers and the farmers can then be defined by:

$$W = n_0 \pi_0^* + s_0^* \tag{A.20}$$

Detailed Resolution of Market Equilibrium with Two Products

Because $\tilde{\theta}$ refers to a farmer who is indifferent between the type *0* and the type *1* products, it is implied that for this farmer, $u_0 = u_1$. From this equality, $\tilde{\theta}$ can be determined:

$$\tilde{\theta} x_0 - a_0 p_0 = \tilde{\theta} x_1 - a_1 p_1 - p_L, \tag{A.21}$$

$$\tilde{\theta} = \frac{a_1 p_1 + p_L - a_0 p_0}{x_1 - x_0} \tag{A.22}$$

Recall the demand functions for product type *0* and product type *1*:

$$\begin{cases} Q_0 = Na_0\left(\tilde{\theta} - \hat{\theta}\right) \\ Q_1 = Na_1\left(1 - \tilde{\theta}\right) \end{cases} \tag{A.23}$$

Substituting the derived expressions for $\hat{\theta}$ and $\tilde{\theta}$ into the demand functions and assuming a given level of p_L gives:

$$\begin{cases} Q_0\left(p_0, p_1, p_L\right) = Na_0\left(\dfrac{a_1 p_1 + p_L - a_0 p_0}{x_1 - x_0} - \dfrac{a_0 p_0}{x_0}\right) \\ Q_1\left(p_0, p_1, p_L\right) = Na_1\left(1 - \dfrac{a_1 p_1 + p_L - a_0 p_0}{x_1 - x_0}\right) \end{cases} \tag{A.24}$$

To determine the inverse demand functions, both demand functions can be solved a price. Those two price functions can be set equal to each other and then solved for the other price. For example, solve for p_0 from both demand functions. Then solve for p_1 from $p_0^0 = p_0^1$. Solving $Q_0\left(p_0, p_1, p_L\right)$ for p_0 gives:

$$p_0^0 = \frac{x_0}{a_0}\left(\frac{Na_0 a_1 p_1 + Na_0 p_L - Q_0 x_1 + Q_0 x_0}{Na_0 x_1}\right) \tag{A.25}$$

Solving $Q_1\left(p_0, p_1, p_L\right)$ is then:

$$p_0^1 = -\left[\frac{Na_1 x_1 - Na_1 x_0 - Na_1^2 p_1 - Na_1 p_L - Q_1 x_1 + Q_1 x_0}{Na_0 a_1}\right] \tag{A.26}$$

Equating p_0^0 and p_0^1 and solving for $p_1\left(Q_0, Q_1, p_L\right)$ yields:

$$p_1\left(Q_0, Q_1, p_L\right) = -\left[\frac{Na_0 a_1 p_1 + a_1 Q_0 x_0 - Na_0 a_1 x_1 + a_0 Q_1 x_1}{Na_0 a_1^2}\right] \tag{A.27}$$

Simplifying and rearranging this expression, $p_1\left(Q_0, Q_1, p_L\right)$ is then given by:

$$p_1\left(Q_0, Q_1, p_L\right) = \frac{x_1}{a_1}\left(1 - \frac{Q_0}{Na_0} \cdot \frac{x_0}{x_1} - \frac{Q_1}{Na_1}\right) - p_L \tag{A.28}$$

Similar derivation from the demand functions using p_1^0 and p_1^1 to determine $p_0\left(Q_0, Q_1, p_L\right)$ yields:

$$p_0(Q_0,Q_1,p_L)=\frac{x_0}{a_0}\left(1-\frac{Q_0}{Na_0}-\frac{Q_1}{Na_1}\right) \tag{A.29}$$

Using $p_0(Q_0,Q_1,p_L)$ in the profit function for seller *k* of product type *0* displays:

$$\pi_{0k}=\frac{x_0}{a_0}\left(1-\frac{\left(q_{0k}+\sum_{j=1}^{n_0-1}q_{0j}\right)}{Na_0}-\frac{n_1q_1}{Na_1}\right)q_{0k}-c_0q_{0k} \tag{A.30}$$

Recall, since all firms adopt same strategy, $Q_1=q_1n_1$. Taking the partial derivative of π_{0k} with respect to q_{0k} to determine the profit maximizing level of q_{0k} is given by:

$$\frac{\partial\pi_{0k}}{\partial q_{0k}}=\frac{x_0}{a_0}\left(1-\frac{\left(q_{0k}+\sum_{j=1}^{n_0-1}q_{0j}\right)}{Na_0}-\frac{n_1q_1}{Na_1}\right)-\frac{x_0q_{ok}}{Na_0^2}-c_0=0 \tag{A.31}$$

Recalling that under a symmetric Cournot-Nash equilibrium, $q_{ok}=q_{0j}$ for any *j*, $j=1,2,3,\ldots,(n_0-1)$, the first-order condition for profit maximization by the n_0 sellers is then simplified to:

$$\frac{\partial\pi_{0k}}{\partial q_{0k}}=\frac{x_0}{a_0}\left(1-\frac{q_{0k}(n_0+1)}{Na_0}-\frac{n_1q_1}{Na_1}\right)-c_0=0 \tag{A.32}$$

Using $p_1(Q_0,Q_1,p_L)$ in the profit function for seller *r* of product type *1* displays:

$$\pi_{1r}=\left[\frac{x_1}{a_1}\left(1-\frac{n_0q_0}{Na_0}\cdot\frac{x_0}{x_1}-\frac{\left(q_{1r}+\sum_{s=1}^{n_1-1}q_{1s}\right)}{Na_1}\right)-p_L\right]q_{1r}-c_1q_{1r} \tag{A.33}$$

Recall, since all firms adopt same strategy, $Q_0=q_0n_0$. Taking the partial derivative of π_{1r} with respect to q_{1r} to determine the profit maximizing level of q_{1r} is given by:

$$\frac{\partial \pi_{1r}}{\partial q_{1r}} = \frac{x_1}{a_1}\left(1 - \frac{n_0 q_0}{Na_0}\cdot\frac{x_0}{x_1} - \frac{\left(q_{1r} + \sum_{s=1}^{n_1-1} q_{1s}\right)}{Na_1}\right) - p_L - \frac{x_1 q_{1r}}{Na_1^2} - c_1 = 0 \qquad \text{(A.34)}$$

Recalling that under a symmetric Cournot-Nash equilibrium, $q_{1r} = q_{1s}$ for any *s*, $s = 1,2,3,\ldots,(n_1 - 1)$, the first-order condition for profit maximization by the n_1 sellers is then simplified to:

$$\frac{\partial \pi_{1r}}{\partial q_{1r}} = \frac{x_1}{a_1}\left(1 - \frac{n_0 q_0}{Na_0}\cdot\frac{x_0}{x_1} - \frac{q_{1r}(n_1+1)}{Na_1}\right) - p_L - c_0 = 0 \qquad \text{(A.35)}$$

Simultaneously solving the two first-order conditions:

$$\frac{\partial \pi_{0k}}{\partial q_{0k}} = \frac{x_0}{a_0}\left(1 - \frac{q_{0k}(n_0+1)}{Na_0} - \frac{n_1 q_1}{Na_1}\right) - c_0 = 0 \text{, and} \qquad \text{(A.36)}$$

$$\frac{\partial \pi_{1r}}{\partial q_{1r}} = \frac{x_1}{a_1}\left(1 - \frac{n_0 q_0}{Na_0}\cdot\frac{x_0}{x_1} - \frac{q_{1r}(n_1+1)}{Na_1}\right) - p_L - c_0 = 0, \qquad \text{(A.37)}$$

the Cournot-Nash equilibrium quantities are:

$$\begin{cases} q_0^*(p_L) = -Na_0 \cdot \dfrac{-a_0c_0x_1 + x_0x_1 + a_1c_1x_0n_1 + a_1p_Lx_0n_1 - a_0c_0x_1n_1}{x_0(-x_1 - x_1n_0 - x_1n_1 + x_0n_0n_1 - x_1n_0n_1)} \\ q_1^*(p_L) = -Na_1 \cdot \dfrac{-a_1c_1 - a_1p_L + x_1 + a_0c_0n_0 - a_1c_1n_0 - a_1p_Ln_0 - x_0n_0 + x_1n_0}{-x_1 - x_1n_0 - x_1n_1 + x_0n_0n_1 - x_1n_0n_1} \end{cases} \qquad \text{(A.38)}$$

Now, $Q_0^* = q_0^* n_0$ and $Q_1^* = q_1^* n_1$. Substituting Q_0^* and Q_1^* into the inverse demand functions and solving for p_0^* and p_1^* gives:

$$\begin{cases} p_0^*(p_L) = \dfrac{a_0c_0x_1n_0(n_1+1) + x_0(x_1 + (a_1c_1 + a_1p_L - a_0c_0n_0)n_1)}{a_0(-x_0n_0n_1 + x_1(n_0+1)(n_1+1))} \\ p_1^*(p_L) = \dfrac{x_1(x_1 + a_0c_0n_0 - x_0n_0 + x_1n_0) - a_1(p_Lx_1(n_0+1) - c_1(x_1 - x_0n_0 + x_1n_0)n_1)}{a_1(-x_0n_0n_1 + x_1(n_0+1)(n_1+1))} \end{cases} \qquad \text{(A.39)}$$

Substituting p_0^* and q_0^* into the profit function for the seller of product type *0* will give the resulting equilibrium profit level for that firm:

$$\pi_0^*(p_L)=\frac{N(a_0c_0x_1(n_1+1)-x_0(x_1+a_1(c_1+p_L)n_1))^2}{x_0(x_0n_0n_1-x_1(n_0+1)(n_1+1))^2} \quad (A.40)$$

Likewise, the equilibrium optimal profit for a seller of product type *1* can be determined by substituting p_1^* and q_1^* into the profit function and simplifying:

$$\pi_1^*(p_L)=\frac{Nx_1(x_1+a_0c_0n_0-x_0n_0+x_1n_0-a_1(c_1+p_L)(n_0+1))^2}{(x_0n_0n_1-x_1(n_0+1)(n_1+1))^2} \quad (A.41)$$

The profit function for the biotechnology seller is $\pi_B=n_1q_1^*(p_L)p_L+\pi_1^*(p_L)$. Profit maximization for the biotechnology seller with respect to p_L gives the equilibrium license price p_L^*:

$$p_L^*=\frac{(x_1+a_0c_0n_0-x_0n_0+x_1n_0-a_1c_1(n_0+1))(-x_0n_0n_1^2+x_1(n_0+1)(-2+n_1+n_1^2))}{2a_1(n_0+1)(-x_0n_0n_1^2+x_1(n_0+1)(-1+n_1+n_1^2))} \quad (A.42)$$

Then, using the equilibrium license price p_L^*, the surplus of the farmers purchasing type *0* and type *1* product are defined as follows:

$$\begin{cases} s_0^*=N\int_{\hat{\theta}^*}^{\tilde{\theta}^*}u_0d\theta \\ s_1^*=N\int_{\tilde{\theta}^*}^{1}u_1d\theta \end{cases} \quad (A.43)$$

where $u_0=\theta x_0-a_0p_0^*$ and $u_1=\theta x_1-a_1(p_1^*+p_L^*)$. Integrating s_0^* gives the following expression:

$$s_0^*=N\left(\begin{array}{l} -\dfrac{\hat{\theta}^{*2}x_0}{2}+\dfrac{\tilde{\theta}^{*2}x_0}{2}+\dfrac{\hat{\theta}^*\begin{pmatrix}-x_0x_1-a_0c_0x_1n_0-a_1c_1x_0n_1-a_1p_Lx_0n_1\\+a_0c_0x_0n_0n_1-a_0c_0x_1n_0n_1\end{pmatrix}}{-x_1-x_1n_0-x_1n_1+x_0n_0n_1-x_1n_0n_1} \\ -\dfrac{\tilde{\theta}^*(-x_0x_1-a_0c_0x_1n_0-a_1c_1x_0n_1-a_1p_Lx_0n_1+a_0c_0x_0n_0n_1-a_0c_0x_1n_0n_1)}{-x_1-x_1n_0-x_1n_1+x_0n_0n_1-x_1n_0n_1} \end{array}\right) \quad (A.44)$$

The expression for s_1^* is much more complex. Integrating s_1^* gives:

$$s_1^* = N \cdot \frac{\left(\left(\tilde{\theta}^* - 1\right) \left(\begin{array}{l} \left(a_0 c_0 - x_0\right) x_0^2 n_0^3 n_1^3 - x_0 x_1 n_0^2 \left(n_0 + 1\right) n_1 \left(\begin{array}{l} -2a_0 c_0 + 2x_0 + 4a_0 c_0 n_1 \\ -4x_0 n_1 + 2a_0 c_0 n_1^2 - 2x_0 n_1^2 \\ +\tilde{\theta}^* x_0 n_1^2 \end{array} \right) \\ -x_1^3 \left(n_0 + 1\right)^3 \left(\begin{array}{l} 3 - \tilde{\theta}^* - n_1 - 2n_1^2 \\ +2\tilde{\theta}^* n_1^2 + \tilde{\theta}^* n_1^3 \end{array} \right) \\ +x_1^2 n_0 \left(n_0 + 1\right)^2 \left(\begin{array}{l} -4a_0 c_0 + 4x_0 + a_0 c_0 n_1 - \tilde{\theta}^* x_0 n_1 + \\ 4a_0 c_0 n_1^2 - 6x_0 n_1^2 + 2\tilde{\theta}^* x_0 n_1^2 + a_0 c_0 n_1^3 - \\ x_0 n_1^3 + 2\tilde{\theta}^* x_0 n_1^3 \end{array} \right) \\ +a_1 \left(n_0 + 1\right) \left(\begin{array}{l} -2p_L x_1 \left(n_0 + 1\right) \left(\begin{array}{l} -x_1 - x_1 n_0 + x_1 n_1 + x_1 n_0 n_1 + x_1 n_1^2 \\ -x_0 n_0 n_1^2 + x_1 n_0 n_1^2 \end{array} \right) \\ +c_1 \left(\begin{array}{l} 2x_1^2 + 4x_1^2 n_0 + 2x_1^2 n_0^2 - x_1^2 n_1 - 2x_1^2 n_0 n_1 \\ -x_1^2 n_0^2 n_1 + x_1^2 n_1^3 - 2x_0 x_1 n_0 n_1^3 + 2x_1^2 n_0 n_1^3 \\ +x_0^2 n_0^2 n_1^3 - 2x_0 x_1 n_0^2 n_1^3 + x_1^2 n_0^2 n_1^3 \end{array} \right) \end{array} \right) \end{array} \right) \right)}{\left(2\left(n_0 + 1\right)\left(-x_1 - x_1 n_0 + x_1 n_1 + x_1 n_0 n_1 + x_1 n_1^2 - x_0 n_0 n_1^2 + x_1 n_0 n_1^2\right) \left(\begin{array}{l} -x_0 n_0 n_1 + \\ x_1 \left(n_0 + 1\right)\left(n_1 + 1\right) \end{array} \right) \right)} \quad \text{(A.45)}$$

Since it is assumed that one of the n_1 firms is a biotech firm, total welfare is defined by:

$$W = n_0 \pi_0^* + \left(n_1 - 1\right)\pi_1^* + \pi_B^* + s_0^* + s_1^* \quad \text{(A.46)}$$

Two Products: No Complementary Pesticide Needed with GM Seed

Seed that has been genetically modified to express insect resistance or disease resistance does not require a complementary pesticide to complete the protection bundle. The GM seed is a sufficient protection solution. In this case, no product type *1* is necessary and therefore the n_1 firm(s) are all biotech sellers of GM seed. A farmer purchasing product *1* in this case will pay only the license price p_L rather than the license price plus the price of the complementary pesticide $\left(p_L + p_1\right)$. In this case:

$$\begin{cases} u_0 = \theta x_0 - a_0 p_0 \\ u_1 = \theta x_1 - p_L \end{cases} \quad \text{(A.47)}$$

The procedure for solving for this Cournot-Nash equilibrium is identical to the two product case with complementary herbicides except that p_L can now be treated as p_1. Now:

$$\tilde{\theta} = \frac{p_L - a_0 p_0}{x_1 - x_0}, \tag{A.48}$$

$$\begin{cases} Q_0(p_0, p_L) = Na_0\left(\dfrac{p_L - a_0 p_0}{x_1 - x_0} - \dfrac{a_0 p_0}{x_0}\right) \\ Q_1(p_0, p_L) = Na_1\left(1 - \dfrac{p_L - a_0 p_0}{x_1 - x_0}\right) \end{cases}, \tag{A.49}$$

$$\begin{cases} p_0(Q_0, Q_1) = \dfrac{x_0}{a_0}\left(1 - \dfrac{Q_0}{Na_0} - \dfrac{Q_1}{N}\right) \\ p_L(Q_0, Q_1) = x_1\left(1 - \dfrac{Q_0}{Na_0} \cdot \dfrac{x_0}{x_1} - \dfrac{Q_1}{N}\right) \end{cases}, \tag{A.50}$$

$$\pi_{0k} = \frac{x_0}{a_0}\left(1 - \frac{\left(q_{0k} + \sum_{j=1}^{n_0 - 1} q_{0j}\right)}{Na_0} - \frac{n_1 q_1}{N}\right) q_{0k} - c_0 q_{0k}\text{, and} \tag{A.51}$$

$$\pi_{Br} = \frac{x_1}{a_1}\left(1 - \frac{n_0 q_0}{Na_0} \cdot \frac{x_0}{x_1} - \frac{\left(q_{1r} + \sum_{s=1}^{n_1 - 1} q_{1s}\right)}{N}\right) q_{1r} - c_1 q_{1r} \tag{A.52}$$

Like in the previous case with two products, the firms choose quantity to maximize profit in the symmetric Cournot-Nash equilibrium. The first-order conditions then are:

$$\frac{\partial \pi_{0k}}{\partial q_{0k}} = \frac{x_0}{a_0}\left(1 - \frac{q_{0k}(n_0 + 1)}{Na_0} - \frac{n_1 q_1}{N}\right) - c_0 = 0\text{, and} \tag{A.53}$$

$$\frac{\partial \pi_{Br}}{\partial q_{1r}} = \frac{x_1}{a_1}\left(1 - \frac{n_0 q_0}{Na_0} \cdot \frac{x_0}{x_1} - \frac{q_{1r}(n_1 + 1)}{N}\right) - c_0 = 0 \tag{A.54}$$

Simultaneously solving the first-order conditions for equilibrium quantities is then given by:

$$q_0^* = \frac{Na_0\left(a_0c_0x_1\left(n_1+1\right)-x_0\left(x_1+c_1n_1\right)\right)}{x_0\left(x_0n_0n_1-x_1\left(n_0+1\right)\left(n_1+1\right)\right)}, \text{ and} \tag{A.55}$$

$$q_1^* = -\frac{Na_1\left(-x_1-a_0c_0n_0+x_0n_0-x_1n_0+c_1\left(n_0+1\right)\right)}{-x_0n_0n_1+x_1\left(n_0+1\right)\left(n_1+1\right)} \tag{A.56}$$

Again, recall that $Q_0^* = q_0^*n_0$ and $Q_1^* = q_1^*n_1$. Substituting Q_0^* and Q_1^* into the inverse demand functions and solving for p_0^* and p_L^* gives:

$$p_0^* = \frac{a_0c_0x_1n_0\left(n_1+1\right)+x_0\left(x_1+c_1n_1-a_0c_0n_0n_1\right)}{a_0\left(-x_0n_0n_1+x_1\left(n_0+1\right)\left(n_1+1\right)\right)}, \text{ and} \tag{A.57}$$

$$p_L^* = \frac{x_1^2\left(n_0+1\right)-c_1x_0n_0n_1+x_1\left(a_0c_0n_0-x_0n_0+c_1n_1+c_1n_0n_1\right)}{\left(-x_0n_0n_1+x_1\left(n_0+1\right)\left(n_1+1\right)\right)} \tag{A.58}$$

Substituting p_0^* and q_0^* into π_0 gives:

$$\pi_0^* = \frac{N\left(a_0c_0x_1\left(n_1+1\right)-x_0\left(x_1+c_1n_1\right)\right)^2}{x_0\left(x_0n_0n_1-x_1\left(n_0+1\right)\left(n_1+1\right)\right)^2} \tag{A.59}$$

Substituting p_L^* and q_1^* into π_B gives:

$$\pi_B^* = \frac{Nx_1n_1\left(x_1+a_0c_0n_0-x_0n_0+x_1n_0-c_1\left(n_0+1\right)\right)^2}{\left(x_0n_0n_1-x_1\left(n_0+1\right)\left(n_1+1\right)\right)^2} \tag{A.60}$$

The surplus of farmers purchasing type *0* and type *1* product are defined as in the two product (RRW) case:

$$\begin{cases} s_0^* = N\int_{\hat{\theta}^*}^{\tilde{\theta}^*} u_0 d\theta \\ s_1^* = N\int_{\tilde{\theta}^*}^{1} u_1 d\theta \end{cases}, \tag{A.61}$$

but now, $u_0 = \theta x_0 - a_0 p_0^*$ and $u_1 = \theta x_1 - a_1 p_L^*$. Substituting the equilibrium prices into the indirect utility functions and integrating, the farmers' surplus is given by the following expressions:

$$s_0^* = N\left(\begin{array}{l} -\frac{\hat{\theta}^{*2} x_0}{2} + \frac{\tilde{\theta}^{*2} x_0}{2} + \frac{\hat{\theta}^{*}\left(-x_0 x_1 - a_0 c_0 x_1 n_0 - c_1 x_0 n_1 + a_0 c_0 x_0 n_0 n_1 - a_0 c_0 x_1 n_0 n_1\right)}{-x_1 - x_1 n_0 - x_1 n_1 + x_0 n_0 n_1 - x_1 n_0 n_1} \\ -\frac{\tilde{\theta}^{*}\left(-x_0 x_1 - a_0 c_0 x_1 n_0 - c_1 x_0 n_1 + a_0 c_0 x_0 n_0 n_1 - a_0 c_0 x_1 n_0 n_1\right)}{-x_1 - x_1 n_0 - x_1 n_1 + x_0 n_0 n_1 - x_1 n_0 n_1} \end{array} \right) \quad \text{(A.62)}$$

$$s_1^* = N\left(\begin{array}{l} \frac{x_1}{2} - \frac{\tilde{\theta}^{*2} x_1}{2} - \frac{x_1^2 + a_0 c_0 x_1 n_0 - x_0 x_1 n_0 + x_1^2 n_0 + c_1 x_1 n_1 - c_1 x_0 n_0 n_1 + c_1 x_1 n_0 n_1}{x_1 + x_1 n_0 + x_1 n_1 - x_0 n_0 n_1 + x_1 n_0 n_1} \\ + \frac{\tilde{\theta}^{*}\left(x_1^2 + a_0 c_0 x_1 n_0 - x_0 x_1 n_0 + x_1^2 n_0 + c_1 x_1 n_1 - c_1 x_0 n_0 n_1 + c_1 x_1 n_0 n_1\right)}{x_1 + x_1 n_0 + x_1 n_1 - x_0 n_0 n_1 + x_1 n_0 n_1} \end{array} \right) \quad \text{(A.63)}$$

Total welfare is then defined as $W = n_0 \pi_0^* + \pi_B^* + s_0^* + s_1^*$.

APPENDIX B

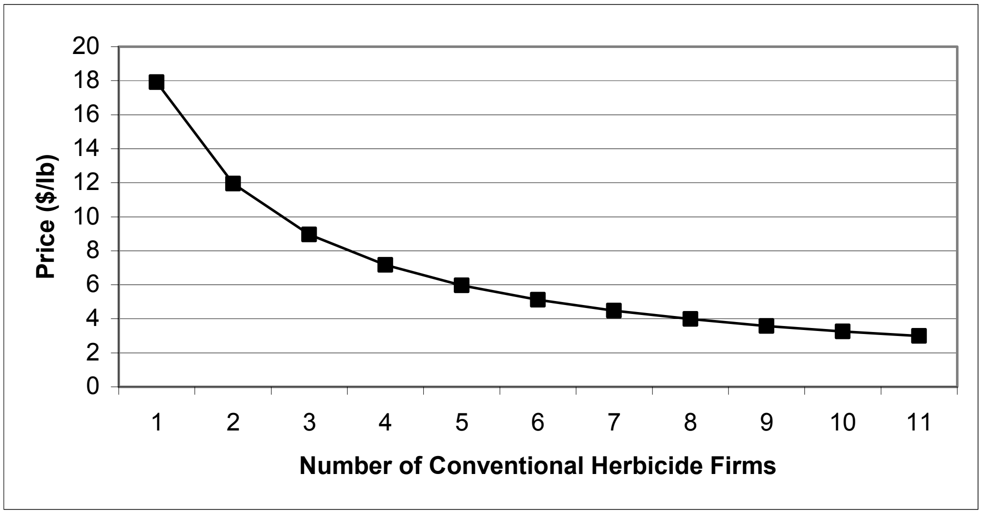

Figure 6. Impact of Conventional Herbicide Producing Firms on Herbicide Price

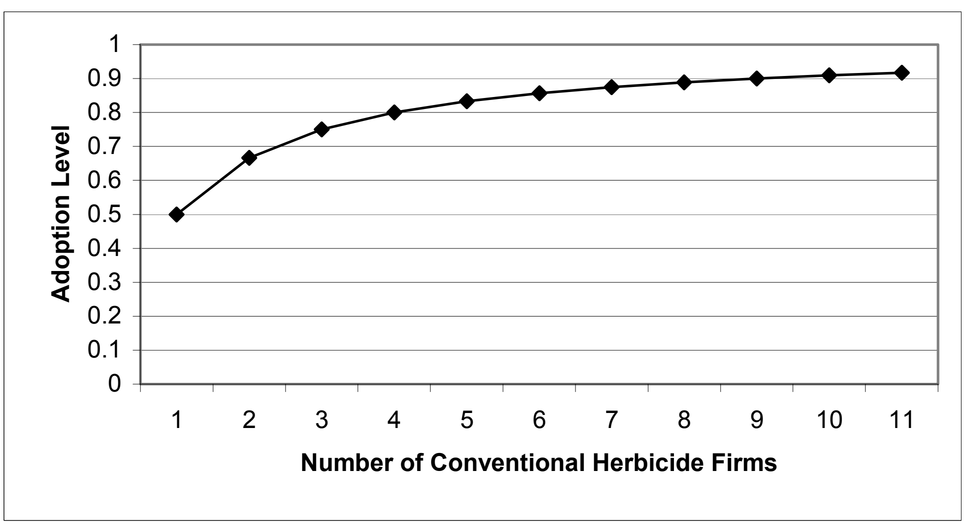

Figure 7. Impact of Conventional Herbicide Producing Firms on Conventional Adoption Levels.

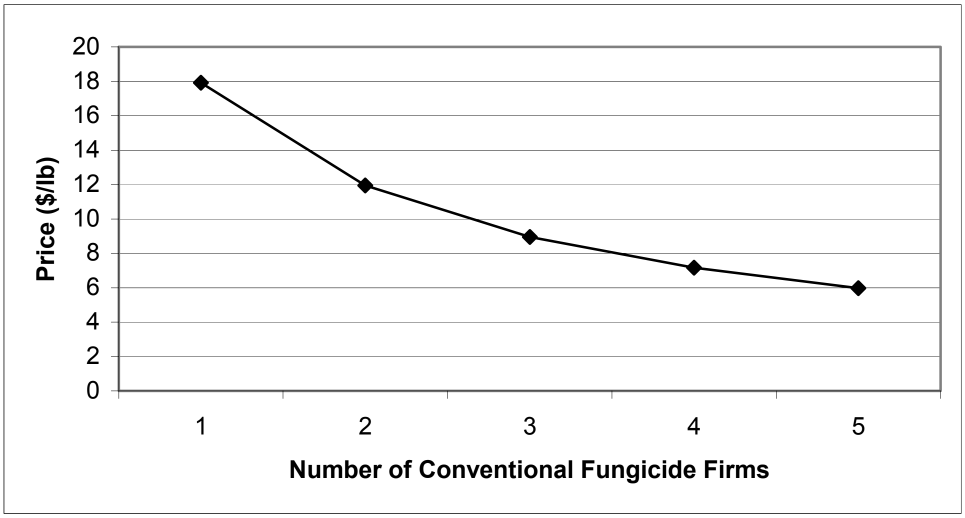

Figure 8. Impact of Conventional Fungicide Producing Firms on Fungicide Price.

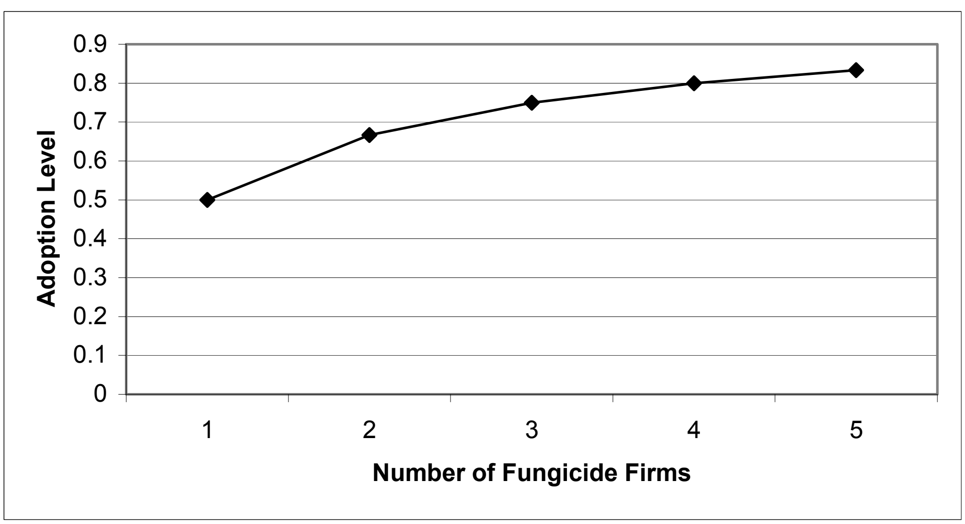

Figure 9. Impact of Conventional Fungicide Producing Firms on Conventional Adoption.

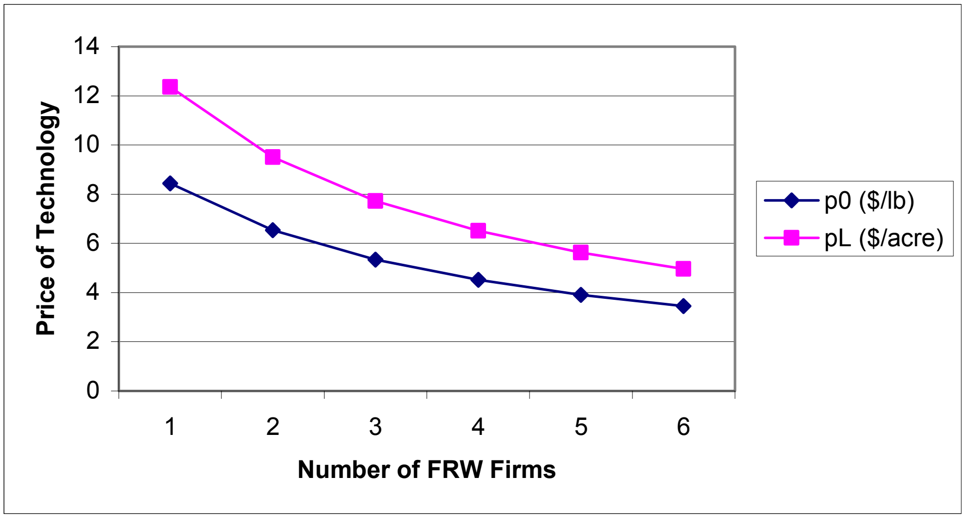

Figure 10. Impact of GM FRW on Technology Prices.

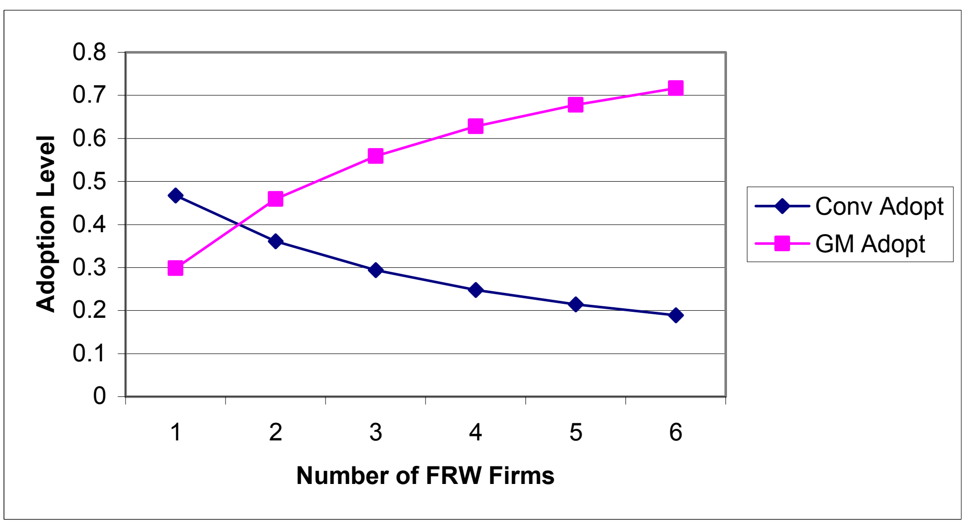

Figure 11. Impact of GM FRW on Adoption Levels.

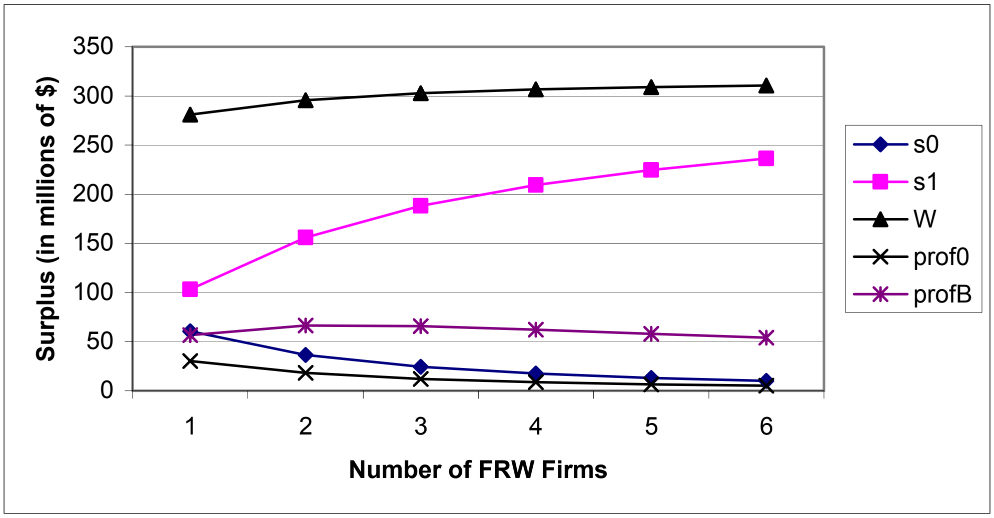

Figure 12. Impact of GM FRW on Producer Surplus and Firm Payoffs.

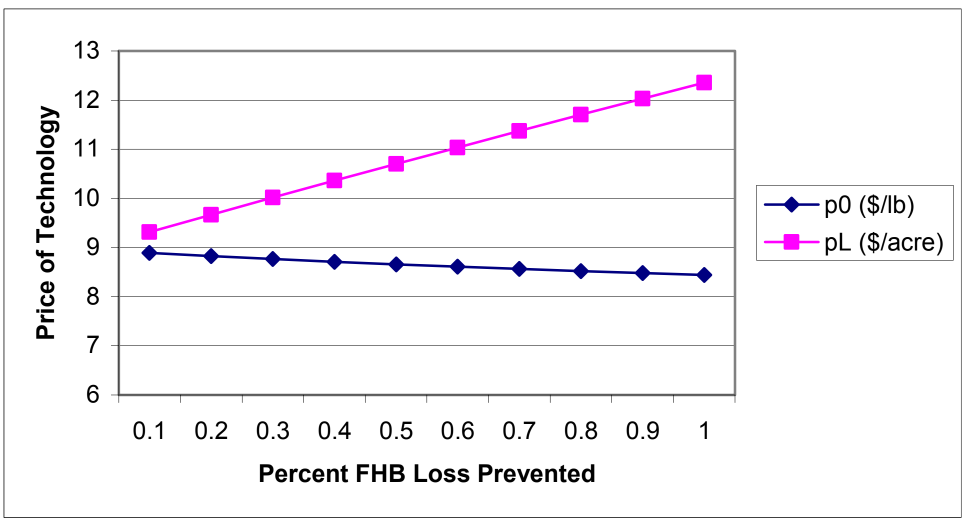

Figure 13. Impact of GM FRW Efficiency on Technology Prices.

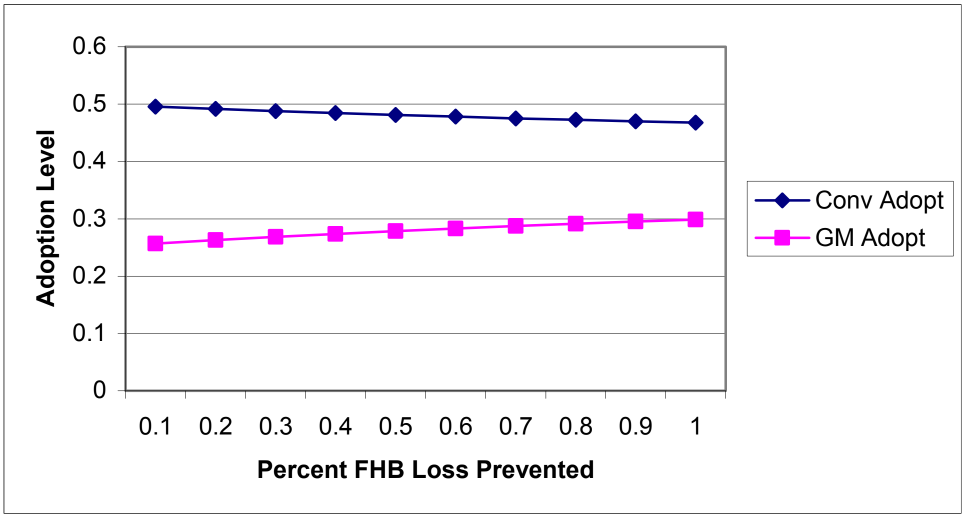

Figure 14. Impact of GM FRW Efficiency on Adoption Levels.

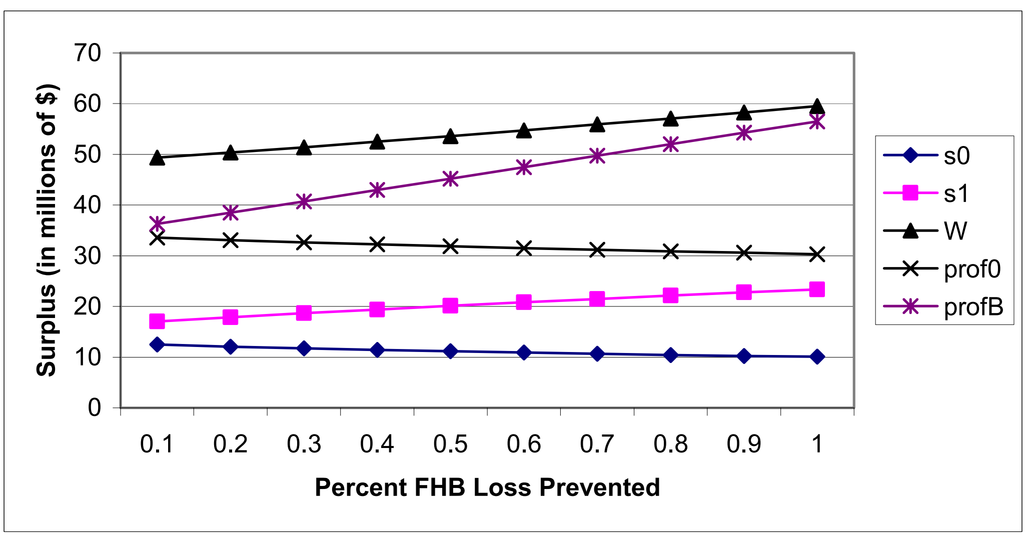

Figure 15. Impact of GM FRW Efficiency on Producer Surplus and Firm Payoffs.

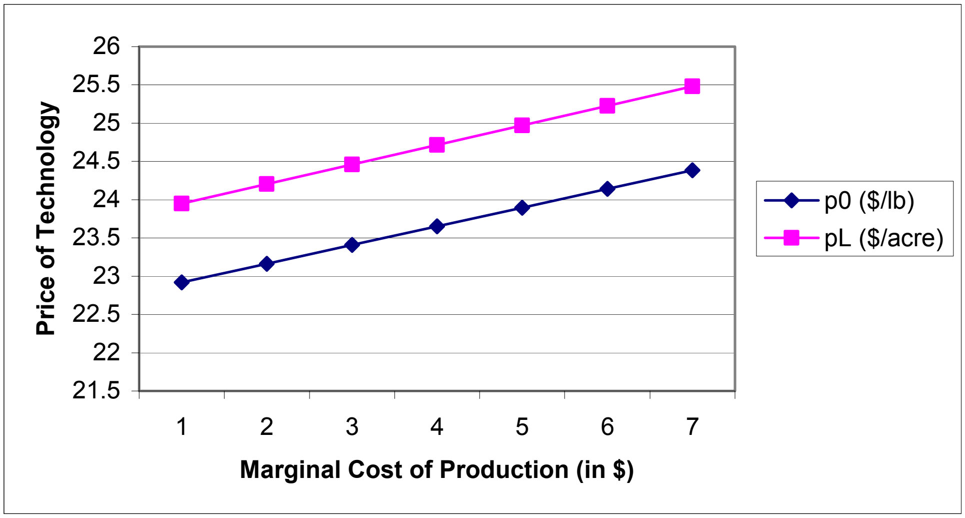

Figure 16. Impact of GM FRW Marginal Cost on Technology Prices.

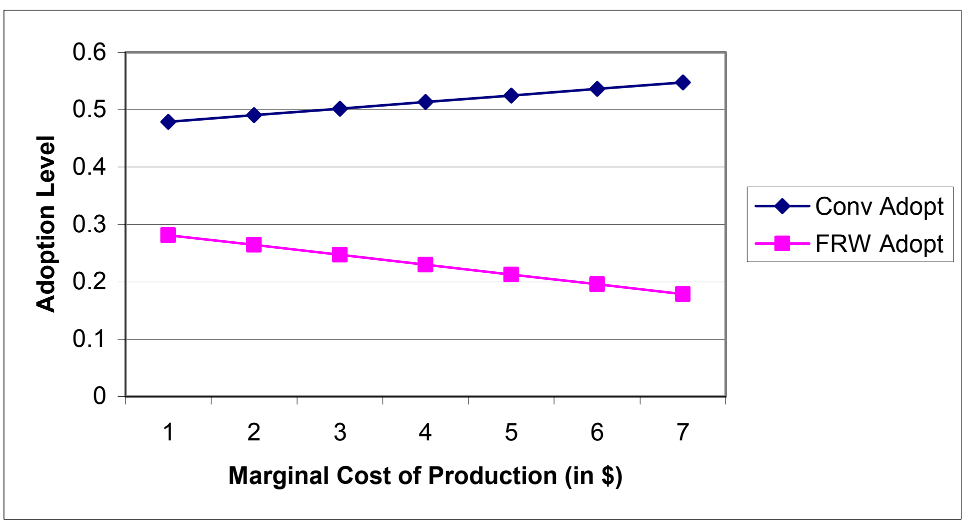

Figure 17. Impact of GM FRW Marginal Cost on Adoption Levels.

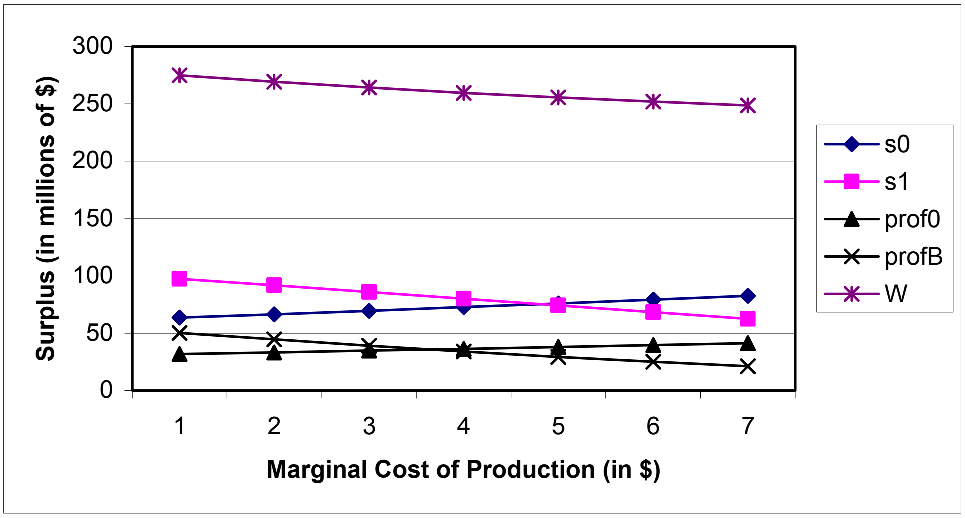

Figure 18. Impact of GM FRW Marginal Cost on Producer Surplus on Firm Payoffs.

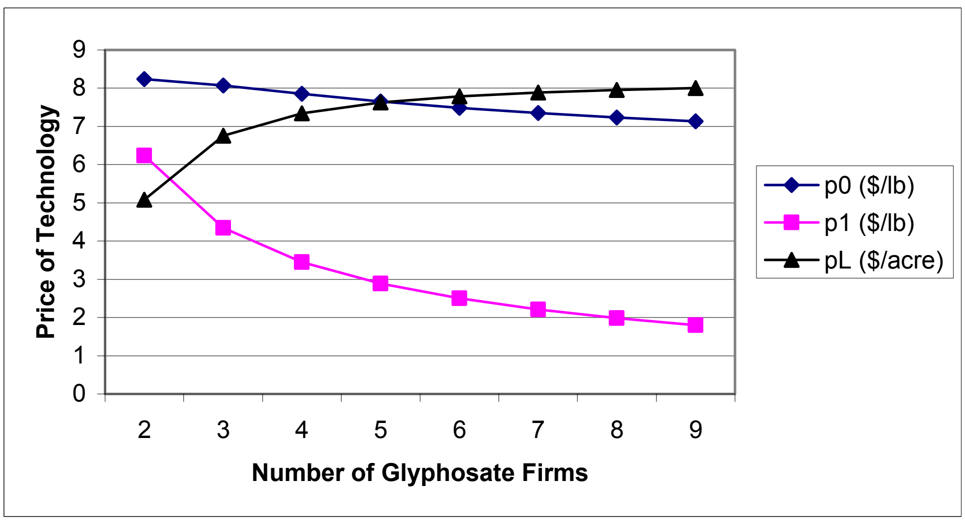

Figure 19. Impact of Glyphosate Producing Firms on Technology Prices.

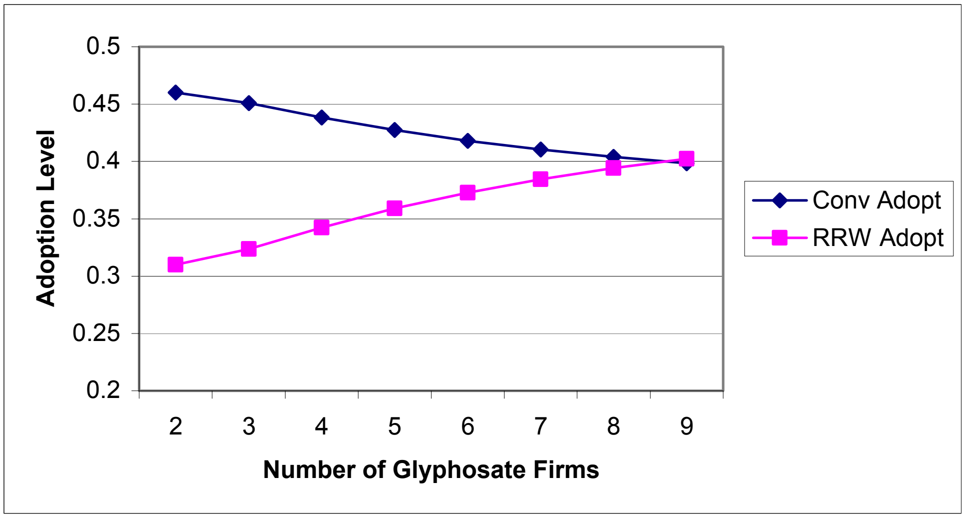

Figure 20. Impact of Glyphosate Producing Firms on Adoption Levels.

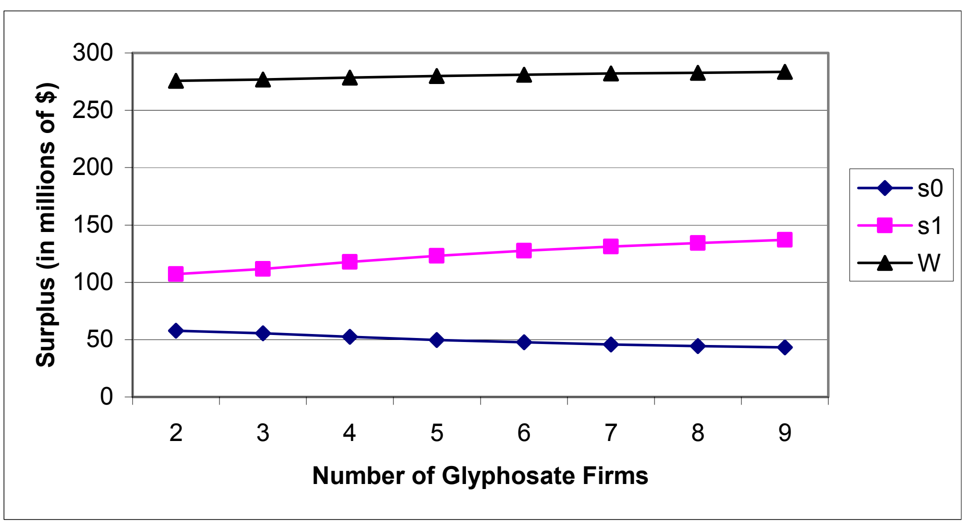

Figure 21. Impact of Glyphosate Producing Firms on Producer Surplus and Total Welfare.

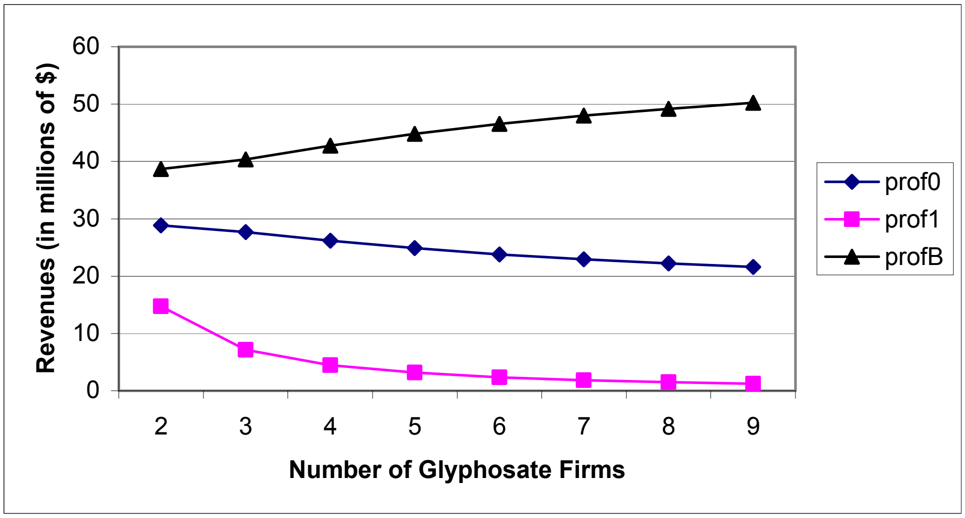

Figure 22. Impact of Glyphosate Producing Firms on Firm Payoffs.

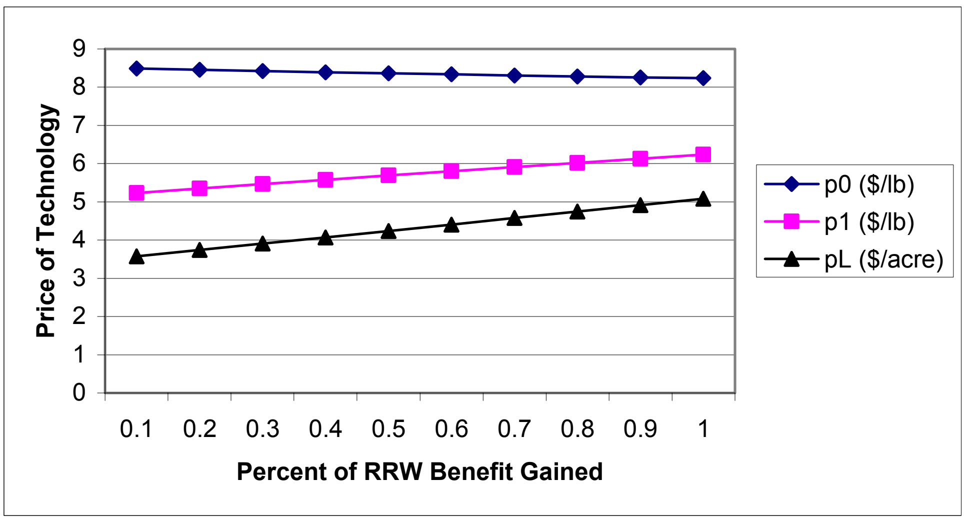

Figure 23. Impact of RRW Efficiency on Technology Prices.

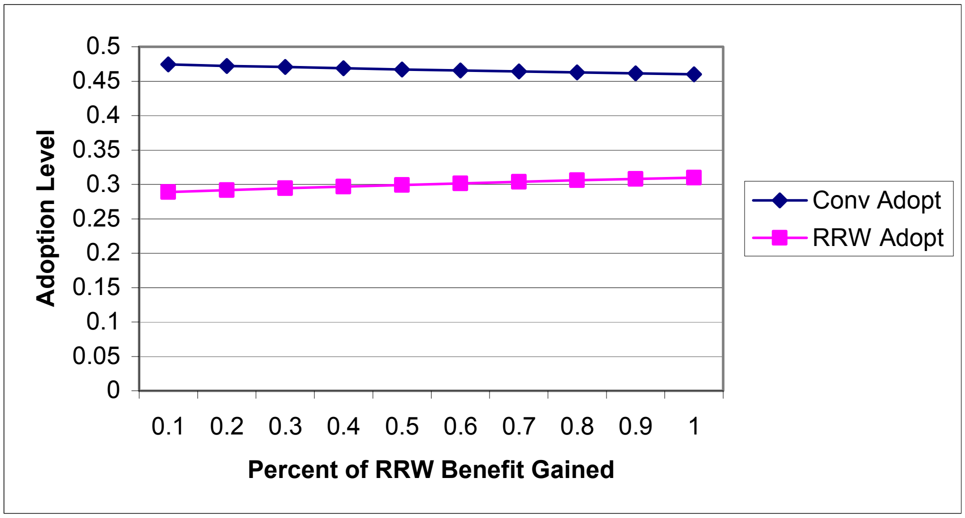

Figure 24. Impact of RRW Efficiency on Adoption Levels.

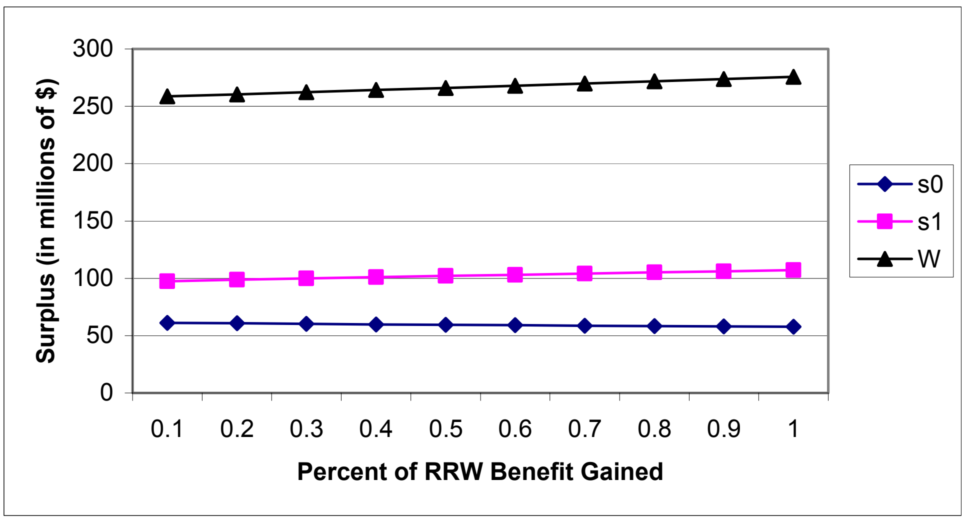

Figure 25. Impact of RRW Efficiency on Producer Surplus and Total Welfare.

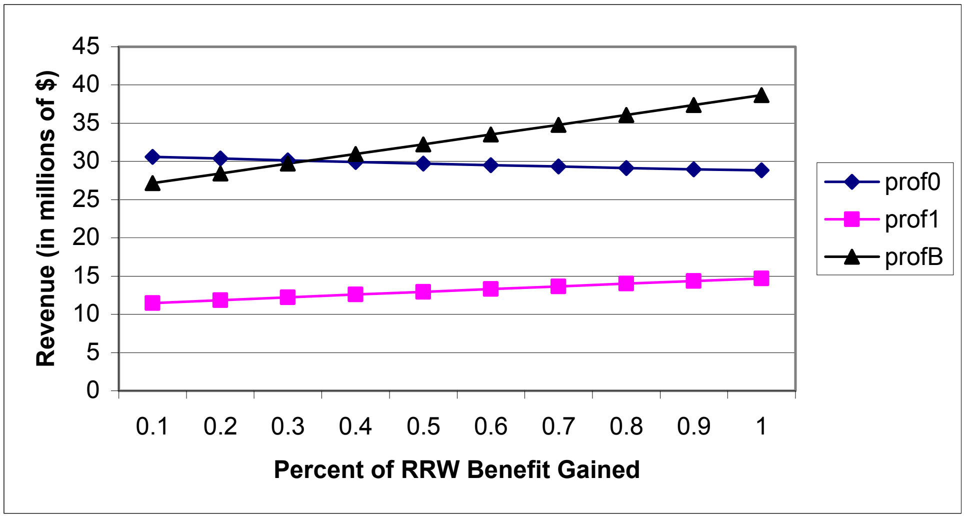

Figure 26. Impact of RRW Efficiency on Firm Payoffs.

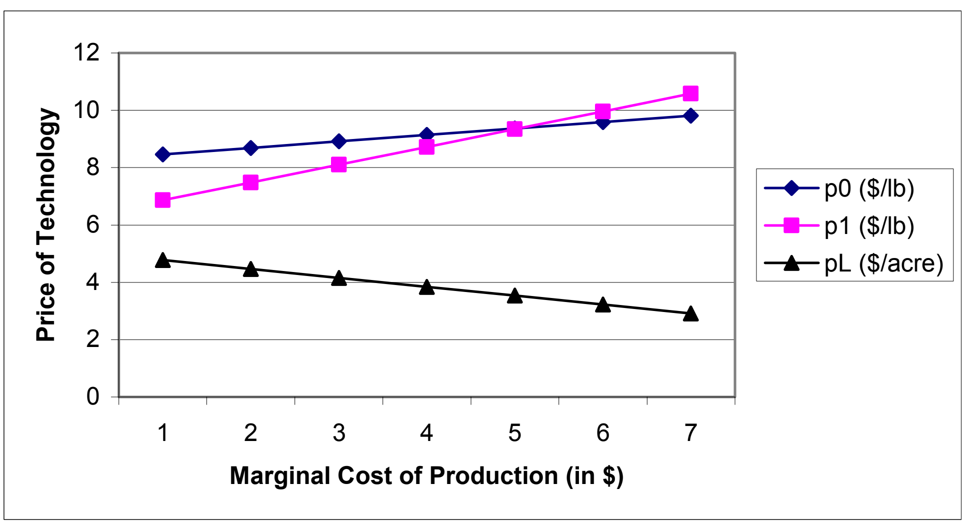

Figure 27. Impact of Marginal Cost of Glyphosate Production on Technology Prices.

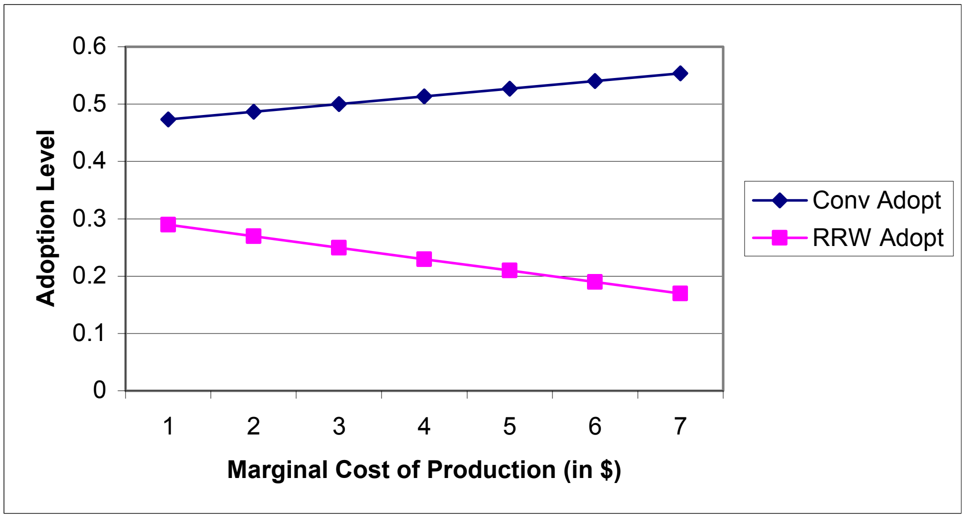

Figure 28. Impact of Marginal Cost of Glyphosate Production on Adoption Levels.

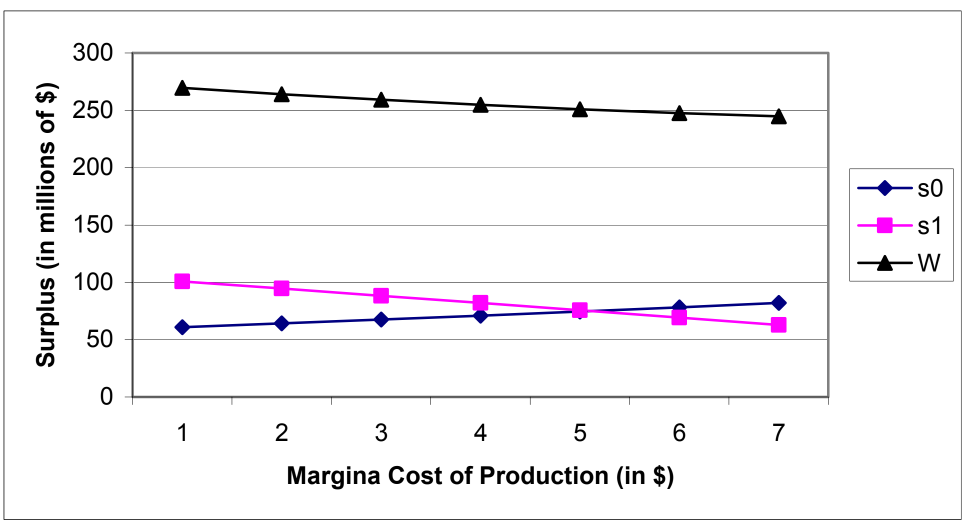

Figure 29. Impact of Marginal Cost of Glyphosate Production on Producer Surplus and Total Welfare.

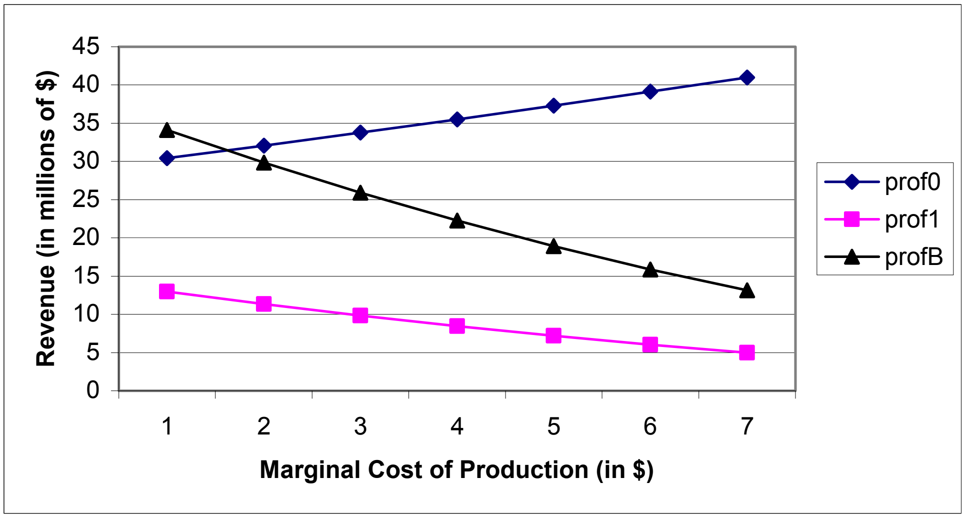

Figure 30. Impact of Marginal Cost of Glyphosate Production on Firm Payoffs.

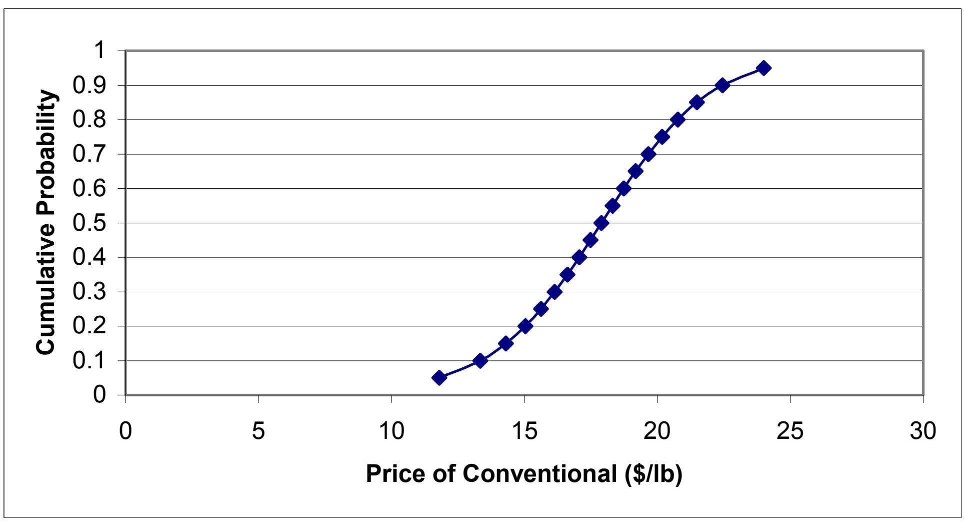

Figure 31. Cumulative Probability Distribution of Prices in Simulation 1.

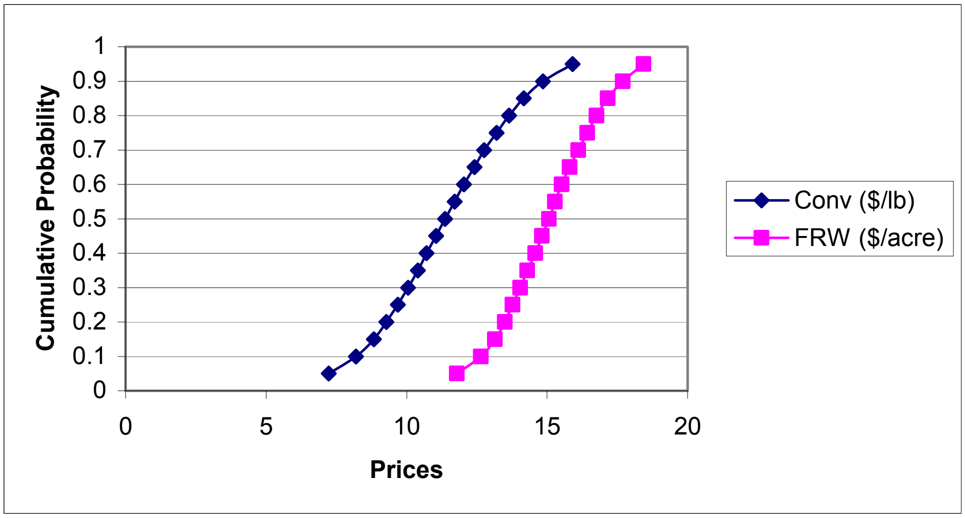

Figure 32. Cumulative Probability Distribution of Prices in Simulation 4.

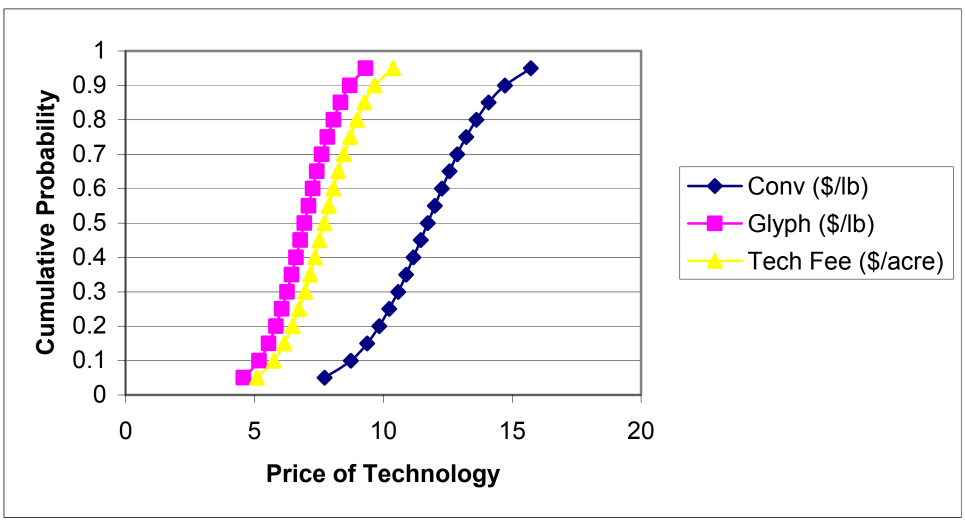

Figure 33. Cumulative Probability Distribution of Prices in Simulation 5.