THE OPTIMAL TIME TO LICENSE AN IRREVERSIBLE BIOTECHNOLOGY: AN
EXAMPLE FROM THE CANADIAN WHEAT INDUSTRY

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Introduction

Agricultural biotechnology creates an opportunity to increase the capacity for food production through Genetically Modified (GM) crops (Ruttan).[1] An example of this technology is genetically modified wheat. Wheat is grown on every continent of the world and is the staple food for approximately two billion people. However, the new wheat technology may be irreversible. Once these genetically modified varieties are released it is impossible to reclaim all of the novel genes from the environment.[2]

Canada is one country that is considering the licensing of this new wheat technology. Wheat is the most important crop to Canadian farmers in terms of the value of production, averaging about 3 billion Canadian dollars per year. Canadian wheat producers' revenues are influenced by the decision to license new wheat varieties, which are the major source of income growth in the industry (Ulrich, Furtan, and Schmitz). The introduction of genetically modified wheat has the potential to increase producer revenue, however environmental concerns remain.

Most GM crops are developed through a process known as genetic engineering. Genetic engineering involves the transfer of genetic material from one organism to another. It allows genes to be transferred between closely related organisms, but the process also enables genes to be crossed between entirely different organisms (Feldmann, Morris, and Hoisington). One example of a crop where GM varieties will soon enter the market (as early as 2003) and which has the potential to significantly impact farm income is herbicide tolerant (HT) wheat developed by Monsanto Ltd. This will be the first wheat variety developed by genetic engineering to be placed on the world market.

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The introduction of a GM-HT wheat variety will have adverse effects on the demand for the crop. Many consumers fear that the consumption of GM-HT varieties will have long-term adverse impacts on human health. The reaction to these fears has been consumer demands for more regulation, demands for product labeling, and in the case of some countries, outright bans on production and importation. Because of the similar appearance to non-GM wheat varieties, if there is not an effective segregation system in place the introduction of GM-HT wheat varieties can spill over to affect the demand for the non-GM varieties.

The decision to license a GM-HT wheat variety depends upon its real option value. There is uncertainty over the future costs and benefits of this new wheat technology, and the introduction of the variety is irreversible. There is a well-developed literature pertaining to the value of an option to invest in an irreversible project under uncertainty (McDonald and Siegel; Pindyck; Dixit and Pindyck). From an empirical standpoint, the real option value approach has been used to evaluate the impact of uncertain government policy on investments in the agriculture sector (Purvis et al.; Winter-Nelson and Amegbeto). The uncertainty over the future price of wheat extends beyond just GM-HT wheat. If a country like Canada chooses to license GM-HT wheat, importers may view all wheat produced in the country to be of the same type. This would have the effect of lowering the price of wheat for all producers regardless of whether they grow GM-HT wheat or the traditional varieties. Once the new varieties are released into the farmer's field it is not easy to divest or reclaim all the genes without a substantial cost, i.e. the technology is irreversible. Thus, the optimal timing for the release of GM-HT wheat technology will depend on this real option value. The contribution of this paper

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will be to extend the use of real option value models to examine the timing of the licensing decision for a new biotech crop such as GM-HT wheat.

We demonstrate large potential gains can be earned through the licensing and adoption of GM-HT wheat varieties. The capitalized rents earned from this new technology are in the range of $175-$300 per acre. In 2001, this rent is equal to the price of cropland for many farmers in western Canada, and therefore represents an attractive option. The distribution of the gains between producers and the innovating firm depends upon the ability of the innovating firm to act as a monopolist and the cost of segregating GM-HT wheat from traditional wheat varieties. The real option value of the new wheat technology, and thus the decision to license the new wheat varieties, depends upon whether the government considers the change in revenue of both the suppliers of the new technology and producers, or only the change in producer revenue. The results in this paper show there is considerable value in waiting to license GM-HT wheat from the producers perspective, given that segregation is currently not possible at a cost that producers would pay and still be better off with the new technology. We show that introducing a competing technology reduces the amount innovating firms can charge producers. With a competing technology available there is a value in waiting to release GM-HT wheat from both society and the producers perspective.

In the second section we discuss the benefits of introducing GM crops. Section three provides an overview of the world wheat market. The impact of introducing GM-HT wheat on Canadian wheat exports is discussed in this section. In section four we show how the value of waiting for information affects the adoption of new wheat technologies. In Section five we develop an empirical model that incorporates the stochastic effects of

price and environmental costs on the optimal time to license GM-HT wheat. Section six presents the model results and a sensitivity analysis. Section seven examines the optimal licensing decision in the presence of a competing technology that lowers costs and increases yields. Section eight provides the conclusions.

Genetically Modified Organisms

The process of genetic engineering has allowed researchers to transfer a number of desirable traits into plants. These traits are categorized as input traits, such as insect resistance and herbicide tolerance, and output traits, such as improved crop nutritional content. Crops inserted with input traits were developed in an effort to improve crop yields and reduce the cost of production (Moschini, Lapan, and Sobolevsky; Falck-Zepeda, Traxler, and Nelson).

The insertion of the Bt gene into plants to develop insect resistant crops is an example of genetic engineering. Bt is bacterium *Bacillus thuringiensis*, which induces plants to produce a protein that is toxic to certain insects (Feldmann, Morris, and Hoisington). The pest resistance obtained from the Bt gene provides benefits in terms of increased yields, reduced chemical use and an increase in quality (such as reduced secondary infections and resulting microtoxins).

Another input trait that has been successfully inserted into plants through the use of genetic engineering is herbicide tolerance (HT). Inserting the HT trait into plants provides resistance to specific herbicides, that is tolerance to herbicides that cannot normally be used on those plants. The most common HT trait inserted into crops worldwide is tolerance to the herbicide Roundup™. The Roundup Ready™ trait was

developed by Monsanto Ltd. and provides plants with resistance to glyphosate herbicides. The gene has been inserted into varieties of cotton, soybeans, corn, and canola. Similar to the case of the Bt gene, the development of the HT technology provides potential benefits in terms of increased crop yields and reduced cost of production (Mayer and Furtan).

World Wheat Market

World wheat production in 2000 was 590 million tonnes (International Grains Council). The United States produces 63 million tonnes or 10.6% while Canada produces 24 million tonnes or 4.0%. Over 85% of Canada's wheat production is exported. Of the 112 million tonne world trade in wheat Canada has approximately 15% market share and the United States 26% (International Grains Council).

The importation of wheat is spread over more than one hundred countries. In 2000 the largest importer of wheat was Iran (7.363 million tonnes) followed closely by Brazil (7.196 million tonnes), Egypt (5.973 million tonnes), and Japan (5.960 million tonnes). Some countries, such as Indonesia (3.739 million tonnes) import wheat from the United States and Canada and then re-export the flour and bakery products into the European Union.

Japan and the European Union have stated they will not import GM-HT wheat. If Canada introduces GM-HT wheat she will have to guarantee these importers that the product they are receiving is GM-HT free. Given the current grading and segregation system, which is based on visual kernel identification, this guarantee is not credible.

Therefore, Canada is not likely to meet the required import standards for these markets and these countries would cease to import wheat from Canada.[3]

If Canada were to license GM-HT wheat the markets that demand GM-HT free wheat would turn to other exporters where GM-HT wheat technology is not licensed, such as Australia, the European Union, and the United States. Canada would then sell its wheat into those markets that are indifferent to GM-HT, such as China. This is trade diversion. Many of the countries that will not import GM-HT wheat are premium wheat markets like Japan and the European Union, and the loss of these markets will result in a decline in the average price for Canadian producers (Furtan, Kraft, and Tyrchniewicz; Carter and Loyns).

Adoption of New Technologies Under Uncertainty and Irreversibility

There are two irreversible costs associated with the introduction of GM-HT wheat. They are increased environmental costs and market (price) impacts. First, GM-HT wheat will become a weed in future crops, which will increase future chemical applications. Second, the price of Canadian wheat could be reduced for two reasons. GM-HT wheat may have to be segregated from non-GM crops through the marketing channel. Wheat producers will pay for this additional marketing cost, which will lower the price received by farmers. Alternatively, if GM-HT wheat is not segregated in a credible manner from non-GM wheat, Canada will lose markets such as Japan and the European Union, which pay a price premium for Canadian wheat.

Real Option Value

The standard procedure for evaluating the introduction of a new agricultural technology is to calculate the expected net present value (NPV) of the investment (Alston, Norton, and Pardy). The NPV of an investment is the difference between the present value of net returns minus the investment costs. The decision rule under the NPV criteria is to invest in a project if the NPV is positive. The problem with the NPV rule is that it ignores the uncertainty of net returns and the irreversible nature of the investment decision.

McDonald and Siegel and later Dixit and Pindyck examine the optimal time to invest in a project with uncertain returns and irreversible investment costs. They calculate the value obtained from the ability to postpone an irreversible investment. This is similar to the value obtained from holding a call option in financial markets. The decision maker holds an option to invest now or postpone the decision to a later date. If the value of the investment opportunity increases, the decision maker has the ability to exercise the option to invest. If the value of the investment opportunity declines, the decision maker can leave the option unexercised. Deciding to make an irreversible investment eliminates the option to wait for more information. Dixit and Pindyck state that the loss of this option value should be factored in as an opportunity cost when determining the total cost of an investment opportunity.

The value of the option on a new GM-HT wheat variety and the impact it has on the licensing decision is illustrated graphically in Figure 1. Based on the NPV criteria one would be indifferent between licensing and not licensing GM-HT wheat at point V_0. At

this point the expected present value of net returns (V) equals the expected irreversible costs (I).

Factoring in the value of waiting for more information, the optimal licensing trigger occurs at some level of returns greater than V_0. To obtain the threshold level of returns required to license GM-HT wheat, we derive both the value obtained from investing (V-I) and the value obtained from waiting, which is F(V). The tangency point of these two curves provides the threshold level of returns required to license GM-HT wheat. Figure 1 illustrates that under the option value approach the threshold level of returns occurs at V_1.

The future net returns and the irreversible cost associated with introducing GM-HT wheat are stochastic variables, which are written as:

(1)
$$dV = \alpha_V \, dt + \sigma_V dz_V \,,$$

(2)
$$dI = \alpha_I \, dt + \sigma_I \, dz_I \,,$$

where: $E[dz_v] = 0$, $E[dz_v^2] = dt$, $E[dz_I] = 0$, $E[dz_I^2] = dt$, $E[dz_v dz_I] = \rho dt$ and ρ is the correlation between V and I. We assume that both variables follow a geometric Brownian motion, which is a non-stationary time stochastic process where α is the drift rate, σ is the standard deviation of the net returns, and dz represents the increment of the Weiner process. The geometric Brownian motion implies that future values of the stochastic variable are log normally distributed with a variance that grows linearly with the time horizon. The use of the geometric Brownian motion is consistent with previous studies that have valued investment projects with uncertain returns and costs. (Purvis et al.; Price and Wetzstein).

A ratio of V and I is used to determine the optimal time to license the GM-HT wheat technology. This ratio will be represented by $v \equiv V / I$. Stochastic calculus is used to find a differential equation describing how the value of the option evolves over time (Dixit and Pindyk). The differential equation along with three boundary conditions is used to find the critical net return/cost ratio required to license GM-HT wheat. The three boundary conditions are as follows:

The first boundary condition states that the value of f (v) approaches zero as (V) approaches zero. This implies that as the net return from GM-HT wheat approaches zero the value of the option becomes worthless.

The second condition is called the value-matching condition, which states that at the optimal licensing point the value of the option to wait i.e. f (v) equals the net returns minus the irreversible costs, (V- I). The value-matching condition for this problem is:

$$(3) \qquad f(v) = v - 1.$$

The third condition is the smooth pasting condition, which requires f (v) and (V-I) to meet tangentially at the optimal licensing point. The smooth pasting conditions are written as follows:

$$(4) \qquad f'(v) = 1.$$

$$(5) \qquad f(v) - vf'(v) = -1.$$

The differential equation is a homogeneous linear equation of second order, so by definition its solution is a combination of any two linear independent solutions. The value of the option thus takes the following functional form:[4]

$$(6) \qquad f(v) = A_1 v^{\beta_1} + A_2 v^{\beta_2}.$$

To satisfy the first boundary condition, that is to ensure that $f(v)$ approaches zero as (V) approaches zero, the coefficient of the negative power of (v) is set equal to zero. Setting $A_2 = 0$ reduces the solution to:

$$(7) \qquad\qquad f(v) = A_1 v^{\beta_1}.$$

Equation (7) along with the remaining two boundary conditions are used to solve for the two unknowns, the constant A, and the critical value v^*, which is:

$$(8) \qquad\qquad V/I = v^* = \frac{\beta_1}{\beta_1 - 1}.$$

The term $\dfrac{\beta_1}{\beta_1 - 1}$ in equation (8) is the option value threshold. The option value threshold is the ratio of returns over costs required to make licensing GM-HT wheat the optimal decision. The term β_1 is the larger root of the fundamental quadratic equation:

$$(9) \qquad \beta_1 = \frac{1}{2} - \left(\frac{\delta_I - \delta_V}{\sigma_v}\right) + \sqrt{\left[\left(\frac{\delta_I - \delta_V}{\sigma_v}\right) - \frac{1}{2}\right]^2 + \frac{2\delta_I}{\sigma_V}},$$

where: δ_V and δ_I are the real discount rates adjusted for the risk and growth rate of V and I, and $\sigma_v = \sigma_V{}^2 - 2\rho\sigma_V\sigma_I + \sigma_I{}^2$.

Empirical Model and Data

We now turn to developing an empirical model that incorporates the stochastic effects of price and the environmental costs on the optimal time to license GM-HT wheat. The application of the real option approach to the case of licensing GM-HT wheat in Canada requires information about the potential stream of benefits and costs, and the uncertainty of the benefits and costs.

Option Value Threshold

We first estimate the licensing threshold (v^*) or the right hand side of equation 8. This requires an estimate of each of the parameters influencing the value of β_1 as shown in equation 9. If we consider the decision to license GM-HT wheat as a social decision made on behalf of Canadian society, risk adjustment would be insignificant, and we can use the real discount rate adjusted only by the expected growth rates in V and I. The net returns V grow over time as the amount of research and the effectiveness of the research increases the yield of new GM-HT wheat varieties.

The licensing threshold (v^*) is a function of several parameters, including the risk and growth adjusted discount rates for V and I, and the variation of v. For our base case, we assume a risk adjusted real discount rate of 5% for both V and I. Given the size of the technological impact we expect little correlation between these costs and benefits and the overall market portfolio. There would however, be a positive correlation between the net returns, V, made up of yield increases and cost savings, and the irreversible costs, I, made up of the negative price impacts and environmental costs. The larger the benefits of the GM-HT wheat technology, the greater the worldwide adoption of GM-HT varieties and the larger the price discount and environmental impacts. For our base case we use a correlation coefficient, ρ, of .5 which implies that in the long run about 1/2 of the expected increase in Canadian GM-HT wheat production benefits will be reflected in lower GM-HT wheat prices and greater environmental costs.

Conventional plant breeding has increased wheat yields in Canada an average of .5% per year since 1978 (Gray, Malla, and Ferguson). The Canadian experience in the canola industry suggests that the introduction of GM-HT varieties would attract private

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investment into wheat research and speed up the rate of yield increase (Gray, Malla, and Ferguson). We assume that future GM-HT wheat yields will increase at a 50% higher rate or by .75% per year rather than .5% per year. This faster rate of yield increase will enhance the benefits from the GM-HT technology by 2.4% per year.[5] Using the correlation coefficient described above, the increase in benefits will cause a growth in expected costs of 1.2% per year, (ρ x 2.4%). Using these growth rates the risk adjusted growth rate of V is 2.6% per year (5%- 2.4%), and the growth rate for I is 3.8% per year (5%-1.2%). The stochastic (Weiner) variation in v, is calculated by the @RISK program using the distribution of each factor affecting V and I. Here it is assumed that over time these variables follow a geometric Brownian motion process as described in equations 1 and 2, and that the variation in these estimates represents an annual movement in this process. These assumptions imply the instantaneous coefficient of variation of v is 6.8% per year. Placing these parameter estimates in equation 9, the threshold ratio is 2.27.

Wheat Industry Returns

The expected net returns (V) from introducing GM-HT wheat are the direct production benefits associated with the new technology. The expected returns are calculated by taking the difference in net industry returns before and after the introduction of GM-HT wheat. To determine the expected net return we examined the impact of introducing GM-HT wheat on two groups in society. The two groups are the adopters of GM-HT wheat and the suppliers of the GM-HT wheat technology.[6]

The change in net returns for adopters of GM-HT wheat varieties is calculated by taking the difference in net returns from producing GM-HT wheat and conventional wheat, which is depicted in equation 10.

$$(10) \qquad R_a = ((P_0 * Y_{ht} - H_{ht} - S_{ht}) - (P_0 * Y_{con} - H_{con} - S_{con})) * Ac_{ht},$$

where: R_a is the change in net returns for adopters of GM-HT wheat, P_0 is the price of wheat with no market impacts, Y_{ht} is the GM-HT wheat yield, H_{ht} is the GM-HT herbicide cost (including technology use charge), S_{ht} is the cost of GM-HT wheat seed, Y_{con} is the conventional wheat yield, H_{con} is the conventional herbicide cost, S_{con} is the cost of conventional wheat seed and Ac_{ht} is the number of GM-HT wheat acres.

The return to the suppliers of GM-HT wheat will depend on the pricing strategy of the firm and the adoption rate of the technology. The pricing strategies used for existing biotech crops suggests that the innovating companies have a considerable level of market power. This market power allows the innovating companies to extract a significant portion of the economic rent created by the new technology (Moschini, Lapan, and Sobolevsky).

We assume the price of the GM-HT wheat technology is set by the innovating firm in order to maximize their profit. In the case of Roundup Ready™ wheat, the pricing structure of the technology will include a Technology Use Agreement (TUA). The TUA is a binding contract, which allows the producer to use a crop variety inserted with the Roundup Ready™ gene in return for a fixed charge per acre. The total benefit to the innovating company (Monsanto Ltd.) will be measured by the TUA price times the expected number of acres seeded to Roundup Ready™ wheat:

$$(11) \qquad R_s = (TUA * Ac_{rr}),$$

where: R_s is the return to the supplier of GM-HT wheat varieties, TUA is the technology use agreement price for Roundup Ready™ wheat, and Ac_{rr} is the number of Roundup Ready™ wheat acres.

The total wheat industry return from the introduction of the new wheat technology is determined by summing the returns for the two groups discussed above. The total wheat industry return after the introduction of the new technology is written as:

(12) $$V = R_a + R_s.$$

The wheat industry return is discounted to obtain an expected present value of returns (see equation 13). The term μ is the risk-adjusted rate of return and α_V is the annual growth rate of the returns.

(13) $$E(V) = \frac{V}{(\mu - \alpha_V)},$$

where: $\delta_V = \mu - \alpha_V$, as in equation 9.

Irreversible Market Cost

The market impacts from introducing GM-HT wheat are treated as an irreversible cost. We assume that after the new technology is introduced into the environment it will be impossible to reclaim all of the genes. Therefore, it would be difficult to revert back to a non-GM production system, making the market costs associated with the technology irreversible.

The irreversible market cost is determined by estimating the expected reduction in the price of Canadian wheat exports due to the introduction of GM-HT wheat. Assuming no segregation of GM-HT and conventional wheat, the price discount will impact all wheat produced in Canada. The irreversible market cost is determined as follows:

(14) $$M = (P_{con} - P_{ht}) * TP,$$

where: M is the total irreversible market cost associated with the new wheat technology, P_{con} is the price of wheat before the introduction of GM-HT wheat, P_{ht} is the price of

wheat after the introduction of GM-HT wheat, and *TP* is the total production of wheat for both adopters and non-adopters of GM-HT wheat.

Irreversible Environmental Costs

The persistence of volunteer GM-HT wheat will impact the profitability of other crops in the farmer's rotation.[7] We focus on the cost of controlling volunteer GM-HT wheat in future crops for both adopters and non-adopters of the new technology.

The cost of controlling volunteer GM-HT wheat depends on the type of crops and tillage system used by the producer. For producers adopting Roundup Ready™ wheat, costs are incurred to control volunteer wheat if a second Roundup Ready™ crop (i.e. canola) is used in the rotation. A second issue is the control of volunteer Roundup Ready™ wheat in zero-tillage systems that rely on glyphosate herbicides for weed control in the spring.[8] Producers that choose to grow a second Roundup Ready™ crop or that use zero-tillage practices would not be able to control volunteer Roundup Ready™ wheat with glyphosate herbicides. A tank-mix of glyphosate with a second herbicide will be required to control the volunteer Roundup Ready™ wheat.[9] Requiring a second herbicide will reduce the producer's net return in future years.

The total environmental cost associated with GM-HT wheat is the sum costs of controlling volunteer GM-HT wheat for both adopters and non-adopters, i.e.

(15) $$E = (C_a * Ac_{ht} + C_n * Ac_{con}),$$

where: E is the total environmental cost of GM-HT wheat, C_a is the per acre environmental cost for adopters of GM-HT wheat, Ac_{ht} is the number of GM-HT wheat acres, C_n is the per acre environmental cost for non-adopters of GM-HT wheat, and Ac_{con} is the number of conventional wheat acres.

The total irreversible cost associated with GM-HT wheat is determined by taking the sum of the total market costs and environmental costs, as shown in equation 16.

(16)
$$I = M + E.$$

The total irreversible cost is discounted to obtain an expected present value of costs (see equation 17). The term μ is the risk- adjusted rate of return, and α_I is the growth rate of the irreversible costs.

(17)
$$E(I) = \frac{I}{(\mu - \alpha_I)},$$

where: $\delta_I = \mu - \alpha_I$, as in equation 9.

Price, Yield, and Cost Data

The expected price discount for GM-HT wheat was modeled using triangular distributions. The expected price discount for wheat after the introduction of GM-HT wheat was between $.35 and $.05 per bushel. The upper bound of this range is based on estimates provided by Kuntz.[10] The most likely price discount for GM-HT wheat was $.20 per bushel. These price discounts were made under the assumption that Canada will be the first country to license GM-HT wheat varieties.

The yield distributions for GM-HT wheat are based on estimates provided by Holzman. The expected yield of GM-HT wheat ranged from 30.20 to 32.56 bushels per acre. The most likely GM-HT wheat yield was estimated at 31.08 bushels per acre. The expected yield for conventional wheat was 29.60 bushels per acre. The yield advantage attributed to growing GM-HT wheat is a result of improved weed control over conventional wheat systems.

Holzman calculated the irreversible environmental cost based on the cost of controlling volunteer Roundup Ready™ wheat for adopters and non-adopters of the new

wheat technology. The expected environmental costs were modeled using a normal distribution with a standard deviation of 10% of the total environmental cost. The environmental cost for adopters is dependent on the type of crops and tillage system used by the producer. For producers using zero-tillage the discounted cost of controlling volunteer Roundup Ready™ wheat is $4.50 per acre. Producers using zero-tillage and planting a second Roundup Ready™ crop incur a discounted cost of $7.00 per acre. The total environmental cost for conventional tillage producers with a second Roundup Ready™ crop is $3.00 per acre. For the environmental cost to non-adopters we assumed it would take ten years before volunteer GM-HT wheat plants spread into neighboring fields and multiplied to a point where a special herbicide application was required to control the infestation.

Model Results and Sensitivity Analysis

Model Results with no Segregation [11]

We first look at how the introduction of Roundup Ready™ wheat impacts the agronomic practice of producing wheat. The direct production benefit realized by the adopters of GM-HT wheat varieties is between $14.93 and $8.72 per acre. The benefits, as calculated by Holzman, are a result of improved crop yields and a reduction in the cost of producing wheat due to the lower cost of weed control.

If GM-HT wheat varieties are introduced and the market impacts, environmental costs, and the cost of the TUA are ignored, the Roundup Ready™ wheat technology has a potential economic benefit of $14.93 per acre annually to the adopters. This would increase land values by $298.60 per acre at a 5% discount rate. When the market price

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impact is taken into account, the benefit decreases to $8.72 per acre, which results in an

increase in land values of $174.40 per acre. This potential gain is equal to the current

value of land used for wheat production in western Canada, thus the new technology is

potentially attractive for wheat producers. However, the final distribution of these

benefits between the innovating firm and adopting producers will depend on the pricing

strategies used by the innovating firm.

The revenue of the innovating firm providing the GM-HT wheat technology is a

function of the rate of adoption of the new wheat technology and the price level of the

TUA. The demand for GM-HT wheat was derived by disaggregating producer's into 24

groups based on their specific farming system. We then determined the reservation TUA

price for each producer group. Because each group has a unique willingness to pay the

demand curve for the new wheat technology is a step function. Facing this demand curve,

the innovating firm will choose the TUA price that maximizes their total profit.

The optimal TUA price for Roundup Ready™ wheat, which maximizes profits for

the innovating firm, is $12.38 per acre (Table 1). This is reached when 88 percent of total

wheat acres are seeded to the new technology. At this level of adoption the annual net

return of non-adopters and adopters is negative. Non-adopters are made worse off

because they are producing wheat with the conventional technology while receiving a

lower market price for wheat due to the presence of GM-HT wheat varieties. Comparing

the net return of adopters before and after the introduction of the new wheat variety we

find they too are worse off at 88 percent adoption. This occurs because of the lack of a

credible segregation system. It is not until we reach 95-100 percent adoption, which

corresponds to a TUA price of $5.00 per acre that producer net returns become positive.

The annual net return to the innovating firm is $229 million (Table 1). Because of the large gain to the innovating firm the total net return of adopters, non-adopters, and the innovating firm is positive except at low levels of adoption (i.e. a high TUA price, as shown in Table 1).[12]

The gains and losses incurred by producers from the release of the new wheat technology are broken down into agronomic benefits, environmental and market costs. The agronomic benefits result from the yield enhancement and lower production costs. The environmental costs are the extra costs required too control volunteer weeds, which are on-farm and off-farm costs. The irreversible market cost is the price drop that results when importers decide Canada is no longer capable of guaranteeing a supply of conventional wheat varieties.

The expected present value of returns and costs is used to determine the optimal time to license the new wheat technology (see Table 2). The ratio of returns over costs is compared to the option threshold value to determine when it is optimal to license the new wheat technology. In the case of no segregation, if all the market participants are included (i.e. the innovating firms and the producers) the returns to cost ratio is 3.23. This is greater than the threshold value of 2.27, which means society benefits from the immediate licensing of the new wheat varieties. If only producer revenue is considered the expected returns to cost ratio is .93, which implies an expected loss from the licensing of GM-HT wheat. Therefore, there is a value in waiting to license the new technology.

The question is whose revenues are to be included in the calculation of the wheat industry returns: the innovating firm, the wheat producers, or both? If the total change in industry revenue is included the decision will be to license the new technology based on

the option value criteria. If only the producer's revenues and costs are included in the calculation the decision is not to license the new technology.

Model Results: Zero Segregation Fees

One way to increase the benefits to producers is to segregate GM-HT wheat from traditional wheat. Producers gain because the non-adopters will not face the market price decline, which is a result of GM-HT wheat production. Therefore, producers will have a choice between the new technology at a lower wheat price and the traditional technology at the higher price, which they did not have without segregation.

In the hypothetical case of zero segregation fees, the expected present value of returns and costs for Roundup Ready™ wheat are shown in Table 2. Using the same process to calculate the TUA price as in Table 1, the optimal TUA price is $6.25 per acre. The optimal TUA price is lower in the case of segregation with zero fees because producers can now choose between the two technologies without being penalized for the drop in the market price. In this case the sum of producer net returns is positive. When all industry returns are included, the return/cost ratio is 3.67, which is greater than the licensing threshold value. When only producer returns and costs are included the return/cost ratio is 2.37, which is also above the threshold value. In the case of zero segregation fees, the optimal decision would be to license the new wheat technology.

Model Results: Costly Segregation

Next, we calculate the maximum segregation charge per bushel that producers are willing to pay.[13] The maximum segregation charge is the fee that makes producers indifferent between waiting and proceeding with licensing the new technology. We consider two separate cases where different producers pay for the segregation fee. In the

first case we assume that all wheat producers pay a per bushel segregation fee. For the

second case, following Akerlof we assume that only the non-adopters will pay the

segregation fee because they are the ones to benefit from the additional information.

These results are shown in Table 3.

If all producers are required to pay a segregation fee the maximum they would be

willing to pay in the case of Roundup Ready™ wheat is $.01 per bushel (Table 3). This

charge is calculated starting with a zero segregation fee and increasing the fee until the

licensing threshold is reached.[14] If only non-adopters are required to pay for segregation

the maximum they would pay is $.08 per bushel.

How close are the segregation fees to those expected by industry experts? Zero

tolerance is not credible given the commercial handling system in place in western

Canada. At a one percent tolerance for GM-HT wheat in a sample, the expected costs of

segregation are over $1.00 per bushel (e.g. segregation costs for GM-HT canola are

approximately $1.00 per bushel at a one percent tolerance level) (Smyth and Phillips). At

a 5 percent tolerance the expected industry costs will be in the neighborhood of $.20 per

bushel. The estimated cost of segregating non-GM corn in the United States is $.20 per

bushel (Lin). Given importing countries such as the European Union have set GM

tolerance levels at 1 percent, segregation does not appear to be economical. At a tolerance

level of 5 percent a segregation system is currently not possible given the maximum

segregation fee that will make the decision to license GM-HT wheat optimal from a

producers perspective.

Sensitivity Analysis

The optimal threshold value is a function of a number of parameters. The value these parameters take is uncertain because of the growth rate in wheat yields, increasing environmental costs, and changing consumer acceptance of GM-HT wheat. This in turn will have an impact on the optimal threshold value. Table 4 shows how the optimal threshold ratio varies with changes in these parameter values.

In the base case, as described earlier, the optimal threshold value is 2.27. An increase in the discount rate to .1, decreases the threshold value to 1.76, which increases the opportunity cost of waiting. A decrease in the real discount rate has the opposite impact increasing the threshold value to 3.66. An increase in the growth rate of GM-HT wheat returns that could be brought about by more rapid yield improvements has a very small positive effect on threshold values, increasing the threshold value from 2.27 to 2.34. The elimination of the instantaneous correlation in costs and benefits has two effects. First, it increases the differential between the benefit and cost growth rates, which reduces the threshold, and second it increases the variance of the ratio over time, which raises the threshold. In the case shown in Table 4 the net effect of eliminating the correlation reduces the threshold value to 2.06. While increasing the correlation ratio from .5 to .8 increases the threshold value to 2.49. The variation in v will also influence the threshold value. A reduction in σ_v reduces the threshold value, while an increase in σ_v increases the threshold value.

The optimal threshold value varies from 1.73 to 3.66 (Table 4), which is within the range of values found by McDonald and Siegel. At the high threshold value given no segregation costs, society would be just indifferent to licensing the new wheat technology

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(Table 2). At the other extreme in the case of no segregation, if only producer returns are included the trigger of 1.76 is still greater than .93 (Table 2) thus there is value to waiting.

Optimal Pricing Strategy with Competing Technologies

The optimal pricing strategy of a firm introducing a new technology depends upon the price of other competing technologies available on the market. In the case of GM-HT wheat a competing technology is the Clearfield™ wheat technology.[15] Clearfield™ wheat is also a HT wheat technology that provides potential yield advantages and cost of production savings. Clearfield™ wheat was developed through *mutagenesis* and current import restrictions and labeling requirements have not included products developed by *mutagenesis* (for a complete technical description of *mutagenesis* see McHughen). The price charged to producers for the Roundup Ready™ wheat technology will depend on the price charged for the Clearfield™ wheat technology. The two pricing decisions must be solved simultaneously.

The introduction of Clearfield™ wheat will benefit the suppliers and adopters of the new technology in a manner similar to that of the Roundup Ready™ technology. The return to Clearfield™ wheat suppliers is measured by the difference in the cost of the Clearfield™ technology and the cost of the conventional technology times the acreage of Clearfield™ wheat seeded. The total benefit to the suppliers of Clearfield™ wheat is expressed as follows.

(18) $$R_s = (D * Ac_{clf}),$$

where: R_s is the return to the suppliers Clearfield™ wheat varieties, D is the cost differential between Clearfield™ wheat and conventional wheat varieties, and Ac_{clf} is the number of Clearfield™ wheat acres. The benefit to producers from adopting Clearfield™ wheat is calculated in the same manner as those calculated for Roundup Ready™ wheat (it is assumed that Clearfield™ and Roundup Ready™ wheat provide the same expected yield benefit).

Using the model described in section six, and assuming no segregation, we derive the Bertrand best response functions for the two innovating firms. The best response functions are shown in Figure 2. R_R is the best response function of Monsanto Ltd. to a given price for the Clearfield™ wheat technology, and R_C is the best response function of Clearfield™ wheat suppliers to a given price for the Roundup Ready™ wheat technology. The solution to the pricing problem is at point a in Figure 2 which corresponds to a $P_R =$ \$11.50 per acre TUA price, and $P_C =$ \$4.00 per acre for the Clearfield™ wheat technology. When the two technologies are available to producers and priced optimally the adoption rates are 21% Clearfield™ and 67% Roundup Ready™. The equilibrium price and adoption rate for the Roundup Ready™ technology is lower than that calculated with the monopoly assumption.

If Clearfield™ wheat is introduced first, followed by Roundup Ready™ wheat, the benefits and costs of Roundup Ready™ wheat are compared to Clearfield™ and conventional wheat, rather than compared to only the conventional wheat technology. In the case of no segregation with competing technologies, if all the market participants are included (i.e. the innovating firms and the producers) the returns to cost ratio from introducing Roundup Ready™ wheat is 2.06. This is less than the threshold value of 2.27,

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which means society benefits from waiting to license the new wheat technology. If only producer revenue is considered the returns to cost ratio is .89, which also implies a value in waiting to license the new technology.

Conclusions

The decision to license GM-HT wheat is irreversible. This irreversibility combined with uncertainty about the future benefits and costs of the technology creates an optimal licensing threshold where expected benefits should exceed expected costs by a ratio of 2.27. Irreversible licensing decisions differ substantially from reversible decisions, creating a new challenge for policy makers.

If the Canadian government considers total industry returns the optimal decision is to license the new technology. If they only consider the returns to wheat producers the decision is to wait to license the new technology. This assumes that segregation is not economically feasible. If segregation could be made credible at a cost to producers of between $.01 and $.08 per bushel, producers will be better off with the decision to license the new technology.

In the case of GM-HT wheat, individuals who adopt have a large impact on those who do not adopt. This occurs because with no segregation the market price of wheat is reduced for all producers. This market externality cannot be corrected through the market place because of the high costs of segregation. While some producers would benefit through the licensing of GM-HT wheat varieties in aggregate they do not. This creates a serious licensing dilemma due to the market failure.

The large gain earned by the innovating firms is a result of market power. In this case the compensation principle applies. If the innovating firms were to reduce their TUA price adopting producers could be made better off. A payment to non-adopters compensating them for their economic loss could also be made leaving all market participants better off with the decision to license the new technology. How such an institutional arrangement can be achieved with credibility remains to be explored.

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1. Genetically Modified (GM) crops are defined as any plant that has recombinant DNA; that is; where DNA has been extracted from one organism and recombined with the DNA of another.

2. The genes cannot be reclaimed for two reasons. First, in the process of harvesting some kernels (1-5 %) of wheat are left in the field. These genetically engineered seeds can lay dormant in the soil for up to five years, before they germinate in subsequent crops. Given the widespread use of herbicides (particularly glyphosate) the GM-HT wheat will reproduce well in many cropping systems. Once these seeds are mixed into a subsequent wheat crop they will be impossible to isolate. Second, DNA from transgenic varieties can be transferred into traditional crop varieties, as was found in corn (Quist and Chapela).

3. This outcome is evident in canola where the European Union has ceased imports of all varieties of canola from Canada subsequent to the introduction of GM-HT canola varieties.

4. Provided β_1 and β_2 are roots of the fundamental quadratic:
$$Q = \frac{1}{2}(\sigma^2{}_V - 2\rho\sigma_V\sigma_I + \sigma^2{}_I)\beta(\beta-1) + (\delta_I - \delta_V)\beta - \delta_I = 0$$

5. This is calculated by applying the accelerated growth rate to gross wheat returns divided by the net benefits of the GM-HT technology.

6. We ignore changes in domestic consumer welfare because over 85% of Canadian wheat production is exported and Canada is a price taker on the world wheat market with the exception of market premiums realized for Canadian wheat quality characteristics.

7. Volunteer wheat refers to seeds that spill from farm equipment during harvest and germinate in future years. Volunteer wheat can persist in the form of a weed for up to five years after wheat was initially planted.

8. Glyphosate is the active ingredient in the Roundup™ herbicide.

9. The term tank-mix refers to the combination of two herbicides to perform one chemical application.

10. Kuntz identified ten key export markets that Canada risks losing if she were too introduce GM-HT wheat. They are Algeria, Brazil, Iran, Italy, Japan, Malaysia, Morocco, South Korea, United Kingdom, Venezuela, which constitute 35% of total Canadian spring wheat exports.

11. We assume that if Canada licenses a GM-HT wheat variety without a credible segregation system importing countries will assume all wheat in Canada is GM-HT wheat.

12. When calculating the economic rent created from introducing Roundup Ready™ wheat we assumed that the conventional wheat technology is priced competitively.

13. This is an approximation of the maximum segregation cost that makes producers indifferent to adopting the new technology. When segregation occurs the rate of adoption is affected which affects the Roundup Ready™ TUA.

14. This assumes the TUA price does not change with the level of segregation fees.
15. Clearfield™ wheat, developed by mutation breeding is not considered a genetically modified organism and in 2001 would not face GM trade restrictions in the EU or other countries. Roundup Ready™ wheat varieties are GM and do face import bans in the EU and potentially in other countries.

Table 1. Annual Net Returns for Roundup Ready™ Wheat, at Selected TUA Price Levels, with no Segregation (000's of dollars)

TUA Price ($/acre)	% of Total Acres Seeded to Roundup Ready Wheat	Net Return[a] (Monsanto)	Net Return (Adopters)	Net Return (Non Adopters)	Net Return (Wheat Industry)
$5.00	100.00%	$105,625	$94,259	$0.00	$199,884
$12.38	88.08%	$229,800	-$36,885	-$14,905	$178,010
$16.00	54.99%	$185,872	-$39,093	-$56,287	$90,492
$20.00	22.26%	$94,053	-$23,223	-$97,220	-$26,390

Source: authors calculations

[a] We assume that the price of GM-HT wheat seed is set competitively such that it is equal to the marginal cost of reproduction and distribution. Therefore, the net return from the TUA sale is equal to Monsanto's producer surplus.

Table 2. Expected Present Value of Returns and Costs for Roundup Ready™ Wheat (000's of dollars)

	No Segregation	Segregation at Zero Cost
GM-HT Wheat Price Discount (Non Adopters)	$.20 per bushel	$0 per bushel
Optimal TUA Price[a]	$12.38 per acre	$6.25 per acre
Average Annual Agronomic Benefit (Adopters)	$5.00 per acre	$11.13 per acre
Average Annual Environmental Cost (Adopters)	$1.10 per acre	$1.10 per acre
Average Annual Environmental Cost (Non Adopters)	$.225 per acre	$.225 per acre
Roundup Ready™ Wheat Acres	18,590,000	18,590,000
Conventional Wheat Acres	2,535,000	2,535,000
	No Segregation	Segregation at Zero Cost
Present Value of Returns (Monsanto)	$8,851,700	$4,468,750
Present Value of Returns (Adopters)	$3,574,381	$8,182,028
Present Value of Market Loss (Adopters)	$2,896,126	$2,896,126
Present Value of Market Loss (Non Adopters)	$394,926	$0
Present Value of Environmental Costs (Adopters)	$539,121	$539,120
Present Value of Environmental Costs (Non Adopters)	$15,010	$15,010
Wheat Industry Return/Cost Ratio	3.23	3.67
Producer Return/Cost Ratio	0.93	2.37

Source: authors calculations

[a] The expected present value of returns and costs is calculated using a 5 % discount rate. The growth rate of returns and costs is 2.4% and 1.2 % respectively.

Table 3. Maximum Segregation Fee Producers will Pay

	All Producers Pay (Segregation Fee -$.01 per bushel)	Non Adopters Pay (Segregation Fee- $.08 per bushel)
	(000's of dollars)	(000's of dollars)
Present Value of Returns (Adopters)	$8,182,028	$8,182,028
Present Value of Market Loss (Adopters)	$3,040,933	$2,896,126
Present Value of Market Loss (Non Adopters)	$19,746	$157,971
Present Value of Environmental Costs (Adopters)	$539,120	$539,120
Present Value of Environmental Costs (Non Adopters)	$15,010	$15,010
Producer Return/Cost Ratio	2.27	2.27

Source: authors calculations

Table 4. Optimal Threshold Values for Alternative Parameters Estimates

| Parameters	Base values	high μ	low μ	high α_V	low α_V	no $\rho_{V,I}$	high $\rho_{V,I}$	Low σ_v	High σ_v
α_V	**0.02**	**0.02**	**0.02**	**0.05**	**0.01**	**0.02**	**0.02**	**0.02**	**0.02**
μ	**0.05**	**0.10**	**0.03**	0.05	0.05	0.05	0.05	0.05	0.05
$\rho_{V,I}$	**0.50**	0.50	0.50	0.50	0.50	**0.00**	**0.80**	0.50	0.50
δ_V	**0.03**	0.08	0.00	0.00	0.04	0.03	0.03	0.03	0.03
δ_I	**0.04**	0.09	0.01	0.03	0.04	0.05	0.03	0.04	0.04
σ_v	**0.07**	0.07	0.07	0.07	0.07	0.08	0.06	0.03	0.14
β_1	**1.79**	2.32	1.38	1.74	1.80	1.94	1.67	2.36	1.44
Optimal v*	**2.27**	**1.76**	**3.66**	**2.34**	**2.25**	**2.06**	**2.49**	**1.73**	**3.25**

Source: authors calculations
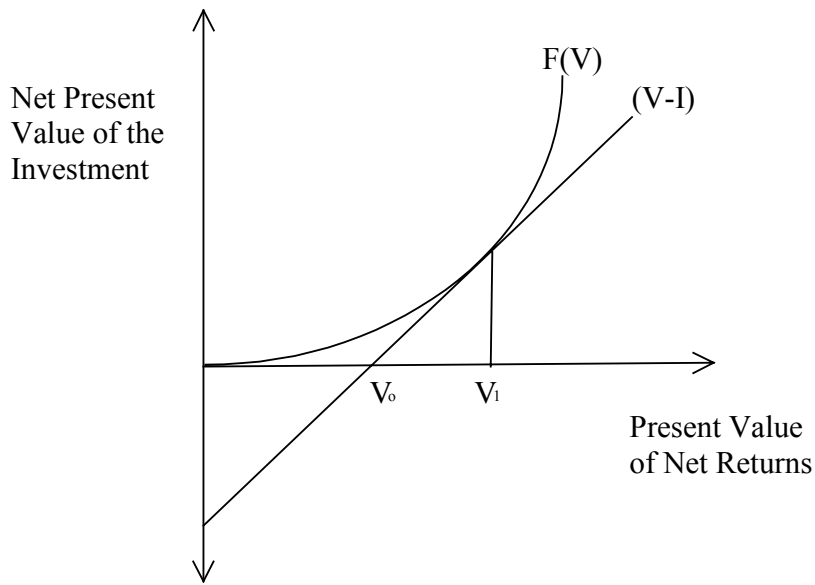
Figure 1. Optimal Time to License GM-HT Wheat
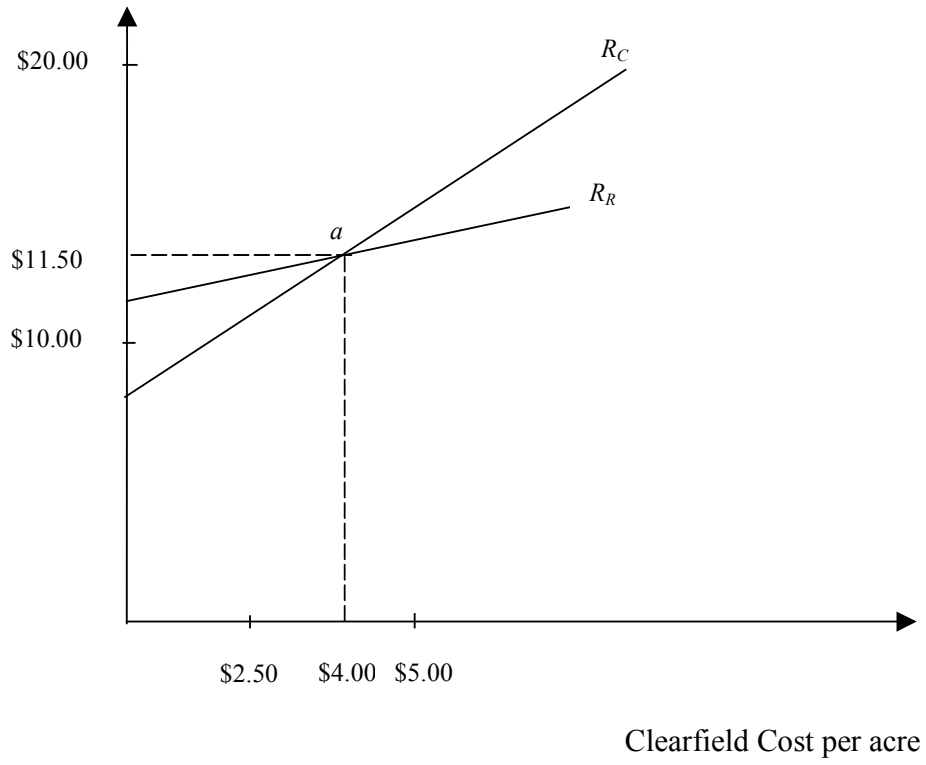
TUA Cost per Acre

Figure 2. Bertrand Best Response Functions for
Roundup Ready™ and Clearfield™ Wheat