ENVIRONMENTAL CONCERNS AND RISKS OF GENETICALLY MODIFIED CROPS: ECONOMIC CONTRIBUTIONS TO THE DEBATE

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INTRODUCTION
The adoption and release of genetically modified (GM) crops is the focus of a contentious debate. On the one hand, this new technology has been adopted rapidly by many producers. It is estimated that 40.5 million hectares were planted worldwide in 1999 (The Economist 1999), an increase of 13 million hectares from 1998 and four times the amount planted in 1997 (James 1998). The popularity of GM crops is owed to genetic modifications that have added traits such as herbicide tolerance and pest resistance that lower average input costs (ERS 1999).

On the other hand, despite broad acceptance in some farming circles, and the potential for numerous environmental, health and other benefits, the release of GM crops is the subject of international scrutiny and controversy regarding their safety (see in this issue, Perdikis and Kerr; Hobbs and Plunkett). Of particular concern in both the popular press (e.g., Bonham 1999) and some scientific articles (Butler et al. 1999) is the potential for the widespread release of GM crops to result in environmental externalities, including irreversible environmental damage. In part, this view is fostered by concerns that GM crops are being released too quickly and without adequate knowledge of their long term environmental impacts (Mander and Goldsmith 1996; Butler et al. 1999) or, in some countries, without procedures to deal with environmental problems that may occur (Hruska and Lara Pavón 1997).

Currently the decision to release a GM crop within Canada or the United States is based on an assessment of the risks of environmental, health and other potential damages. Although considerable research is being undertaken to understand these risks, opinions differ regarding the probability of environmental damage. In this paper, a simple theoretical framework is used to demonstrate that the current decision framework could be improved by considering additional factors such as economic benefits and potential costs. In some cases, this additional information could lead to decisions that are the polar opposite of those suggested under the existing risk assessments. It is demonstrated that even when the probability of an adverse event occurring is high (low), there may be net benefits (net costs) from releasing the GM crop.

Releases of GM crops are complicated by the potential for irreversible environmental damage that can change the long term profitability of production decisions. The frameworks presented clearly demonstrate that economic analysis can be used to improve current decisions to release GM crops.

POTENTIAL ENVIRONMENTAL BENEFITS AND COSTS
Much debate surrounding the release of GM crops into the environment centers around the promise of environmental, production and other benefits versus the chance of environmental damage. If the probability of environmental damage was known with certainty the assessment of whether or not to release a GM

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crop would be open to less debate. Some potential environmental benefits and costs are summarized in the following sections.¹

**Potential Benefits**
Probably the most common genetic modification to agricultural crops that results in environmental benefits is the addition or modification of genes to create resistance to certain insect pests or to tolerate specific herbicides.² The most successful strategy for insect resistance has been to transfer genes from *Bacillus thuringiensis* (*Bt.*) to agricultural crops. The *Bt.* produces proteins that are toxic to some insects. Novartis AG, a large Swiss pharmaceutical firm, developed *Bt.* corn that kills the European Corn Borer without the use of insecticides. Similarly, varieties of canola, flax, corn, cotton and other agricultural crops have been modified to permit them to resist broad-spectrum herbicides such as glyphosate, glufosinate, bromoxynil and bialaphos. Crops with “built in” resistance to insect pests can reduce the application of insecticides (ERS 1999) and potentially decrease environmental externalities such as chemical residues and deaths of non-target organisms. Herbicide tolerant crops enable producers to use herbicides more effectively, killing weeds with fewer chemical applications (ERS 1999). It is anticipated that genetic engineering can be used to make crops resistant to major diseases and environmental stresses that traditionally have caused large losses, thereby not only stabilizing yields but also reducing the use of fungicides and other agents that inhibit the onset of diseases.

**Potential Costs**
Although many scientists consider biotechnology to be environmentally benign, a growing number are expressing concern about the potential for environmental damages from GM crops; (many studies have been summarized by Clark 1997; 1998; 1999 and Krimsky and Wrubel 1996). The following sections summarize the major potential problems.

*Evolution of Resistance in Target Organisms*
The development of herbicide resistant GM crops encourages regular use of a single herbicide that, over time, could lead to an increase in herbicide resistance of weed populations. Herbicide resistance leads to the unwanted persistence of weedy plants in agricultural areas and can increase production costs. In a worldwide survey, Holt and LeBaron (1990) noted that more than one hundred species of weeds had become resistant to one or more herbicides. Heap (1999a) indicated that this figure has increased to 216 herbicide resistant weeds worldwide in 1998, of which 74 resistant weeds are present in the US and 24 in Canada (Heap 1999b).

There also is potential for insect resistance as a result of frequent exposure to *Bt.* crops. It has become evident that plants give off varying dosages of *Bt.*, depending on their growth stage, weather conditions and other factors. This can create conditions that encourage and facilitate the development of resistance (Clark 1999). Evidence is accumulating that at least some insects will become resistant to *Bt.* sprays (Tabashnik 1994).³ These are used routinely to control insects by organic farmers and in integrated pest management schemes. Wide-scale resistance to *Bt.* would have devastating effects on their abilities to produce products profitably.

*Risk of Out-Crossing with Wild and Weedy Relatives*
Major agricultural crops such as oats, barley, canola, sorghum, potatoes and alfalfa are genetically similar to weedy relatives. It is possible that GM crops will cross pollinate with wild relatives (where they exist), thereby transferring the resistance genes (or other modified traits) to fertile, hardy weeds that could be difficult to control. The Canadian Food Inspection Agency has conceded that gene flow from Monsanto’s Roundup Ready canola is possible but they believe it will not result in increased weediness or invasiveness of these relatives (Lammers-Helps 1998). Rissler and Mellon (1996) noted that the significance of gene flow will be dependent on factors such as the proximity of the GM crop to wild and weedy relatives and the ability of the new gene to confer a competitive advan-
tage upon the weedy relative. Out-crossing could result in a number of undesirable environmental consequences including altered community structure, food chain composition and genetic and biologic diversity in addition to the persistence of weeds on agricultural lands or adjacent wild habitat (Rissler and Mellon 1996; Adam and Kohler 1996; Saat 1996).

Possible Contamination of Terminator Genes in Domestic Crops

The so called terminator genes (two genes from bacteria and one from a plant) can be added to crops to prevent seed germination in the year following planting and harvesting. The potential exists for pollen from terminator plants to fertilize neighboring fields. This could be a serious problem in developing countries where a high proportion of crops are grown from farmer-saved seed (Clark 1999). On the other hand, sterile seed cannot contaminate a gene pool. If plants with terminator genes cross-pollinate with a related species, the seed produced would not germinate if the trait was passed on (Country Guide 1998).

Other Unintended Environmental Effects

It is possible that GM crops may themselves become weeds and persist unwanted on agricultural lands. In addition, GM crops that produce pesticides or pharmaceutical products could kill non-target and even beneficial insects and fungi (Rissler and Mellon 1996).

CURRENT RISK ASSESSMENT

Current decisions to release GM crops take a product based approach rather than a process based approach (Dron and Weil 1997; CFIA 1997). Neither Canada nor the US have passed specific laws that relate to the use and release of GM crops (Mann 1999; CFIA 1997), opting instead to use existing regulations and institutions. In Canada, the release of GM plants is assessed by several departments of the federal government, including Environment Canada, Health Canada and Agriculture and Agri-Food Canada. In the United States, USDA/APHIS (Animal Plant Health Inspection Service) and EPA (Environmental Protection Agency) play the most prominent roles in decision making. Both Canada and the US have taken similar risk-based approaches in their environmental assessments prior to approval and release of GM crops. Risks that GM crops might pose to the environment, humans or non-target organisms are assessed before approvals are granted. Information regarding field trial design, the manner of genetic modification, proximity to wild and weedy relatives (among other factors) are used in the assessment process (CFIA 1994; personal communication, APHIS and EPA). Under limited circumstances, the EPA conducts benefit assessments to evaluate whether releasing the GM crop will result in positive economic benefits (but they do not evaluate net benefits).

One of the major concerns in the release of GM crops is that off-farm environmental effects of biotechnology will not be effectively internalized in private decisions. Incomplete or non-existent markets for “environmental services” means that individual production decisions can result in externalities that alter the provision or quality of environmental services and lead to inefficient use of societal resources. These economic consequences are not counted in the decision criteria currently used by agencies to determine whether or not a GM crop can be released. The following analysis demonstrates that accounting for the social costs and benefits of GM crops in addition to the risk of environmental damage can result in more efficient decision criteria regarding the release of a GM crop.

ECONOMIC ISSUES REGARDING GENETICALLY MODIFIED CROPS

The economic benefits of GM crops are reasonably well known. However, the costs of undesirable and perhaps irreversible environmental outcomes are harder to estimate. The economics discipline is well suited to assessing tradeoffs and can contribute to development of public policy by providing a rigorous and defensible framework to evaluate costs and benefits associated with introducing GM crops as well as insights into investment decisions in the face of irreversibility.
Current Decision Criteria – The “Probability Rule”

The current decision rule regarding the approval and release of genetically modified crops is represented in the following stylized framework. The decision to release a GM crop into the environment is based on the probability ($p$) of an adverse event occurring, where $0 < p < 1$. Let $p^T$ represent some threshold probability of an adverse event that determines whether a GM crop can be released. If $p \leq p^T$ the GM crop is approved for release and any quantity of the crop can be planted. If $p > p^T$ the GM crop should not be released. This decision rule can be called the probability rule.

Economic Decision Criteria - The “Net Benefit Rule”

A framework that is frequently used to examine the tradeoffs between the potential costs and benefits of undertaking a project is benefit-cost analysis (Arrow et al. 1996). Incorporating economic factors into the decision to release GM crops allows decision makers to assess whether or not the economic benefits of release ($B$) exceed the costs ($C$) as in (1).\(^3\)

$$B - C > 0$$

The benefits and costs generally occur over a time period greater than one year and then should be discounted by an appropriate discount factor (Zerbe and Dively 1994).

Assume initially that the proposed release will take place over an environmentally homogeneous area and all costs and benefits occur over time period $t$. The benefits $B_t$ from release are known with certainty as are some costs $C^k_t$. The environmental costs associated with the adverse event $C^e_t$ occur with probability $p$. The discount factor is $d_t$, where $d_t = 1/(1 + r)^t$ and $r$ is the social rate of time preference. The decision rule for release of GM crops becomes

$$d_t (B_t - C^k_t - pC^e_t) > 0$$

If the discounted benefits of release exceed the discounted probability weighted costs of release then this net benefit rule indicates that the crop should be released. If the discounted net benefits are less than zero, then the crop should not be released.

Comparison of Decision Outcomes Under the Probability and Net Benefit Rules

Four possible outcomes could occur when evaluating the release of a GM crop (Table 1). In cases (i) and (iv), the probability rule and the net benefit rule result in the same decision. However, the remaining cases result in different decisions depending on whether the probability or net benefit rule is applied. In case ii) the GM crop would be released under the probability rule as $p \leq p^T$. However, the net benefit rule shows that the net benefits from release are negative and, therefore, the crop should not be released. The opposite situation is reflected in case iii).

The example above clearly illustrates that a decision rule based on the probability of an adverse event occurring with no regard for net economic benefits may lead to imprudent releases of some GM crops and pose an impediment to the release of other economically beneficial GM crops. It is apparent that a high probability of an adverse event, such as outcrossing, may not be sufficient reason to prevent release of the crop if the net benefits from release are positive. Perhaps more worrisome is case ii) where the release of the GM crop is associated with a low probability of an adverse event but the weighted costs outweigh the eco-

<table>
<thead>
<tr>
<th>Positive Net Benefit</th>
<th>Negative Net Benefit</th>
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<tbody>
<tr>
<td>Low Probability</td>
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<tr>
<td>(i)</td>
<td>$p \leq p^T$ and $d_t(B_t - C^k_t - pC^e_t) &gt; 0$</td>
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<tr>
<td>High Probability</td>
<td></td>
</tr>
<tr>
<td>(ii)</td>
<td>$p \leq p^T$ and $d_t(B_t - C^k_t - pC^e_t) &lt; 0$</td>
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Table 1. Possible Probability and Net Benefit Outcomes
nomic benefits from release. Under the current decision framework it is possible for this scenario to occur.

IMPLEMENTING THE "NET-BENEFIT RULE"

The current decision framework for the release of GM crops can lead to outcomes that result in a net economic loss for society. Net benefits to society can be improved by considering economic benefits and costs. However, a number of information requirements must be resolved if the net-benefit rule is to be implemented.

The potential economic benefits and environmental costs can be estimated using standard tools within the economics discipline. If the magnitudes of benefits or costs are uncertain, the analysis could be conducted several times to assess the sensitivity of outcomes to changes in initial assumptions.

Although the probability of an adverse event occurring cannot be known with certainty, it may be described in qualitative terms; for example "low", "medium" or "high". Even without obtaining the objective probability of an adverse event, the economic framework can improve decisions by identifying a threshold probability level, on a case by case basis, at which the net-benefits from release are positive. With information about potential economic benefits and costs the framework can be used to work back to a threshold probability \( p^T \), below which there are net-benefits from the release of a GM crop. If the likelihood of an adverse event occurring is "high" and the estimate of \( p^T \) is close to zero, then the release of the crop is not likely to result in net benefits. Similarly, if \( p^T \) is close to one and qualitative estimates place the probability of an adverse event as "low", then releasing the crop may result in positive net benefits to society. Of course there are a number of problematic cases such as when the estimate of \( p^T \) is close to zero and the probability of an adverse event is low.

INVESTMENT UNDER IRREVERSIBILITY

The example above indicates that economic analysis can contribute valuable information to the decision making process currently used for the release of GM crops even in the face of uncertain environmental costs. However, it does not provide any insights into decision making under the potential for irreversibility. Henry (1974: 1006) stated that a decision can be considered irreversible "if it significantly reduces for a long time the variety of choices that would be possible in the future". This situation is common in many actions that affect the environment (Viscusi 1985). For example, the decision to cultivate new varieties or types of agricultural crops may affect the stability of local ecosystems and change plant communities and wildlife habitats. An irreversible outcome might impose constraints on the range of actions that can be taken at a later date (Miller and Lad 1984) and lead to long run welfare losses (Fisher and Krutilla 1974).

Many models of irreversibility consider problems of large capital investments (e.g., dams) that cannot be removed once they have been put in place (Arrow and Fisher 1974; Fisher and Krutilla 1974; Viscusi 1985). These ideas can be applied to the problem of planting GM crops that could result in future irreversible environmental damages.

A two-period decision model of planting decisions that incorporates irreversible environmental damage is developed below. In each period a producer chooses between planting or not planting a GM crop. It is assumed that any environmental costs associated with planting a GM crop exhibit downward irreversibility (that is, environmental costs incurred as a result of planting a GM crop in period 1 remain at the start of period 2 and add to costs in period 2).

Define the following:

\[ B_t = \text{benefits in period } t, \text{ where } t = 1, 2. \]

\[ C^e_t = \text{costs (excluding environmental costs) in period } t \]

\[ C^e_t = \text{environmental costs in period } t \]

\[ d_t = \text{discount factor} \]

\[ C^1 \leq C^2 \text{ costs associated with environmental damage are irreversible.} \]

The problem is to maximize the discounted present value (PV) of a decision to plant a GM crop in the first period, the second period, both periods, or not at all (net of the irreversible
environmental costs). Four cases arise:

Case 1. If \( C_1 > B_1 - C_{x1} \) and \( d_2C_2 > d_2(B_2 - C_{x2}) \), PV is maximized by not planting a GM crop in either period and \( PV_{max} = 0 \).

Case 2. If \( C_1 > B_1 - C_{x1} \) and \( d_2C_2 < d_2(B_2 - C_{x2}) \), PV is maximized by not planting a GM crop in period 1 but choosing to plant a GM crop in period 2, thus \( PV_{max} = d_2(B_2 - C_{x2} - C_2) \).

Case 3. If \( C_1 < B_1 - C_{x1} \) and \( d_2C_2 < d_2(B_2 - C_{x2}) \), PV is maximized by planting a GM crop in both periods. In this case \( PV_{max} = (B_1 - C_{x1} - C_2) + d_2(B_2 - C_{x2} - C_2) \).

Case 4. If \( C_1 < B_1 - C_{x1} \), indicating a GM crop should be planted in period 1; but \( d_2C_2 > d_2(B_2 - C_{x2}) \), indicating that it should not be planted in period 2, what action should be undertaken to maximize PV? This is the most interesting case because the problem of irreversibility must be faced. If the environmental costs associated with planting the GM crop in period 1 were reversible then \( PV_{max} = (B_1 - C_{x1} - C_2) \). However, by assumption, any environmental costs incurred in period 1 are irreversible and continue in period 2 as \( C_1 \leq C_2 \), leaving 2 choices. The first is to plant a GM crop in period 1 if \( C_1 + d_2C_2 < B_1 - C_{x1} \) in which case \( PV_{max} = (B_1 - C_{x1} - C_2) - d_2C_2 \). The second choice is not to plant a GM crop in either period if \( C_1 + d_2C_2 > (B_1 - C_{x1}) \) in which case \( PV_{max} = 0 \). The outcomes in both cases show that the net present value from planting a GM crop under a situation of irreversible environmental damage is less than would be the case where damages are reversible. Irreversibility can reduce the long term benefits from planting GM crops and makes them a less attractive cropping choice.

**DISCUSSION AND CONCLUSIONS**

Urban (1998) noted that the "how" of food production has significant consequences for soil, water and air quality, and these environmental concerns likely will shape much of food consumers’ demands in the future. A highly efficient and sustainable agricultural industry is in the best interests of everyone. New technologies will remain a major component of commercial agriculture.

The economic pressure to develop and market commercial products within a relatively short time frame has meant that GM crops have been released without a complete understanding of how the genetic modifications may manifest themselves in the environment. As noted by Krimsky and Wrubel (1996), none of the experts suggest there are no risks. However, large differences of opinion exist about the probabilities and costs of adverse environmental effects.

Basing decisions to release new crops purely on environmental, health and other risks can reduce societal welfare. The present decision framework does not account for irreversibility or provide any guidelines regarding how to proceed in the face of irreversibility. Economic analysis can provide a valuable contribution to the way decisions are made regarding the release of GM crops by ensuring that releases result in net benefits to society. The simple framework constructed in this paper illustrates that under irreversibility a more conservative approval and release path is warranted.

It is clear that there is a need for well-documented studies of the risks involved in large-scale approval of biotechnology products in agriculture. In addition, the distributional consequences of technological adoption merit further examination. Management strategies that limit the environmental consequences of genetically modified organisms need to be studied. Release of herbicide or insect resistant plants without adequate resistance management programs in place courts potential disaster. In North America, farmers who choose to grow Bt corn must sign an agreement to grow "refuge" corn (a similar but non-Bt hybrid) alongside the Bt variety. It is hoped that any European Corn Borers that begin to develop resistance will have a good supply of susceptible corn borers with whom to mate, thus slowing the onset of Bt resistance (Whetter 1998). This type of environmental management strategy, while not eliminating potential problems, at least works towards minimizing them.
NOTES

1 There may be additional benefits and costs from releasing GM crops (e.g., health effects and improvements in production) that are not discussed in this paper.

2 Modifications that provide other benefits are discussed in Marks, Freeze and Kalaitzandonakes in this issue.

3 Georghiou and Lagunes-Tejeda (1991) stated that more than 500 species of insects are resistant to one or more insecticides and cross-resistance to several types of insecticides has become common.

4 In an open letter dated October 4th, 1999, Monsanto CEO Robert Shapiro expressed a commitment not to commercialize gene protection systems that render seed sterile, such as the terminator genes, until a “full airing of the issues is complete” (Monsanto 1999).

5 Benefit-cost analysis does not guarantee that the decision to release a GM crop is economically efficient unless the release maximizes the present value of net benefits (Tietenberg 1996).

6 It is implicitly assumed that the producer bears all the resulting environmental costs.

REFERENCES


