Uncertainty aversion in Australian regulation of agricultural gene technology

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Abstract

There is potential for over-provision of environmental harms and under-provision of environmental benefits associated with GM crops. As a result, strong public regulation is needed to ensure that full social values are considered. However, one reason for opposition to GM crops is a lack of public trust in regulatory institutions and science, and the limited opportunities afforded to public-participation and non-scientific concerns. We aim to demonstrate the trade-off between social cost and managing the risks of gene flow arising from environmental release of GM canola in Australia, using the framework of a probabilistic risk assessment and safety-rule decision mechanism.

Keywords: safety-rule, uncertainty, biotechnology regulation, canola.

Introduction

Biotechnology has been described as the next great wave of technological change, yet genetically modified crops (GM crops) are often described as a continuum of the husbandry techniques used in thousands of years of agriculture. Broadly defined, biotechnology refers to the use of biological processes for commercial purposes (Polya 1999). On the other hand, modern biotechnology or gene technology describes the newly developed processes of molecular biology used to insert relatively few genes into an organism's genome to form new combinations of genetic material (Tester 2001).

Despite rapid development and global adoption of GM crops, and despite assurances by proponents of gene technology, public opinion does not accept GM crops as an extension of familiar agricultural products and conventional crop improvement techniques (Jackson and Villinski 2002). Instead, public responses to agricultural gene technology are seen as part of a wider shift in social attitudes to viewing technology and scientific advances as a cause rather than a solution to social problems. Focus groups assessing Australian attitudes towards GM crops reflect this observation, as well as mistrust of the profit motive underlying biotechnology research and the independence of the Australian Gene Technology Regulator (Dietrich and Schibeci 2003). Although such concerns have not proven an insurmountable barrier to commercialisation of GM crops, there remains an opportunity to enhance trust in gene technology regulation in Australia.

In this paper we outline a mechanism for public participation in the regulatory process in Australia, using the framework of a probabilistic risk assessment and safety-rule decision mechanism. Advantages of this framework include its explicit treatment of uncertainty and its emphasis on the policy parameters, namely acceptable risk and the margin of safety. In the next section we discuss the relevance of our case study, GM herbicide tolerant canola, and then we outline some applications of the safety rule decision mechanism from the literature. We conclude by describing how this framework might apply to GM canola.

Background

A significant objection to the Australian system to regulate gene technology, the *Gene Technology Act 2000 (Cth)* (the *GT* Act), is the prominence given to science-based risk assessment. The Gene Technology Regulator's[1] decision to approve commercial release of GM herbicide tolerant canola is a case in point. Although the Regulator determined that the risks posed by GM canola were no greater than those of non-GM canola, her decision was criticised for excluding consideration of socio-economic and philosophical objections to gene technology. This exclusion is according to the scope of the risk assessment procedures under the *GT* Act. However, Lawson (2002) has argued that the decision to allow environmental release of GM canola (or any genetically modified organism) was the outcome of the type of value-judgements the *GT* Act intended to exclude. Having accepted the possibility of adverse consequences from environmental release, the Regulator's decision to approve release implied that she considers those consequences acceptable, and that the benefits of GM canola exceed the costs. Lawson and Hindmarsh (2006) have also argued that the Regulator makes a further value-judgement in setting the threshold value for unacceptable risks, and in deciding that risks below the threshold value are acceptable.

A significant concern over environmental release is whether conventional and organic cropping systems (including non-canola cropping systems) can co-exist with GM canola. Contamination of non-GM canola on-farm is a hazard associated with the risk of gene flow to wild or weedy relatives and non-GM canola.

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[1] The Gene Technology Regulator is Dr Sue Meeks.

Gene flow is the natural process of the movement of genes between individual organisms. In plants this occurs mainly by pollen from one plant successfully cross-pollinating a flower on another plant, which in turn produces a viable seed (Glover 2002). It is certain that 100% effective segregation of GM and non-GM canola is impossible, and likewise a zero tolerance threshold for adventitious presence of GM material in organic produce (Brookes 2004), which may block access to some markets. There are also potential hazards for agricultural and natural ecosystems as a result of gene flow from GM canola. Because canola belongs to the *Brassicaceae* family, which includes species that are agricultural weeds in most states, the likelihood of hybrid formation with weedy or wild relatives is an issue. A potential consequences of crop-to-wild relative gene flow is loss of biodiversity, especially if the wild species is rare (Messeguer 2003). However, crop-to-crop gene flow may lead to greater agricultural risks than those from the movement of transgenes for herbicide tolerance to wild relatives (Ellstrand 2001). One hazard that has already been realised is volunteer canola plants stacked with transgenes for resistance to more than one herbicide.

Canola (*Brassica napus*) is predominantly self-fertilising, but it has some potential for out-crossing, and it is on account of this attribute that gene flow from GM canola has the potential to impact farm or local environments in Australia. The frequency of hybrid formation between canola and the most significant agricultural weeds is low and the impact depends on the transgene and the trait it encodes as well as the environment of the recipient plant. However, estimates of potential rates of crop-to-crop out-crossing vary around 30%. Research shows pollen dispersal follows a leptokurtic distribution with most pollen travelling less than 10 metres from its source. However, wind and insect borne pollen have been found at distances of 1.5km and 4km, respectively (Salisbury 2002) and Australian studies show a more variable pollen distribution (Rieger *et al.* 2002).

Complete containment of transgenes is both impractical and impossible; therefore strategies to keep containment within certain thresholds include isolation distances and rows of refuge crop. Isolation distances of 4km have been proposed to prevent unwanted out-crossing on a commercial scale (Timmons *et al.* (1996) in Downey 1999), while the UK Supply Chain Initiative on Modified Agricultural Crops (SCIMAC) guidelines specify a precautionary approach of 50m for non-GM canola, and 200m for certified canola seed crops and registered organic canola (Brookes 2004). Otherwise, recommended isolation distances for contamination thresholds range from 1.5 to 30 metres for a less than 1% threshold of seed purity, 10-120 metres for 0.5% seed purity, and 100-400 metres for a less than 0.1% threshold (Salisbury 2002). However, Kareiva and Marvier (2000) note that barren zones can increase the mean amount or distance of gene flow out of plots, and Reboud (2003) suggests that removing border rows to trap pollen after flowering is a more effective strategy for short distances.

Because transgene escape is inevitable, the possible impacts of transgenes on ecosystems and the likely contamination of non-GM producers are significant concerns. Our intention is to help provide another opportunity for public participation in the belief that this will help bring about a social consensus on agricultural gene technology. One suggested reason for the lack of a social consensus is that agricultural gene technology is a 'technology in search of applications', that GM crops are an autonomous rather than induced innovation (Hacking (1986) in Batie and Ervin 2001). Because autonomous innovations arise out of scientific advances rather than consumer or producer demand, they are less likely to be guided by full social values. Welsh and Ervin (2006) argue that public participation can generate incentives to develop GM crops that reflect social values, such as GM crops with publically identified preferred traits like non-toxic approaches to pest control. However, the prevalence of herbicide tolerant and insect resistant GM crops worldwide suggests such traits will persist even with incentives to develop GM crops outside the traditional 'pesticide paradigm' of pest control (Welsh and Ervin 2006, p. 168).

There is an opportunity for considering non-scientific concerns without detracting from the scientific risk assessment and precautionary approach specified by the *GT* Act. Johnson *et al.* (2006) note that the outcome of scientific risk assessment is not the only factor on which the decision to allow commercial release of GM crops is made. That decision is made based on the acceptable level of risk, a political decision that should take into account social values. Focusing on the risk of gene flow from environmental release of GM canola, our aim then is to demonstrate the trade-offs between managing the risk of gene flow and the costs of achieving varying levels of acceptable risk for a given margin of safety, using the framework of a probabilistic risk assessment with a safety rule decision mechanism. Both parameters are central to public debates over risk regulation, and amount to value-judgements rather than scientific rules: Thus, it is important to know the economic impacts of alternative parameter specifications (Haight 1995). We hope that this research will provide an opportunity for public participation in the decision-making process for approving release of GM crops into the Australian environment; specifically, the choice of the acceptable level of risk.

Applications of the safety rule decision mechanism

Even though gene flow from GM canola is no more likely than gene flow from conventional canola, because gene technology makes gene flow across evolutionary barriers possible it presents regulators with a novel category of risk. Nevertheless, agricultural gene technology shares some common attributes with other technologies that pose environmental risks. This includes a high degree of uncertainty about the magnitude of the risks posed that is held in distinct aversion by both regulators and the public. Uncertainty about the factors underlying environmental processes complicates prediction of future outcomes, so that a mechanism to take into account that uncertainty is vital for environmental decision making. Unlike risky decisions in which the decision maker can identify all the possible outcomes and probabilities for each management strategy, environmental management decisions are more often characterised by true uncertainty, whereby there is not enough information to identify all outcomes and/or their probabilities of occurrence (Marshall *et al.* 1998). Evaluations of environmental health risk using benefit cost analysis ignore uncertainty arising from stochastic environmental effects when employing estimates based on average risk (Lichtenberg *et al.* 1989). Traditional probability-based models of risk in decision-making such as expected utility may not deal appropriately with uncertainty in environmental decision making or be consistent with the management objective. In these cases, policy responses commonly demonstrate an aversion to uncertainty and a corresponding desire for a policy approach that is precautionary in nature. For example, regulators may be required to undertake to protect health within a minimum standard of safety or to ensure population viability of endangered species.

The safety rule decision mechanism corresponds more closely to the terms of environmental legislation that require regulators to balance social cost against ensuring adequate protection. The safety rule condition specifies that risk be constrained to remain below a given maximum allowable or acceptable level (such as a risk standard) within a given margin of safety (Lichtenberg *et al.* 1989). In the event that the realisation of adverse outcomes is uncertain, regulators can act to limit the frequency with which the maximum acceptable levels of those outcomes are exceeded.

Consider the methodology proposed by Lichtenberg and Zilberman (1988), who combine a probabilistic health risk assessment with a safety-rule decision mechanism. Uncertainty is a principal characteristic of many environmental health problems and consistently an obstacle to developing appropriate policies to address them. The authors define risk as the probability that an individual selected randomly from a population contracts an adverse health effect. Because the relationship between risk and the variables that generate it is not known with certainty, health risk estimates used for policy evaluation are subject to error, and uncertainty is defined as a measure of the magnitude of this error. Their methodology takes into account this uncertainty by specifying probability distributions for the factors that cause risk, and examines the characteristics of the optimal mix of policies for achieving a given risk standard with a given margin of safety. The regulator acts to limit the frequency of violations of this predetermined standard; that is, to ensure that an adverse outcome exceeds some maximum allowable level no more than an accepted fraction of the time.

The log of overall health risk is $Y = \sum_{i=1}^{n} X_i$, where $X_i, i = 1,...,n$ denote the log of the *i*th parameter. The authors assume that the original parameters have a joint lognormal distribution such that $X_i, i = 1,...,n$ have a joint normal distribution. X_i have mean M_i and variance S_i^2, and X_i and X_j have covariance $\sum_{i \neq j} r_{ij} S_i S_j$. If the social cost of regulation is R, then the regulator's problem is to choose a set of policies to minimise R subject to the constraint that $\Pr\{Y \geq Y_0\} \leq 1 - P$.

If $Y(P)$ is the level of log risk exceeded with probability $1-P$, $F(P)$ is the critical value of the standard normal distribution which is exceeded with probability $1-P$, and $Y(P)$ is a normally distributed random variable, $F(P) = \left[Y(P) - EY\right] / S_Y$, then

$$Y(P) = EY + F(P)S_Y = \sum_{i=1}^{n} M_i + F(P)\left[\sum_{i=1}^{n} S_i^2 + \sum_{i \neq j} r_{ij} S_i S_j\right]^{1/2}. \tag{1}$$

The constraint that $\Pr\{Y \geq Y_0\} \leq 1 - P$ is equivalent to the condition $Y(P) \leq Y_0$, namely

$$Y(P) = EY + F(P)S_Y = \sum_{i=1}^{n} M_i + F(P)\left[\sum_{i=1}^{n} S_i^2 + \sum_{i \neq j} r_{ij} S_i S_j\right]^{1/2} \leq Y_0. \tag{2}$$

The above specification implies that regulatory decisions are based on two parameters: maximum allowable log risk (Y_0) and the margin of safety P, which Lichtenberg and Zilberman (1988) note are central to public debates over risk regulation. Moreover, log risk is expressed as a combination of mean risk and uncertainty, where uncertainty is weighted by the constant $F(P)$. The authors interpret $F(P)$ as an expression of the regulator's aversion to uncertainty. Setting $P = \frac{1}{2}$ $(F(P) = 0)$ is the equivalent of neutrality with respect to log risk, and the higher P, the larger $F(P)$ and the greater the weight placed on uncertainty. Lichtenberg *et al.* (1989) argue that this corresponds to a 'disaster-avoidance' approach to decision-making. By focusing on unacceptably bad outcomes, this approach is in line with apparent regulatory and public preferences.

The model has been applied to groundwater contamination (Lichtenberg *et al.* 1989) and pesticide regulation (Harper and Zilberman 1992) among other health risk issues. Willett and Willett (2007) apply the safety-rule framework to examine the opportunity costs of health-based restrictions on pesticides in groundwater under uncertainty. The regulator acts to minimise the opportunity cost of an environmental policy decision, measured as the difference in profit levels with and in the absence of pesticide regulation. Profitability levels are based on a protocol using stochastic simulation and mathematical programming techniques to describe farming activities. Lichtenberg *et al* (1989) also consider the instrument choices and social costs when the choice of risk standard is no longer exogenous to the analysis, by examining the trade-off curve between social cost and risk under any given margin of safety. Trade-off curves are derived by solving the cost minimisation problem for every relevant risk standard under a given margin of safety. The solution for each risk standard represents the cost-efficient portfolio of policies for that risk standard and margin of safety, $R^*(Y_0, P)$. Substitution into the social cost function yields an uncertainty-adjusted cost curve for risk reduction, $R(Y_0, P)$.

Safety-rule decision mechanisms are also used in the literature on conservation planning, such as in Haight (1995) and Marshall *et al*. (1998). Haight (1995) employs a safety-rule decision mechanism in allocating a forest area between the competing uses of timber production and habitat preservation. The decision problem is to maximise the present value of timber harvest revenue subject to maintaining species population viability. Because population dynamics during the management period are uncertain, the viability constraint is expressed as a safety-rule, $\Pr\{N < S\} \leq \alpha$, where N is population size at the end of the management period, S is a predefined target population size, below which the population is subject to an unacceptable risk of extinction, and α is the maximum acceptable risk the standard will not be achieved. The margin of safety $(1-\alpha)$ is the minimum acceptable probability of achieving the standard, in recognition of the uncertainties in population prediction. Marshall *et al*. (1998) use the same model form to evaluate the trade-offs among the costs of alternative warbler management strategies and the elements S and α of the objective function, where stochastic simulation is used to translate Warbler natural history and management parameters into possible distributions of population sizes at the end of the management period.

Lichtenberg (2006) has suggested that the safety-rule decision mechanism can be applied to agricultural gene technology regulation. He identifies three general categories of (environmental) risk-generating factors of agricultural gene technology:

- I, the rate at which the genetically modified organism (GMO) is introduced into the environment, e.g. land allocated to growing transgenic crops;

- F, environmental fate or transport, the rate at which the GMO disseminates through the environment, e.g. the movement of pollen or other vectors of genetic material; and
- S, the susceptibility of relevant (non-target) organisms to the GMO, e.g. the presence of weedy relatives or hybridisation rates.

The incremental environmental risk created by the introduction of potentially dangerous GMOs is modelled as the product of these factors, $R = I \times F \times S$, where each factor (and therefore incremental risk R also) is subject to uncertainty, and hence a random variable. Incremental environmental risk R refers to the risk from intentional environmental release

Lichtenberg (2006) categorises policies in the same way as the risk-generating factors:

- x_i, is the social cost of policies that restrict the introduction of potentially hazardous organisms, e.g. planting restrictions and moratoria;
- x_f is the social cost of policies attempting to limit the dissemination of genetic material through the environment, e.g. setbacks for field transgenic crops, contained facilities for research; and
- x_s is the social cost of policies that limit susceptibility, e.g. limiting plantings to areas where the transgenic crop has few wild relatives.

Again, the regulator chooses regulatory instruments x_i, x_f and x_s to minimise the social cost $\left(x_i + x_f + x_s\right)$ of meeting the constraint that the probability of violations of the nominal standard M (acceptable risk) does not exceed the margin of safety.

$$\Pr\{R \geq M\} = \Pr\left\{I\left(x_i\right)F\left(x_f\right)S\left(x_s\right) \geq M\right\} \leq 1-\alpha \tag{3}$$

After taking a logarithmic transformation and letting lower-case letters represent natural logarithms, the safety-fixed constraint is written as

$$\Pr\left\{r\left(x_i, x_f, x_s\right) = i\left(x_i\right) + f\left(x_f\right) + s\left(x_s\right) \geq m\right\} \leq 1-\alpha\,. \tag{4}$$

Then, if the three risk-generating factors, I, F and S, are lognormal then the constraint can be written as

$$\begin{aligned} r(\alpha) \equiv\ & \mu_i\left(x_i\right) + \mu_f\left(x_f\right) + \mu_s\left(x_s\right) + Z(\alpha)\Big[\sigma_i^2\left(x_i\right) + \sigma_f^2\left(x_f\right) + \sigma_s^2\left(x_s\right) \\ & + \rho_{if}\sigma_i\left(x_i\right)\sigma_f\left(x_f\right) + \rho_{is}\sigma_i\left(x_i\right)\sigma_s\left(x_s\right) + \rho_{fs}\sigma_f\left(x_f\right)\sigma_s\left(x_s\right)\Big]^{1/2} \leq m. \end{aligned} \tag{5}$$

The necessary condition for any regulatory instrument k in use $\left(x_k > 0\right)$ is given by

$$\frac{\partial r(\alpha)}{\partial x_k} = \frac{\partial \mu_k}{\partial x_k} + \frac{Z(\alpha)\Sigma}{x_k}\tau_k \eta_k = \frac{1}{\lambda}, \; k = i, f, s, \tag{6}$$

where Σ denotes the standard deviation of the uncertainty-adjusted risk level $r(\alpha)$, $\tau_k = \left[\sigma_k^2(x_k) + \sum_{l \neq k} \rho_{kl}\sigma_k(x_k)\sigma_l(x_l)\right] / \Sigma$ is risk-generating factor $k's$ share of total uncertainty about risk, and $\eta_k = \left[x_k / \sigma_k\right]\left[\partial \sigma_k / \partial x_k\right]$ is the elasticity of uncertainty about risk-generating factor k with respect to policy, and λ is the shadow price of the constraint and the marginal cost of attaining the nominal standard m with a margin of safety α. Lichtenberg and Zilberman (1988) suggest that the efficient mix of regulatory policies will be a portfolio of activities, some with a relative advantage in reducing mean risk, and others in reducing uncertainty about risk.

An advantage of the safety-rule mechanism is that decision-making under uncertainty is modelled in an obvious way that corresponds closely to environmental legislation and political debate. However, unlike benefit-cost analysis, a safety rule mechanism does not directly assess the trade-offs between aggregate economic benefits and environmental risks (Harper and Zilberman 1992) or address the distribution of the costs associated with regulation. Nevertheless, it is especially relevant to agricultural gene technology regulation and the risk assessment procedures undertaken by the Regulator. The curves derived by Lichtenberg *et al.* (1989) may not directly address the trade-offs between aggregate economic benefit and risk inherent in environmental regulation, in the manner of uncertainty-corrected benefit-cost analysis (Harper and Zilberman 1992). However, they demonstrate the economic impacts of different values of the policy parameters the margin of safety, α, and acceptable risk, m, in a manner that facilitates public debate over their appropriate values, matters central to concerns about Australian regulation of agricultural gene technology.

Analytical framework

We consider the risk of gene flow from GM canola. Adherents to the precautionary principle have argued that environmental release of GM canola (and other GM crops) should be delayed until there is deeper understanding of its impact on natural ecosystems, and co-existence with non-GM cropping systems can be guaranteed. However, the ACIL Tasman (2007a) report suggests that there are greater costs to Australian producers from preventing commercialisation. GM crops have been grown and consumed safely in the 10 years since commercialisation. Prohibiting commercial production in Australia means foregone agronomic and environmental benefits, while delays to protect market access and price premiums for conventional and organic canola are counterproductive, as there are (at best) minimal premiums to protect, and market access is not materially affected.

The agronomic benefits of canola stem from its role in cropping rotations, where it is typically used as a break crop in cereal production. Canola is itself profitable, but many of its benefits in production emerge when it is followed by wheat. In comparison with wheat-wheat rotations, wheat grown after canola shows yield improvements of 20 per cent on average and quality improvements of 1.3 per cent increases in protein levels (Norton *et al.* 1999). In some cases canola is reported to reduce yields in following cereal crops because of its high nutrient requirements, and nutrient replacement requirements increase production costs. Weed management and herbicide resistance are obstacles to including canola in cropping systems and the seeds of Brassica weeds can contaminate canola seed oil. Conventionally bred Triazine-tolerant canola (TT canola) provided a management solution when weeds were otherwise intractable in conventional canola varieties, but at a yield penalty of 20 per cent and with a reduction in seed oil content of 2 per cent. Moreover, some Brassica weeds are showing signs of Triazine-resistance development. Clearfield canola is another conventionally-bred herbicide (imidazolinone) resistant variety of canola, which does have an agronomic advantage over conventional canola. GM canola offers improved weed control, the need for fewer tillage passes, and potential yield advantages from earlier sowing and, in the case of InVigor® canola, better canola varieties (Canola Council of Canada 2001).

We propose a probabilistic gene flow risk assessment and safety rule decision mechanism. We consider the risk of gene flow from GM canola rather than GM crops as a whole because a case-by-case approach is recommended for environmental release of GM crops (Glover 2002; Messeguer 2003), and because canola is the subject of considerable scientific assessment of the potential for gene flow. The Regulator maximises the joint profit of a GM and non-GM producer given strategies to manage gene flow from GM canola, subject to the probabilistic constraint that contamination remains below a threshold value with a given margin of safety. Previous applications of the safety-rule decision mechanism maximise revenue from competing production activities (as in Haight 1995) or minimise the social costs of regulation (as in Lichtenberg and Zilberman 1988). Because the problem is concerned with setting (socially acceptable) thresholds for co-existence of GM and non-GM canola, the objective is to maximise joint profit of a potential GM and non-GM producer, subject to management strategies to limit gene flow from GM canola. Profit of the potential GM canola producer is π_{GM} and π_{NGM} is profit of the non-GM canola producer. The threshold value is initially assumed to be the contamination threshold for labelling as GM or non-GM.

Profitability levels are determined based on Willett and Willett's (2007) protocol that uses stochastic simulation and mathematical programming techniques. The mathematical programming model is defined as follows. The GM and non-GM producers' problem is to choose a canola variety to maximise farm profit. Let index $k\left(k=1,2\right)$ denote the production system technology. Willett and Willett (2007) designate land according to hydraulic soil groups as they are concerned with pesticide contamination of groundwater. We instead define production systems according to whether they are a certified GM-free $\left(k=1\right)$ (for example, organic canola) or a conventional production system $\left(k=2\right)$. Let index $i\left(i=1,...,I\right)$ denote canola variety. We assume that conventional production systems can grow conventional $\left(i=1\right)$, conventionally-bred herbicide tolerant $\left(i=2\right)$ or GM canola varieties $\left(i=3\right)$. Organic or certified GM-free production systems $\left(i=1\right)$ do not adopt GM canola. We define the following notations:

$P_{ik} \equiv$ Price of canola variety i under production system k ;

$\phi_{ik} \equiv$ Yield of canola variety i under production system k ;

$s_{ik} \equiv$ Seed costs/technology fee per hectare for canola variety i under production system k ;

$h_{ik} \equiv$ Herbicide cost per hectare for canola variety i under production system k (including application costs);

$c_{ik} \equiv$ Production costs per hectare for canola variety i under production system k ;

$L_{ik} \equiv$ Hectares of land under production system k used to produce canola variety i ;

$\bar{L}_k \equiv$ Hectares of land under production system k available; and

$\tau_{ik} \equiv$ Per hectare profit margin for canola variety i under production system k .

The second component of the model is the constraint that the probability of gene flow from GM canola does not exceed the acceptable level within a margin of safety. Lichtenberg (2006) defines risk, $R=IFS$ .This specification of risk as the product of the random variables I , F , and S , follows from the models of (human) health risk from environmental contaminants such as pesticides. Instead, we employ Damgaard and Kjellsson's (2005) model of canola gene flow. They estimate the probability of foreign pollination from a GM donor field in a recipient (non-GM) field as a function of separation distance, buffer zone, and recipient field width by a meta-analysis of Australian, EU and North American field trial data. They model two effects: G_a, the effect of dilution of foreign/GM pollen in the recipient field, and G_n, the effect of distance between the GM and non-GM fields. The average probability of foreign pollination with buffer zone, G_a, between adjacent fields is given by:

$$G_a = \frac{1}{X-Z}\int_Z^X g_a(x)\,dx, \tag{7}$$

where:

$X =$ The width of the recipient field, measured as a perpendicular transect from the border with the GM donor field;

$Z =$ The width of the buffer zone, which is not harvested as GM-free; and

$g_a(x) =$ Models the decrease in the probability of foreign pollination at distance x from the common border. This is described by an exponentially decreasing function of distance x:

$$g_a(x) = \begin{cases} \frac{1-\theta_1}{2}\exp(-\theta_{2n}x) & x \le d \\ \frac{1-\theta_1}{2}\exp(-\theta_{2n}d)\exp(-\theta_{2f}(x-d)) & x > d \end{cases}, \tag{8}$$

where:

$\frac{1-\theta_1}{2} =$ The expected proportion of foreign pollination at the border of two adjacent fields;

$\theta_1 =$ The proportion of seeds resulting from self-pollination. The remaining proportion of seeds results from equal amounts of pollination from the donor and recipient fields; and

$d =$ A transition point where the relatively fast decrease in the probability of foreign pollination is reduced from θ_{2n} to θ_{2f}. That is, most canola pollen is found within 10m of its source (Salisbury 2002).

Damgaard and Kjellsson (2005) define the average probability of foreign pollination when the donor and recipient fields are non-adjacent, G_n, as:

$$G_n = \theta_3 \exp(-\theta_4 Y), \tag{9}$$

where:

$\theta_3 =$ The average probability of foreign pollination if the two fields were adjacent;

$\theta_4 =$ Measures the decrease in the average probability of foreign pollination with increasing distance between the fields; and

$Y =$ Distance between non-adjacent fields.

Damgaard and Kjellsson (2005) use the data points of the field trials to determine the Bayesian posterior distribution of the parameters, with $d = 3$. The distribution of G_a is found by random sampling of the joint posterior distribution of θ_1, θ_{2n} and θ_{2f}, and G_n is found by random sampling of the joint posterior distribution of θ_3 and θ_4. As G_a and G_n are assumed to be independent, the combined effect of dilution of foreign pollen and distance between fields is found by multiplying G_a and G_n together (Damgaard 2008).

We define the following variables for management of gene flow from GM canola:

$X_{ik} \equiv$ Field width (in meters) for canola variety i under production system k;

$Y_{ik} \equiv$ Separation distance (in meters) for canola variety i under production system k;

$Z_{ik} \equiv$ Buffer zone width (in meters) for recipient field for canola variety i under production system k;

$W_{ik} \equiv$ Length (in meters) of the field border for canola variety i under production system k;

$\omega_{ik} \equiv$ Volunteer management costs for canola variety i under production system k;

$\bar{M}_k \equiv$ Threshold value for percentage foreign pollination in recipient field under production system k; and

$\alpha \equiv$ Margin of safety for the level of gene flow out of land type k $(0 < \alpha < 1)$.

Also:

Define the profit margin per hectare of canola variety i under production system k, $\tau_{ik} \equiv P_{ik}\phi_{ik} - s_{ik} - h_{ik} - c_{ik}$; and

$L_{ik} = W_{ik}.X_{ik}$.

For the case of a GM producer and a certified non-GM producer, joint profit is:

$$\pi_{GM} + \pi_{NGM} = W_{32}\left[\tau_{32}\left(X_{32} - Y_{32}\right) - X_{32}.\omega_{32}\right] + W_{11}\left[\tau_{11}\left(X_{11} - Z_{11}\right) + \tau_{32}.Z_{11}\right] \qquad (10)$$

subject to:

$$\sum_{i=1}^{I} L_{ik} \le \bar{L}_k\,, \quad k = 1,2 \qquad (11)$$

$$\Pr\left\{R \ge \bar{M}_k\right\} = \Pr\left\{G_{a_{11}}.G_{n_{11}} \ge \bar{M}_{k,k=1}\right\} \le 1 - \alpha \quad k = 2 \qquad (12)$$

The objective function (10) is the joint profit of the GM and certified non-GM producers. Without management strategies to restrict average probability of foreign pollination, joint profit is $\tau_{32}L_{32} + \tau_{11}L_{11}$. Separation distances reduce the area planted to GM crops by $W_{32}.Y_{32}$. Canola grown in buffer zones can still be harvested and sold at the GM price. Equation (11) sets restrictions on land availability. The probabilistic constraint (12) requires that average probability of foreign pollination in the certified non-GM production system remain below a threshold value, $\bar{M}_k$, with a margin of safety, α. As seen in (7) to (9), average probability of foreign pollination depend on X_{11}, Z_{11} and Y_{32}.

Some previous simulation results

Without commercial release, information on GM canola in Australian production systems is restricted to field trials and estimates. The most recent investigation into the economic impacts of adopting GM crops is the ACIL Tasman report commissioned by the Victorian Department of Primary Industries as part of the review of the Victorian moratorium on GM crops (ACIL Tasman 2007b). Their report details cost-benefit estimates of the impact of the GM canola moratorium and includes gross margin analysis of three varieties of GM canola, two varieties of conventionally-bred herbicide tolerant canola and conventional canola. The expected performance of the six canola production systems is the basis of the assumptions for yields, seed oil content, prices of the varieties, and input costs. Table 1 details some of the assumed varietal impacts.

Table 1: Assumed varietal impacts

Impact	**Canola Variety**					
	Conventional	Triazine Tolerant	Imidazolinone Tolerant	GM-OP RR®	GM-hybrid RR®	GM-Hybrid InVigor®
			Relative Differences (%)			
Yield	100	95	100	100	120	120
Grain Prices	100	100	100	100	100	100
Seed Cost	100	100	100	100	150	150
			Absolute Differences (%)			
Oil Content	42	42	42	42	44	44
Technology Fee ($/ha)	0	0	0	25	60	0

(ACIL Tasman 2007b)

Monsanto report from their Roundup Ready® canola trials (in ACIL Tasman 2007b) that the Roundup Ready canola variety gives gross margins 20 per cent higher than conventional canola varieties due to higher yields and lower input costs. However, a Clearfield non-GM variety had significantly higher yields than the Roundup Ready® and other non-GM varieties. Bayer CropScience trials of InVigor® canola varieties report yield advantages of between 9 and 38 per cent. Conversely, ACIL Tasman (2007a) report that Finney (2003) finds conventional canola production systems generate higher gross margins than Roundup Ready®, InVigor® and 'GM-free' canola. Finney assumed yield advantages of 7 per cent and 17.5

per cent over conventional canola for Roundup Ready® and InVigor®, respectively. Growing costs for Roundup Ready® were 97 per cent of conventional canola costs and InVigor® had additional costs of \$28/ha for seed and \$54/ha for using Liberty® herbicide. However, ACIL Tasman (2007a) note that identity preservation costs of 12.5 per cent of the grain value influenced this outcome. If instead the identity preservation costs were set at 10 per cent consistent with other estimates, then InVigor® canola generates a higher gross margin.

Other on-farm impacts on gross margins of GM canola compared with non-GM canola, averaged across the report's 2003-2016 projection period, include: a \$93 increase in income; a \$48 increase in seed/technology access costs; a \$19 decrease in chemical costs; a \$27 increase in fertiliser costs; an \$11 decrease in other management costs (including sowing, spray applications, windrowing and harvesting); and a \$2 increase in off-farm transport. The report finds that on average non-GM canola varieties have a gross margin approximately \$45 lower than for the three GM varieties across the projection period (ACIL Tasman 2007b). Other data requirements include similar gross margin analyses of canola in organic production systems.

The parameter values in the models of the effect of foreign pollen dilution, G_a, and the effect of distance between fields, G_n, were estimated by Damgaard and Kjellsson (2005). Estimated values for $d = 3$ are: $\hat{\theta}_1 = 0.84$; $\hat{\theta}_{2n} = 0.43$; $\hat{\theta}_{2f} = 0.07$; $\hat{\theta}_3 = 5.87 \times 10^{-3}$; and $\hat{\theta}_4 = 6.01 \times 10^{-3}$.

In the pipeline

At this stage our model has several serious omissions, which we intend to address. First, we have considered two farms, whereas our research objective requires industry wide consideration of the trade-offs between managing gene flow from GM canola and the cost of achieving a given standard within a margin of safety. This would also require assumptions about potential adoption rates. We have also only considered a single period, whereas a more useful assessment would consider a longer period so as to take into account inter temporal gene flow. For example, an additional source of foreign pollen is volunteer GM canola plants from earlier seasons. A further consideration is the impact of GM canola on subsequent cropping rotations. For example, Roundup Ready® canola has resulted in higher yields in following wheat (ACIL Tasman 2007b). One impact that is beyond the scope of this research is inclusion of environmental impacts of GM canola. Although estimates exist of changes in pesticide active ingredient applications and changes in pesticide toxicity (for example, Brookes and Barfoot 2006), estimates of the monetary value of such changes are needed before these environmental effects can be included.

Conclusion

We have presented a tentative framework to assess the trade-offs between managing gene flow from GM canola and the costs of keeping the average probability of foreign pollination below a given acceptable level with a margin of safety. We have considered here only a GM producer and a certified non-GM producer. However, when the framework is extended to consider industry trade-offs, the results can be an input in public debates over the value of the parameter acceptable risk. Acceptable risk is a policy parameter that should reflect social values, and in this way this study will potentially facilitate achievement of a social consensus on agricultural gene technology and enhance trust in the regulatory processes.

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