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RESEARCH PAPERS

The economic and environmental cost of delayed GM crop adoption: The case of australia's GM canola moratorium

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ABSTRACT. Incorporating socio-economic considerations (SECs) into national biosafety regulations regarding genetically modified (GM) crops have opportunity costs. Australia approved the cultivation of GM canola through a science-based risk assessment in 2003, but allowed state moratoria to be instituted based on potential trade impacts over the period 2004 to 2008 and 2010 in the main canola growing states. This analysis constructs a counterfactual assessment using Canadian GM canola adoption data to create an S-Curve of adoption in Australia to measure the environmental and economic opportunity costs of Australia's SEC-based moratoria between 2004 and 2014. The environmental impacts are measured through the amount of chemical active ingredients applied during pest management, the Environmental Impact Quotient indicator, and greenhouse gas emissions. The economic impacts are measured through the variable costs of the weed control programs, yield and the contribution margin. The environmental opportunity costs from delaying the adoption of GM canola in Australia include an additional 6.5 million kilograms of active ingredients applied to canola land; a 14.3% increase in environmental impact to farmers, consumers and the ecology; 8.7 million litres of diesel fuel burned; and an additional 24.2 million kilograms of greenhouse gas (GHG) and compound emissions released. The economic opportunity costs of the SEC-based moratoria resulted in foregone output of 1.1 million metric tonnes of canola and a net economic loss to canola farmers' of AU$485.6 million. The paper provides some of the first quantified, post-adoption evidence on the opportunity cost and environmental impacts of incorporating SECs into GM crop regulation.

KEYWORDS. biotechnology, Cartagena Protocol on Biosafety, food security, innovation, opportunity cost, socio-economic considerations

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1. INTRODUCTION

The commercialization and adoption of genetically modified (GM) crops in numerous early adopting countries reached their 20th anniversary in 2017. In spite of a rapidly growing body of literature on the economic, environmental and health benefits arising from the adoption of GM crops,[1] environmental non-governmental organization (eNGOs) are still campaigning for barriers to further adoption, if not outright bans, on GM crops and the technologies used to create them. The eNGO community's strategy is to rigorously apply the Cartagena Protocol on Biosafety (CPB) as part of developing countries biosafety regulations and regulatory framework. Through the use of socio-economic considerations (SECs), the opponents of biotechnology and GM crops are able to establish barriers to the adoption of agricultural innovations. Often this debate to restrict the release of biotechnology and GM crops is so fixated on perceived risks and impacts to biodiversity that evidence of environmental, food security and producer benefits are often overlooked or undervalued.

Negotiated in 2000 and coming into effect in 2003, the CPB initially showed some potential as an international environmental agreement that could serve a valued role. However, it has evolved into an agreement that is no longer based strictly on scientific risk assessments, but allows for the implementation of spiritual, ethical and cultural issues, that in most instances, have no data and no methodology capable of assessing the issue, let alone providing informed insights into the substance of the matter.[2] This politicization of risk has resulted in socio-economic issues such as gender rights and land tenure becoming part of the assessment process for GM crops in some countries that are a party to the CPB. The inclusion of SECs within the CPB framework allows countries to develop biosafety legislation in which no negative socio-economic impact from the commercialization of a GM crop is allowable.[3] This use of the precautionary principle, with ambiguous interpretations of how to evaluate SECs, may allow SECs to act as a trade barrier to protect vested interest,[4] and stands in contrast to 20 years of evidence which shows that GM crops continue to be welfare enhancing with no negative effects on human health.[5,6]

With eNGO organizations lobbying for the outright rejection of biotechnology, instead of following scientific, evidence-based policy, it is critical to be able to quantify the environmental and economic cost of rejecting the technology. To enable such evidence to be compiled, GM canola adoption data from Canada has been modeled into an adoption S-Curve that has been applied to Australia. Australia approved GM canola for production in 2003, which was followed by moratoriums imposed by state governments, lasting up to six years in the three main canola growing states and ongoing in other states. Through the use of the Canadian GM canola adoption curve, it becomes possible to estimate what the environmental and economic benefits of GM canola could have been for Australia in 2014, had the moratoria not been implemented. Quantifying the opportunity cost of a GM crop delay, will serve to inform policy-makers in developing countries regarding the option of not including GM crops as part of the solution to improving domestic food security and farmer incomes. While there are a number of studies, primarily in Europe but also in Australia, that estimate the ex-ante costs and benefits from adopting GM crop,[7-9] this analysis is one of the first studies that evaluates post-adoption evidence to assess the opportunity costs of a moratoria on a GM crop.

Section 2 provides a summary of the benefits of GM canola adoption in Canada and the regulatory approval process in Australia. Sections 3 of the paper presents the methodology, with Section 4 offering a discussion of the data. In Section 5 some concluding thoughts are offered as well as possible impacts to developing nations.

2. GM CANOLA ADOPTION IN CANADA AND AUSTRALIA

Socio-economic considerations are a broadly defined set of social issues that attempt to protect certain interests of a society. These interests include, but are not limited to, protection of the benefits to producers or society, consumer choice, the environment, ethical and equitable outcomes, food security and safety, impacts to biodiversity and international trade concerns.[2] The nature of these concerns are naturally subjective, as issues such as ethical outcomes are not universally defined and are a by-product of cultural heritage. The absence of definition does not make SECs any less strongly held by some members of civil society, but their inclusion in regulatory policy making does allow for ambiguous interpretations

The European Union's (EU) use of SECs encourages discrimination against GM foods, despite their own research assessment that shows no harm.[10] This absence of harm is coupled with over 20 years of evidence and numerous major scientific bodies declaring no additional risks compared to conventional crop varieties.[6,11,12] The impact of SECs is not only felt domestically but can have direct consequences on other nations. While developed countries can provide evidence and are able to accept market fluidity consequences, developing nations are far more limited in their choices and may be starkly affected by another country's adoption of a SEC-based moratorium.[13]

The development of GM crops and the regulatory policy that accompanies them has varied across jurisdictions and cultural environments. Comparing the development and effect of regulations in jurisdictions with many similarities, but some key differences, offers insight into the impact of these policies. The national similarities between Canada and Australia, developed commonwealth nations that have resource-based economies with large-scale agricultural farm production, allows for an analysis of GM crop policy and its impacts in two broadly homogenous countries.

2.1. *GM canola regulation and adoption in Canada*

The Canadian Food Inspection Agency's (CFIA) decision to approve glyphosate tolerant and glufosinate ammonium herbicide tolerant GM technologies for application in canola were the first two plants with novel traits (PNTs) approved in Canada. These GM canola technologies were found to have no significant difference in effects on the environment when compared to non-GM canola. There were no adverse effects in the five main environmental impact assessment categories (weediness, gene flow, plant pest, non-target organisms and biodiversity) and the comparison to current livestock feed culminated in GM canola varieties within the same acceptable limits as comparative non-GM canola varieties. Canola varieties incorporating either of the two GM herbicide tolerant technologies were regarded as being 'substantial equivalents' to the comparative non-GM canola varieties in use.[14,15]

In conjunction with the CFIA approval, Monsanto's Roundup Ready® and AgrEvo's (now part of Bayer) LibertyLink® canola were approved for human food use under the Health Canada guidelines. The decision document noted that the method of gene transference, together with the novel gene traits and the proteins expressed by the novel gene trait are not present in the refined canola oil. This absence of the novel trait and the protein expressed in refined oil coupled with the nutritional and toxicological components, were found to have no statistically significant difference between GM and non-GM canola oils. As the oil is the only part of the canola seed consumed by humans there was no observed safety risks to human health or safety.[16,17]

GM canola was introduced in Western Canada in 1995 through an identity preserved production and marketing system, with unrestricted commercial production beginning in 1997.[18] The subsequent adoption was relatively rapid, with 12% in the initial year, 64% by 2002 and 93% by 2010.[19] In 2007, a producer survey was undertaken to learn more about the producer level impacts that were being observed one decade after commercialization.

The survey revealed that the new technology generated between \$1.063 billion and \$1.192 billion net direct and indirect benefits for producers over the 2005–2007 period, partly attributed to lower input costs and partly attributed to better weed control.[20] One major concern following introduction was the potential for herbicide tolerant (HT) traits to outcross with weedy relatives or for GM canola to become a pervasive and uncontrollable volunteer in non-canola crops, either of which would offset some producer gains. The survey largely discounted that concern. More than 94% of respondents reported that weed control was the same or had improved following the commercialization of GM canola, less than one quarter expressed any concern about herbicide resistance in weed populations, 62% reported no difference in controlling for volunteer GM canola than for regular canola and only 8% indicated that they viewed volunteer GM canola to be one of the top five weeds they need to control.

In addition to the economic benefits the survey identified significant environmental benefits associated with GM canola, such as reduced tillage passes and increased carbon sequestration in the soil. The option to apply either glyphosate or glufosinate ammonium as a post-emergent, non-selective knockdown herbicide on the respective GM canola crop has allowed farmers to significantly reduce their number of cultivations. As a result of the improved weed control options from the adoption of GM canola 64% of Canadian canola growers are now using zero or minimum tillage as their preferred form of production system. The decreased number of tillage passes reported over the survey period, improved moisture conservation, decreased soil erosion and contributed to carbon sequestration. This change in tillage use resulted in an estimated 1 million tonnes of carbon either sequestered or no longer released under land managed by GM canola production, between 1995 and 2007.[21] Accordingly, Canada's GM canola hectares now sequester approximately 280 thousand tonnes of carbon annually.[22]

The commercialization and wide spread adoption of GM canola has changed weed management practices in Western Canada. There have been significant changes regarding the use and application of pre-emergent and post-emergent herbicides for weed control in canola. The research shows that from an occupational health and safety perspective for the operator when comparing canola production in 1995 and 2006 the toxicity of agro-herbicides applied to canola has decreased by 53%, and that there has been a decrease in producer exposure to chemicals of 56%.[23] From an environmental perspective, during the same period the research shows there has been a decreased application of chemical active ingredient of 1.3 million kg.[21] The associated environmental impact per hectare from the decrease in active ingredients applied using the Environmental Impact Quotient indicator (EIQ/ha), further discussed in the Methodology section of this paper the indicator incorporates the amount of herbicide applied per hectare multiplied by the toxicity of the herbicide, resulted in a decrease from a factor of 47.4 in 1995 down to a factor of 29.5 in 2006 of the top five herbicides,[23] the main difference during this period being the adoption of GM canola. If GM canola had not been developed and Canadian canola farmers continued to use previous production technologies, the amount of active ingredient applied to control weeds in 2007 would have been 38% above what was actually applied.

2.2. *GM canola regulation and adoption in Australia*

In 1988, the Genetic Manipulation Advisory Committee (GMAC) was established to oversee the development or introduction of novel genotypes produced via genetic manipulation that are unlikely to occur in nature or may pose a public health or environmental risk. In 2000, Australia began to develop a rigorous framework for regulating and analyzing the effects of biotechnology and GM crops, the outcome was the Gene Technology Act 2000.[24] The Act stipulates the method GMOs are reviewed under to assess their risk to the human health and safety and the environment. A new division was created within the Ministry of Health, the Office of the Gene Technology Regulator (OGTR), to conduct a Risk Assessment and develop a Risk Management Plan (RARMP) to be used in the review process for certification of new GM crops. Beyond the OGTR licensing of a product for cultivation, all new foods or food ingredients derived from GM crops must be assessed by Food Standards Australia New Zealand (FSANZ) (previously known as ANZFA – the Australia New Zealand Food Authority) before the product can be marketed.

ANZFA's assessment of Monsanto's Roundup Ready® and Aventis CropScience's (presently Bayer CropScience) InVigor® varieties were completed in 2000 and 2001 respectively. These two GM canola variety assessments found there to be no allergenic concerns, no significant differences in nutritional impacts and that the refined oil for human consumption contained no proteins or GM traits, indicating that these GM canola varieties posed no safety or public health concerns.[25,26] The ANZFA assessments also considered the possible effects of GM canola grown and imported from other jurisdictions, namely Canada, and predated the OGTR assessment and cultivation of these two GM canola varieties in Australia.

Australia's first approval of a GM crop for commercial cultivation was the 1996 approval of the insect tolerant Ingard® cotton by Monsanto. This was followed by the 2003 approval of InVigor® canola, with Roundup Ready® canola approved later that year.[27,28] The certified commercial cultivation of these two GM herbicide tolerant canola technologies was on the basis that the risk of human health and environmental safety issues is minimal, are able to be effectively managed by the industry, and are lower than the societal and environmental benefits arising from their approval.[29]

In response to the certification of GM canola in 2003, representatives and stakeholders in the grain industries, specifically the wheat sector, grew concerned about the potential international trade impacts that could arise due to the adventitious presence of GM material in non-GM grains.[30,31] These trade related concerns influenced various state governments with some but not all enacting an SEC-based amendment to the Act which allowed individual states to impose moratoria on the introduction of GM canola.[32]

In 2003, moratoria were adopted in the main canola growing states of New South Wales, Victoria, South Australia, Tasmania, Western Australia (WA) and the Australian Capital Territory, but not in Queensland or the Northern Territory. These moratoria were instituted to allow grain producers and their supply chains time to evaluate the possible impacts on trade, market effects, benefits to producers from planting GM compared to non-GM canola and methods for segregation and coexistence of GM and non-GM canola. Despite some initial inertia from within the grains industry, industry stakeholders finally came together and began a process to mitigate possible trade effects through supply chain management for the coexistence of GM and non-GM crops.[33] The Australian GM canola production moratoria were in effect in the key canola producing states of New South Wales and Victoria until 2008 and Western Australia until 2010 and remain in place in South Australia and Tasmania.

The adoption path of GM canola has followed two distinctly different avenues for dealing with broadly similar issues in the Canadian and Australian contexts. The Canadian regulatory framework made use of existing regulatory departments; Australia developed a new regulatory office for biotechnology. The Canadian canola industry came together to ensure access to international markets through self-regulation; the fractured Australian grains industry were concerned about trade implications, lobbied state governments to impose a moratorium. The Canadian government assessed GM canola on science-based policy; the Australian government used science-based policy to approve GM canola, then allowed state governments to impose SEC-based moratoria on its cultivation due to the international trade concerns of industry stakeholders. The analogous science-based regulatory approval process of GM crops provides for a comparison in which the adoption of a SEC is the main policy difference, and the focus of this analysis.

3. METHODOLOGY

Previous research on the ex-ante benefits of adopting GM crops have followed a number of different methodologies. A study on the adoption of sugar beets in the EU used a theoretical model of option pricing to assess the short and long-run impacts of the moratoria, finding there was a small short-term benefit associated with irreversible costs and a large long-term cost from reversible benefits from not adopting.[7] In Ireland, an assessment was done on ex-ante profit margins between conventional and GM sugar beets, finding significant potential gross margin increases to producers adopting GM sugar beets.[8] Similarly in Australia, the state of Victoria conducted an ex-ante review, with a cost-benefit analysis, on the possible impact of GM canola in the state.[9] This analysis will follow a methodology similar to that of the Australian analysis, and incorporate aspects of the literature that assess the ex-post impacts of GM crops globally and from adopting herbicide tolerant and GM canola in Canada.[20,21,34,35]

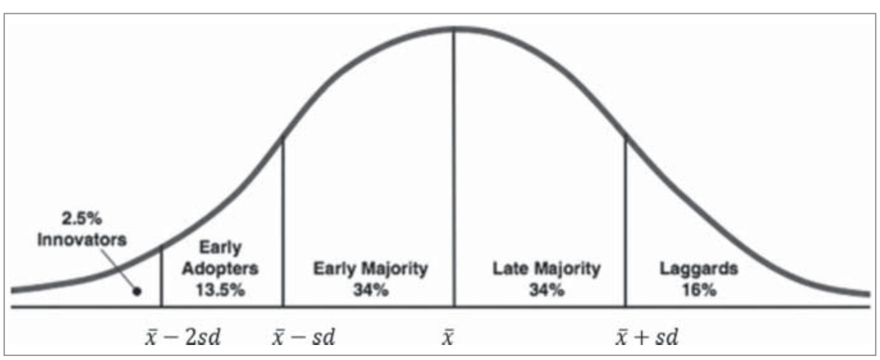
Canadian survey data was collected in 2007 by researchers at the University of Saskatchewan to evaluate the economic and environmental impact of GM canola in Western Canada for the 2005 and 2006 crop years.[20,21,23] The Australian data sets were obtained by surveys conducted by the Birchip Cropping Group on behalf of the Grain Research and Development Corporation. These surveys were undertaken annually in the first three years post-removal of the state moratoria, 2009 to 2011 in New South Wales (NSW) and Victoria and 2011 to 2013 in Western Australia.[36-38] These datasets for the respective countries offer insight into the adoption of GM canola through their strongly correlated surveys, as the Australian survey was based off the Canadian.

A counterfactual scenario of potential adoption is used to evaluate the opportunity costs had these moratoria not been imposed in Australia. The Australian opportunity costs of delay are measured through a normalized S-Curve, constructed from the Canadian experience, using environmental and economic impact factors. The S-Curve was first identified by Ryan and Gross in their evaluation on the adoption of hybrid corn in Iowa,[39] and has been used extensively to assess other agricultural innovation,[40-42] including an assessment of the economic impacts associated with the adoption of herbicide tolerant canola in Canada.[35]

Following Rogers work on the diffusion of innovations we assume a normalized bell-curve of adopters (Figure 1).[43] This bell-curve begins with producers that are the innovators, a group that is risk neutral and quickest to adopt new innovations, and progresses to the laggards, a group hesitant to adopt innovations until their benefits have been proven and adopted by the majority.[43] It is the size of these adopter types and the benefits of the innovation specific to the region that determine the slope and rate of adoption. More specifically Griliches noted that "the rate of acceptance is a function of the profitability.... defined as the increase in yield..., times the price of [that yield], and minus the difference in the cost."[42] This difference in profitability is strongly indicative of the quick adoption in Canada and the slower adoption in Australia, due in part to a high technology fee on GM canola.

Canada's adoption of GM canola coincided with, and increased the adoption of, zero-tillage/

FIGURE 1. Adopter categorization on the basis of innovativeness.



min-tillage (ZTMT) cultivation practices, a low impact soil practice that incorporates herbicide spraying instead of tillage for weed control. The strong benefits of ZTMT were associated with GM canola adding to the economic gains and positive views held by producers towards the new seed.[23] On the other hand, at the time of GM canola's introduction in Australia there was already high adoption of ZTMT cultivation, a strong presence of conventional HT canola, and a Technology Access Fee on GM canola that largely equaled the productive benefits. The cumulative impact of these factors seems to reflect Griliches conclusion, in which rapid adoption in one country and slow adoption in another likely stem from profitability. It is these differences in profitability that the normalized curve was chosen instead of the accelerated adoption curve observed in Canada. Canada's rate of adoption of GM canola and the associated normalized bell-curve used to estimate Australia's adoption are shown in Figure 2.

Figure 3 illustrates the counterfactual scenario of adoption using the aggregate of the normalized bell curve to create an S-Curve with an adoption ceiling level of 80%. This ceiling follows ACIL Tasman's, a consulting agency, cost-benefit analysis on GM canola prepared for the state of Victoria's ex-ante assessment of GM canola impacts,[9] and on the Grains Research and Development Corporation evaluation on the adoption of ZTMT in Australia,[44] that was highly correlated with GM canola adoption in Canada. This adoption ceiling takes into account GM canola's adoption as largely a displacement of Triazine Tolerant canola, approximately 80–85% of Australia's canola area[38]; the presence of Bayer's InVigor breeding program, which was discontinued shortly after the GM canola moratoria were instituted; and Australia's adoption of GM cotton which was approved in 1996 and reached 92% adoption by 2006, cottonseed is used analogously to canola seed and is an integral component of vegetable oil in Australia.[45] This ceiling is believed to be representative of Australia's GM canola adoption due to the redevelopment of Bayer's glufosinate-tolerant, InVigor, canola breeding program in 2013 with a Roundup Ready cross-licensed variety,[46] and Canada's canola production which consists of approximately 46% GM glufosinate-tolerant canola and 47% GM Roundup Ready canola.[19]

Within this framework the cumulative of the normalized bell-curve of new adopters is truncated such that the first year of adoption is 2.5% following Rogers theory on innovators[43]; Canada's first year post-approval of 4% adoption, regarded as seed build up[19]; and the 2008 first year adoption level of 3% in New South Wales and Victoria.[47] Following from this start the S-Curve results in a counterfactual level of 59% adoption by 2014 juxtaposed to the 19% actual adoption level in Australia under the moratoria. The opportunity costs of the moratoria are thus measured as the area below the counterfactual scenario and above the actual Australian experience, a cumulative area of

FIGURE 2. Canadian and Australia's normalized bell-curve of GM canola adoption.

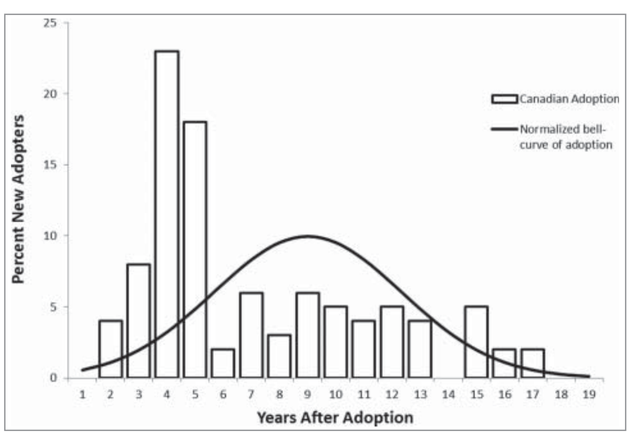
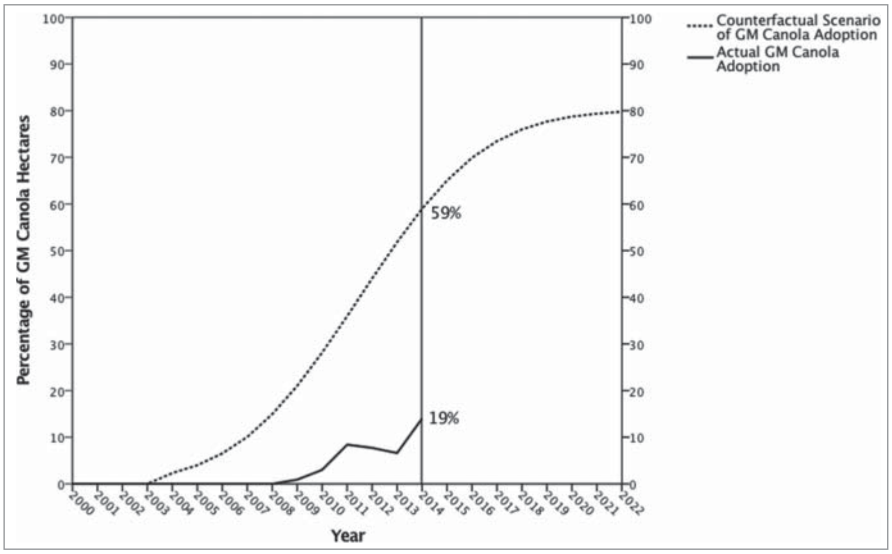


FIGURE 3. Australian s-curve of actual and counterfactual adoption.



4.591 million hectares of foregone GM canola production in the entirety of Australia between 2004 and 2014.

The impact analysis on non-GM canola compared to GM canola follows a weighted per hectare evaluation of differences in the environmental and economic impact factors. The weighting process gives a more accurate depiction of impact per hectare within Australia as it gives large canola producers with more hectares a greater weight than smaller producers. The weighting process assesses the annual impact of each variety, which is aggregated into a regional impact of New South Wales and Victoria in the east and Western Australia in the west. We then create a weighted non-GM canola basket of the three non-GM canola varieties, conventional, Triazine Tolerant, and Clearfield varieties. The weighted per hectare regional impacts are then combined in a simple average to account for the difference in aggregate hectares observed in the surveys between regions, in which the two regions have similar aggregate amounts of canola hectares in production.[48] This analysis evaluates the variables against application of GM canola rates across the entirety of Australian canola hectares planted during this time period.

The environmental impact factors are established based on the framework established by Brookes and Barfoot on the global environmental impact of genetically modified crops,[34,49] and previous studies on the adoption of GM and herbicide tolerant canola in Canada and Australia.[21,23,38] The environmental impacts are assessed through the amount of herbicide active ingredients applied, the toxicity of those ingredients using the Environmental Impact Quotient (EIQ), fuel use, and greenhouse gas emissions (GHG). The EIQ complements the amount of herbicide active ingredients applied to a hectare by offering insight into the toxicity of the different herbicides and the associated impacts those ingredients have on farm workers, consumers and environmental ecology.[50] The impact to GHG emissions is calculated through diesel fuel use and is indicative of the change in machinery practices and the degree of environmental externalities arising from GM canola production compared to the non-GM canola basket.

The EIQ was developed by Kovach et al.,[50] and is updated annually by Cornell University, as a means to collate the data on the variety of chemicals used in Integrated Pest Management Systems. The EIQ is composed of three main categories of pesticide contact, the farmworker, consumer, and ecological impact. It should be noted, that pesticides here refers to all forms of pest management including herbicides, pesticides, and fungicides. The equation attempts to ensure that the environmental impact of the components increase with potential exposure, thus short-lived compounds have a lower impact value than long-lived compounds, which exhibit greater possibility for exposure through their longevity. The strength of the EIQ comes from its approximation of pesticide effects used in similar contexts, whereby a relative comparison of the impacts between chemicals can take place. It should be noted, that the EIQ is an indicator only, allowing for comparison, and does not take into account all possible environmental effects.

To find the aggregate environmental impact (EI), we first find the EIQ per hectare of herbicides in the GM canola and the non-GM canola basket variables (k) (Tables 1 and 2 respectively). To do so we multiply the EIQ per ingredient (i), by the amount of active ingredient(AI) in each litre of herbicide, by the application rate of herbicide per hectare summing across all herbicides applied in each region (j). We then take a simple average across the two regions to find the Australian EIQ_k (/ha) of the non-GM canola basket and GM canola variables.

$$EIQ_k/ha = \frac{\Sigma_j^J \Sigma_i^I \mathrm{EIQ}_i(/kg) * AI_i\ (kg/l) * Application\ Rate_{jk}\ (l/ha)}{J} \quad (1)$$

The Australian EIQ_k/ha is then multiplied by the amount of Australian hectares planted to the two respective variables in the counterfactual and actuality to show aggregate EI (Equation 2). The difference in the EI between the two scenarios shows the environmental impact of herbicides arising from the SEC-based moratoria as a by-product of foregone changes in herbicide programs.

$$EI = \Sigma_k^K \mathrm{EIQ}_k/ha * Hectares_k \quad (2)$$

The second environmental indicator will evaluate the effects to greenhouse gas emissions (GHG) through change in diesel fuel use. The change in diesel fuel use is measured as the by-product of changes in machinery practices between the non-GM basket and GM canola varieties. The analysis will forego impacts from carbon sequestration in soil due to the proliferation and high adoption of ZTMT in Australia prior to GM canola's release. Herbicide tolerant canola is associated with a lower number of spray applications and a reduction in cultivation practice, which will make up the main components of total machinery pass hectares.

Following Brookes and Barfoot's framework on environmental impacts from biotechnology, an emissions impact of 2.67 kg of carbon dioxide per litre of tractor diesel burned will be carried on in this analysis.[49] In addition to the release of carbon dioxide, the burning of diesel in farm machinery, such as tractors, releases organic and inorganic compounds that have negative environmental impacts and are included in this analysis.[36,37] The GHG and compound emissions released per litre of diesel burned and the aggregate opportunity cost associated with the moratoria are highlighted in Table 3.

The economic impacts are more self-explanatory and assess the variable cost of weed control, yield and the contribution margin. The variable cost of weed control complements changes in yield across varieties, which allows for the calculation of the contribution margin. The contribution margin is a simple revenue minus variable cost calculation that has been used to assess the impacts of GM and HT canola in Canada.[35,51] These factors of production are chosen as herbicide tolerant traits are associated with a reduction in the cost of production through lower expenditure on inputs such as herbicides, labor, machinery and fuel. However, as these crops are developed and commercialized by private companies a technology fee is charged on seeds, which offsets some of the benefits to producers.[52]

The variable cost of weed control programs takes into account the per liter costs of herbicide; the cost of cultivation, seeding and

TABLE 1. Australia EIQ/ha of GM canola herbicides.

			NSW		WA		Australia	
	AI (kg/l)	EIQ (/kg)	Use Rate (ml/ha)	EIQ/ha	Use Rate (ml/ha)	EIQ/ha	Use Rate (ml/ha)	EIQ/ha
(a) Glyphosate	0.54	15.33	64.50	0.53	202.49	1.68	133.49	1.11
(b) Roundup	0.54	15.33	633.80	5.25	386.60	3.20	510.20	4.22
(c) Sprayseed	0.25	31.39	497.63	3.90	469.99	3.69	483.81	3.80
(d) Trifluralin	0.48	18.83	727.94	6.58	561.72	5.08	644.83	5.83
(e) Dual®	0.96	12.5	6.52	0.08	0.00	0.00	3.26	0.04
(f) Select®	0.24	17	0.00	0.00	0.30	0.00	0.15	0.00
(g) Hammer®	0.24	20.18	0.16	0.00	0.51	0.00	0.33	0.00
(h) Atrazine	0.9	22.85	0.00	0.00	15.83	0.33	7.91	0.16
(i) Simazine	0.9	21.52	0.67	0.01	0.00	0.00	0.34	0.01
(j) Edge®	0.5	19.36	4.68	0.05	96.13	0.93	50.41	0.49
(k) Logran B®	0.75	—	0.00	0.00	0.00	0.00	0.00	0.00
(l) Glean®	0.75	26.57	0.82	0.02	0.00	0.00	0.41	0.01
(m) Chaser®	0.96	22	0.00	0.00	0.00	0.00	0.00	0.00
(n) Boxer Gold®	0.92	17.89	0.00	0.00	10.39	0.17	5.20	0.09
(o) Select®	0.24	17	12.66	0.05	15.33	0.06	14.00	0.06
(p) Verdict®	0.52	20.2	3.21	0.03	0.03	0.00	1.62	0.02
(q) Lontrel®	0.3	18.12	2.96	0.02	1.77	0.01	2.36	0.01
(r) Atrazine	0.9	22.85	0.00	0.00	14.64	0.30	7.32	0.15
(s) Simazine	0.9	21.52	0.00	0.00	0.00	0.00	0.00	0.00
(t) Intervix®	0.048	20.39	0.00	0.00	0.00	0.00	0.00	0.00
(u) On Duty®	0.7	21.48	0.00	0.00	0.00	0.00	0.00	0.00
(v) Targa®	0.2	22.14	0.00	0.00	0.17	0.00	0.17	0.00
(w) Roundup®	0.69	15.33	962.16	10.18	809.59	8.56	885.88	9.37
Total				26.70		24.01		25.35

* The non-GM variable is a weighted average of the conventional, TT and Clearfield varieties.

spraying; and the technology access fee for GM canola. These costs are weighted by the type of herbicide, cultivation implement used and number of spray applications to find a cost per hectare (Table 4). The technology fee varies throughout the years of the data sets, so an average annual technology fee will be used in this analysis. The fee was initially charged based on a Planting Seed Fee and an End Point Royalty Fee that together aggregated into the Technology Access Fee (TAF). In 2012, the TAF was simplified to only the Planting Seed Fee (Table 5). The TAF was initially set quite high based on expectation of producer benefits, but overtime it decreased as adoption was slow and the expected benefits were not being realized. As this paper uses a weighted-average of the initially high TAF, that is above the actual TAF used post 2012, it can be expected that these results underestimate the economic impact.

The second factor in the economic impact is the difference in yield per hectare. While it has been found that there are few potential yield gains associated with many GM crops,[52] GM canola has been found to have moderate yield increases over its non-GM counterparts in Canada.[35,51] In Australia the most prevalent canola variety grown is triazine tolerant canola, which is associated with a yield decrease of 10–30% compared to non-triazine tolerant varieties.[9] The large displacement of triazine tolerant canola by GM canola, offering similarly effective weed control without a decrease in yield, impacts the net yield per hectare in the non-GM canola basket compared to GM canola.

The final economic factor evaluates the contribution margin on canola (Table 6), revenue minus variable cost to calculate producer benefits, developed by Fulton and Keyowski.[53] This contribution margin has been used to assess the economic impacts in Canada of HT canola and changes in the canola sector.[35,51] The contribution margin estimates the annual variable income used to cover fixed costs, such as land, and farmer earnings. To calculate revenue, yield is multiplied by

TABLE 2. Australia EIQ/ha of non-GM Canola Herbicides.

			NSW		WA		Australia	
	AI (kg/l)	EIQ (/kg)	Use Rate (ml/ha)	EIQ/ha	Use Rate (ml/ha)	EIQ/ha	Use Rate (ml/ha)	EIQ/ha
(a)Glyphosate	0.54	15.33	202.67	1.68	427.30	3.54	314.99	2.61
(b)Roundup	0.54	15.33	755.01	6.25	452.12	3.74	603.59	5.00
(c)Sprayseed	0.25	31.39	28.67	0.21	236.34	1.85	132.51	1.04
(d)Trifluralin	0.48	18.83	922.95	8.34	359.86	3.25	641.44	5.80
(e)Dual®	0.96	12.5	11.30	0.14	9.51	0.11	10.41	0.12
(f)Select®	0.24	17	2.02	0.01	10.38	0.04	6.20	0.03
(g)Hammer®	0.24	20.18	0.78	0.00	0.95	0.00	0.86	0.00
(h)Atrazine	0.9	22.85	617.23	12.69	1365.94	28.09	991.54	20.39
(i) Simazine	0.9	21.52	208.53	4.04	76.15	1.47	142.31	2.76
(j) Edge®	0.5	19.36	10.58	0.10	34.90	0.34	22.74	0.22
(k) Logran B®	0.75	—	0.14	—	0.52	—	0.33	—
(l)Glean®	0.75	26.57	0.03	0.00	0.00	0.00	0.01	0.00
(m) Chaser®	0.96	22	0.93	0.02	0.46	0.01	0.70	0.01
(n) Boxer Gold®	0.92	17.89	6.32	0.01	6.92	0.11	6.62	0.11
(o)Select®	0.24	17	179.65	0.73	315.92	1.29	247.79	1.01
(p)Verdict®	0.52	20.2	13.43	0.14	7.40	0.08	10.42	0.11
(q)Lontrel®	0.3	18.12	36.19	0.20	15.20	0.08	25.70	0.14
(r)Atrazine	0.9	22.85	611.68	12.58	1219.63	25.08	915.67	18.83
(s)Simazine	0.9	21.52	124.82	2.42	14.91	0.29	69.87	1.35
(t)Intervix®	0.048	20.39	82.69	0.05	23.23	0.02	52.96	0.05
(u)On Duty®	0.7	21.48	82.69	0.03	0.17	0.00	1.06	0.02
(v)Targa®	0.2	22.14	1.96	0.01	29.58	0.13	15.55	0.07
(w) Roundup®	0.69	15.33	10.83	0.11	6.88	0.07	8.86	0.09
Total				49.90		69.62		59.76

* The non-GM variable is a weighted average of the conventional, TT and Clearfield varieties.

the annual price of canola,[48] to find an average canola price in AU$ per metric tonne for the period 2004 to 2014. Additionally, we assume that there is not a price premium for non-GM canola due to Canada's market dominance as the primary exporter of canola, with approximately 70% market share, whereby they set the benchmark international price.[45] There has been little verifiable evidence, and a limited amount of small examples, to indicate jurisdictions are willing to pay a premium for non-GM over GM canola.[9,45,54]

The variable costs use the average variable cost of the weed control program, seed cost,

TABLE 3. Greenhouse gas and compound emissions.

	Substance	Emissions Factor (Kg/l)	Emissions Facor * Change in Fuel Use (million kg)
Greenhouse Gas Emissions	Carbon Dioxide	2.67	23,264.06
Greenhouse Compounds Emissions	Carbon Monoxide	0.03234	281.78
	Formaldehyde (methyl aldehyde)	0.001254	10.93
	Oxides of Nitrogen	0.0528	460.05
	Particulate Matter: 2.5um	0.00528	46.01
	Particulate Matter: 10.0um	0.00561	48.88
	Polycyclic aromatic hydrocarbons	0.000003102	0.03
	Sulfur dioxide	0.00002409	0.21
	Volatile Organic Compounds	0.00792	69.01
	Total Compound Emissions		916.89
Total Emissions			24,181

Adapted from Brookes and Barfoot, 2014; GRDC, 2012, 2014.

TABLE 4. Australian variable costs of weed control (AU$/ha).

	Conventional	TT	Clearfield	RR (GM)	Non-GM*	Canada GM[35] (CA$/ha)
Cultivation	$1.47	$0.49	$1.09	$0.61	$0.83	—
Sprays	$7.17	$9.73	$6.84	$5.96	$9.04	—
Herbicide	$47.21	$55.85	$61.59	$30.88	$55.06	—
Cost of Weed Control	$55.86	$66.07	$69.51	$37.44	$64.94	$30.93
TAF	—	—	—	$27.28	—	$37.07
Variable Cost of Weed Control Program	$55.86	$66.07	$69.51	$64.72	$64.94	$67.99

*The non-GM variable is a weighted average of the conventional, TT and Clearfield varieties.

TAF and pre-farm-gate segregation cost limited to GM canola hectares. The variable weed control program costs uses values found earlier in the analysis with respective cost per input. The seed costs are found using gross margin information guides for the non-GM canola varieties and a Roundup Ready guide for GM canola.[55,56] The segregation costs are the low end of pre-farm gate prices, but are only applied to GM canola instead of the suggested universal application in an attempt to impose the costs solely on GM canola adopting farmers for which on-farm segregation is required.[54]

4. DATA AND RESULTS

The resulting environmental opportunity costs from delaying the adoption of GM canola in Australia are sizable with continued impacts today. The foregone hectares of GM canola production resulted in an additional 6.5 million kg of herbicide active ingredients applied in Australian (Table 7). The application of these herbicides had a negative environmental impact of 14.3% as measured through the EIQ.

In addition to the herbicidal impact from the continuation of non-GM conventional canola varieties, there is also a foregone benefit of changes in machinery use associated with fewer spraying applications in GM canola. These changes in machinery use resulted in over 7 million extra hectare passes in Australia, burning an additional 8.7 million liters of diesel fuel. The environmental impact associated with the burning of this diesel fuel released 24.2 million kg of GHG and compound emissions, equivalent to approximately 5,000 cars being driven for one year.[57]

TABLE 5. Roundup ready canola technology access fee (AU$/ha).[36,37]

		2008	2009	2010	2011	2012
Planting Seed Fee	**Rate**	$3.00/kg	$3.00/kg	$3.00/kg	$3.00/kg	$6.00/kg
	NSW & Victoria (@3.5kg/ha)	$10.50	$10.50	$10.50	—	—
	WA (@2.5kg/ha)	—	—	$7.50	$7.50	$15.00
End Point Royalty	**Rate**	$12.60/t	$13.50/t	$13.20/t	$13.20/t	—
	NSW & Victoria (@yield/ha)	$12.42 (0.986t/ha)	$22.23 (1.647t/ha)	$26.99 (2.045t/ha)	—	—
	WA (@yield/ha)	—	—	$12.21 (0.925t/ha)	$19.62 (1.486t/ha)	–(1.278t/ha)
TAF	NSW & Victoria	$22.92	$32.73	$37.49	—	—
	WA	—	—	$19.71	$27.12	$15.00
	Average Australia	$27.28				
	Canada TAF (CA$/ha)[35]	$37.07				

TABLE 6. Australian canola varieties' contribution margins (AU$/ha).

		Conventional	TT	Clearfield	RR (GM)	Non-GM*
NSW and Victoria	Revenue[48] (Yield mt)	$902.70 (1.731)	$728.45 (1.397)	$891.75 (1.710)	$914.57 (1.753)	$805.08 (1.543)
	Seed Cost[55,56]	$54.00	$63.00	$58.00	$63.00	$60.00
	Variable Cost of Weed Control	$47.62	$64.13	$65.07	$39.03	$61.68
	TAF	—	—	—	$33.79	—
	Segregation Cost[50]	—	—	—	$11.51	—
	Margin	$801.08	$601.32	$768.68	$767.24	$683.40
Western Australia	Revenue[48](Yield mt)	$658.59 (1.263)	$527.96 (1.012)	$691.30 (1.325)	$676.34 (1.297)	$545.64 (1.046)
	Seed Cost[55,56]	$54.00	$63.00	$58.00	$63.00	$60.00
	Variable Cost of Weed Control	$64.09	$68.01	$73.95	$35.86	$68.19
	TAF	—	—	—	$20.77	—
	Segregation Cost[50]	—	—	—	$11.51	—
	Margin	$540.50	$396.95	$559.34	$545.20	$417.44
Australia	Revenue[48](Yield mt)	$780.64 (1.497)	$628.20 (1.204)	$791.52 (1.518)	$795.46 (1.525)	$675.36 (1.295)
	Seed Cost[55,56]	$54.00	$63.00	$58.00	$63.00	$60.00
	Variable Cost of Weed Control	$55.86	$66.07	$69.51	$37.44	$64.94
	TAF	—	—	—	$27.28	—
	Segregation Cost[50]	—	—	—	$11.51	—
	Margin	$670.79	$499.13	$664.01	$656.23	$550.42

* The non-GM variable is a weighted average of the conventional, TT and Clearfield varieties.

TABLE 7. Australian environmental opportunity costs of moratoria, 2004–2014.

Impact category	Actual	Scenario	Difference	Percentage change
Chemical active ingredient (kg)	53 million	46.5 million	6.5 million	12.3% decrease
Environmental Impact (Σ_k^K $\text{EIQ}_k/ha * Hectares_k$)	1.1 billion	944 million	158 million	14.3% decrease
Field equipment passes (ha)	104 million	97 million	7 million	6.8% decrease
Fuel (liters)	202 million	194 million	8.7 million	4.3% decrease
GHG and compound emissions (kg)	562 million	538 million	24.2 million	4.3% decrease

These environmental impacts (Table 7) come in strong contrast to much of the hypothetical controversy against GM crops. The aggregate impacts in this case study have illustrated that GM canola has a lower environmental impact compared to the non-GM canola basket established through the application of lower amounts of less toxic herbicides and a reduction in GHG emissions.

The aggregate economic impacts follow a similar story line to the environmental impacts. The economic factors of changes in variable costs of weed control, yield, and the contribution margin indicate that GM canola possesses

TABLE 8. Australian economic moratoria opportunity costs, 2004–2014.

Economic category	Actual	Scenario	Difference	Percentage change
Yield (mt)	25 mt	26 mt	1.1 mt	4.2% increase
Contribution margin (AU$)	$10.7 billion	$11.1 billion	$485.6 million	4.5% increase

economic benefits compared to the non-GM canola basket (Table 8). The yield impact from the moratoria resulted in an opportunity cost of 1.1 million tonnes of foregone canola production. Pricing this foregone canola production based on the Australian delivered price for canola per metric tonne from 2004–2014, the foregone yield benefit is approximately AU$551 million (~US$495 million) of revenue to the Australian economy.[48]

The contribution margin, an evaluation of revenue minus the variable costs of production, calculated the per hectare trade-off of GM canola production versus a non-GM canola basket. This margin includes the average revenue, calculated using yield and the average canola price between 2004 and 2014, and the variable cost of production, consisting of the variable cost of weed control, seed, and segregation costs. GM canola carries the additional variable costs of a technology access fee, for the use of the patented trait and a cost for the on-farm segregation of GM seed. The impact of the contribution margin indicates an AU$486 million (~US$431 million) opportunity cost of foregone producer benefits associated with the moratoria.

5. CONCLUSIONS

The policy discussion on GM crops tends to involve the environmental benefit of protecting biodiversity from the risk a new crop trait may hold, possibly through cross-pollination of wild relatives. This discussion does not usually incorporate the risks that are innate to the conventional varieties already in production and cultivation, such as the toxicity of active ingredients applied in the form of pesticides and herbicides.

If the goal is to minimize agriculture's impact to the environment then the adoption of the more environmentally friendly and sustainable GM crop is likely the best solution, as negative environmental impacts are higher through the continuation of non-GM, conventional crops. Similarly, delays in approving GM crops may be denying farmers potential economic benefits that have been shown to accrue in jurisdictions in which farmers have had the choice of GM and non-GM crop varieties. Although benefits vary based on crop, trait, and on a country-by-country basis, evidence suggests most adopters do gain.

The Cartagena Protocol on Biosafety advocates that countries have the right to implement the Precautionary Principle to the fullest extent should the approval of a GM crop variety fail to guarantee with 100% certainty that biodiversity would not be impacted following commercial approval. Such a rigorous application of the Precautionary Principle has developing countries following the lead of European nations, banning the commercialization of GM crops, or implementing moratoriums on the assessment, regulation and commercialization of GM crops, similar to that of Australia. As is evident from the assessment of Australia's moratorium, the costs to a developed nation are substantial, but they may be more impactful in the developing world to food insecure and poorer farmers.

The impacts of these results offers some insight to other countries delaying the adoption of GM technology, especially in the developing world. In Africa, the influence of European policy and the Cartagena Protocol on Biosafety in delaying the adoption and cultivation of GM crops is best illustrated through the impact to income. Klümper and Qaim's meta-analysis report of 147 studies on GMO crops found declines in chemical use of 37%, yield increases of 22%, and farmer profit increases of 68%.[58] Poor weed control is arguably the single biggest contributor to low maize yields for African smallholder farmers,[59] which can be benefitted by GM herbicide tolerant traits that allow for more efficient use of a post-emergent broad-spectrum herbicide which has a positive impact on weed control, therefore yield. In India Bt cotton-adopting households increased their incomes by 82%, with vulnerable households, earning less than US$2/day, increasing their incomes by 134%.[60] Similiary, Bt cotton adopters in China increased their income by US$500/ha,[61] and GM maize farmers in the Philippines had a mean net income 50% higher than non-GM maize farmers.[62]

In addition, the benefits from the reduction in chemical inputs accrues not only to GM crop adopters, but also spills over to non-adopters. Benefits from the adoption of GM corn in the USA were estimated to be US$3.2 billion in 2010, with US$2.4 billion going to non-GM corn adopters due to the area wide suppression of corn borers.[63] In China, non-Bt cotton fields had the amount of insecticide applied drop from in excess of 40 to less than 10 kilograms per hectare.[64]

GM crops have been shown to decrease yield losses, which can increase income; reduce inputs such as herbicides and pesticides, which have negative health effects and financial costs[58]; and reduce input applications, which frees up time and is associated with higher off-farm incomes,[65] with the larger impacts being observed in developing opposed to developed countries. Thus, the policy of preventing the adoption of GM crops may harm the environment and effectively limits farmers' abilities to choose what is best for them and their land. This research has shown that the presence of moratoria that are not based on scientific-evidence, but rather on socio-economic considerations, has resulted in a negative impact to the developed country of Australia. This opportunity cost of delay, when coupled with evidence from developing countries adopting GM crop, indicates that in general we may be doing more harm than benefit by inhibiting access to this beneficial agricultural innovation.

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