

# The Loss from Underutilizing GM Technologies

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This article introduces a framework based on a real-option approach to assess the economics of delaying the introduction of genetically modified (GM) technologies in agriculture due to concerns about their unintended effects (unexpected environmental side effects). We applied our framework to analyze the consequences of delaying the introduction of Golden Rice, GM corn in much of the world, and GM wheat and rice globally. In the case of Golden Rice, we found that delay of more than 10 years of introduction of the technology may result in several millions of eyesights lost. The damage of the technology must be greater than between \$2.7 and \$29 billion of discounted net benefits expected to be gained from the technology under various assumptions. The analysis also suggests that restriction of the adoption of GM in corn, rice, and wheat is justified if the net present value of the damage is above \$300 billion to \$1.22 trillion, depending on assumptions about impacts and interest rate. Finally, the value of information gained in this year must be at least between \$27 and \$82 billion to justify the one-year delay in the introduction of GMOs. The analysis shows that precaution is very costly.

**Key words:** genetically modified crops, irreversibility, Golden Rice, adoption, ban, regulation, price, yield effect.

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## Introduction

While the discovery of DNA and the resulting biotechnology led to a wide array of applications in medicine, the utilization of genetic engineering (GE) in agriculture has been quite limited despite the many benefits it has yielded (Barrows, Sexton, & Zilberman, 2014a). Heavy regulation of GE technology—in particular practical bans and costly approval processes—limited the application of the technology to only a few crops and a few countries. In the process, an inventory of GE innovations in various stages of development, including some that are ready for commercialization, have been accumulated. In this article, we present a methodology to quantify the cost underutilization of the potential of GE in agriculture and provide several case studies to illustrate this method.

## Conceptual Framework

Economists have advocated the use of benefit-cost analysis that considers environmental impacts to assess the use of new projects and technologies (Palmer, Oates, & Portney, 1995). Traditional benefit-cost analysis would suggest executing a project if expected discounted benefits exceed expected discounted costs, but when it comes to projects with irreversible, uncertain outcomes, Arrow and Fisher (1974) suggested considering the option of delaying the decision to gain new information.

Indeed, many environmental agencies have used the delay option in regulation of new technologies like GE varieties, which have been taken to an extreme with the use of the “precautionary principle” (Cross, 1996)<sup>1</sup> for environmental and health regulation. However, the framework presented in Arrow and Fisher (1974) suggests that excessive delay can be very costly, and we develop a simple framework to illustrate this with application to regulation of GM technologies.<sup>2</sup>

Let us consider a technology that may produce, with a low probability  $q$ , an externality that costs  $Z$  in the future as well as other net benefits that can be estimated.  $Z$  represents the expected discounted externality costs throughout the life of the technology, discounted to time 0. These costs include unforeseen environmental, health, and other costs that are unintended and generated by the technology.<sup>3</sup> Because of uncertainty about the impact, the expected discounted externality costs may also include costs that represent risk aversion.<sup>4</sup> When a new technology is available for commercial use, its dif-

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1. Gollier, Jullien, and Treich (2000) developed an economic framework interpreting the precautionary principle to address concerns about risks and uncertainties.
  2. The real option approach of Dixit and Pindyck (1994) introduced a framework to determine the optimal timing for adoption of new technologies or introduction of new projects.

fusion is gradual. Let  $B_t$  be the expected net reversible benefit of a technology  $t$  years after its introduction. Thus, the expected net benefit after the first year is denoted  $B_1$ . The net present value (NPV) of a technology, excluding externality costs, is  $NPV = \sum_{t=0}^T \frac{B_t}{(1+r)^t}$ .

If the potential benefit with full adoption of a technology at year  $t$  is  $B_t^F$  and the diffusion rate (percentage of the potential benefit that is actually utilized) is  $P_t$ , then the  $NPV = \sum_{t=0}^T \frac{B_t^F * P_t}{(1+r)^t}$ . Assuming that it takes one period to establish the technology, initial diffusion at  $P_0=0$ .

To decide whether to delay the introduction of the technology, we assume that the externality cost—if it occurs—is greater than the NPV; otherwise, the technology should be introduced regardless. If expected externality costs are smaller than the NPV, namely  $NPV > qZ$ , then the technology should be introduced when it is available. If the opposite is true, the technology should be banned.

Now suppose that  $Z > NPV > qZ$  and that a one-year delay would allow the decision-maker to know whether the externality costs occur. In this case, the decision-maker has to consider the net gain from taking advantage of new information, which we denote as  $G$ . To determine this net gain, note that if it is discovered that the externality will occur, then the delay avoids the costs equal to  $Z - NPV$  (the net cost of the externality), as the decision-maker would not introduce the technology; on the other hand, if the externality does not occur, benefits materialize one period later. From today's point of view, the expected net benefits if the technology is introduced after a delay and it is assured to be safe is  $q \cdot 0 + (1 - q) \cdot [NPV / (1 + r)] = (1 - q) \cdot [NPV / (1 + r)]$ . Comparing

this with the expected benefits of immediate introduction of  $NPV - qZ$  yields the net gains from delay:

$$G = (1 - q) [NPV / (1 + r)] - [NPV - qZ]. \quad (1)$$

Thus, it is worthwhile to wait if  $G > 0$ . Using Equation 1, this condition can be rewritten as:

$$Z > \delta NPV \quad (2)$$

The term  $\delta = \frac{1+r/q}{1+r}$  is greater than one. It indicates that delaying adoption is justified if the externalities are at least  $\delta$  times as big as the NPV, and immediate adoption is justified if the ratio of externality cost to benefits is smaller than  $\delta$ . This suggests that the less certainty there is that the externality will occur, the greater the externality damage needs to be relative to the technology in order to justify delay. For example, if there is a 0.1 probability that the externality will occur, the odds of it not occurring are 9:1 (there is a 9-times larger chance it will not be realized). Using a 10%-discount rate and a probability of 0.1, we obtain a value of 1.82. In the case of a 0.01 probability of occurrence,  $\delta$  approaches 10.

Equation 2 guides our analysis of delay. First, we can discuss the likelihood and magnitude of the externality cost (to gauge the odds of the externality not occurring). Then, we provide benchmarks to quantify the net gain from the technology and the cost of delay. Since there are a large number of GM technologies, we will use a few case studies to obtain orders of magnitude. We will consider GM technologies for which approval has been delayed (e.g., Golden Rice), and we infer from studies on the benefits of GM technologies in use (GM in corn, soybean, and cotton) what would have been the benefit had the adoption been expanded or use allowed in other crops.

### **The Likelihood and Magnitude of the Externality Cost**

The environmental and health side effects of GM have been a major cause for opposition, and therefore it has gotten much attention from national regulators and scientific societies. The National Research Council (NRC) report from 2010 suggested that it actually improved water quality, reduced damage from pesticides, and reduced greenhouse gas (GHG) emissions. It recommended that better tracing of the impact of GM on water quality was needed, and found that concerns about human health, gene flow, and other environmental effects from GM applications are containable. It con-

3. We can introduce more complex formulae where the level of the environmental cost  $I$  is treated as a random variable, assuming many values, but the quality of the results will be the same.
4. One can expand the analysis to explicitly consider several environmental risks associated with use of biotechnology and other risky biological technologies, nanotechnology, and traditional technologies under different scenarios. Using this expanded analysis, one can develop a portfolio approach where the role of biotechnology is clearly defined. The recent report from the Global Challenges Foundation by Pamlin and Armstrong (2015) presents a statistical base for different global risks. It considers GMOs as part of the "synthetic biology" category, which entails a very low catastrophic risk.

cluded that GM food is as safe as conventional food and did not see any cause for alarm about large, unexpected environmental risks, and determined that GM has significant potential to improve societal well being.

Paarlberg (2009, pp. 26-27) documented that major organizations have found that “[there are] no new risks to human health or the environment from GMOs approved by regulators so far.”<sup>5</sup> The European Commission concluded in its 2010 report that:

“The main conclusion to be drawn from the efforts of more than 130 research projects, covering a period of more than 25 years of research, and involving more than 500 independent research groups, is that biotechnology, and in particular GMOs, are not, per se, more risky than conventional plant breeding technologies” (European Commission, 2010, p. 16).

Much of the scientific objection to GMOs is arising from ecologists. However, the leading ecologist of our time, E.O. Wilson (who coined the term “biodiversity”) stated:

“I’ll probably get it in the neck from my conservationist colleagues, but we’ve got to go all out on genetically modified crops. There doesn’t seem to be any other way of creating the next green revolution without GMOs” (Douglas, 2001, p. 2).

This suggests that the environmental costs of GMOs are containable, and the likelihood of a major ecological catastrophe because of them is very small. In terms of our model, the odds of a high externality cost occurring are quite low, and as we show below, the cost has to be immense in order to justify the delay.

5. The agencies Paarlberg considers include: Research Directorate General of EU (2001), French Academy of Sciences (2002), French Academy of Medicine (2003), UK Royal Society (2003), British Medical Association (2004), German Academies of Science and Humanities (2004), OECD (2000), Director-General of World Health Organization (2002), International Council for Science (ICSU; 2003), Food and Agriculture Organization of the UN (2004).

## The Benefit from GMOs and the Cost of Delay: Lessons from Case Studies

### Golden Rice

Golden Rice is a genetically modified rice variety that includes enhanced amounts of beta-carotene, which contains vitamin A. Consuming 60 grams of Golden Rice per day is sufficient to prevent vitamin-A malnutrition. Wesseler and Zilberman (2014) estimated the cost of regulatory delay of approval of Golden Rice in India alone to be US\$1.7 billion. This study can provide numbers that allow us to assess the potential of Golden Rice if adopted globally. Table 1 in Wesseler and Zilberman (2014) suggests that the cost of introducing the technology in terms of provision of seeds and dissemination are very small (much less than 10%) of the total benefits in India, and we can assume that the same is true elsewhere; we can ignore these costs for simplicity and use a conservative estimate of the benefit from eyesights saved.

The benefits of Golden Rice stem from its ability to prevent blindness from vitamin-A deficiency. As a conservative estimate, we assume that the net value of a year of eyesight is  $VE = \$500$  (Wesseler & Zilberman, 2014).<sup>6</sup> The number of new eyesights saved during the  $t^{\text{th}}$  year after the introduction of Golden Rice is  $N_t = P_t * 500,000$ , where  $P_t$  is the fraction of the 500,000 new cases of blindness prevented each year. We assume an S-shaped diffusion curve, and for simplicity use a modified version of the model presented in Griliches (1957):

$$P_t = k / (1 + e^{-(a+bt)}) \text{ for } t > 0 \text{ and } P_0 = 0, \quad (3)$$

where  $k$  is the maximum diffusion rate,  $a$  is a measure of the strength of initial diffusion, and  $b$  is the indicator of the speed of diffusion. Since our unit of measurement is an eyesight-year, the accumulative number of *eyesight-years* benefitting from the technology  $T$  years after its introduction (this is the summation of the *eyesights* saved since the introduction of the technology) is  $AN_T = \sum_{t=0}^T N_t$ , assuming that once individuals begin consuming Golden Rice, they continue to do so and blindness is avoided for life. Thus, the benefit from Golden Rice from eyesight  $t$  years after the introduction of the tech-

6. Wesseler and Zilberman (2014) used this rather conservative estimate in their study, but they explicitly subtracted the cost of the technology. Since these costs are very low relative to the benefits, we consider \$500 to be the net benefit of one individual year of vision.

**Table 1. Expected benefits from different levels of Golden Rice adoption.**

k	Total number of eyesights saved (1000's)		Total number of eyesight-years saved (1000's)		Total benefit generated, 10% interest rate (millions of \$)		Total benefit generated, 4% interest rate (millions of \$)	
	One-year delay	Accumulative	One-year delay	Accumulative	One-year delay	Accumulative	One-year delay	Accumulative
0.2	86	2,588	1,167	35,016	277	2,733	312	7,800
0.5	214	6,408	2,858	85,738	657	6,576	756	18,900
0.8	340	10,214	4,536	136,081	1036	10,368	1,196	29,900

nology is  $VE * AN_t$ . Assuming that the technology lasts  $T$  years, the net discounted benefit from the technology if there is zero delay (the subscript is the indicator of the number of years delay and the superscript is the life of the technology) is:

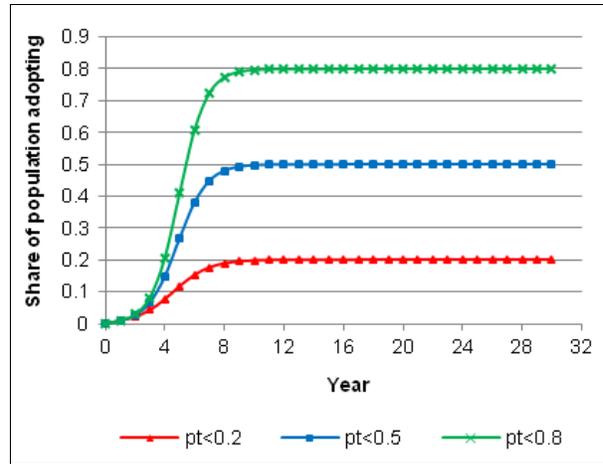
$$B_0^30 = \sum_{t=0}^T \frac{VE * AN_T}{(1+r)^T}$$

We calculated the number of eyesight-years saved and the expected net benefit from Golden Rice assuming low (20%), medium (50%), and high (80%) final diffusion rates of the technology 10 years after adoption.

We also consider two scenarios: one where the technology will be replaced after 30 years ( $T = 30$ ) and another where the technology lasts indefinitely ( $T = \infty$ ). The expected number of eyesights saved and the discounted net benefits under 4% and 10% discount rates are presented in Table 1, assuming that the technology lasts for 30 years.

As can be seen in Figure 1, assuming 20%, 50%, and 80% global adoption of Golden Rice and that the technology is impactful for 30 years (a conservative assumption suggesting that after 30 years it is replaced instantaneously), the number of eyesights saved is between 2.6 million and 10.2 million, and the number of eyesight-years saved are between 35.0 million and 136.1 million. Assuming a \$500 value assigned to a year of gained eyesight, the discounted net benefits based on a 10% interest rate over this 30-year period are between \$2.7 billion and \$10.4 billion. Under a 4% interest rate, the benefits over this 30-year period are between \$7.8 billion and \$29.9 billion, respectively. With a 30-year lifespan of the technology and 10% discount rate, the cost of a one-year delay of the technology is between \$277 million and \$1 billion.

If we assume the technology has an infinite lifespan, it will drastically affect the net benefit of the technology under the more plausible 4% social discount rate. In this case, the range of cumulative net discounted benefits from adoption increases to be between \$27.7 and \$109.3 billion. The cost of a one-year delay in adoption under



**Figure 1. Share of adoption of Golden Rice.**

the 4% interest rate is between \$1.1 and \$4.3 billion, respectively. This suggests that the economic cost of delay—assuming a rather low annual cost of eyesight loss of \$500—is between \$280 million and \$4.3 billion, depending on adoption rate and the effective life of the technology.

**Major Agricultural Commodities**

GM varieties have been introduced on 52% of cotton-grown cropland, 25% of global corn agricultural land, and 70% of the total soybean area (Barrows et al., 2014a). Barrows et al. (2014a) estimated that the adoption of GM increased the supply of corn by 10%, cotton by 20%, and soybean by 30%, and prices without GM would have been 13%, 30%, and 33% higher for corn, cotton, and soybean, respectively. A recent meta-analysis by Klumper and Qaim (2014) suggests that GM technology increases crop yields by an average of 22%, and the impact is greater in developing versus developed countries (approximately double). They find that GM also decreases pesticide use by 37% and increases per-acre farmer profits by 68% on average.

While the impact of these new technologies is substantial and prevented a challenging food situation in the new millennium from getting worse (Barrows et al., 2014b), regulation prevented much more intensive

**Table 2. Average annual price, quantity, and welfare effect of adoption of GM corn.**

	$\eta = 0.35$			$\eta = 80$		
	Price	Quantity (millions of tonnes)	Change in welfare (billions of \$)	Price	Quantity (millions of tonnes)	Change in welfare (billions of \$)
<b>Original supply</b>	\$237.08	821.9	\$0	\$237.08	821.9	\$0
<b>7.5% increase</b>	\$213.81	852.2	\$10.2	\$222.63	864.3	\$10.5
<b>10% increase</b>	\$206.91	862.0	\$13.3	\$218.23	878.3	\$13.8
<b>15% increase</b>	\$194.17	881.4	\$19.1	\$209.95	905.8	\$20.2

gains. For example, 75% of the corn land is not utilizing GM, and GM is not utilized in rice or wheat. In the case of corn, the analysis by Qaim and Zilberman (2003) as well further analysis in Qaim (2009) suggests that the yield effect of GM traits tends to be higher in developing countries where there is lower utilization of chemicals and greater exposure to pests than in developed countries that have milder climatic conditions, and thus Bt corn may have a higher yield effect in Africa and India (where it is not adopted) than in the United States.<sup>7</sup> Furthermore, the development of a new trait that can address the maize-streak virus in corn (Shepherd et al., 2007), which is endemic to Africa and causes 30% or more in crop losses, has been constrained by regulatory and related financial constraints. Moreover, Bt corn can also reduce the damage from aflatoxin in storage (Wu, 2006), which is much more severe in developing countries, and thus increases both quantity and quality of corn available to consumers.

Today between 55% and 60% of corn produced is not GM (James, 2007). If we conservatively assume that adoption of the currently available GM technologies increases yields in the rest of the world by 15-25%,<sup>8</sup> then the overall supply effect will be 7.5-15% once adoption is completed, which we assume to take 10 years (this is approximately the amount of time it took for GM cotton to reach near full adoption). To assess the impact of this extra adoption, we assume that the elasticities of supply of all are equal to 0.35<sup>9</sup> and a range of absolute elasticities of demand from 0.35 to 0.8 for corn

and 0.35 to 0.7 for wheat and rice, which is consistent with the meta-analysis of Andreyeva, Long, and Brownell (2010). In Tables 2, 3, 4, and 5, we denote the absolute elasticity of demand as  $\eta$ .

Because of randomness of demand and supply for food, the impacts vary in each of these years, so we calculated the average effect over this period.<sup>10</sup> Between 2004 and 2013, the global annual expenditure on corn was between \$129 and \$263 billion, with an average of \$163 billion (in 2013 USD).<sup>11</sup> Table 2 suggests that the price of corn will decline 10% to 18% when the adoption of the technology is completed. It also shows that for the low supply increase scenario of 7.5%, the average annual gain from the technology is between \$10.2 and \$10.5 billion, depending on the elasticity of demand. For the high supply increase scenario (15%), the average annual increase in social welfare, on average, is between \$19.1 billion and \$20.2 billion annually. Under our scenarios, the increase in social well being is equivalent to gaining between 6% and 12% of the average annual amount spent on corn. This may be a modest gain from an American perspective, but it is substantial from the perspective of poor nations where corn plays a major role in people's diets and the economy.

While about 50% of the corn produced today is GM, GM traits are not being used in wheat and rice. Both Bt and herbicide tolerance—as well as other traits—can be inserted in wheat and rice, but regulators around the

7. This is the case of Bt cotton, where the yield effect in the United States tends to be smaller than in Africa and India (Qaim, 2009).

8. As we mentioned before, Qaim (2009) suggested that the yield effect of Bt corn in the Philippines and South Africa was above 30%. The damage from the maize-streak virus in corn is estimated to cause 30% or more in yield losses (Shepherd et al., 2007). So, combining several traits may result in a much larger yield effect. In Europe, the yield effect may be smaller, so a 15% average is similar to the yield effect of GM corn thus far.

9. These are the same order of magnitude used in the literature (Rajagopal, Sexton, Roland-Holst, & Zilberman, 2007) and larger than the elasticities for food crops used by Fisher, Hanemann, Roberts, and Schlenker (2012). Lower elasticities tend to increase the cost of delay of introduction of GM, so our estimates are conservative.

10. Our analysis does not explicitly take into account random shocks of demand and supply and the role of inventory and other policies in adjusting to them. These are topics for future research.

11. This is based on global production statistics from the Food and Agricultural Organization of the United Nations (FAO) and world price statistics from Mundi.

**Table 3. Average annual price, quantity, and welfare effect of adoption of GM wheat.**

	$\eta = 0.35$			$\eta = 0.7$		
	Price	Quantity (millions of tonnes)	Change in welfare (billions of \$)	Price	Quantity (millions of tonnes)	Change in welfare (billions of \$)
<b>Original supply</b>	\$300.48	657.7	\$0	\$300.48	657.7	\$0
<b>10% increase</b>	\$262.23	689.8	\$13.4	\$274.40	700.9	\$13.8
<b>15% increase</b>	\$246.10	705.3	\$19.3	\$263.03	722.0	\$20.2
<b>20% increase</b>	\$231.58	720.5	\$24.7	\$252.59	742.7	\$26.1

**Table 4. Average annual price, quantity, and welfare effect of adoption of GM rice.**

	$\eta = 0.35$			$\eta = 0.7$		
	Price	Quantity (millions of tonnes)	Change in welfare (billions USD)	Price	Quantity (millions of tonnes)	Change in welfare (billions USD)
<b>Original supply</b>	\$566.45	682.8	\$0	\$566.45	682.8	\$0
<b>10% increase</b>	\$494.34	716.1	\$26.2	\$517.30	727.6	\$27.1
<b>15% increase</b>	\$463.93	732.2	\$37.7	\$495.85	749.5	\$39.4
<b>20% increase</b>	\$436.56	748.0	\$48.3	\$476.16	771.0	\$51.1

world effectively prevented the utilization of GM traits in these crops (NRC, 2010). We assume that the order of magnitude of the yield effect in other crops applies to both wheat and rice, and thus we simulate scenarios of a 10%, 15%, and 20% increase in supply under full adoption of GM in both crops. Note that we assumed 7.5%, 10%, and 15% yield effect for the 50% of corn output not produced using GM traits. Tables 3 and 4 present the simulated annual impacts of full adoption of GM with wheat and rice under average conditions for the last 10 years, continuing to assume an elasticity of supply of 0.35 and absolute elasticities of demand of 0.35 and 0.7.

Table 3 suggests that the price effect of introducing GM wheat ranges from 13% to 23%. For the low supply increase scenario of 10%, the average annual gain from the technology is between \$13.4 and \$13.8 billion, depending on the elasticity of demand. For the high supply increase scenario (20%), the average annual increase in social welfare, on average, is between \$24.7 billion and \$26.1 billion annually.

Table 4 suggests that the price reduction from introducing GM rice will be between 12% and 23%.<sup>12</sup> For the low supply increase scenario of 10%, the average annual gain from the technology is between \$26.2 and \$27.1 billion, depending on the elasticity of demand. For the high supply increase scenario (20%), the average annual increase in social welfare, on average, is between \$48.3 billion and \$51.1 billion annually. The overall change in welfare is between \$26 and \$51 billion

dollars annually, which is below the estimated \$64 billion annual increase in total welfare from adoption of GM in rice reported by Demont and Stein (2013).

In Table 5, we use the same approach, and assuming that full adoption in the rest of the world will take 10 years from the moment of introduction, the discounted net present value of adoption of GM corn technology under the conservative assumption of a 30-year economic life of the technology with a discount rate of 4% ranges between \$136 and \$268 billion; with a 10% discount rate, it is between \$61 and \$121 billion. If we assume an infinite life of the technology, the net present value of the discounted social benefits of the technology is between \$214 billion and \$423 billion for a 4% discount rate and between \$67 billion and \$132 billion for a 10% discount rate. Following Equation 2, these results suggest that even if corn may pose some unintended risks, delaying its introduction in developing countries is justified if the expected discounted damage is above \$61 to \$423 billion (depending on the discounting factor and life of the technology).

For wheat, the discounted net present value of adoption of the technology over 30 years with a discount rate of 4% ranges between \$178 and \$347 billion, and with a 10% discount rate, between \$81 and \$157 billion. Under a one-year delay, the estimated welfare loss under a 4% discount rate is between \$7.1 and \$13.9 billion, and with a 10% discount rate, between \$8.1 and \$15.7 billion.

For rice, the discounted net present value of adoption of the technology over 30 years with a discount rate of 4% ranges between \$349 and \$679 billion, and with a 10% discount rate, between \$158 and \$307 billion. Under a one-year delay, the estimated welfare loss under

12. The price effect in rice and wheat is the same because we assume the same elasticities and relative shifts in supply.

**Table 5. Discounted net present value (in billions of \$) of adoption of GM corn, wheat, and rice.**

Elasticity	$\eta = 0.35$				$\eta = 0.8$			
	4%		10%		4%		10%	
	30 years	Infinite	30 years	Infinite	30 years	Infinite	30 years	Infinite
<b>Corn (7.5%)</b>	136	214	61	67	139	220	63	69
<b>Corn (15%)</b>	254	402	115	126	268	423	121	133
<b>Wheat (10%)</b>	178	282	81	88	184	290	83	91
<b>Wheat (20%)</b>	328	518	148	162	347	548	157	172
<b>Rice (10%)</b>	349	551	158	173	360	568	163	178
<b>Rice (20%)</b>	641	1,013	290	318	679	1,073	307	337
<b>Total (low)</b>	663	1,047	300	328	682	1,078	309	338
<b>Total (high)</b>	1,223	1,933	554	606	1,294	2,045	586	641

a 4% discount rate is between \$14.0 and \$27.2 billion, and with a 10% discount rate, between \$15.8 and \$30.7 billion.

## Conclusions

This article introduces a simple framework to assess the economics of delaying the introduction of GM technologies due to concerns about their unintended effects (externalities). We found that the delay is not justified if the expected discount benefits of adoption of the technologies are at least greater than the expected damages. We applied our framework to analyze the consequences of delaying the introduction of Golden Rice, GM corn in much of the world, and GM wheat and rice globally. In the case of Golden Rice, we found that delay of more than 10 years of introduction of the technology may result in several millions of eyesights lost. The damage of the technology must be greater than between \$2.7 and \$29 billion of discounted net benefits expected to be gained from the technology under various assumptions.

The result suggests that introduction of GM traits in corn (wherever it is not allowed), wheat, and rice after full adoption can improve annual social welfare by between \$50 and \$97 billion. The discounted net present value of the aggregate welfare gain from adoption of the GM technologies over a 30-year lifespan is between \$300 and \$554 billion based on a discount rate of 10% and between \$663 billion to \$1.22 trillion based on a 4% discount rate. Equation 2 suggests that restriction of the adoption of GM in corn, rice, and wheat is justified if the net present value of the damage is above \$300 billion to \$1.22 trillion depending on assumptions about impacts and interest rate. The less certain we are about the existence of the damage, the higher is the lower bound justifying adoption. The results also suggest that the cost of a one-year delay in approval of the technology ranges from \$27 to \$82 billion. The value of infor-

mation gained in this year must be higher than at least \$27 billion to justify the one-year delay.

The scenarios considered above are rather conservative—they ignore the likely possibility that demand may grow. Simulations with a 1% annual demand growth suggest that the aggregate discounted benefits increase between 20-70%, depending on the crop and scenario.<sup>13</sup> Furthermore, with the introduction of GM there may be additional innovations that increase the productivity of the technology, which may increase supply further and thus increase the gain from the technology. The analysis here is limited to a few crops; GM traits have large potential in applications for vegetables and fruits and can play a major role allowing adaptation to climate change, which increases their value and the costs of banning them.

Given the estimated benefits of adoption of Golden Rice and other various traits in corn, wheat, and rice, the potential cost of these technologies must be immense (one of our estimates suggests that they must be above \$1 trillion) to justify delaying the introduction of these technologies. Various opponents of the technologies and society as a whole need to seriously think about whether the gain from the delays in the introduction and bans on the use of GMOs justify the potential gains from its use.

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13. For example, the net present value after 30 years under the 4% discount rate scenario, 15% supply increase due to GM adoption, and 1% annual increase in demand for corn results in a welfare gain of \$437 billion compared to a \$254 billion gain under the same conditions without the annual demand growth.

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