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Assessing the environmental impact of changes in pesticide use on transgenic crops

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Abstract

Two main traits that have been introduced into genetically modified crops that are currently on the market, viz., herbicide and insect resistance, likely affect pesticide use on these crops. Various surveys have been carried out, such as those of the USDA-ERS and NCFAP, comparing the pesticide use on genetically modified versus conventional crops. Environmental indicators for pesticides may aid in comparing the outcomes of such assays in terms of environmental impact. Previously we applied one indicator, the Environmental Impact Quotient, to pesticide-use data for commercial biotech crops from a recent survey by NCFAP and found that, by this method, the impact paralleled the decreased use of pesticides. The output of many environmental indicators, while lending themselves to comparison of pesticides, is abstract and there may be a need for specific indicators that lend themselves for comparison with other agricultural factors or that are expressed in more tangible terms, e.g., monetary indicators. IUPAC recently initiated a project on the assessment of the environmental impact of altered pesticide use on transgenic crops, with the aim of providing input for risk–benefit analysis of the adoption of genetically modified crops. In conclusion, the use of appropriate environmental indicators enables the assessment of the economic and environmental effects of agricultural biotechnology, including that of altered pesticide use.

Keywords: plant biotechnology; genetically modified crops; pesticides; environmental impact; pesticide-use surveys; environmental indicators; risk-benefit analysis

Introduction

Modern biotechnology has enabled the transfer of genes from biologically unrelated species, opening up avenues for genetic modifications that were hitherto inaccessible by conventional methods of genetic amelioration. The large-scale commercial cultivation of genetically modified (GM) crops started in 1996 and since then has increased at a rapid pace in terms of cultivated acreage, amounting to a global 58.7 million hectares in the year 2002, an area somewhat larger than the total area of France (James 2002). Main countries for GM crop cultivation are the United States of America (US), Argentina, Canada and China.

The most important GM crops are soybean, maize, cotton and canola, while the most important traits that have been conferred by genetic modification are herbicide

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tolerance and insect resistance. Herbicide tolerance allows for over-the-top application of weed-control agents (herbicides), which would otherwise harm the crop, hence facilitating weed management. Many insect-resistant crops have been modified to express small amounts of insecticidal proteins (*Bt*) from the soil bacterium *Bacillus thuringiensis*, which itself has been used over decades as a biological insect-control agent. The presence of the *Bt* proteins thus substitutes for the application of insecticides aimed at the insect pests against which these proteins afford protection.

Given the fact that both herbicide tolerance and insect resistance deal with pest management, and, in particular, with the way that pesticides are used in crops, changes in the types and amounts of pesticides that are used on GM crops can be anticipated. For herbicide-tolerant crops, for example, a shift towards the herbicides that can be used on the herbicide-tolerant GM crop is likely to occur. An example is provided by the pesticide use on soybeans in the US from 1995 till 2002. As shown in Figure 1, the fraction of GM soybeans (predominantly herbicide-tolerant) among the American soybean acreage has steadily increased from 1996 onwards, accounting for 75% of soybean acreage in 2002. Figure 2 shows that the percentage of soybean acreage to which glyphosate is applied has also increased, whereas that of other herbicides has decreased. In terms of percentage of the total amounts of pesticides used, glyphosate has also expanded in these years (Figure 3). It is likely that the adoption of glyphosate-resistant GM soybeans has contributed to this enlarged market share of the glyphosate herbicide. In this paper, we wish to elaborate on the issue of the changed pesticide use on GM crops and the potential environmental implications of this change.

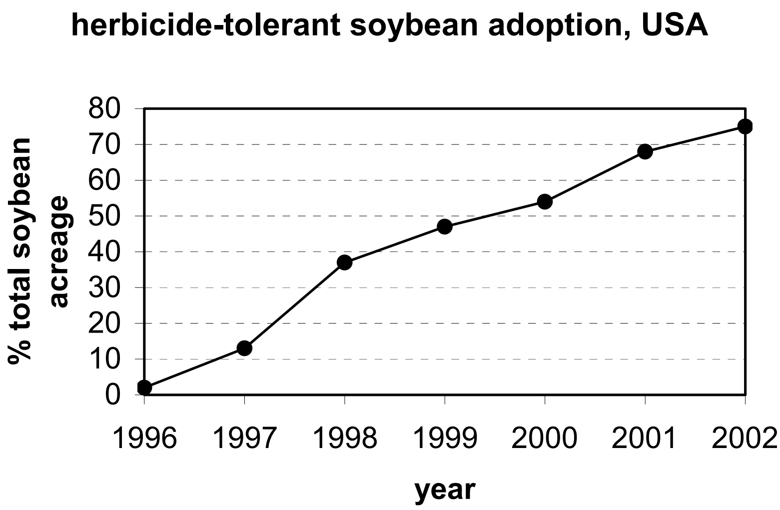

Figure 1. Adoption of GM soybeans in the US, percent of total acreage (data from James (2001) and NASS (2003b))

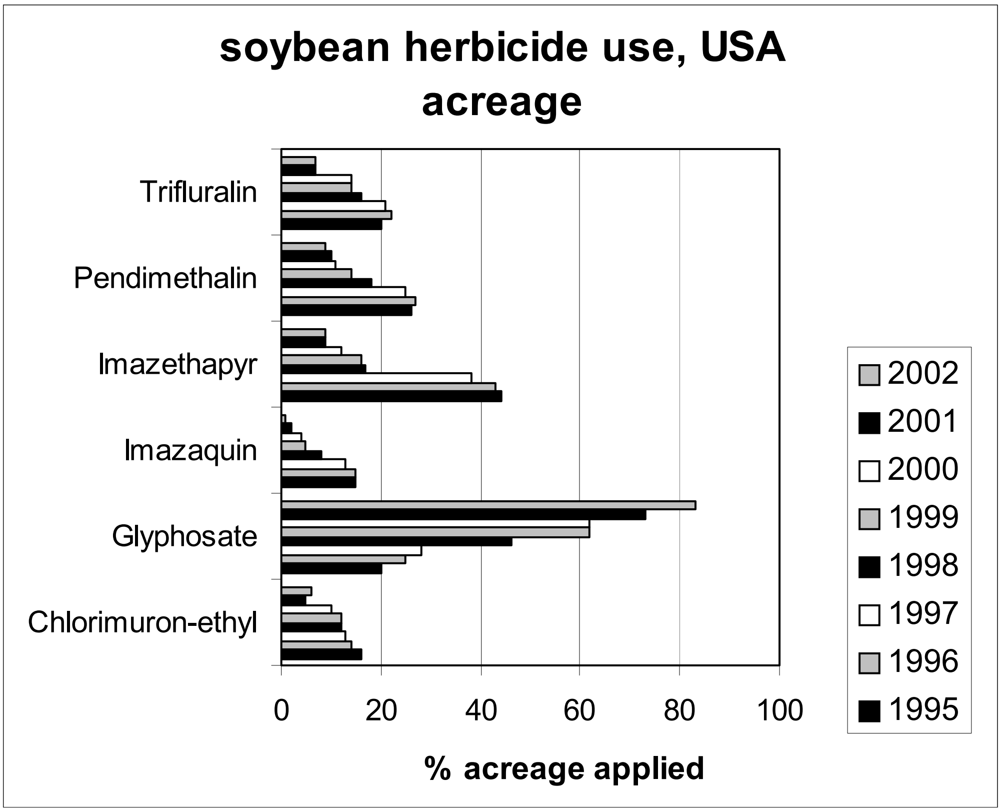

Figure 2. Use of selected herbicides on soybeans in the USA, percent of total acreage (data from NASS (2003a), herbicides selected with minimally 10% acreage in 1995)

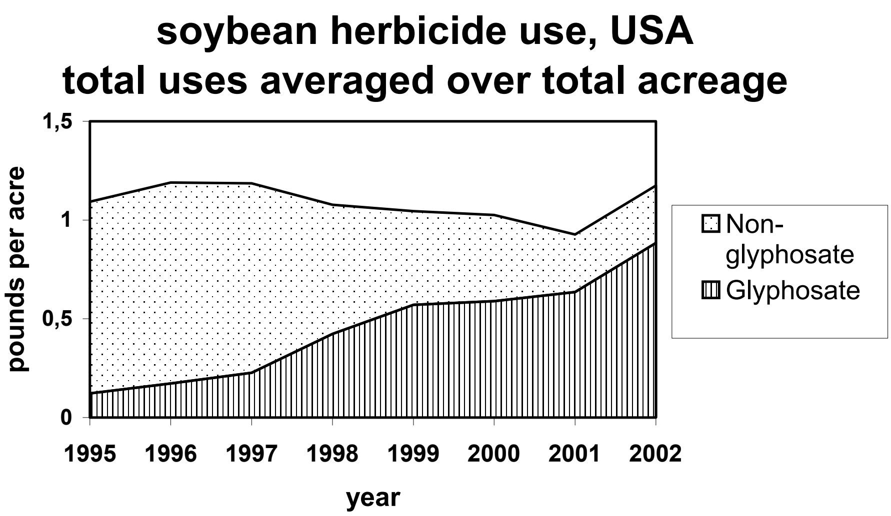

Figure 3. Herbicide use on soybeans in the USA, average active ingredient per area, 1995-2002 (data from NASS (2003a))

Reports on pesticide use on GM crops

The topic of pesticide-use surveys in GM-crop cultivation has been more extensively reviewed in our previous report (Kleter and Kuiper 2003). Organizations that periodically survey the use of pesticides in GM crops include the Economic Research Service of the United States Department of Agriculture (USDA-ERS) and the National Center for Food and Agricultural Policy (NCFAP), both in the US. In general, the USDA-ERS surveys randomly select farms and use statistical models to correct for certain background factors (e.g., farm size, farmer education) that may have influenced the decision to adopt GM crops. NCFAP, on the other hand, generally employs data from experts of industry, universities and extension services on pesticide use and alternatives. Recently, NCFAP released a comprehensive survey of (potential) savings of pesticides on 40 GM crops (Gianessi et al. 2002), including both commercialized and not yet commercialized crop types. Additional data on this issue have also been released by other institutions, such as on Canadian canola (oilseed rape) by the Canola Council of Canada (Serecon Management Consulting and Koch Paul Associates 2001) and G. Stephenson (University of Guelph; personal communication).

Most of these surveys compare pesticide use in terms of amounts of active ingredients of the pesticide used per area (e.g., kg a.i./ha), numbers of applications per crop, or monetary costs of pesticides (e.g., farmers' savings). It can be envisioned, though, that the environmental impact associated with these reported changes in pesticide use do not correlate in a linear fashion, given that the environmental attributes of pesticides may vary from one to another. A famous quote in toxicology, for example, is "*sola dosis facit venenum*" (Paracelsus), i.e. it is only the dose that makes a poison, pointing towards the dose–effect relationships of toxic compounds. Some pesticides, for example, are very potent compounds acting at low doses, whereas others are applied in relatively high doses to achieve a comparable degree of pest control. Also, in their toxicological action on non-target organisms and their environmental behaviour, pesticides may differ widely from each other. The survey outcomes in terms of amounts of active ingredients per area may therefore not reflect the true environmental effect of the changed pesticide use on GM crops.

A limited number of reports have appeared dealing with the environmental impacts associated with the altered use of pesticides on GM crops. Wauchope and co-workers (2002), for instance, compared the profiles of pesticides in surface water in American watershed areas as a function of the adoption of GM herbicide-tolerant maize. These authors predicted that GM-maize adoption would cause a shift to low or no residues of comparatively benign herbicides used on these crops (glyphosate, glufosinate). Another report on field trials with GM herbicide-resistant fodder beets in Denmark showed that biodiversity was increased due to the flexibility in weed control, allowing for herbicide applications at later time points during cultivation and thereby for weeds to grow and associated fauna (arthropods) to develop (Strandberg and Bruus Pedersen 2002).

In our previous report, we applied an environmental indicator to the amounts of pesticides that, according to the comprehensive NCFAP study (Gianessi et al. 2002), had been used on commercial GM crops in the USA. This environmental indicator, the Environmental Impact Quotient (EIQ), is a factor that is applied to the amount of active ingredient used per acre, yielding outcomes that are predictive of the impacts of different pesticides. These outcomes allow for comparison of these pesticides with each other on their environmental effects. Below we will discuss indicators in more detail. The data calculated thus show that the predicted reduction in environmental impact of the pesticides used on GM crops more or less paralleled the reduction in the active amounts of ingredients per area (Table 1, Kleter and Kuiper 2003).

Table 1. Changes in amounts versus environmental impact of pesticides on GM crops [1]

Crop	Difference transgenic versus non-transgenic, %		Method of comparison
	Pesticide use, lbs a.i./A	Environmental impact, EI/A	
Canola, HR	-55	-48	transgenic versus alternative spray programmes for non-transgenic canola
Cotton, HR	-18	-11	Year-2000 figures (transgenic) versus those of base year (non transgenic)
Cotton, IR	-78	-78	statewise determined number of sprays to control pink bollworm / bollworm (non transgenic) times the average amount of pesticides per spray
Maize, HR	-30	-32	substitution scenarios for spray programmes
Maize, IR	-100	-100	no pesticides (transgenic) versus average pesticide use to control European corn borer (non transgenic)
Soybean, HR	-38	-25	glyphosate (transgenic) versus statewise differentiated, equally effective programmes

[1] adapted from Kleter and Kuiper (2003), pesticide use and method of comparison from Gianessi et al. (2002)

Indicators for the environmental impact of pesticides

As mentioned above, an environmental indicator, the EIQ, has been used in our previous work to predict the impact of alterations in pesticide use on GM crops. Whereas some indicators may serve very specific purposes, e.g. avoidance of toxicity to non-target organisms (honeybees), drinking-water contamination, or local environmental impact, the EIQ is a comparatively general indicator. The EIQ, for instance, incorporates the impacts on farm worker (applicator and harvest worker), consumer and ecology (non-target organisms: fish, birds, honeybees and other beneficial insects) (Kovach et al. 1992). Calculation of these separate impacts, which are united in the final EIQ, is based on inherent properties of a given pesticide, e.g. toxicity towards certain organisms and exposure of these organisms due to environmental behaviour (among others: residues on plants, binding to soil, leaching). These inherent properties are assigned ratings, i.e. from 1 to 3 or 1 to 5, with increasing degree of toxicity or harmfulness, based on whether they are within or beyond predefined boundary values (Table 2). Given that zero is not included in the rating, environmentally neutral or benign substances would still attain a non-zero minimum score, which limits the distinction between these and more hazardous substances (Levitan, Merwin and Kovach 1995). The EIQ (total, farm worker, consumer or ecology) is multiplied with the amount of active ingredient used per area (e.g. pounds per acre) to obtain the field-use rating (EI/A). The field ratings for different pesticides lend themselves for comparison of the environmental impact. An example of this is shown in Table 3, where the EI/As, both composed and for subcomponents (e.g. farm worker), for glyphosate use and use of an alternative herbicide mix on GM soybeans in South Carolina are compared. Input data on the amounts of active ingredients have been obtained from Gianessi et al. (2002), who compares the application rate of glyphosate with that of alternative mixes selected for each US state that are equally effective for weed control. The values of the alternative mix in South Carolina are the lowest obtained, which indicates that glyphosate treatment may not always be optimal in terms of calculated environmental impact. However, overall comparison of the total EI/A and its individual components for glyphosate versus alternative mixes in all states of the USA yields favourable figures for the use of glyphosate. Most of the improvement by glyphosate use is to the benefit of the consumer and farm-worker components of the EI/A, which are almost reduced by half (Table 4).

In addition, as noted above, the outcomes of these calculations show that the decrease in environmental impact of pesticides used on GM crops parallels the decrease in amounts of pesticides per standard area used on these crops. In other words, the replacement pesticides do not show particularly more benign environmental properties, which in theory would have decreased the impact of these pesticides beyond the observed reduction in applied amounts. This is also evident from the similarity of the apparent EIQs, i.e. the weighted, aggregate EIQs for the pesticides in both groups that underlie the comparison (Table 5).

In addition to the EIQ, a number of other indicators have also been developed for predicting pesticide impact on the environment. These indicators have been reviewed by several authors (Levitan, Merwin and Kovach 1995; Reus and Middleton 1999) and may serve various purposes, such as a decision-making tool for farmers and extension workers, or a guide for policy decisions by governments. In addition, the input required for performing the calculation of the environmental impact may differ, such as the environmental diffusion of pesticides, toxicity of pesticides to humans or wildlife, and the actual environmental exposure to these pesticides. The EU-sponsored project CAPER, for example, reviewed and compared eight European environmental indicators for pesticide use, i.e. the Environmental Yardstick, the Hasse Diagram, SYNOPS, Ipest, p-EMA, EPRIP, SyPep and PERI. While all these indicators include water contamination by pesticides, they incorporate other environmental compartments and organisms in varying ways. In addition, some of these indicators take actual exposure into account (Environmental Yardstick, SYNOPS, SyPep, EPRIP), while others focus only on inherent pesticide properties (p-EMA, PERI) and the remaining indicators rank intermediate between these two groups (Hasse Diagram, Ipest) (Reus and Middleton 1999).

It should be noted that the outcomes of environmental-impact calculations, such as the one in the example described above, yield abstract numbers, which allow for comparison of pesticides with each other. However, this may not allow for comparison with other non-pesticidal impacts within the same agricultural systems, or may not be tangible for other stakeholders' understanding. One alternative that both provides an avenue for comparison with other impacts and yields outcomes that are tangible for other stakeholders, is to calculate the environmental impact in monetary terms. In their review of pesticide environmental indicators, Levitan, Merwin and Kovach (1995) discerned three types of monetary indicators for environmental impacts of pesticides:

- Single-index systems, where monetary costs, environmental impacts and other scores are added into a composite score.
- Imputing monetary values to environmental impacts, for example as costs for remediation or the costs that farmers would be willing to pay for avoiding these risks.
- Separate indices for environmental and economic impacts, by using an xy-graph with each impact index on one axis.

In addition, it may also be interesting to discern reversible and irreversible effects, both in economic and (eco)toxicological terms, especially with a view on long-term effects of GM-crop adoption. To our knowledge, such a distinction in economic terms would still need to be made, while in some environmental indicators, the toxicological parameter of chronic toxicity to humans and animals has been incorporated into the risk calculation, although not outstanding as a separate feature of the outcome.

Table 2. The EIQ equation

Component	Equation	Input variables (ratings)
Farm worker	C(DT*5)+(DT*P)	C = chronic toxicity (1-3-5) DT = dermal toxicity (1-3-5) P = plant surface residue half-life (1-3-5)
Consumer	(C*(S+P)/2*SY)+(L)	C = chronic toxicity (1-3-5) S = soil half-life (1-3-5) P = plant surface residue half-life (1-3-5) SY = systemicity (1-2-3) L = leaching potential (1-2-3)
Ecology (fish, birds, honeybees, other beneficial insects)	(F*R)+(D*(S+P)/2*3)+(Z*P*3) + (B*P*5)	F = fish toxicity (1-2-3) R = surface loss potential (1-3-5) D = bird toxicity (1-3-5) S = soil half-life (1-3-5) P = plant-surface residue half-life (1-3-5) Z = bee toxicity (1-3-5) B = beneficial arthropod toxicity (1-3-5)
Total	(Farmworker + Consumer + Ecology)/3 = {[C(DT*5)+(DT*P)] + [(C*(S+P)/2*SY)+(L)] + [(F*R)+(D*(S+P)/2*3)+(Z*P*3)+(B*P*5)]}/3	
Field-use rating (EI/A)	EIQ * %active ingredient * rate (lbs/A)	

Reference: Kovach et al. (1992)

Table 3. Comparison of the calculated environmental impact of herbicide regimes on GM soybean in South Carolina [1]

Herbicide		Rate lbs/A	Environmental impact							
Brand	Ingredient		Farm worker		Consumer		Ecology		Total	
			EIQ	EI/A	EIQ	EI/A	EIQ	EI/A	EIQ	EI/A
Glyphosate										
Roundup	glyphosate	0,95	16,0	15,20	7,0	6,65	74,3	70,59	32,4	30,78
Alternative herbicide mix										
Classic	chlorimuron	0,01	13,3	0,13	10,0	0,10	69,9	0,70	31,1	0,31
First Rate	cloransulam[2]	0,016	21,2	0,34	7,8	0,12	57,2	0,92	28,7	0,46
Assure-II	quizalofop	0,1	17,6	1,76	7,6	0,76	129,9	12,99	51,7	5,17
			Total	2,23	Total	0,98	Total	14,60	Total	5,94

EIQ = environmental-impact quotient;
EI/A = field-use rating of environmental-impact quotient

[1] Calculations as applied by Kleter and Kuiper (2003), based on pesticide-use data from Gianessi et al. (2002)

[2] No EIQ known for this herbicide, average EIQ for herbicide class used

Table 4. Calculated environmental impacts of glyphosate and alternative herbicide mixes used on soybeans [1]

EI/A	Alternative mixes			Glyphosate
	High	Low	Average	
Total	59,62	5,94	40,93	30,78
- Farm worker	48,70	2,23	29,89	15,20
- Consumer	18,94	0,98	12,80	6,65
- Ecology	112,89	14,60	80,13	70,59

EI/A = field use rating of environmental-impact quotient

[1] Calculations as applied by Kleter and Kuiper (2003), based on pesticide-use data from Gianessi et al. (2002)

Table 5. Apparent EIQs derived from the calculations of environmental impact of pesticides used on GM versus non-GM crops [1]

Crop (GM trait)	GM / non GM	Apparent EIQ			
		Total	Farm worker	Consumer	Ecology
Canola (HT)	GM	32,4	16,0	7,0	74,3
	non GM	28,0	15,4	8,4	60,3
Cotton (HT)	GM	28,3	17,4	7,7	59,9
	non GM	26,1	18,1	7,9	52,4
Cotton (IR)	GM	28,0	15,3	5,8	63,0
	non GM	28,0	15,3	5,8	63,0
Maize (HT)	GM	29,4	16,9	8,0	63,4
	non GM	30,3	15,4	7,9	66,3
Maize (IR)	GM	n.a.	n.a.	n.a.	n.a.
	non GM	49,4	53,4	14,0	80,7
Soybean (HT)	GM	32,4	16,0	7,0	74,3
	non GM	26,8	19,6	8,4	52,5

EIQ = environmental-impact quotient; apparent EIQ = aggregate for pesticide mixtures or parallel pesticide treatments, weighted for the relative contribution of each pesticide according to its rate (and for HT soybeans, each US state according to its share in total acreage); HT = herbicide-tolerant; IR = insect-resistant; n.a. = not applicable.

[1] Based on calculations applied by Kleter and Kuiper (2003) to pesticide-use data from Gianessi et al. (2002)

IUPAC project on GM crops

Recently, a three-year project “Impact of transgenic-crop cultivation on the use of agrochemicals and the environment” started under the umbrella of the International Union for Pure and Applied Chemistry. The purpose of this project is to investigate the environmental effects that the altered pesticide-management practices in GM-crop cultivation have, and, in a broader context, to provide tools for risk–benefit analysis for policymakers, in order to weigh the risks inherent to GM-crop cultivation against its benefits. To this end, the initial phase of this project will focus on the collection of data on altered pesticide use on GM crops and the characterization of the associated hazards. Such data may come from the surveys discussed above. Subsequently, based upon calculations, the actual risks will be characterized, for example by the use of the environmental indicators, as discussed above. Finally, a comparison will be made with other environmental issues than pesticide use that may incur during the risk assessment of GM-crop cultivation. Finally, these data will be integrated into a risk–

benefit analysis, which should enable policymakers to make decisions about GM-crop cultivation. The international project team brings together specialists from various fields of pesticide science, e.g. ecology, chemistry and toxicology. The project is scheduled to continue through February 2005 (IUPAC 2003).

Conclusions

As discussed above, there is a need to translate the figures on altered pesticide-use practices during cultivation of GM crops (including data from surveys like those of the USDA-ERS and NCFAP) into terms of impact on the environment. To this end, environmental indicators may prove instrumental in quantifying such impacts of pesticides. In our previous work, we employed the EIQ, which has the advantage that it is generally applicable, that EIQs have been established for a great number of pesticide active ingredients, and that farm worker, consumer and ecology components have been incorporated. Whereas the outcomes enable a comparison between different pesticide regimes, these results are rather abstract and may not be amenable to comparison with other issues in agriculture.

One alternative may be to apply environmental indicators that express the impact in terms of financial costs. For damage to fish, for example, direct effects, such as market value and penalties for causing fish mortality, and indirect effects, such as the attraction of sport-fishing tourists, can be taken into consideration for estimating the financial side of the environmental impact (Pimentel and Greiner 1997). Another way would be to translate the outcomes into ‘low’, ‘intermediate’ and ‘high’ risk levels, as is done for water contamination in the US State of Michigan by the web version of the NAPRA (National Agricultural Pesticide Risk Analysis) model (MSU 2003). NAPRA helps to predict the levels of pesticides that will be emitted from farm fields into ground and surface water following pesticide applications, and compares these values with safety threshold values, taking into account the local climatic conditions over the last 50 years and geographical characteristics (NWCC 2003). In addition, the Organisation for Economic Co-operation and Development (OECD) is developing environmental indicators for agriculture, including pesticide use, which may facilitate the holistic approach of assessing GM technology without focus on a specific issue. Three publications about these indicators have already been released, whereas the fourth volume, which describes how to incorporate the agro-environmental indicators into policy decisions, is forthcoming (OECD 1997; 1999; 2001). For example, three indicators for pesticide-use risk to aquatic systems have been developed and will be tested on national data from member states for further refinement, while additional indicators for human and terrestrial organisms will also be developed (OECD 2001).

Similar to ‘health economics’ for new medicines in their pre-market approval process, futuristic tools can be envisioned that enable the (mandatory) assessment of environmental and economic benefits of an agricultural technology prior to their market introduction.

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