Pest Management Science *Pest Manag Sci* **64**:479–488 (2008)

Review

Comparison of herbicide regimes and the associated potential environmental effects of glyphosate-resistant crops versus what they replace in Europe

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Abstract: While cultivation of transgenic crops takes place in seven of the EU member states, this constitutes a relatively limited part of the total acreage planted to these crops worldwide. The only glyphosate-resistant (GR) crop grown commercially until recently has been soybean in Romania. In addition, large-scale experimental European data exist for GR sugar and fodder beets, and, to a lesser extent, GR oilseed rape. These GR crops are likely to have an impact both on the use of herbicides and on the environmental impact of the latter. From the data on these GR crops, it appears that quantities of herbicides applied to GR beets are decreased while those on GR soybean are slightly increased compared with their conventional counterparts. Depending on the parameters used for prediction or measurement of environmental impacts of GR crops, generally similar or less negative impacts were observed compared with conventional crops. Favourable environmental effects of the glyphosate-containing herbicide regimes on GR crops appear feasible, provided appropriate measures for maintaining biodiversity and prevention of volunteers and gene flow are applied.

Keywords: transgenic crops; glyphosate resistance; herbicide usage; environmental impact; European Union

1 INTRODUCTION

The aim of this article is to highlight the various issues that surround the potential environmental impact of the introduction of glyphosate-resistant (GR) crops into EU agriculture, if this occurs. In particular, the potential changes in pesticide usage and agricultural practices that go together with the adoption of GR crops will be considered. This review follows on from previous reports by a project team of the International Union of Pure and Applied Chemistry that focused on the environmental impact of changed pesticide usage on transgenic crops.[1–6] In this project, data have been collected on pesticide usage and its environmental impact. In addition, predictions of environmental impact have been made on the basis of some of these data using the environmental impact quotient (EIQ) methodology, which involves the use of a universal indicator.[1–6] Much of the literature on GR crops tested in field trials in the EU pertains to sugar beet and the closely related fodder beet. Therefore, beet will serve as the prime example of the environmental issues that would be associated with the trait of glyphosate resistance. Sugar beet is a root crop and an important source of input for sugar production within the EU. Although the adoption of GR beets is also envisaged to have an economic impact on the farmers, this is beyond the scope of this report.

2 THE STATUS QUO OF GR CROPS IN EUROPE

More than 10 years after the first large-scale introduction of transgenic crops in 1996, the total area planted to these crops in 2007 amounted to 102 million ha in 22 countries. Six out of these 22 countries were within the European Union (EU), i.e. Spain, France, Czech Republic, Portugal, Germany and Slovakia. In spite of this number of EU countries growing transgenic crops, their relative share in the cultivated area was modest, accounting for 68 500 ha of transgenic, corn-borer-resistant maize, predominantly in Spain.[7] In other areas of Europe, transgenic crops have only reached the field testing stage.

At the beginning of 2007, Romania and Bulgaria joined the EU as new member states. Interestingly,

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(*Received 22 March 2007; revised version received 3 July 2007; accepted 3 July 2007*)

DOI: 10.1002/ps.1513

Romania has been growing transgenic glyphosate-resistant soybean since 1999.[8] Because of its accession to the EU, Romania has now to implement the community's legislation, including that on transgenic crops. At the time of writing, the EU had approved transgenic glyphosate-resistant (GR) soybeans for various purposes, including food and feed, but not for cultivation. A renewal of this application and an extension towards cultivation within EU territory were due for submission to the regulatory authorities. The request for renewal thus has to be considered by risk assessors and risk managers before it can receive formal approval. It is therefore not yet certain if cultivation of GR soybean can continue.

In fact, a number of transgenic crops have already been approved for environmental release in the EU under Directive 2001/18/EC, which covers applications such as cultivation, breeding, import and processing. For cultivation, glufosinate-resistant oilseed rape and maize, as well as insect-resistant maize and maize carrying both traits, have been approved. Cultivation additionally requires registration of crop varieties and of the herbicide applied to the specific crop, in this case glufosinate and the formulation containing it. GR crops that have been approved for environmental release include soybean and oilseed rape, both for import and processing, but not for cultivation.

3 POTENTIAL CHANGES IN HERBICIDE USE FROM GR CROP ADOPTION

As mentioned above, GR crop cultivation in Europe has occurred to a limited extent. For this reason, most studies to date focus on the *potential* changes in herbicide regime and the associated environmental and economic impacts of GR crop adoption scenarios. Many long-term policies of national authorities aim to reduce the quantities of herbicides and other pesticides applied to crops. This section therefore considers the potential changes in the quantities of herbicides used that GR crop adoption could bring, while the next section focuses on the environmental impact related to these changes.

3.1 Sugar beet

Coyette *et al.*[9] analysed the potential impact of the introduction of GR sugar beet in the EU. The yield of the sugar beet crop can be severely impacted by weeds, including weed relatives of the cultivated beet that compete with the crop and that may be difficult to control. Weed management strategies have therefore been developed that include multiple post-emergence applications of herbicides in tank mixes at low doses following a higher pre-emergence application of a single herbicide. It is noted that the post-emergence spraying programme may be vulnerable to delays in the intervals between sprays, necessitating higher volumes being used at later instances for maintaining efficient weed control.[9]

These authors used various scenarios based on current practices of weed management in the top six beet-producing countries of the EU, i.e. Germany, France, the UK, Holland, Spain and Belgium. These countries accounted for a total of 1 398 000 ha of conventionally cultivated sugar beet in 2000, to which 4 482 000 kg of active ingredients (AI) were applied within a single year. This included 335 000 kg of glyphosate and 4 147 000 kg of other herbicides. The average cumulative application rate of herbicides varied between 2.4 and 4.1 kg AI ha^{-1}, averaging 3.2 kg AI ha^{-1}. The most predominant herbicide used on beets was metamitron, followed by chloridazon, ethofumesate, phenmedipham and glyphosate. Contrary to glyphosate applied to GR crops, glyphosate is applied post-emergence to conventional sugar beet in a directed fashion.[9]

Three scenarios for adoption of GR beet were envisaged by Coyette *et al.*,[9] with varying key criteria for adoption, including: (i) a technical scenario in which GR beet would be chosen because of insufficient control of problematic weeds, soil erosion and toxicity of herbicide in conventional beet cultivation; (ii) a 'potential market' scenario based on other, more subjective factors, such as ease of weed management and more flexible timing of herbicide applications; and (iii) a scenario in which all beets are GR, i.e. '100% market'. On average, GR beet accounted for 56% of all the areas cultivated with sugar beet in the technical scenario, and for 84% in the potential market scenario. It is noted that the adoption rate in the technical scenario may vary from one year to another, depending upon the weed infestation level during the pertinent season. The reduction in quantities of combined herbicides applied to beets amounted to 28% in the technical scenario, 35% in the potential market scenario and 43% in the 100% market scenario.[9]

A case study by Gianessi *et al.*[10] at the National Centre for Food and Agricultural Policy (NCFAP) extended the 100% scenario to two additional EU countries, Italy and Denmark. Similarly to the previously mentioned study, NCFAP considered that applications of conventional herbicides were on average 3.2 kg AI ha^{-1}, while those on GR beet were 1.9 kg AI ha^{-1}. Total herbicide use on conventional sugar beet was thus considered to amount to 5 336 000 kg AI in total, while 100% GR beet adoption was estimated to reduce this by 2 100 000 kg AI.

GR sugar beet has also been tested for its environmental impact in terms of the biodiversity in and around agricultural fields in the UK's farm-scale evaluations (FSE). The FSE were a large-scale, 3 year field trial carried out with three crops, including glufosinate-resistant spring and winter oilseed rape, glufosinate-resistant maize and GR sugar and fodder beets. Field trial locations were dispersed all over the UK, and an adjacent-field design was followed, in which the half-fields with either the transgenic crop or its conventionally grown counterpart shared the same history of use, thereby reducing the spatial variability.[11,12]

The herbicides applied in the FSE to conventional beets were similar to those in national pesticide surveys, indicative of the proximity of these trials to the real-world situation. Whereas up to six herbicide applications were made on conventional beet fields, a maximum of two applications were made on GR beet fields. The number of various herbicide active ingredients applied to GR beet fields was reduced, while the same also pertained to their quantities, which were reduced by 36% in GR sugar beet fields and 41% in GR fodder beets.[11]

Another project that compared the impact of transgenic GR and glufosinate-resistant beet on weed populations compared with conventional beet was BRIGHT, which is the acronym for Botanical and Rotational Implications of Genetically modified Herbicide Tolerance.[13] In this project, various rotations involving herbicide-resistant and conventional varieties of oilseed rape and sugar beet were carried out during 4 years. The herbicide resistance trait in oilseed rape was for glufosinate only. Three out of five rotations included sugar beet, i.e. the glufosinate-resistant, GR and conventional varieties grown in various locations across the UK. In these rotations, sugar beets alternated with cereals and oilseed rape. While the number of herbicide sprays applied to conventional beets per season varied between two and four sprays, on average 2.7 sprays, the number applied to herbicide-resistant beets was decreased, e.g. on average 1.3 sprays to GR beet. None of the treatment programmes for conventional beets provided complete weed control, whereas the use of broad-spectrum herbicides glufosinate and glyphosate alleviated the need for additional hand labour, which typically requires 35 hours of handwork per hectare in conventionally grown beets.[14] In addition, in cases where herbicide-resistant rape had previously been grown, tank mixes of glyphosate with either metamitron or triflusulfuron-methyl were applied to beets to control volunteers. It was also noted that the use of broad-spectrum herbicides on herbicide-resistant beets facilitated the control of weed beets that are otherwise difficult to control.[13]

3.2 Soybean

Brookes[8] describes the situation surrounding the cultivation of GR soybean in Romania up to the year 2003. At that time, the country grew 66 000 ha of soybeans and ranked fourth among the greatest soybean-producing countries of Europe, after Italy, Serbia and Montenegro and France. GR soybean accounted for an estimated 48% of all soybean plantings in Romania in 2002, partly derived from farmer-saved seeds besides certified seeds. In fact, the area cultivated with soybean decreased from approximately 190 000 ha at the beginning of the 1990s, after which it experienced various political changes, technical setbacks and meteorological impacts. In addition, weed pressure has increased since then, in part owing to a favourable climate and diminished use of herbicides, partly replaced by manual weeding. In particular, Johnson grass, *Sorghum halepense* (L.) Pers, is mentioned as a problematic weed that is difficult to remove with herbicides other than glyphosate.

Brookes[8] also notes that the conventional herbicide treatments vary widely from the full recommended application programme to only partial or no application. Based on farmer surveys, it was estimated that, on average, 1.98 herbicide sprays were carried out on a soybean crop. The number of post-emergence sprays was 1.34, whereas the recommended full treatment would have amounted to 3–4 sprays. The most used conventional herbicides in Romania were imazethapyr and trifluralin. An increasing share of glyphosate in the total quantity of herbicides used on soybean has been observed since the introduction of GR soybean in 1999, up to 61% in 2002, with an average overall herbicide application rate of 0.8 kg AI ha^{-1}. Nevertheless, Brookes[8] indicates that no firm conclusions can be drawn on the basis of these data because of the suboptimal application rates before this era and the varying sources of information.

In a follow-up study on the impact of the first 10 years of commercial transgenic crop cultivation, Brookes and Barfoot[15] estimated that, during the period of GR soybean cultivation, herbicide use had slightly increased, i.e. by 5.2% in 2005, compared with the scenario in which all Romanian soybean had been non-transgenic. As mentioned above, this increase related to the comparatively low average use of conventional herbicides, caused by financial constraints. While the cost of purchasing seeds plus herbicide packages of RR soybeans tended to be higher in Romania than elsewhere, the incentives for adoption included a higher yield of higher-quality seeds owing to improved weed control.[8,15]

3.3 Oilseed rape

The BRIGHT project described above also investigated the impact of two transgenic herbicide-resistant winter oilseed rape varieties, i.e. GR and glufosinate-resistant, compared with conventional oilseed rape. In addition, a conventionally bred imidazolinone-resistant variety was also included in the first year. Three rotations were thus tested: the first with oilseed rape in the first and last year of the experiment; the second with oilseed rape in the first year and sugar beet in the third year; and the third with oilseed rape in the third year. In the other years, cereals were grown in rotation with these crops. Each rotation was carried out on three sites. GR oilseed rape was treated with one spray of glyphosate in all locations, whereas that for the glufosinate-resistant and conventional variety varied between one and two applications.[13]

4 ENVIRONMENTAL IMPACT

4.1 General

In the previous section, the potential changes in the quantities of pesticides used on GR crops within a European scenario have been discussed. However, pesticides differ from each other with regard to their environmental behaviour and toxicological profile, such as different dose–response relationships, the organisms sensitive to toxic effects and the nature of toxic effects caused by the pesticide. In order to be able to compare the environmental impact of different pesticide regimes, various indicators have been developed that convert the data on pesticide used to parameters that can be compared. Some indicators relate only to the environmental behaviour, such as leaching to groundwater, taking into account, for example, local soil and meteorological conditions, while other indicators also take into account the broader impact of pesticides, such as effects on non-target organisms. The use of outputs of indicators can vary, depending upon the purpose of the outcomes, which includes advice by extension services to farmers on environmentally benign spray regimes or a foundation for decisions by policy makers regarding pesticide legislation.

An example of a universal type of indicator is the environmental impact quotient developed by Kovach *et al.*,[16] which originally was developed for extension advice on integrated pest management in horticulture. The EIQ has since then been further updated, and many authors have used it for estimating and comparing the environmental impacts of pesticide spray programmes not only in North America but also in other regions of the world. For example, Cross and Edwards-Jones[17,18] used the EIQ to assess in retrospect the long-term trends in pesticide use on crops in the UK and the associated environmental impact. It was thus observed that pesticide use and environmental impact had declined during the 1990s and early 2000s. However, for vegetables, this was for the greater part caused by reduction in crop land, which related in part to higher yields per hectare and in part to replacement with increased imports of crops requiring high pesticide usage. In addition, Qualitom, a European project on tomatoes, compared pesticide treatment of tomato crops in three subsequent years and various locations, mostly in the EU.[19] For this purpose, environmental risk indicators were applied, including the EIQ and the IPEST indicator, the latter for the behaviour of pesticides in the environment (e.g. leaching, runoff, evaporation). The results showed that the impact expressed as EIQ and IPEST values varied between locations and seasons. A correlation was observed between pesticide usage and environmental impact. The EIQ values correlated with the applied quantities of active substances, and both the EIQ and IPEST indicators correlated with the number of pesticide applications.[19]

The EIQ equation contains various components pertaining to the effects on farm workers, consumers and ecology. The ecology component considers the toxicity to fish, birds, honey bees and other beneficial insects. An abstract numerical value is assigned to each component, based on the data that are available on toxicity and environmental behaviour of the pesticide, with higher values being associated with less favourable characteristics. An EIQ value is thus assigned to an active ingredient that may form part of a pesticide formulation. The application rate of each active ingredient in the applied pesticide multiplied by the EIQ thus generates an abstract numerical output (Fig. 1).[16]

The EIQ has been applied to Romanian GR soybean (see Section 4.2),[15] and the authors' team has previously used this methodology to estimate the impact of changes in pesticide use on transgenic crops in the USA, based on quantitative usage data published by NCFAP, and in Canada. The outcomes in general indicate a decline in pesticide usage on each type of transgenic crop, including herbicide-resistant soybean, maize and oilseed rape. This also holds true for the associated environmental impact according to the EIQ equation.[1–6] However, given the different agricultural landscapes and practices in Europe, these conclusions for Northern America are not directly applicable to the European situation.

In Europe, various indicators for the environmental effects of pesticides have been developed and employed in practice. Various initiatives have compared indicators while aiming for harmonization. For example, the European CAPER project compared eight indicators and compared the ranking of 15 pesticide regimes by these indicators with respect to each other. The indicators differed from each other with respect to the environmental compartments and organisms considered, such as humans and soil organisms, while they all considered toxicity to aquatic organisms. In addition, some indicators need input data pertaining to local environmental conditions, such as weather and soil. These differences probably account for the fact that the rankings of the 15 pesticides by these indicators are not the same.[20]

HAIR, which is the acronym for HArmonized environmental Indicators for pesticide Risk, is a unique project funded by the EU, aiming to establish a harmonized environmental pesticide risk indicator. Contrary to indicators like the EIQ, which capture multiple effects with a single outcome, it distinguishes between different components, focusing on different effects and compartments. This follows on from the activities of the Organization for Economic Cooperation and Development (OECD) in the same field.[21]

For example, HAIR develops indicators and dedicated databases and software for the estimation of groundwater contamination and pesticide risks for aquatic and terrestrial organisms, as well as for humans, including workers, bystanders and consumers. For example, HAIR has developed the HAPERITIF indicator for consumer risks, combining

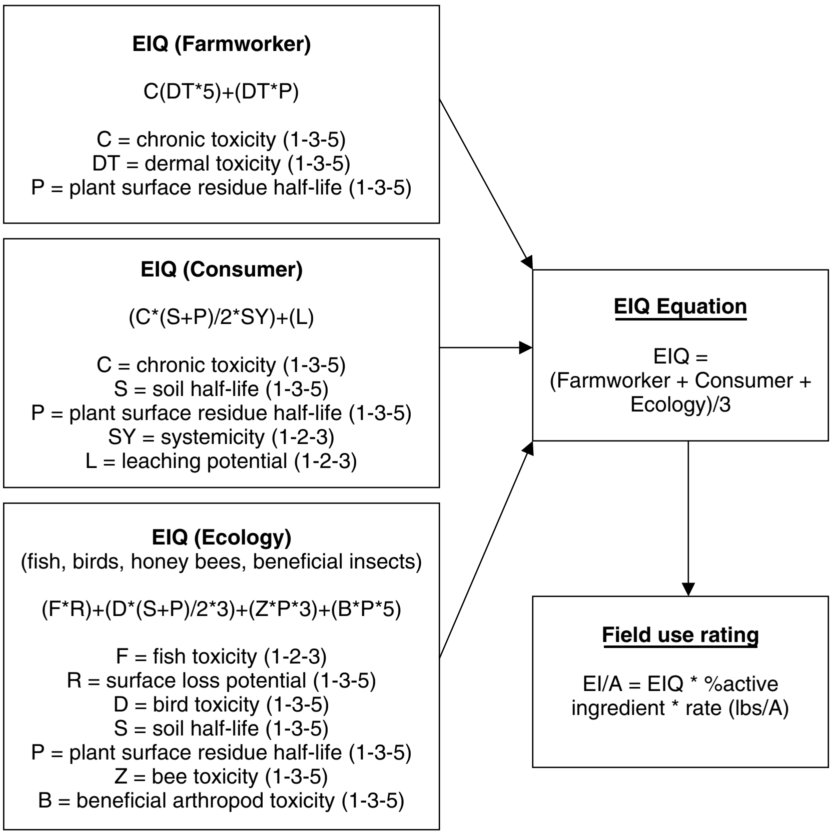

Figure 1. Components of the EIQ equation.[16]

data on toxicity of pesticides and consumption data, while recognizing that estimates based on pan-European consumption data are desirable but not yet feasible. Risks for consumers and other organisms are calculated as the probable level of exposure to a particular pesticide divided by a measure for its toxicity, i.e. the less toxic a pesticide, the lower the risk at a given level of exposure. Data on the agricultural, soil, landscape and meteorological data for Europe have been collected for each cell in a grid laid over the map of Europe. This enables users to estimate the risk of the application of a given pesticide within a cell having a minimum size of 10 by 10 km in Europe. In addition, HAIR aims to aggregate the indicators, both by integrating the data from geographical cells towards a pan-European level and by combining outcomes for different effects. The HAIR project was initiated in 2004 and was to be concluded in 2007 (see the website for a summary of results).[21] To the present authors' knowledge, the indicators developed by HAIR have not yet been applied to GR crops.

Besides predictions based on the use of indicators, field trials like the FSE mentioned above aimed to obtain information on the biodiversity in fields of GM crops under conditions approaching real life. Parameters considered in the fields and their margins during the FSE trials included: (i) the diversity of weeds, such as prevalence, biomass, dominance, species and seed dispersal; (ii) the diversity of invertebrates, such as soil-dwelling, gastropod and aerial species; and (iii) interactions between species at the higher trophic levels. The FSE analysed changes in the biodiversity in fields of transgenic and conventional crops owing to the herbicide treatments applied to these crops and their conventional counterparts that were the cause of the differences observed. The outcome of these trials has been published in a series of peer-reviewed papers, and it has also been given major attention by the media and regulatory agencies.[11,12,22–28]

In more detail, the outcome of the FSE has shown that weed biomass and weed seed shedding after application of herbicides were less in fields with GR beet and glufosinate-resistant oilseed rape than in conventionally managed fields. On the other hand, positive effects on weed and invertebrate populations were observed in fields of glufosinate-resistant maize. For dicotyledonous, i.e. broad-leaved, weeds, the anticipated long-term effects of herbicide management were negative for GR beet and glufosinate-resistant oilseed rape but positive for glufosinate-resistant maize.[12] A study into farmland bird populations on some of the fields used for the FSE generally confirmed the observations on the abundance and diversity of weeds and insects, which are a feed resource for these birds.[29]

For example, based upon the impact of the various herbicide treatments on biodiversity in the FSE, the Advisory Committee on Releases to the Environment (ACRE) recommended that, in future, other proposed changes in agricultural practices should also be tested for their environmental impact. A subcommittee on wider issues subsequently studied the possible consequences of the outcomes of the FSE from a broader perspective, such as for novel technologies not involving GM crops or for indirect environmental effects of GM crops. The report published by this subcommittee recommended considering benefits of a novel technology besides its risks, something that is not yet commonly done for the regulatory assessment of environmental effects of GM crops. Besides the environmental effects per se, the report also recommended considering social and economic impacts as well. In addition, it was also recommended that the reversibility of the effects of the introduction of the novel technology and possible additional measures to mitigate or compensate for them should be considered. For this purpose, a risk matrix was developed in which the various environmental, social and economic effects were offset against the benefits, negative impacts and possible mitigating measures. The methodology of comparing a novel technology with an existing one was termed 'comparative sustainability assessment' (CSA). The application of this matrix was exemplified by a number of cases, including the introduction of invasive plants and animals, but also the example of GR ryegrass. Such ryegrass has not yet been introduced into the UK, but it is technologically possible to obtain it both through conventional techniques and through genetic modification. While it was envisaged that GR ryegrass could facilitate management of weeds, its dissemination to other areas where glyphosate is used to control weeds would require additional risk measures, such as additional herbicide treatments.[30]

4.2 Soybean

Brookes and Barfoot[15] applied the EIQ methodology to the quantities of herbicides used on conventional and GR soybean in Romania during the period 1999–2005. While the quantities of herbicides used on GR were found to have increased by 1.22–5.59% (average 3%) during this period, the overall environmental impact according to the EIQ equation decreased by 1.52–6.45% (average 4%). This predicted decrease in environmental impact is indicative of an environmentally more benign profile of glyphosate compared with other herbicides applied to GR soybean, with an EIQ field rating of 23 ha^{-1} for conventional soybeans and 21 ha^{-1} for GR soybean.[15]

4.3 Sugar and fodder beets

As described above, data for other GR crops besides GR soybean in the EU environment can only be based on predictions or data from field trials. The only large-scale field trial that has taken place in the EU with a GR crop has been the FSE trial with GR sugar and fodder beets, as described above. For these crops, various biodiversity-related parameters were measured, including the abundance of weeds and invertebrates. Based on the published outcomes of the trials with beets, ACRE predicted that, owing to the observed decreases in weed biomass, seed shedding (seed rain) and seed banks in GR beets, cultivation of these beets would have adverse ecological effects on organisms at higher trophic levels compared with conventional beets.[12] Table 1 provides more details of the outcomes of the FSE for biodiversity of weeds and invertebrates. For many parameters, a decline in abundance was noted for the GR beet. Interestingly, the abundance of springtails was generally increased, which can be explained by the increased weed detritus in the fields of GR beet. In addition, the incidence of carabid beetles feeding on these springtails was also increased.

A follow-up study investigated the weed seed banks in fields of crops tested in the FSE, including GR and conventional beets, during the 2 years after each trial. The results showed that, after an initial decline in seed banks in GR beet fields compared with conventional fields during the first year after a trial, this was not sustained for the second year, except for one weed species, i.e. *Persicaria maculosa* Gray. As a possible explanation, the authors of the study hypothesized that this could be caused by a recovery of dicotyledonous, i.e. broad-leaved, weeds in follow-up cereal crops cultivated on the same fields.[31] Another study considered the weed seeds in beet and canola fields used for the FSE that are feed for farmland birds. The densities and calculated energy content of seeds that could be used by seed-eating, i.e. granivorous, birds in fields of GM and conventional crops were compared. The results showed that in GR beet fields the densities of seeds were less than in conventional fields for 16 out of 17 bird species, and the energy of seeds was less for 15 species.[32] An additional study on the actual bird populations in some of the fields employed for the FSE showed that, late in the growing season, after application of glyphosate, the yellowhammer bird species and the granivores bird species group were more abundant in conventional beet fields than in GR fields. During winter, on bare, ploughed fields after sugar beet harvest, granivores were again more abundant in fields of conventional beet.[29]

The BRIGHT project described above investigated the impact of 4 year rotations including GR sugar beet on the abundance of weeds. It should be noted that, owing to a different experimental design, BRIGHT and FSE are not directly comparable. It was observed that the herbicide treatment of the sugar beet, i.e. glyphosate, glufosinate or conventional treatment, did not influence the abundance of weeds in follow-up cereal crops. Sugar beet in general did increase the weed seed bank in these rotations, regardless of the herbicide used.[14]

Concerns have also been raised about the impacts of new crop management strategies on wildlife, in particular farmland birds, where, for example, a decline has been reported to be linked with changes in conventional farming practices. Sugar beet is an important crop in this regard, because birds are able

Table 1. Conspicuous differences between GR and conventional beets in the FSE[a,b]

Item	Group	Parameter	+/−	Observation (GR versus conventional beets)
Weeds	Total	Density	(+)	Initial: total weeds, dicotyls
			(+)	Intermediate: monocotyls
			(−)	Final: total weeds, dicotyls, reproductive dicotyls, reproductive monocotyls, monocotyls with less than four leaves
			(−)	First following year: monocotyls
		Biomass	(−)	Total weeds, dicotyls, monocotyls
		Seed rain	(−)	Total weeds, dicotyls, monocotyls
		Seed bank	(−)	First following year: total weeds, dicotyls
		# species	(+)	Initial: total weeds
		Dominance	(−)	Intermediate: total weeds
	Species[c]	Biomass	(−)	Five species
		Emergence	(+)	Six species, dicotyls, monocotyls
		Survival	(−)	Eight species, dicotyls, monocotyls
		Reproduction	(−)	Three species, dicotyls, monocotyls
		Seed bank	(+)	Consecutive years: two species
			(−)	Consecutive years: dicotyls, monocotyls (slight)
Invertebrates	Soil-dwelling	Springtails	(+)	Isotomidae over the year (pitfall and Vortis)
			(+)	Total and specific species in various months (pitfall or Vortis)
		Carabids	(+)	*Loricera pilicornis* over the year (pitfall)
			(+)	*Trechus quadristriatus* in August (pitfall)
			(−)	*Harpalus rufipes* over the year and in August (pitfall)
			(−)	*Amara* in August (pitfall)
		Spiders	(+)	*Pardosa* over the year, *Oedothorax* in May, *Erigone* in July (pitfall)
	Aerial	Heteroptera	(−)	Heteroptera over the year
		Bees	(−)	Total bees and *Apis mellifera* over the year
		Butterflies	(−)	Total butterflies over the year and in August
Field margin	Plants	Flowering	(−)	Tilled margin: total plants over the year and in July and August
			(−)	Asteraceae in July and August and Fabaceae in July
			(+)	Brassicaceae in July
		Seed set	(−)	Tilled margin: over the year and in August
			(−)	Field verge: in August
		Spray damage	(+)	All three sections: over the year and in July and August
			(+)	Tilled margin: in June
	Insects	Aerial	(−)	Total butterflies in July and *Aglais utricae* butterflies over the year
		Heteroptera	(−)	Field verge: herbivorous Heteroptera in June
		Bees	(−)	*Apis mellifera* in June
			(+)	Bumblebees and long-tongued bees in June
	Groups		(−)	Herbivores and parasitoids in August
Trophic level	Crop	Canopy	(−)	Height in August
	Insects	On crop	(−)	Parasitoids in June
				Significant predator–herbivore relationship in July
		On weeds	(−)	Herbivores and parasitoids over the year and in August
				Significant herbivore–biomass, predator–herbivore and parasitoid–herbivore relationships in August
				Increase in detritivore-to-herbivore ratio
		On soil surface	(+)	Detritivores in August
		Aerial	(−)	Pollinators over the year and in July and August
				Significant relationship between pollinators and weeds in August

[a] FSE, farm-scale evaluations; (+), increase; (−), decrease; #, number of; pitfall/Vortis: methods for collection of invertebrates in fields; field verge and tilled margin: areas surrounding the crop field.

[b] Table reprinted from Kleter *et al*.[3] Data summarized from literature.[23–28]

[c] Twelve species surveyed.

to nest in spring in this crop, which is not possible in other, winter-sown crops, such as winter cereals. However, modifications of the herbicide regimes in GR sugar beet, such as banded spraying leaving unsprayed areas open for weed and insect community development, have been shown to have a positive effect on arthropod populations and weed biomass and seeds, which can serve as feed for farmland birds.[33–35]

A broadly focused approach for assessing the environmental impact of GR sugar beet was followed by Bennett *et al.*,[36] who performed a 'life cycle assessment' (LCA). This kind of assessment considers the inputs needed in terms of energy and the waste emissions discharged into the environment across the whole chain of production, application and disposal of a product. It has thus been used to assess the environmental impact of a variety of products and activities, covering a complete system and not just an isolated product or activity. It therefore allows a comparison of, but not an absolute outcome for, the environmental impacts of different products or processes. LCAs take into account the 'stressors', i.e. conditions that may lead to an impact, such as the production of greenhouse gases which may lead to global warming. The initial steps of an LCA involve the identification of the impact categories that are the target of research, such as global warming, which impact on human, animal or environmental health, or resource availability.[37]

For the LCA of GR sugar beet, conventional herbicide programmes in the UK and Germany were compared with the glyphosate-utilizing program in the same countries. The LCA took into account the production and transport of the herbicides, as well as the equipment used for their application and the environmental dissemination of the active ingredients. Outputs included the energy requirements, global warming potential (carbon dioxide emissions), ozone depletion, ecotoxicity (expressed as equivalents of chromium), acidification of the environment (sulphur dioxide equivalents), nutrification (phosphate equivalents), summer smog (nitric oxides), toxic particulates (particles of 10 µm or less) and carcinogenicity of emissions (equivalents of polyaromatic hydrocarbons). It was observed that on all these points the herbicide regime on GR sugar beet had lower impacts. For example, in the comparison with the most benign conventional herbicide treatment, the GR sugar beet showed approximately 50% less energy use, 50% less ozone depletion, 19% less global warming potential and 7% less acidification. The most conspicuous decrease was in ecotoxicity by 89%, down to 11% of the lowest impact of conventional beet herbicides, which is related to the toxicity profiles of the active ingredients of the various herbicides used. Some of the other parameters, such as energy consumption and carbon dioxide emission, were predominantly related to the manufacture and transport of herbicides for GR sugar beet, and additionally with field operations for conventional sugar beet.[36]

4.4 Other GR crops

The BRIGHT project mentioned above tested three rotations with herbicide-resistant oilseed rape varieties. GR and glufosinate-resistant oilseed rape offered more flexibility for the control of broad-leaved weeds, because glyphosate and glufosinate could be applied at later stages of crop development than the conventional herbicides, which included, for example, metazachlor. In a number of locations, glyphosate appeared to provide the most effective weed control. However, as with sugar beet, it was noted that occasional differences and/or effects on weed seeds and populations occurred that could be related to herbicide treatment, but these were only linked to one location and/or season and therefore cannot be considered consistent. The authors caution that also the cultivation technique of ploughing applied in BRIGHT might have played a role in this, and that the results may not be extrapolated to other tillage practices, such as no-till. The effect of alternating oilseed rape with cereals appeared to be bigger than the impact of alternative herbicide regimes.[13]

A number of European field trials carried out with GR crops other than beet, oilseed rape and soybean and their impact on biodiversity have been reported, but, owing to the limited size of these trials, they are not considered here. It should be noted that the impact on biodiversity is one of the key areas considered by the environmental risk assessment that has to be compiled for applications for approval of environmental release of transgenic crops under EU Directive 2001/18/EC.

5 DISCUSSION AND CONCLUSIONS

Owing to the market and regulatory environment in the EU, the commercial cultivation of transgenic crops has been limited. The only GR crop that has been grown until recently in EU member states is GR soybean in Romania before its accession to the EU. It is noted that various other GR crops have been approved for import and processing within the EU, which constitute less of an environmental issue because they are not cultivated there. The data considered above covered GR sugar beet, with which large-scale field trials have been carried out, and GR soybean, which has been cultivated commercially in Romania.

On the basis of these data it appears that, in the weed-sensitive crop of sugar beet, savings in quantities of herbicides applied to beet fields can be achieved by adoption of GR beets. The same may hold true for the general environmental impact, albeit that, under the specific circumstances of the FSE, GR sugar beet showed less favourable results for some biodiversity parameters. These data also underscore the importance of rotation schemes, as the BRIGHT project showed no effect of herbicide treatment of beets on weed populations in subsequent cereal rotation crops. In addition, an LCA of the chain from production of the herbicides to their field application showed more favourable results for GR beet in terms of, for example, ecotoxicity, energy use and global warming potential. The discrepancy between the outcomes of the LCA and those of the above-mentioned field experiments lies in the different focus, with the LCA focusing on a whole system and the field experiments only on the biodiversity of various biological species.

For GR soybean in Romania, it should be taken into account that the impact of this soybean has to be distinguished from various other confounding background developments in the time since its adoption in 1999. One such change is a temporary decrease in the use of herbicides on conventional soybean on account of financial constraints. The general impression is that herbicide usage has increased slightly while the environmental impact has decreased. These data for beet and soybean also show that it is not always possible to extrapolate directly from the data previously assessed for the impacts of the same crops in the USA owing to differences in agricultural practices in the various regions.

Another environmental issue of importance to the cultivation of GR crops in the EU that has not been considered in this report is gene flow of herbicide resistance, as this is not directly related to impacts of changed herbicide management. It is recognized that the transfer of herbicide resistance traits to wild relatives through pollen flow may in the long term impair the effectiveness of the herbicide used on GR crops. In addition, there may also be an issue of the impact on the biodiversity of the wild relatives themselves, such as for weedy maritime beets being related to cultivated beets. While evidence has been found for previous crossing between maritime and cultivated beets in Europe, the identity of maritime beets has remained high.[38] The GR crop itself may become a volunteer in subsequent rotations, requiring the use of other herbicides in these rotations to control the volunteer. For example, in the BRIGHT project, triflusulfuron-methyl was used to control volunteers of herbicide-resistant oilseed rape in the follow-up rotations of beet crop. Interestingly, the report by Lutman *et al*.[38] considered the issue of management of such volunteers from GR and glufosinate-resistant crops in subsequent rotations. With regard to the potential environmental impact of the herbicide treatment of these volunteers in various follow-up crops, estimations using two different indicators showed that the impact remained within the common range of conventional practice.

In conclusion, GR crops may provide alternative weed management options with potential significant and positive effects on the environment if applied under the appropriate conditions for maintaining agro-biodiversity in crop fields and preventing volunteers and gene flow.

ACKNOWLEDGEMENT

Financial support from the Dutch Ministry of Agriculture Nature and Food Quality, the American Chemical Society and the International Union for Pure and Applied Chemistry is gratefully acknowledged.

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