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Environmental and human health impacts of growing genetically modified herbicide-tolerant sugar beet: a life-cycle assessment

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Summary

There is ongoing debate concerning the possible environmental and human health impacts of growing genetically modified (GM) crops. Here, we report the results of a life-cycle assessment (LCA) comparing the environmental and human health impacts of conventional sugar beet growing regimes in the UK and Germany with those that might be expected if GM herbicide-tolerant (to glyphosate) sugar beet is commercialized. The results presented for a number of environmental and human health impact categories suggest that growing the GM herbicide-tolerant crop would be less harmful to the environment and human health than growing the conventional crop, largely due to lower emissions from herbicide manufacture, transport and field operations. Emissions contributing to negative environmental impacts, such as global warming, ozone depletion, ecotoxicity of water and acidification and nutrification of soil and water, were much lower for the herbicide-tolerant crop than for the conventional crop. Emissions contributing to summer smog, toxic particulate matter and carcinogenicity, which have negative human health impacts, were also substantially lower for the herbicide-tolerant crop. The environmental and human health impacts of growing GM crops need to be assessed on a case-by-case basis using a holistic approach. LCA is a valuable technique for helping to undertake such assessments.

Introduction

Throughout history, the advent of new technology has been controversial. For example, there was an anti-vaccination society which actively campaigned against the use of smallpox vaccine developed by Jenner, and the introduction of the pasteurization of milk met with stiff opposition. The use of genetically modified (GM) crops is the most recent example of a new and controversial technology in agriculture. Although 67 million hectares of GM crops were grown globally in 2003 (James, 2003), highlighting the importance of this emerging technology, there is an ongoing debate about its possible impact on the environment and human health (Conner *et al*., 2003; UK Government, 2003a). The International Council of Science (Persley, 2003) has called for science-based environmental impact assessments to compare GM crop technology with present agricultural practices. Similarly, the recent UK GM Science Review (UK Government, 2003b) identified a number of potential benefits and risks associated with GM crops, including those associated with the environment. The report acknowledges scientific uncertainty and notes that a case-by-case approach should always be adopted in assessing GM crop technology. Although the recently published results of the 3-year Farm Scale Evaluations have assessed the effects of introducing GM crops on the abundance and diversity of farmland wildlife (see Various authors, 2003), to date, no attempt has been made to consider the effects on the environment and human health of the whole system using a 'cradle to grave analysis', such as life-cycle assessment (LCA).

LCA is a recognized method for assessing environmental and human health impacts associated with a product or process, and is conducted according to recognized international standards (International Organization for Standardization ISO 14040 series; Guinee, 2002). LCA is defined as 'an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to effect environmental improvements' (SETAC, 1991), and 'the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product or system throughout its life cycle' (ISO, 1997). Although LCA has been applied to industrial processes and products, it has only recently been applied in agriculture (Audsley *et al*., 1997; Renner *et al*., 2001; Wightman *et al*., 1999).

Previous studies have shown that the introduction of GM crops results in a marked reduction in pesticide use (Carpenter *et al*., 2002; Gianessi *et al*., 2003; Phipps and Park, 2002). In the case of sugar beet, it has been estimated that the introduction of GM herbicide-tolerant sugar beet alone would result in a significant reduction in pesticide use (e.g. see Coyette *et al*., 2002). However, none of these studies has assessed the likely environmental or human health impacts of GM crops using a method such as LCA, which applies a systematic and objective approach to comprehensively identify and list environmental burdens and analyse their impact in terms of categories of importance to the environment and to human health.

Following accepted guidelines, LCA was used to estimate the environmental burdens associated with growing GM herbicide-tolerant and conventional sugar beet in the UK and Germany. The analysis concentrated on aspects of the production system that differ between the GM variety and the conventional crop. This paper presents the results and outlines the analytical method of this LCA.

Results

Weed control in sugar beet

As sugar beet is sensitive to weed competition, a relatively complex weed control programme has been developed, and over 120 herbicides using 19 active ingredients have been approved for use in sugar beet (May, 2001). Traditionally, a sequence of herbicide mixtures containing up to five active ingredients has been used to control weeds, together with mechanical weeding in 50% of the crop. Popular post-emergent herbicidal spray active ingredients include phenmedipham, metamitron, ethofumesate, desmedipham, triflusulphuron-methyl, lenacil and chloridazon.

GM herbicide-tolerant sugar beet has been genetically modified to be tolerant to the herbicide glyphosate, which is a broad-spectrum, non-selective herbicide that kills plants by binding to an enzyme (EPSPS), which prevents the production of essential amino acids in the plants. Thus, weed control within the GM crop can be achieved by applying glyphosate in place of the suite of herbicides referred to above.

Table 1 shows typical herbicide spray regimes used in the UK and Germany for a conventional sugar beet variety and a GM variety tolerant to glyphosate (Coyette *et al*., 2002; May, 2001,

Table 1 Typical herbicide spray regimes for conventional sugar beet in the UK and Germany compared with the regimes for the herbicide-tolerant (Ht) variety

		Application: dose rates (kg/ha)				
	Herbicide name	Pre	Post 1	Post 2	Post 3	Total (kg/ha)
UKA	Chloridazon FL	3				3
	Phenmedipham EC		1.75	2.5		4.25
	Goltix WB		1.25			1.25
	Venzar Flo			0.4		0.4
	Mix				2	2
UKB	Betanal Progress OF		0.75	0.5	0.75	2
	Debut		0.03	0.03	0.03	0.09
	Goltix WG		1.25			1.25
	Venzar Flo			0.4	0.4	0.8
UK Ht	Glyphosate		2.34	2.34		4.68
Germany	Rebell		1	1	1	3
	Goltix WG		1	1	1	3
	Betanal Progress OF		0.8	0.8	0.8	2.4
Germany Ht	Glyphosate		2.34	2.34		4.68

The names and amounts of the active ingredients contained within each formulation, their relative toxicities and the amounts applied to the sugar beet crop for each regime are given in the supplementary online material.

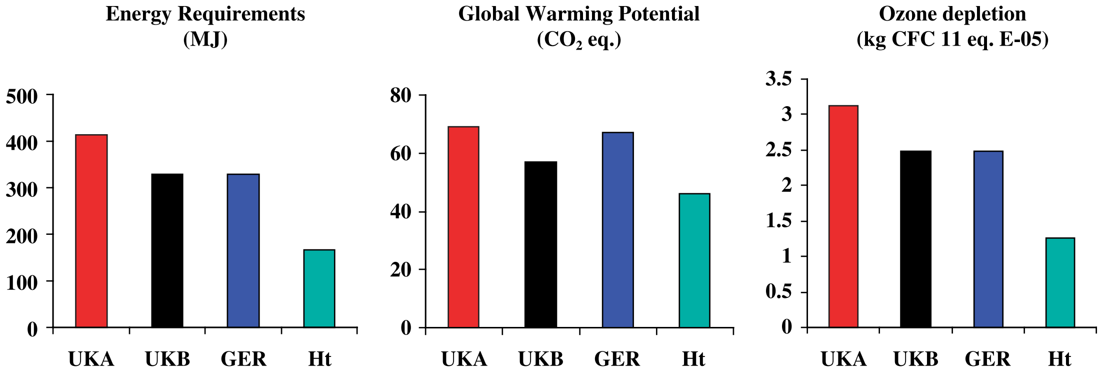

Figure 1 The impacts of typical herbicide regimes for conventional compared with genetically modified (GM) herbicide-tolerant (Ht) sugar beet in the UK and Germany in terms of extracted energy use (MJ), global warming potential [kg carbon dioxide (CO_2) equivalent] and ozone depletion [kg chlorofluorocarbon (CFC) 11 equivalent] per functional unit.

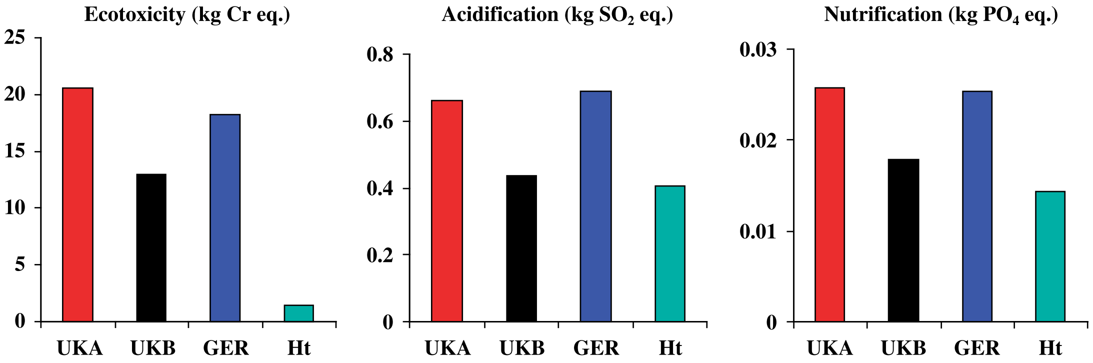

Figure 2 The impacts of typical herbicide regimes for conventional compared with genetically modified (GM) herbicide-tolerant (Ht) sugar beet in the UK and Germany in terms of ecotoxicity [kg chromium (Cr) equivalent], acidification [kg sulphur dioxide (SO_2) equivalent] and nutrification [kg phosphate (PO_4) equivalent] per functional unit.

2003; Rouchouze, 2001). It can be seen that the herbicide-tolerant variety typically requires fewer spray applications, less herbicide and no mechanical weeding.

LCA impact analyses

Results of the LCA impact analyses are shown in Figures 1–3. The functional unit in this LCA is 50 000 kg fresh weight of sugar beet. The GM sugar beet regimes in the UK and Germany are largely the same in terms of herbicide application and growing practices, and therefore only one result is shown.

Figure 1 compares the impacts of the different sugar beet growing regimes on extracted energy (i.e. fossil fuel) use (MJ), global warming potential [kg carbon dioxide (CO_2) equivalent] and ozone depletion [kg chlorofluorocarbon (CFC) 11 equivalent]. It can be seen that the extracted energy use is lowest for the GM system (around 50% lower than the UKB system). It is worth noting that, for the GM system, most of the energy requirement is related to the manufacture and transport of the herbicide (glyphosate), whereas, for the other systems, a higher proportion is related to the energy used for field operations, tractor movements, etc. In terms of global warming potential and ozone depletion, the GM system is also the lowest, being around 50% lower than the UKB system in the case of ozone depletion and 19% lower in terms of global warming potential.

Figure 2 shows the relative impacts on ecotoxicity [kg of chromium (Cr) equivalent in water], acidification [kg sulphur dioxide (SO_2) equivalent] and nutrification [kg phosphate (PO_4) equivalent]. The impact on ecotoxicity is substantially lower for the GM system when compared with the conventional regimes, being just 11% of the UKB estimate. This measure relates almost entirely to the toxicity of the active ingredients of the sprays from field application, rather than any toxic effects resulting from the manufacture or transport of the spray, or emissions associated with the machinery and diesel used for field operations. Acidification of the environment for the GM system is lower than for the UKA and German conventional regimes, and slightly (7%) lower than for the UKB regime. Most of this acidification comes from emissions

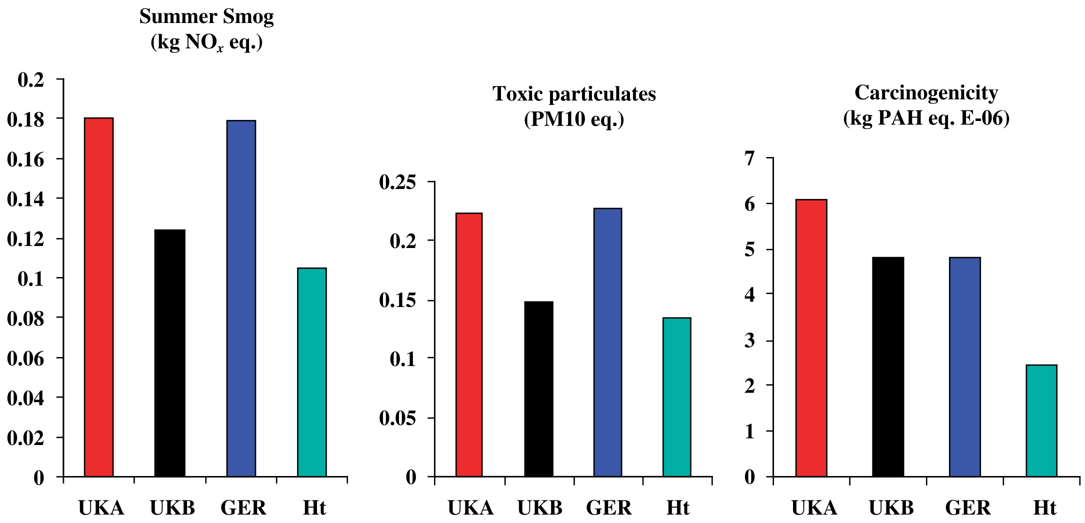

Figure 3 The impacts of typical herbicide regimes for conventional compared with genetically modified (GM) herbicide-tolerant (Ht) sugar beet in the UK and Germany in terms of summer smog [kg nitrous oxide (NO_x) equivalent], toxic particulates [particles of 10 μm or less in size (PM10) equivalent] and carcinogenicity [kg polycyclic aromatic hydrocarbons (PAH) equivalent] per functional unit.

associated with herbicide manufacture and transport, followed by those associated with the machinery for field operations. Nutrification of water and soil is lowest for the GM system and, again, this is associated with manufacture, transport and field operations and not with the active ingredients of the spray formulations themselves.

Figure 3 shows the relative impacts for three different categories of generic importance to human health as well as the environment: the production of summer smog [expressed in kg nitrous oxide (NO_x) equivalent] and the production of toxic particulate matter [particles of 10 μm or less in size (PM10) equivalent], both of which can cause respiratory problems, and the carcinogenic nature of emissions [kg polycyclic aromatic hydrocarbons (PAH) equivalent]. In each case, the GM system has lower values than the conventional systems.

Discussion

The potential impact of GM crops on the environment and human health, compared with conventional crops, is a key topic within the GM debate. In the case of GM herbicide-tolerant sugar beet, the results of the LCA suggest that the herbicide spray regimes and husbandry associated with growing the GM variety would result in fewer emissions that can potentially harm either the environment or human health when compared with the typical herbicide regimes currently being used on sugar beet in the UK and Germany. Clearly, these results are dependent on the number of herbicide spray applications under each growing system, as well as the nature of the herbicides applied. Indeed, sensitivity analyses revealed that assumptions concerning the number of applications and amount of herbicide applied to the crop were most important in affecting a number of impacts. For example, if an additional post-emergence application of glyphosate is assumed for the GM herbicide-tolerant crop, the resulting emissions would give rise to larger environmental/human health impacts than the UKB system in terms of global warming, acidification, nutrification, summer smog and toxic particulates. However, under this assumption, the GM system would still produce lower impacts than either the German or UKA systems and lower energy requirement, ozone depletion, ecotoxicity and carcinogenicity impacts than the UKB system.

It should be noted that the analysis presented here does not address issues concerning the risks and possible effects of gene transfer in the environment.

There are a number of limitations of LCA. First, it is clear that LCA focuses on environmental and some human health impacts, but does not address economic, social or other aspects. Secondly, any LCA involves a number of technical assumptions (e.g. the nature of spray regimes) and some ‘value choices’ (e.g. impact categories). It is important that such assumptions are transparent with justification as to their use, and we have endeavoured to ensure this in the study reported here. The results for the impact categories reported here are indicative of the results found for a wide range of key environmental and human health impact categories considered as part of the LCA. Thirdly, as with any analysis, there are data limitations. Guinee (2002) notes that, for any LCA, ‘in practice, data are frequently obsolete, incomparable or of unknown quality’. In the LCA reported here, some data were relatively dated (.e.g. data on herbicide ingredient manufacture), but were largely comparable (e.g. more recent manufacturing data for glyphosate were available, but were not used because this would have biased the LCA results in favour of the glyphosate-using system). Some data were of a certain 'unknown quality', but had been used in other LCA studies, and were the best data available at the time of the study.

It is hoped that the preliminary LCA described here, although relating to just one case study of a GM crop in two countries in Europe, will stimulate interest in the use of LCA, alongside other tools, to help assess the potential environmental and human health impacts of GM crops and add to the current GM debate. The comparative environmental and human health impacts associated with other GM crops grown in other parts of the world need to be assessed on a case-by-case basis. Moreover, the significance of increased plantings of GM crops for the environment and human health globally needs to be considered.

Experimental procedures

To apply the LCA, conventional and herbicide-tolerant sugar beet production systems for the UK and Germany were defined and then modelled using Pira Environmental Management System (PEMS) LCA software (PIRA, 1998). The models within PEMS concentrated on those aspects that differed between the conventional and GM systems – these being primarily the different herbicide spray regimes for each system. Models for the manufacture of each of the various herbicide active ingredients and spray formulations applicable to the different systems were also built within PEMS (the estimation of emissions associated with the manufacture of active ingredients is based on data regarding the manufacture of similar chemicals in chemical groups from Green (1987), where a number of active ingredients, including glyphosate, are in a group of their own). These models included the manufacture, packaging and transport of the herbicides and the use of farm machinery for field operations. Inventories of inputs and outputs in the form of energy and natural resource use, waste products and emissions into the environment (comprising around 250 different chemical compounds/categories), associated with each part of the defined systems, were compiled on spreadsheets and linked to the PEMS models. Models of spray dispersion (Birkved, 2003) were used to estimate the amounts of each spray formulation that were deposited on to plants, reached the soil, evaporated or drifted into the air, and were likely to be lost by drainage, to groundwater and by biodegradation in top soil, taking account of the half-life of each active ingredient and the growth stage of the crop at the time of spraying.

The effect of emissions and energy use on the environment was estimated by reference to a number of impact categories. This was made possible by characterizing emissions in terms of a common unit, such as CO_2 equivalent in the case of global warming potential, CFC 11 (CCl_2F_2) equivalent in the case of ozone depletion, Cr equivalent in the case of aquatic ecotoxicity, SO_2 equivalent in the case of acidification, PO_4 equivalent for the nutrification of soil and water, NO_x equivalent for summer smog, toxic particulate matter expressed as PM10 and carcinogenicity expressed in PAH equivalent. Several characterization methods were applied to check the robustness of the estimated impacts. Each method produced similar results. The characterizations used for the analyses presented here are those from the Multiple Pathway Method (Dobson *et al*., 1996) and the characterization default of the PEMS software. A large number of data sources were used to compile the inventories of burdens. Data sources of particular importance include those on sugar beet growing systems (Buckmann and Petersen, 2000; Dewar *et al*., 2000), those on emissions associated with field operations (Audsley *et al*., 1997), those on herbicide manufacture (Audsley *et al*., 1997; Green, 1987) and those on the toxicity of the spray formulations (Hauschild, 2000; Richardson and Gangolli, 1994; Tomlin, 1997). The LCA inventories produced from the analyses and the characterization methods used are available as Supplementary Material, together with a table showing the amounts of active ingredients contained in the herbicide formulations and their relative toxicities.

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Supplementary material

The following supplementary tables are available from http://www.blackwellpublishing.com/products/journals/suppmat/PBI/PBI076/PBI076sm.htm. **Table S1** Active ingredients of herbicide formulations and their relative toxicities. **Table S2** LCA inventories of emissions. **Table S3** Characterization methods and multipliers used for each impact category.

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