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Article

Herbicide-tolerant Transgenic Soybean over 15 Years of Cultivation: Pesticide Use, Weed Resistance, and Some Economic Issues. The Case of the USA

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Abstract: Genetically modified (GM) herbicide-tolerant (HT) crops have been largely adopted where they have been authorized. Nevertheless, they are fiercely criticized by some, notably because of the herbicide use associated with them. However, how much herbicide is applied to GMHT crops compared to conventional crops, and what impacts does the use of herbicide have? The paper first presents some factors explaining the predominance of GMHT crops. Then, trends in the use of herbicide for GM crops are studied in the case of the most widespread HT crop: HT soybean in the USA. The trends in the toxicity of herbicides applied to HT soybean are also addressed, as well as the appearance of glyphosate-resistant (GR) weeds. Lastly, the paper examines the spread of GR weeds and its impact. How are farmers, weed scientists, and the industry coping with this development, and what are the prospects of glyphosate-tolerant crops given weed resistance? In conclusion, some issues of sustainability and innovation governance raised by genetically modified herbicide-tolerant crops are discussed.

Keywords: Genetically Modified Organism (GMO); pesticide; herbicide-tolerant crop; crop protection; environment; weed; glyphosate; transgenic crop; innovation; technological change; sustainability

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List of Acronyms

ai:	active ingredient of a pesticide
APHIS:	USDA Animal and Plant Health Inspection Service
Bt:	variety resistant to some insects through Bt toxin
CT:	conservation tillage
GM:	genetically modified
GMHT:	genetically modified herbicide-tolerant
GR:	glyphosate-resistant (for weeds)
HT:	herbicide-tolerant
USDA:	United States Department of Agriculture
USDA-ERS:	USDA Economic Research Service
USDA-NASS:	USDA National Agricultural Statistics Service.

1. Introduction

Transgenic crops continue to be a bone of contention: people are heatedly debating their economic, social, environmental, and health impacts, as well as their usefulness. This is particularly the case for herbicide-tolerant (HT) crops: not only are they genetically modified (GM), they also require the use of pesticides. However, today, HT transgenic crops represent the majority of genetically modified organism (GMO) cultivated surfaces across the world. Of the 148 million ha of GMO in 2010, 83% were herbicide-tolerant, a trait which can exist alone or associated with one or two others, such as resistance to certain insects. This testifies to the success of this trait which provides farmers with a new means of weed control. However, the expansion of HT crops has surprised many people: in fact some expected biotechnology would lead to innovations avoiding chemicals through a better use of biological capacities and a valorization of life processes. Moreover, HT crops requiring the use of a broad-spectrum herbicide were the first to be marketed. Others still believe that this type of trait has little or no value to either farmer or the society at large, and it benefits mainly the firms marketing the traits and/or the associated herbicide.

On the contrary, other sources point out this method's advantages for farmers, leading to its high adoption, as well as some environmental advantages, when authorized. However, the expansion of glyphosate-tolerant crops has led to high annual applications of glyphosate over a large area. Glyphosate use has significantly increased in certain countries due to several factors: an increase in GM crops tolerant to it; the development of generics making it less expensive; the increase in its use in the non-agricultural sector, and development of conservation tillage. This increased use of glyphosate, also often without sufficiently alternating it from one year to another, induced the appearance of glyphosate-resistant (GR) weeds. Over the last few years, the latter have complicated weeding and often induced the application of additional herbicides.

The goal of this paper is to give an agro-economic and agro-environmental appraisal of HT crops in relation to the use of herbicides, as well as some outlook about HT crops given GR weeds. The safety assessment of HT crops is not examined here as it falls within the biological assessment, not the socio-economic one. As the impacts of HT crops are the subject of much controversy, it appears useful to better assess the various agro-economic consequences and issues of this most widespread kind of GM crops, all the more so because other HT crops should be marketed within the next few years. Admittedly, many papers have dealt with the adoption and impacts of HT crops. However, a great part of studies were carried out when HT crops were rather recent, and few have studied the impacts on herbicide use [1]. Rather few make an assessment after years of cultivation, and even fewer assess HT crops over time. However, this perspective is necessary to reveal changes and analyze some phenomena that occur only after a certain number of years of use. This is the case for an important issue: glyphosate-resistant weeds. Indeed, the emergence of GR weeds can change the advantages of growing glyphosate tolerant crops. Therefore, what are the consequences of the appearance of GR weeds for farmers, and what are their reactions? What are the responses of the different actors involved, particularly those heading up the principal biotech seed companies? Will they change the characteristics of HT crops, or switch to other kinds of GM crops? More generally, what does the future hold for HT crops? These issues are important because of the polemic and because of their consequences.

However, the outcome of using GMOs depends on the agricultural, economic, social, and regulatory context of their implementation, as well as on the given period of investigation. GM crops need thus to be analyzed on a case by case basis. Here, several illustrations focus on the case of soybeans in the USA where GM crops are the most widely used. This example is also chosen because since 1996 soybean has been the most prevalent transgenic crop, and this holds true to this day: in 2010 it represented 52% of the overall GMO cultivated surface. In addition, in 2010, 81% of soybean cultivated in the world were transgenic, and in 2011 this percentage rose to more than 99% in Argentina and 94% in the USA [2,3]. Moreover, HT soybean plays an important role in international trade: more than 90% of traded soybean is transgenic [4].

In addition to scientific and agricultural literature surveys, this study is based on the collection and analysis of statistical data on trends in GMO adoption rate, crop practices, herbicide use, seed and herbicide prices, and the development of herbicide-resistant weeds as well as surveys of some actors. Moreover, we look through the proceedings of agricultural conferences, and analyzed annual reports, plus investor and conference presentations made by the firms involved in GM seeds.

After the introductive part (1), this paper will successively tackle the extent to which this weed control method is adopted and its factors of development (2); the effects of HT crops expansion on the use of herbicides as well as some of its agro-environmental impacts (3); some prospects of HT crops given the emergence of glyphosate-resistant weeds (4).

2. The Importance of GMHT Crops: Data and Explanatory Factors

2.1. The Preponderance of GMHT Crops

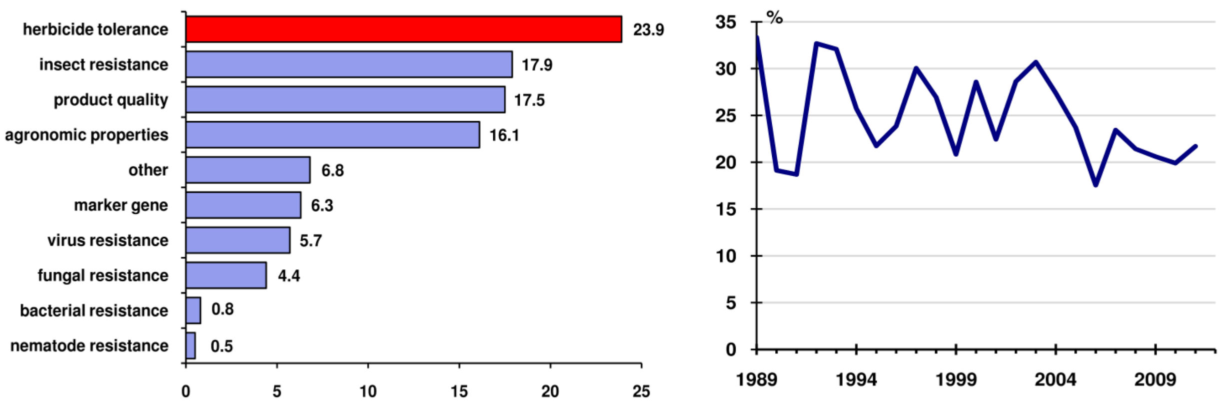
In 2010, GM crops represented almost 10% of world's total cultivated land (approximately 1,525 million ha, including permanent crops). However they are unequally distributed: three countries represent 78% of transgenic crop surface areas, two crops themselves alone represent 83%, and the single trait of herbicide tolerance was present in 83% of GM crop area (alone or associated with another) (Table 1). In 2010, GMHT crops represented approximately 8% of all cultivated land. The proportion of GMHT crops in all cultivated land is already high, if we take into account that the number of species presenting this trait is limited: soybean, corn, cotton, canola, and a few others in small surfaces. However, if the number of cultivated GM species is limited, many more have been tested in the field.

Table 1. Distribution of GM crop acreage in the world in 2010 (area in Million ha; from [2]).

By country	Area	% total	By crop	Area	% total	By transgenic trait	Area	% total
USA	66.8	45	Soybean	73.3	52	Herbicide tolerance	89.3	**61**
Brazil	25.4	17	Corn	46.0	31			
Argentina	22.9	16	Cotton	21.0	12	Herbicide tolerance & Insect resistance	32.3	**22**
India	9.4	6	Canola	7.0	5			
Canada	8.8	6	Sugar beet	0.5	<1	Insect resistance (Bt)	26.3	17
China	3.5	2	Alfalfa	0.1	<1			
Paraguay	2.6	2	Other (squash, papaya)	<0.2	<1	Virus resistance or other	<0.1	<1
Pakistan	2.4	2						
TOTAL	**148**	**100**	**TOTAL**	**148**	**100**	**TOTAL**	**148**	**100**

This preponderance of HT crops could be led to change quite rapidly if the presence of multiple new different traits was noted in the field trials of GM plants or among those close to commercialization. Therefore the field trials taking place in the USA—where they are by far the most numerous—were studied: HT plants appear to have been and be still significant, however at a much lower proportion than in cultivation (Figure 1). Their proportion has diminished very little over time, but a little more since 2003. In 2011, a revival is noted, linked to the development of GR weeds. It is therefore probable that other HT plants will still be launched, or the same plants tolerant to another herbicide(s). This is what is observed in the pipelines of the major firms, even if other traits are also present (see below).

Figure 1. In the USA, percentage of field trials of GM plants expressing a herbicide-tolerance trait, 1989–27 July 2011 (approximately 26,260 field trials; some field trials concern two or more traits. The percentages are calculated as a proportion of total tested traits, not the number of field trials.). Source: author's calculations from APHIS database [5].

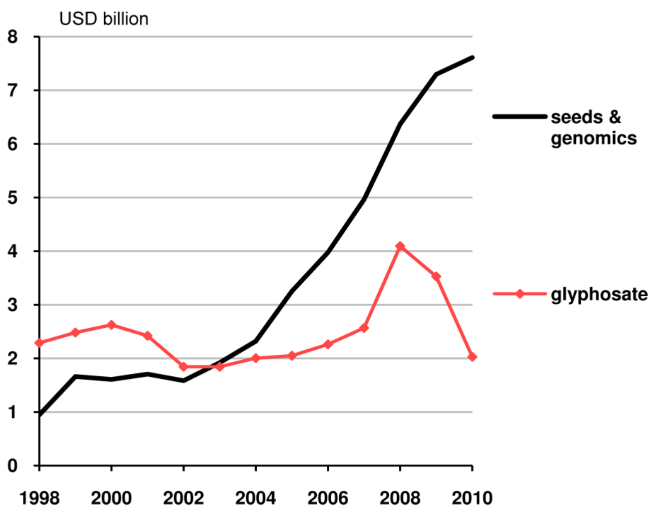


a. overall in all field trials from 1989 to 27 July 2011. *b. by year, percentage of herbicide-tolerance field trials in the total number of tested traits.*

Several factors explain the preponderance of the herbicide tolerance trait in existing crops and trials. Firstly, it is a monogenic trait that was relatively easier to isolate and introduce through transgenesis than other traits involving numerous genes. It was present from the first field tests at the end of the 1980s. Secondly, through the sale of glyphosate, it ensured revenue for firms like Monsanto while the firm developed its research in biotechnology. Indeed, Monsanto transformed its organization from a purely chemical company to a biotech and seed company, which required research and investments that need considerable lengths of time to become profitable. High glyphosate gross profit was essential for Monsanto so long as seeds and genomics were in the early stages of development (Figure 2). Thirdly, HT soybean (and other HT crops) has been well adopted by farmers as it meant easier and simplified weeding requiring less labor time for various crops (see below). Moreover, GMOs in the USA have benefited from a favorable context for their development and have been vigorously promoted within the farming sector.

It should be noted that not all HT varieties are transgenic [6]. Others exist through mutagenesis or conventional breeding methods, but, until recently, they generally raised both less interest because their efficiency was lower, and less controversy because they were not GMOs. Furthermore, they were not greatly used in terms of surface area. In Europe, some non-GMHT crops have been recently launched, based on the assumption that they can avoid both the regulatory burden of GMOs and any opposition from environmental associations. Yet, the destruction of some of these crops perceived as "hidden GMOs" by activists shows that in reality things could be different. This paper will above all consider the case of GM glyphosate tolerance, without analyzing glufosinate-tolerant GM crops. Indeed, the latter have not been widely used over the past 15 years.

Figure 2. Amount of glyphosate, as well of seeds plus genomics, in the net sales of Monsanto (from Monsanto annual reports, in USD billion). Monsanto also sells also some other products, but they are much less noteworthy. As of 2003, the financial year runs from 1 September to the end of August.



2.2. Explaining the High Adoption of HT Crops: the Case of HT Soybean in the USA

Which factors have driven the high level of adoption in the USA? Numerous factors play a role. Indeed, the development of any innovation in agriculture can generally be explained by a combination of institutional, economic, agronomic, social, and cultural factors. In particular, the rapid development of biotechnology in the USA was favored by the context of the country, and farmers found advantages in the use of GM soybean which overcome its drawbacks. A brief presentation of the agro-economic benefits and inconveniences of growing HT soybean is presented here, without taking into account the more recent development of GR weeds and its impacts which are specifically dealt with further on. At the farming level, one of the principal advantages of HT soybean for farmers comes from the fact that weeding is simplified, at least in the short term. Previously farmers used several herbicides and some weeds were still difficult to control. GM varieties allow for easier weed control because only one or two products, and fewer applications, are needed. Moreover, the period when weed treatments can be applied is slightly longer, offering greater flexibility of work and diminishing the risk of intervening too late if weather conditions prevent treatment at the appropriate time. Furthermore, the herbicides used previously were in certain cases fairly persistent and could affect subsequent crops and even the soybean itself [7-14].

The difference in gross margins between HT and conventional soybean is difficult to quantify as there are no accessible representative data evaluating them, only several research works [1]. In addition, according to the US 2007 Census, there were more than 279,110 farms growing soybean in 2007, with a soybean average surface of 93 ha, and there are wide variations in the overall cost of soybean production between farms [15]. Moreover, seed, herbicide and soybean prices have varied over the past few years. However, in the USA, HT soybean is of variable, quite often positive, economic interest [1,16,17]. The additional cost of GM seeds is more than offset by several factors:

- lower herbicide costs due to the use of less expensive weedkillers;
- in the first few years of adoption, a decrease in the amount of herbicide and in the number of applications leading to lower weed control expenses;
- sometimes slightly higher yields due to better weed control;
- a higher rate of adoption of conservation tillage facilitated by HT crops, which induces some cost reduction [18-21];
- a slight decrease in work hours, greater flexibility and simplification of weed control freeing up time for other activities (other productions, off-farm activities, family) [22-24];
- in addition, seed prices are set by firms so that GM seeds are attractive for farmers and sold.

Thus, in general, several factors roughly compensate for the extra cost of GM seeds and make GM crops worthwhile for farmers. However, advantages and disadvantages are not static, but evolve over time, especially with changes in prices. For example, for soybeans in the USA, since 1995 there has been a rising cost of seeds, but lower prices of herbicides from 1998 to 2007 (Figure 3). Indeed, the diffusion of HT soybean having brought about the replacement of certain formerly used weedkillers by glyphosate, the agrochemical firms producing them reduced their prices from 1997 to 2005 to limit market losses. Hence, in a first step, there was an overall reduction in herbicide costs for all growers, whether they used HT varieties or not [8]. However, after 2007, the total cost of herbicide per ha increased again, and the price of glyphosate—decreasing since 1998 because its patent expired in 2000 in the USA—experienced high fluctuations (Figure 4) [25] The latter are notably linked to global generic production which, for a time, was less than demand then in excess of demand, particularly due to strong Chinese exports. As for seeds, they have seen their prices increase on average since 1996, particularly after 2000. This increase affects not only the GM but also the conventional seeds. Thus, within the production costs of soybeans, seeds increased while herbicides decreased from 1998 to 2008 (Figure 3).

Gene flow between neighbouring crops of conventional soybean and GM soybean does not present great problems. Soybean, which is 99% autogamous, poses few risks in terms of cross-pollination with neighboring non-GM crops of the same species, unlike canola and corn. However, vigilance is required in a number of different areas. In particular in the seed processing industry it is necessary to avoid GM seeds being accidentally mixed with seeds certified as "GM free". Downstream it is necessary to avoid the adventitious mixing of GM soybean with "non-GM" grains which some farmers produce in order to sell them at a premium in specific markets.

Thus, HT soybean presents various agro-economic benefits for farmers, which explains its rapid adoption [26]. In the USA, HT corn has spread more slowly in comparison, on the one hand because it was less beneficial than HT soybean given the other weed control possibilities, and on the other hand due to rotation requirements. Indeed, a corn-soybean succession where both are glyphosate-tolerant risks posing problems for the control of possible corn volunteers among the soybean.

Figure 3. Seed and pesticides as a percentage of soybean production costs, 1975–2010 (from 1997 an increasing part of soybean is GM). Source: author's calculations from USDA-ERS data on the production cost of soybean [27].

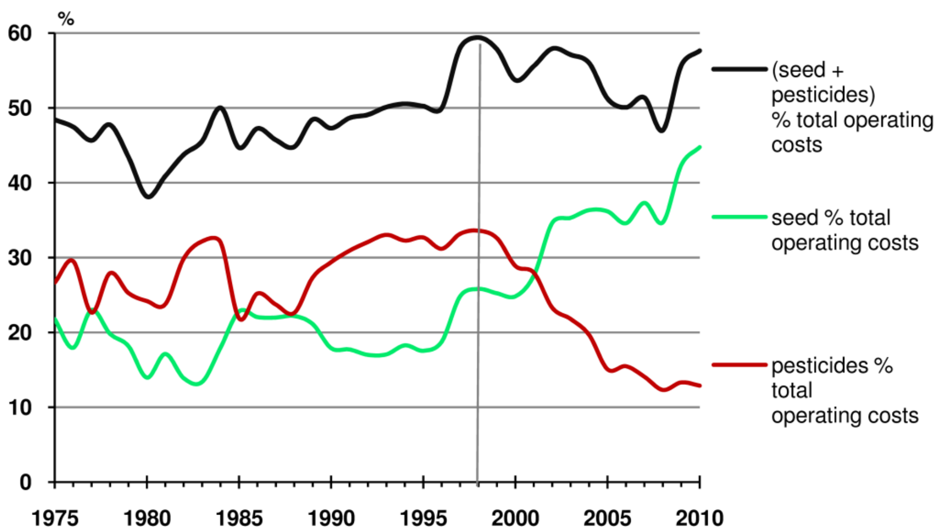
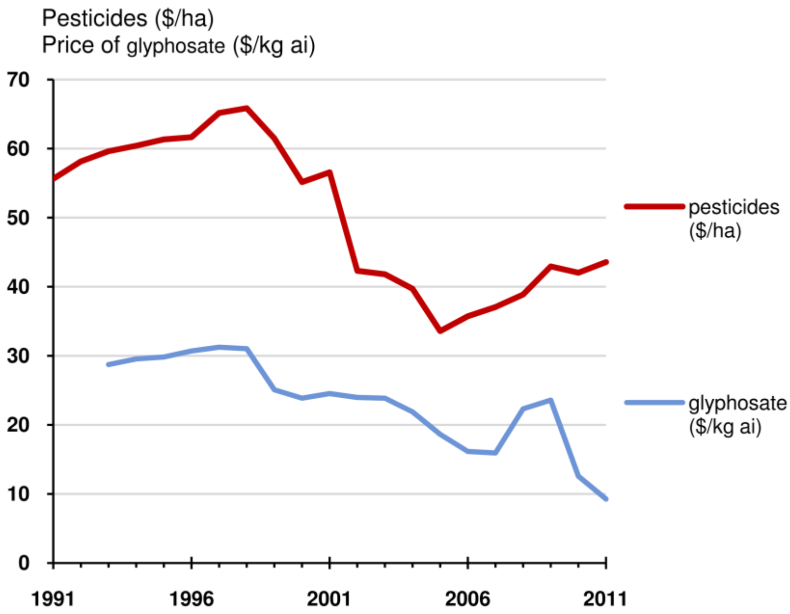


Figure 4. Price of glyphosate (USD per kg of active ingredient), and costs of all pesticides in soybean production costs, 1991–2011. Source: author's calculation from USDA-ERS [27], and USDA-NASS [28]. Note: 2011 data are provisional.



3. Trends in Herbicide Use with HT Crops

3.1. Questions Arising over Sources and Methods

The trends in the use of pesticides with GM crops are to be looked at case by case as they vary according to the new trait type introduced, the plant considered, the pedoclimatic conditions and the context. Some studies have sought to analyze herbicide use with HT varieties. However, this remains highly difficult to apprehend as there are very few accessible, detailed surveys enabling a comparison of the herbicides applied to conventional and HT crops. Furthermore, supposing that this comparison were possible, it would have to be checked that it was carried out "all things being equal elsewhere", meaning that the conventional and HT crops were cultivated in similar conditions. In other words, that there are no other factors introducing a source of treatment difference than the type of varieties (e.g., farmers could choose GM varieties where the weed infestation is the highest). Ideally, the various factors of heterogeneity should be separated before establishing the effects of using transgenic varieties [29]. Indeed, it would be erroneous to attribute to HT varieties, savings or increases in herbicide use induced by other concomitant factors such as changes in herbicide prices or cultural practices. In addition, comparing two agricultural practices should take into account that both evolve over time.

However, it is often difficult to compare the amount of herbicides applied to HT crops and conventional crops, because of several factors: (i) HT varieties can be grown by the most innovative farmers: the comparison is not therefore "all things being equal"; (ii) the variability between plots and between farms is high and may exceed that between the two types of crops; (iii) an analysis for a given year is insufficient, a longer period needs to be studied. Last but not least, there is very little available statistical data that compares the use of herbicides between HT and conventional varieties on large representative samples, a fortiori over a long period. Indeed, this type of survey is time and labor costly and expensive if it is carried on representative and large enough samples (for each crop the quantities of all sprayed pesticides should be noted). In the USA, in particular, if, for a long time, the USDA did conduct surveys of farmers about their use of the various chemicals per crop, the results were provided for their acreage as a whole and not differentiating GM from conventional varieties [30]. Data comparing the two types of varieties exist only for one year, very close to the beginning of it commercialization, 1997–1998 [29,31-33]. Thus, trends in the use of the various types of herbicides can only be analyzed overall per crop without separating GM from conventional varieties. Furthermore, since 2007, for budgetary reasons, this survey has been extremely curbed, hence it is practically impossible to analyze the trends after 2006. Other sources—for example surveys conducted by marketing research companies such as GfK Kynetec—provide very expensive and confidential data that cannot be published in a detailed manner due to their proprietary nature. Lastly some turn to data according to experts' appraisals, estimating herbicide use on HT and conventional crops.

Thus, I used the results of USDA-NASS surveys. These inquiries are sample surveys involving the majority of States which produce field crops, but with a variable number of States depending on the year. The surveys always include the major soybean producing States, but the number of States producing low quantities varies depending on the year. To eliminate these variations, I have brought the herbicides used back to the total surface of soybean included in the survey each year, thus establishing the mean doses of herbicides per ha. The values can be compared from one year to the next as the States that are not surveyed grow low quantities and so have rather little influence on the average. However, given the sampling variation from one year to the next, these doses of herbicide by global ha of soybean must be considered cautiously: these are approximate evaluations. Were also used some results of the accessible GfK Kynetec surveys which have the advantage of giving herbicide application for HT and conventional varieties. However, for recent years, as the proportion of conventional varieties is quite low (less than 11% since 2006), the sampling error for the latter can be quite high.

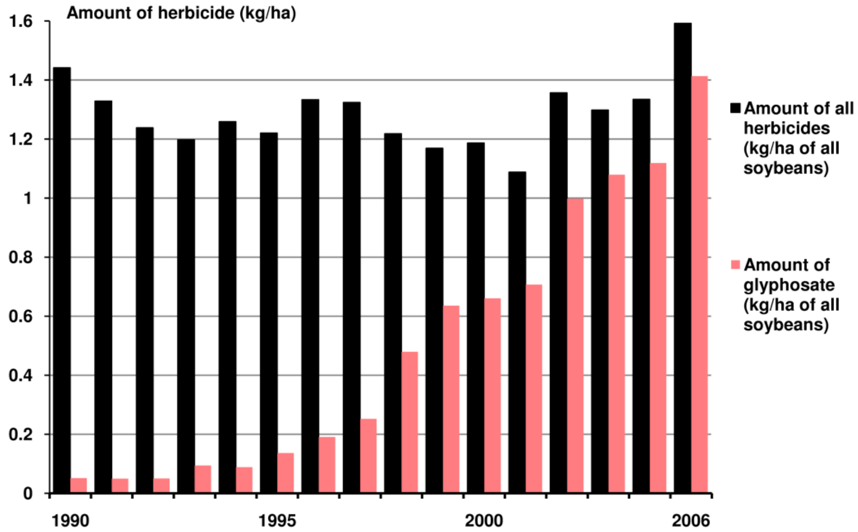
3.2. Trends in Herbicide Use on Glyphosate-Tolerant Soybean

With HT soybean, the usual conventional herbicides are for the most part removed and substituted with glyphosate [34-36]. Thus, on total soy acreage from 1990 to 2006, the progression in HT varieties leads to a progressive substitution of many herbicides formerly applied with glyphosate. The percentage of soy acreage treated with glyphosate increased from 20% in 1995 to 96% in 2006. In contrast, other herbicides such as imazethapyr, trifluralin, imazaquin, pendimethalin were widely used in 1995, and much less in 2006: from 1995 to 2006, the acreage treated with imazethapyr decreased from 44% to 3%, and that treated with pendimethalin decreased from 26% to 3%.

In terms of the quantity of herbicides applied over a given surface area of soybean, that of glyphosate has of course increased due to the rapid expansion of the HT varieties. The total quantity of herbicides sprayed on soybean initially decreased from 1996 to 2001, but seemed to undergo an increasing trend from 2002 (Figure 5). In this way, globally, on a given surface area of soybean, the total level of herbicide use in 1996 seems to have been reached again in 2002 and overtaken in 2006.

However, one cannot deduce from these observations that compared to conventional soybean, HT soybean requires less herbicide in the first years, but then more, since other factors intervene in the trends of herbicides used, such as the increased adoption of conservation tillage as well as the changes in herbicide prices and conventional practices.

Figure 5. Quantity of herbicides and in particular of glyphosate on total US soybean acreage, 1990–2006 (in kg/ha of soybean) (there are no data for 2003). Source: author's calculations based on USDA-NASS [30].



These observations based on the USDA-NASS surveys are rather well corroborated by those resulting from the GfK Kynetec surveys, which in addition provide information on each type of soybean. It appears that HT soybean crops use more herbicide than conventional soybean, and this gap increases over time. Soybean GM crops use on average 4% more herbicide in 1998, 16% more from 1999–2002, 30% more from 2003–2009. For HT soybean, herbicide applications increased from 1999 to 2009, particularly in the past few years; on the contrary, for conventional soybean weedkiller applications remained rather stable beyond annual variations. Finally, the herbicide use of HT soybean appears higher than that of conventional soybean.

Yet all the studies conducted on this topic do not lead to similar results, essentially because of the sources used and, above all, the period considered. Indeed, in the first few years, from 1996 to 2001, USDA-NASS surveys show a decrease in the amount of all active ingredients applied per ha, but from 2001 to 2006 there was an increase which is corroborated by the fact that it appears in both surveys, those by USDA-NASS as well as those by GFK Kynetec. However, several studies based on the first years data consider that there is a reduction in herbicide use with HT soybean. Some other authors made use of the assessments established according to experts' accounts. More precisely, weed scientists, in the states growing soybean, were asked to indicate *"herbicide programs that would provide weed control equivalent to glyphosate"*. However, if this method can provide interesting comparisons, it does not give the actual amount of herbicide being applied to conventional soybean. Several studies using this approach concluded that herbicide use with HT soybeans was lower [4,12,13,37,38].

This assertion was taken up very widely by many organizations and the agbiotech industry as it was a way to promote the GM crops. However, Benbrook [39] found an increase in herbicide use with HT crops, but by making several extrapolations from the USDA-NASS data. The National Research Council "Committee on the impact of biotechnology on farm level economics and sustainability" noted: *"depending on the metrics used, the substitution of glyphosate for other herbicides has resulted in the use of fewer alternative herbicides by growers of HR crops. However, glyphosate is often applied in higher doses and with greater frequency than the herbicides it replaced. Thus, the actual amount of active ingredients (glyphosate and other herbicides) applied per acre actually increased from 1996 to 2007 in soybean and cotton but decreased over the same period in corn"* [36]. This assessment of a decrease in herbicide use on HT soybean in the first years of adoption, followed by an increase, particularly within the last few years, is confirmed by other results, such as data from the Agricultural Resource Management Survey (ARMS) which includes a survey of Crop Production Practices. However, there are significant variations in herbicide use between the states: southern states use greater amounts of herbicides.

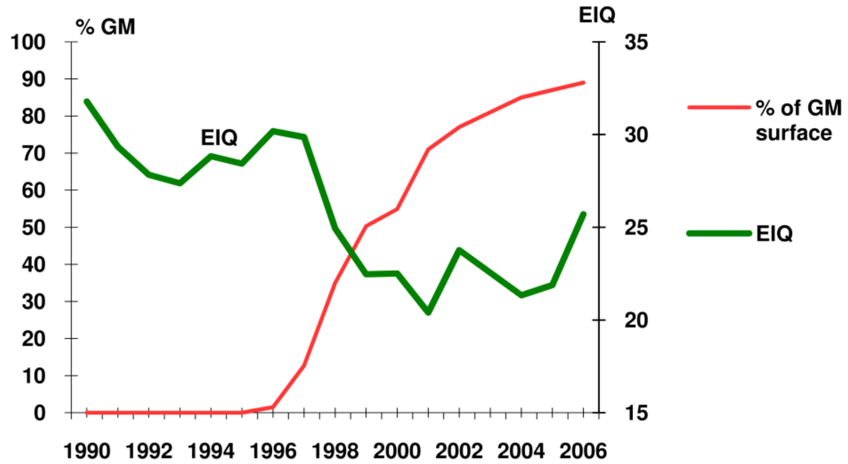
3.3. Environmental Impacts of the Change in Herbicide Use

A simple evaluation of the quantity of weedkiller applied to HT and conventional crops is insufficient because herbicide quantity alone is not a valid indicator of the effect of HT crops on the environment. It is useful to balance each herbicide with indicators that take into account its environmental and toxicological impacts. Numerous parameters exist on the matter, assessing herbicide impacts on human health, animal health, various organisms (bees, birds, mammals, *etc*.) and several environments (soil, water, *etc*.). The use of composite indicators elaborated by combinations of basic indicators is necessary in order to carry out global evaluations: through different methods they aggregate the various data on the toxicity and ecotoxicity of each pesticide. However, these composite indicators are numerous [40]. Amongst them, the EIQ, Environmental Impact Quotient, perfected by Kovach *et al*. [41], was used here. It simultaneously takes into account three important aspects: effects on workers, effects on consumers and water, and ecological effects, and could be applied to the majority of herbicides sprayed on soybean. For its calculation, the different effects of each herbicide are established on the basis of its toxicity parameters related to the applicators and agricultural workers on the one hand, to consumers and leaching on the other, and finally to fish, birds, bees, beneficial insects and soil organisms. The EIQ of the pesticides are frequently updated to take into account new scientific results on their effects [41]. Regarding its calculation method, the higher the EIQ, the higher the environmental impact, *i.e.*, the more the herbicide is considered toxic.

The EIQ was here taken for each herbicide sprayed on soybean, then overall for all herbicides used annually by multiplying the amount of each herbicide used per ha by its EIQ, and by then adding the values. So, for each year, the field EIQ value of all soybean herbicides per ha was assessed, a kind of environmental footprint of these herbicides (Figure 6). This impact indicator decreased from 1994–1996 (29.15) to 2001 (20.4), but tends to increase in 2002 (23.8) and 2006 (25.7). The toxicity of the herbicides used, considered overall, seems therefore to have decreased with the adoption of GM crops. However, this decrease tends to level off over time and particularly in 2006 as the quantities sprayed increase. Other studies using another indicator or analyzing different HT crops over less than

10 years also review a decrease in the level of toxicity of the herbicides applied [14,42,43]. However, the pesticide risk indicators only take into account the active ingredients because agrochemical manufacturers generally do not disclose adjuvants. Surgan, Condon and Cox [44] showed that this can underestimate the risks of some pesticides such as glyphosate.

Figure 6. Evolution of the Environmental Impact Quotient (EIQ) of soybean from 1990 to 2006 (field value per ha). Source: author's calculations based on USDA-NASS [30] and EIQ value for each herbicide. EIQ is a composite pesticide-risk indicator: the higher the EIQ, the higher the environmental and toxicological impact.



HT crops have had a rather beneficial effect by increasing the adoption of conservation tillage (CT), [19,45,46]. The principle of CT is to maintain a soil cover throughout the year by leaving crop residues on the surface, and practice no-tillage or reduced tillage. Its advantage is to foster soil microbial life and avoid disturbing the soil, thus reducing erosion. This practice can also help to reduce carbon dioxide emissions as well as nutrient losses by leaching. However, as weeds are no longer controlled by tillage, it is often necessary to use more herbicides. The cultivation of HT crops suits well CT because glyphosate allows weed control after crop emergence even if there is no tillage. Conservation tillage was developed in the USA from the mid-1980s and continued to grow thereafter, among other reasons thanks to their good association with HT crops: in 1995, 48.6% of the soybean was cultivated this way and in 2007, 63% [46]. HT varieties were more often grown with CT than conventional varieties [47-49]. However, it is difficult to say whether the choice of HT varieties promotes CT adoption, or *vice versa* [36]. So even if these practices are complementary, one should not necessarily attribute CT benefits to HT crops.

The effects of HT crops on the environment include so many aspects that it is not possible to address all of them here. The paper focused on analyzing the trend in the quantities of herbicide use because it is a topic of debate, but the results vary depending on the context and period. Furthermore the controversy over glyphosate and its formulations is not addressed as it is a complex issue which would require a lengthy investigation. Glyphosate is often seen as having a fairly good toxicological profile, but some studies have reported adverse effects for some organisms, especially related to surfactants [50].

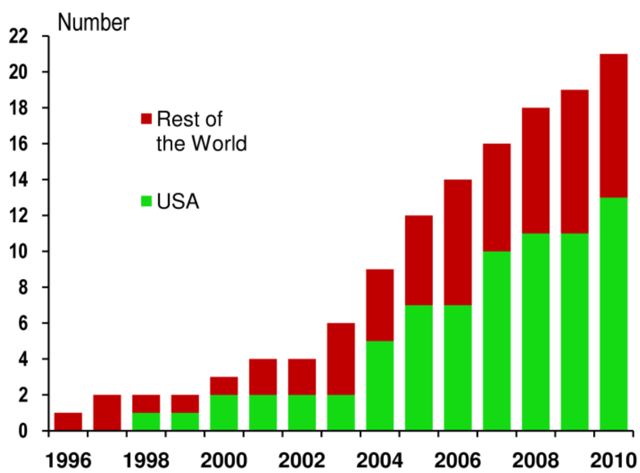
4. Appearance of Glyphosate Resistant Weeds and Prospects for HT Crops

4.1. The Appearance of Glyphosate Resistant Weeds

The significant increase in the use of glyphosate is not only due to the rapid progression of HT crops. In the USA, the glyphosate patent expired in 2000. Afterwards, generics were developed and competition between firms was fierce, especially since it involved a commonly used herbicide. The increased use of glyphosate, whether Monsanto's Roundup or generic versions, notably took place in the case of HT plants, conservation tillage or non-agricultural consumption. Some statistical estimates show that in the USA, the annual agricultural use of glyphosate, in thousands of tons of active ingredient, approximately increased from 3.2 in 1987 to 16.3 in 1997, 32 in 1999, 59 in 2003 and nearly 83 in 2007 [51-54]. Glyphosate use was increased by more than 10 fold between 1993 and 2007, while the total amount of herbicide applied in the US agricultural sector remained approximately constant. Glyphosate therefore became the most widely used weedkiller in the USA and later throughout the world, surpassing atrazine that had been in the number one position.

This high increase has led to the appearance of weeds resistant to glyphosate [19,35,55,56]. Glyphosate-resistant (GR) weeds have already appeared in the USA in different states (totaling 13 weeds in mid-2011), as well as in more than a dozen countries throughout the world (totaling 21 weeds in mid-2011) (Figure 7). This emergence was very predictable because of the high selective pressure for weeds, even if certain properties of glyphosate have slowed emergence down in comparison with other herbicides that have experienced a similar phenomenon [57]. Indeed, this phenomenon of herbicide resistance is not new: the increased use of each herbicide or antibiotic induces a selection pressure which can lead to the appearance of resistance in weeds or bacteria. For weedkillers, it manifested itself as early as the 1950s, and, by early August 2011, there were 365 biotypes and 200 species of weeds resistant to one or several herbicide families worldwide [55]. Resistance to glyphosate has been observed even in countries without varieties tolerant to it and in all the continents [55,58]. In the USA, in 2010, this problem concerned about 4.5 million ha, slightly less than 8% of the total acreage cultivated with HT varieties [59].

Figure 7. Number of weeds that have become resistant to glyphosate in the world and the USA, 1996–mid-2011. Source: author's calculation from [55].



In the 1990s Monsanto considered there was almost no risk of the occurrence of GR weeds [6,60]. Thus advice for good weed management was most likely not provided at the beginning of the diffusion of HT varieties, and the weed scientists who did provide some were hardly listened to. In addition, *"agricultural practices aimed at delaying or preventing the development of herbicide resistance are not viewed as being economical in the short term, and are not readily used by all growers"* [61]. For these authors, at least two factors may be keeping the farmers from adopting better weed management practices: (i) the belief that a new technology will be developed to solve the resistance problems; and (ii) the belief that resistance management strategies will be futile. Actually a survey of growers developed by weed scientists from 6 states in 2005–2006 showed that *"at this time, farmers did not have a high level of awareness of the potential risks to the sustainability of the GR crop systems with regard to evolved glyphosate resistance"*. However, more recent studies show that *"growers are moving towards a better understanding of the implications of their herbicide use practices and thus improved sustainability for GR crops and glyphosate"* [62,63]. Indeed, in the last few years, practices are beginning to change, given all the advice provided by universities, grower associations, as well as by agricultural and seed companies, and given the increasing extent of GR weeds in the field.

4.2. What does the Future Hold for HT Crops?

Various measures are being sought by the actors involved to cope with the development of GR weeds [64-68]. Many extension and university weed scientists have got involved in this issue. They advocate increased research activities, the exploration of new approaches, as well as better weed control management, alternating used active molecules and crops (rotations) [68,69]. The need for "glyphosate stewardship" is stressed: this *"refers to the management decisions and practices subsequently employed to preserve the utility of a crop trait"* [70]. This partial loss in glyphosate efficiency is considered to be a drawback as glyphosate will have to be supplemented or replaced by other herbicides, that are often more noxious and difficult to use in view of its relative profile [71,72]. Hence, there is a risk of loss on an overall environmental level [57]. At the farm level, the main impact is that the use of weed control other than glyphosate application alone is needed, varying from the application of other herbicides to mechanical weeding [73]. This leads to a certain rise in the total amount of herbicide applied, as well as to the loss of some of the advantages farmers derive from glyphosate-tolerant crops, such as easy weed control.

The development of GR weeds has a larger impact. On the one hand, glyphosate is the most widely used weedkiller in the world, in recent years its total market of about USD 5.5 billion represented almost 30% of the global sales of herbicides. In some places its loss of efficiency will have repercussions, especially because since 1997 the number of new herbicide active ingredients on the market has declined, and in the USA the number of patents dealing with new weedkillers has also dropped [59,68,74]. On the other hand, associations opposed to GM crops greeted the development of glyphosate-resistant weeds with sarcastic comments, seeing it as almost a fulfillment of their predictions. However, the appearance of these weeds at various locations does not mean that glyphosate will not be used elsewhere.

Indeed, all to the contrary, companies, such as Monsanto, Pioneer, Dow, Bayer, Syngenta, plan to market HT plants tolerant to other herbicides. Generally they project to combine resistance to glyphosate and other herbicide(s), *i.e.*, to launch HT crops with stacked herbicide-tolerance traits. In addition to being glyphosate-tolerant, the new varieties could be tolerant to dicamba, 2,4-D, ALS inhibitor, mesotrione, or isoxaflutole, *etc*. [59,74-77]. This raises questions because some of the envisaged herbicides do not have a very favorable toxicological profile. Firms also plan to launch other species tolerant to glyphosate and/or other herbicide(s), such as GMHT wheat. However, reluctance has been expressed even in the USA where the most recent marketed HT species (sugar beet and alfalfa) generated litigation by opposing associations.

5. Conclusions

Sustainability of present farming practices is frequently questioned, as well as the means and ways to sustainably deal with many challenges faced by agriculture in the next few decades, such as its ability to feed the world population, provide sufficient income to farmers, preserve natural resources and biodiversity, reduce its pollution, and cope with climate change. Among the means put forward to provide a notable contribution in these areas, the use of science and technology are often proposed. In particular, GMOs and agricultural biotechnology are frequently presented to be full of promise. However, others project that GMOs will increase the probability of worst case scenarios, rather than solving any problems. Therefore it is useful to better evaluate transgenic crops, although until now only HT and Bt crops have been widely cultivated, which limits the appraisal.

This case study of GMHT soybean in the USA shows mixed effects regarding sustainability, particularly since the trends occurring over time have been taken into account and not only the first few years. Some aspects of agricultural sustainability are mentioned here, in particular at the agro-economic and agro-environmental level:

- A substantial proportion of farmers have adopted GMHT crops in some countries: the majority of soybean surfaces are HT in the USA, Argentina, and Brazil, as well as a considerable proportion of corn. More recently, HT sugar beet introduced in the USA in 2008 has been adopted on a substantial proportion of surfaces. This testifies to their advantages for farmers despite the existence of inconveniences: on the one hand, weeding is easier, time is saved, and there is a good association with conservation tillage; on the other hand, a high amount of glyphosate is sprayed, and dependence on a restricted number of seed companies is increased, *etc*. However, several factors explain the development of GMHT crops, not only their ease in use and practicality for farmers.
- Herbicide use with GMHT crops has experienced mixed trends. An analysis of herbicide doses applied to GMHT soybean compared to the conventional one showed that there was a decrease in herbicide use in the first few years, but later an increase in it. However, this trend needs to be further studied since available data are missing for the last few years. In addition, it is not enough to observe herbicide quantities. Above all, it is their toxicological and environmental effects that should be accounted for. From this point of view, for some aspects, there might be a certain improvement in the environmental impacts with GMHT crops compared to conventional crops. However, it is very difficult to draw a general conclusion because, on the one hand, changes in herbicide use with GMHT crops vary depending on the crop and the context, and, on

the other hand, the advantages and inconveniences coexist. In addition, they depend on the considered assessment period, and on the inclusion or not of some herbicide adjuvants.

- The high use of glyphosate, linked to several factors not only to HT crops, has led to the emergence of GR weeds. Many weed scientists regret the overreliance on glyphosate as Stephen Powles (quoted by Service [57]): *"Glyphosate is as important to world agriculture as penicillin is to human health"*. Thus other HT crops are envisaged by agbiotech companies: either other glyphosate-tolerant crops, or HT crops tolerant to another herbicide, and mainly HT crops tolerant to glyphosate plus another herbicide. This could lead to the application of more noxious herbicides such as 2,4-D. The strong 15-year growth of glyphosate use without sufficient alternation of active ingredients and methods of weed control appears rather unsustainable, and may be judged as a technological lock-in [36,73,78].
- HT crops make the use of conservation tillage practices easier, which has positive environmental and economic spin-offs. However, the emergence of some GR weeds threatens to reduce conservation tillage practice throughout affected areas in the world [79].

The use of HT crops could have come closer to sustainable development if it had been implemented differently. At the technical level, this would have required a better rotation of the different types of crop, an alternation of herbicides, the concomitant use of other methods, and the implementation of integrated weed management. The same holds at the company level: the quest for short-term, fast profitability should give way to more sustainable approaches, with the development of more worthwhile GMOs. This is also the case for the social, political, and other economic aspects of these technologies [80,81], which have been only skimmed here. A more sustainable development implies better governance of this innovation: the way in which it is used, which depends on the overall economic system, is probably more at stake than the technological innovation itself.

The issue of GMO impacts being the subject of frequent debates, it must be emphasized that many of "their impacts" do not come from the GMOs themselves, but from the characteristics and objectives they are given via the type of new traits introduced, from the context in which they are inserted and finally, from the way they are used. At the economic level, are not the so-called "impacts of GMOs" actually the result of the impacts of the overall economic system? Strictly speaking, part of "the impacts of GMOs" does not in fact come from genetic engineering in itself, but rather from the way in which it is oriented, used, regulated and implemented in practice. A better governance of GMOs needs to be put into place.

Conflict of Interest

The author declares no conflict of interest.

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