Issues, impacts, and prospects of the first transgenic crops tolerant to a herbicide.

The case of glyphosate-tolerant soybean in the USA

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Abstract. Until today, herbicide-tolerant (HT) transgenic crops have been the most widely used type of transgenic crops. In 2008, worldwide, 63% of all agricultural land devoted to transgenic crops involved HT transgenic ones, and the percentage was higher (85%) when the herbicide-tolerant trait was stacked with another. In addition, other HT crops are foreseen within the next five years if we are to believe the "pipeline" of the companies involved along with field trials. However, herbicide-tolerant crops have been criticized, particularly in Europe, because of the type of trait introduced: herbicide tolerance. Indeed, this trait leads the crops to depend on a herbicide (generally glyphosate) instead of freeing them from some pesticides through a better use of their biological capacities and a valorisation of life processes as biotechnology was expected to do. Therefore, how can we explain the widespread use of HT transgenic crops and what are their fallouts? At first the paper presents the extent of surface areas dedicated to these crops and the factors that have led to the development of these herbicide-tolerant crops. Then, the case of glyphosate-tolerant soybeans in the USA is studied in more detail. Its agro-environmental impacts, particularly with regard to trends in the use of herbicides, are analyzed. Thirdly, we address the factors of adoption, economic performance, benefits, and drawbacks of this soybean as well as its prospects. Finally, the conclusion questions the contribution of HT soybean to more sustainable agriculture.

Keywords: *Genetically modified crop, Agro-economic impact, Sustainability, Soybean*

JEL codes: Q55; O3; O13; O51

Issues, impacts, and prospects of the first transgenic crops tolerant to a herbicide. The case of glyphosate-tolerant soybean in the USA.

Transgenic crops spark numerous debates, particularly in Europe due to their risks feared by some for health, the environment and the agricultural economy. Others, on the contrary, underline their interest for obtaining plants with new traits that it would be difficult to obtain through conventional selection. It is thus important to take stock of their first thirteen years of cultivation since 1996, even if these very first transgenic crops are not representative of all that can be expected from GMOs. This paper more particularly considers transgenic glyphosate-tolerant soybean in the USA. In 2008, soybean represented more than half of the world surface in transgenic crops and already more than 70% of its surface area in the world was transgenic; in the USA, this proportion was 92%. This shows its success. However, this type of herbicide-tolerant (HT) crop has been the subject of much criticism due to the type of trait introduced. Indeed, herbicide tolerance leads to the crop's dependence on a herbicide (generally glyphosate) instead of contributing to freeing it from pesticides through a better use of life processes as was hoped of biotechnology. How then can this diffusion of herbicide-tolerant transgenic crops be explained? What evolution have they brought about in terms of quantities of herbicides used and effects on the environment? On the agro-economic level, is the additional cost of transgenic seeds compensated by a drop in the cost of herbicides used, and what are the agro-economic repercussions of their progression over the last 10 years? Finally, what are their prospects? All these questions are addressed in the text using the case of the most widespread transgenic crop in 2009, glyphosate-tolerant soybean in the USA, and by studying its dynamics over several years.

I. The importance of herbicide-tolerant transgenic crops: situation and explanatory factors

In 2008, transgenic crops represented in the region of 8% of total cultivated land (approximately 1433 million ha). But as has often been underlined, they are unequally distributed: three countries represent 80% of transgenic crop surface areas, two crops themselves alone represent 82%, and the single new trait of herbicide tolerance was present in 85% of transgenic surface areas (alone or associated with another) (table 1).

Table 1. Distribution of transgenic crop acreage in the world in 2008 (in Million hectares) (From James, 2008).

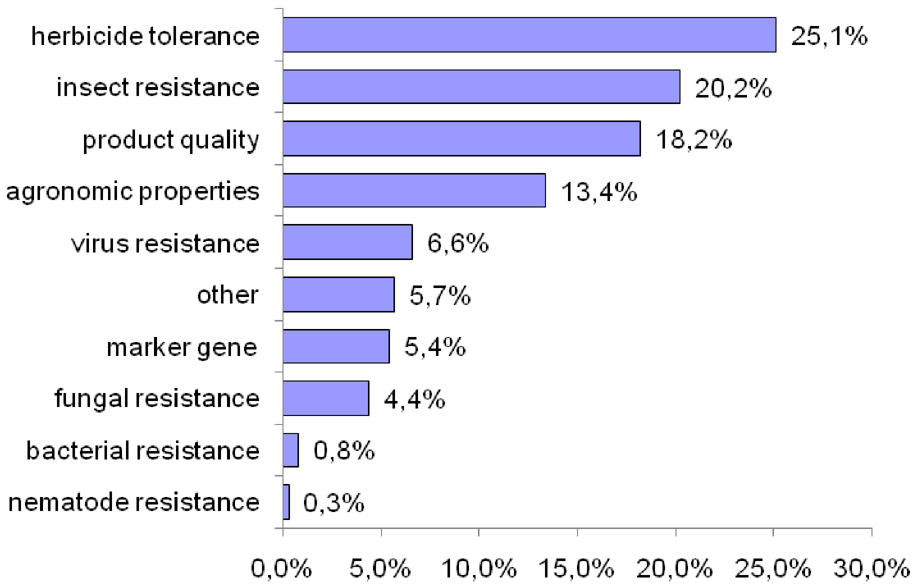
By country	Area (10^6 ha)	%	By crop	Area (10^6 ha)	%	By transgenic trait	Area (10^6 ha)	%
USA	62.5	50	Soybean	65.8	53	Herbicide tolerance	79	**63**
Argentina	21.0	17	Corn	37.3	30			
Brazil	15.8	13	Cotton	15.5	12	Herbicide tolerance & Insect resistance	26.9	**22**
India	7.6	6	Canola	5.9	5			
Canada	7.6	6	Sugar beet	0.3	<1	Insect resistance (Bt)	19.1	15
China	3.8	3	Other	<0.1	<1			
Paraguay	2.7	2	(squash, papaya)			Virus resistance or other	<0.1	<1
South Africa	1.8	1						
TOTAL	**125**	**100**	**TOTAL**	**125**	**100**	**TOTAL**	**125**	**100**

Where does the importance of this herbicide-tolerant trait come from? Several factors can explain it. First of all, it is a monogenic trait that is relatively easy to isolate and introduce through transgenesis compared to 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 organisation from a purely chemical company to a biotechnology and seed company, requiring the type of research and investments that need considerable lengths of time to become profitable. High glyphosate gross profit was essential for Monsanto so long as that of its other sector (seeds and genomics) was still in the early stages of development. Thirdly, HT soybean (and other HT crops) has been adopted well by farmers as it meant easier and simplified weeding requiring less labour time for various crops. Furthermore, it combined well with other techniques being developed, particularly soil conservation practices. Moreover, GMOs in the USA have benefited from a favourable context for their development and have been vigorously promoted on the field by Monsanto.

This importance of HT transgenic crops could be led to change quite rapidly if the presence of multiple new different traits was noted in the field trials or among the transgenic plants close to commercialisation. But such occurrence is relatively low judging from the field trials. If we study those taking place in the USA where they are by far the most numerous, it can be observed that HT plants are the most significant in terms of field trials and that their proportion diminishes very little over time, even if it varies according to the year (fig.1). It is therefore probable that other HT plants will still be commercialised, or the same plants but tolerant to another herbicide. This is what is observed in the pipelines of the major firms.

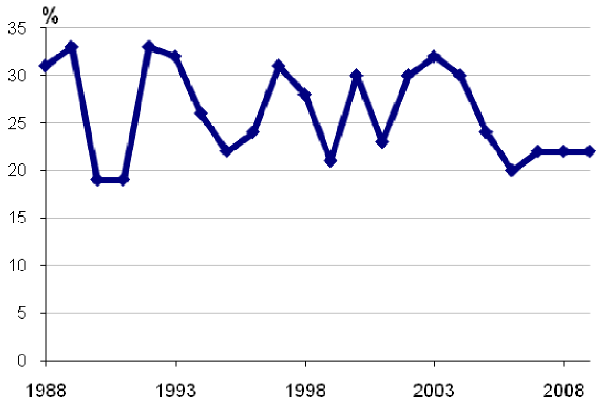
Fig. 1. **In the USA, percentage of field trials of transgenic plants expressing a herbicide-tolerant trait**, 1988-26 May 2009 (approximately 20,130 field trials*) (from APHIS database, 26 May 2009)

a/ overall in all field trials from 1988 to 26 May 2009



* 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

b/ by year, evolution in the percentage of herbicide tolerance field trials in the total number of tested traits.



II. Impacts of the expansion of HT soybean on the use of herbicides

2.1 Questions on sources and methods

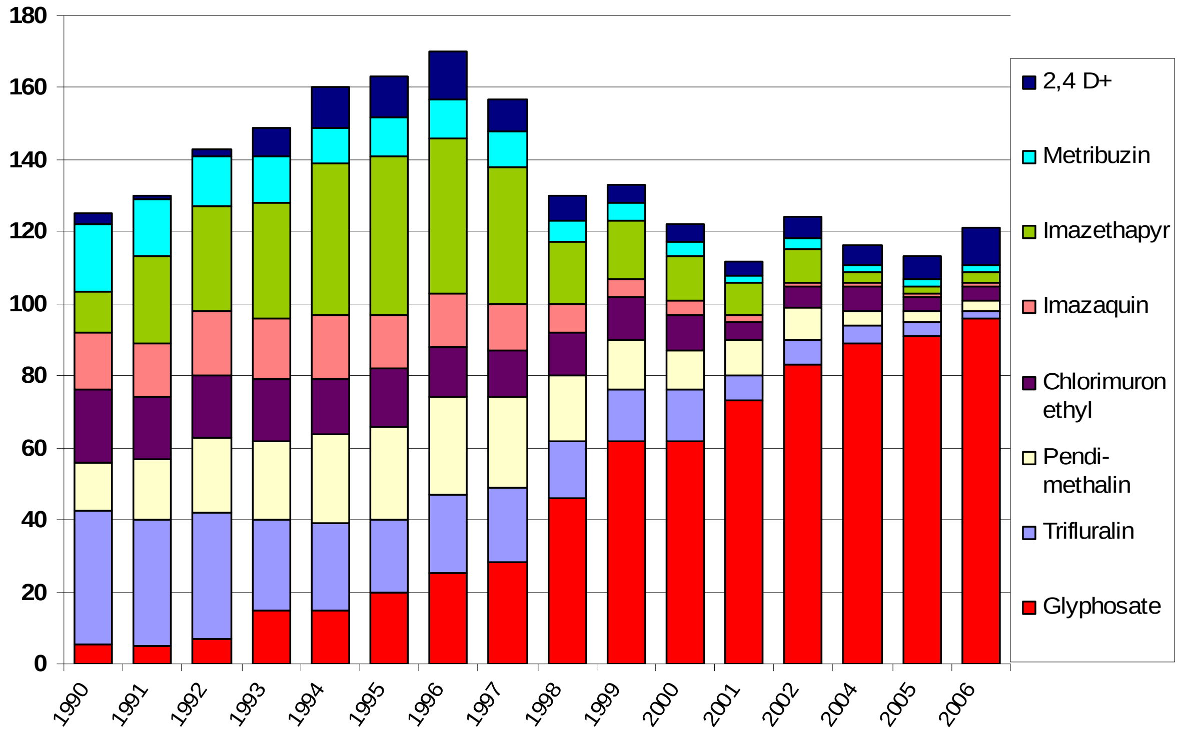
A controversial point often brought up in Europe concerning GMOs is the evolution in the quantity of pesticides used. With HT soybean, the usual conventional herbicides are for the most part removed and substituted with glyphosate. However, conventional herbicides are used in very variable doses per ha, the recommendations can vary from 10 g/ha to 1.3 kg/ha according to the molecule, whereas glyphosate is often spread at a dose of approximately 0.75 kg/ha. So, if for example 1.5 glyphosate treatments replace 3 conventional treatments, the assessment of quantity in kg/ha would be highly variable according to the weedkillers used previously, but it would not have a significant meaning. A simple evaluation of the quantity of herbicide used before and after the development of transgenic soybean is insufficient. To appreciate their environmental and toxicological impact, it is necessary to balance the level of weedkiller use by taking into account the conditions of application and by using toxicity and ecotoxicity indicators.

To assess the impacts of HT soybean, it is necessary to have access to detailed data on the herbicides applied. In the USA, different statistical sources exist in this area, but they rarely allow a comparison on the use of herbicides on transgenic and conventional soybean. Admittedly, sample surveys were carried out each year with farmers on the main crops in order to evaluate the use of fertilizers and pesticides (USDA NASS, 1991-2007). However, since 2007 this survey has no longer been carried out. In addition, these surveys establish this use globally per crop without separating their use on GM and non GM soybean. Thus the trends in the application of herbicides were studied globally for the soybean acreage by using the annual USDA survey on this topic (USDA NASS, 1991-2007). These USDA surveys are sample surveys concerning most of the soybean producing states, but with a variable number of states depending on the year. The surveys always include the major soybean producing states, but the number included of states producing low quantities varies depending on the year. To eliminate these variations, we 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 GM and non GM soybean must be considered cautiously: these are approximate evaluations. In addition to these Agricultural Chemical Usage Surveys, there is another USDA data collection system that provides insights on crop production practices: the Agricultural Resource Management Survey that we also used (USDA ARMS, 2009). Some other organisations do sample surveys of chemical usage per crop, for example a marketing company such as DMRkynetec. However, it is difficult to have access to their proprietary and expensive survey findings.

2.2 Rapid growth in the use of glyphosate progressively replacing a large majority of former herbicides

The trends in soybean treatments from 1990 to 2006 show that the progression in HT varieties leads to a progressive substitution of many herbicides formerly used with glyphosate (Fig. 2). In particular, imazethapyr, trifluralin, imazaquin, pendimethalin were widely used in 1995, and much less in 2006. Thus, from 1995 to 2006 the percentage of soybean acreage treated with imazethapyr decreased from 44% to 3%, the percentage treated with pendimethalin decreased from 26% to 3%.

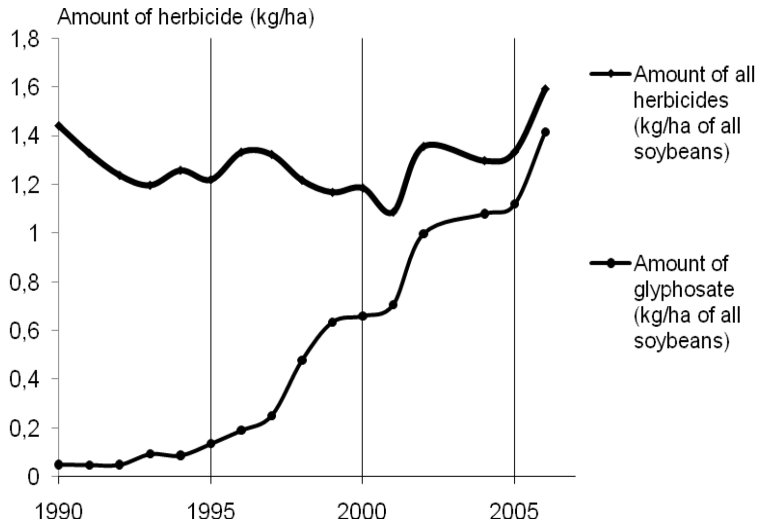
Figure 2. Main herbicides used on total soybean acreage, 1990-2006 (as % of soybean surface treated by each herbicide) (From USDA NASS, 1991-2007). With the development of glyphosate-tolerant soybean, glyphosate replaces the previously used herbicides.



What has the evolution in the number of herbicide treatments been? The use of transgenic soybean has allowed the number of treatments to be reduced (Heimlich et al., 2000; Benbrook, 2004; Fernandez-Cornejo, Caswell, 2006). This reduction is difficult to evaluate considering the diversity in weeding practices as well as the fact that glyphosate is (and was already in 1996) also used with non-transgenic varieties, notably in the case of no till: the available statistics do not allow distinction between the different types of use. USDA surveys show a decrease in the number of treatments from 1996 to 2002, then a slight increase in 2006 (USDA ARMS, 2009).

In terms of the quantity of herbicides used over a given surface area of soybean (Fig. 3), that of glyphosate has of course increased due to the rapid expansion of the transgenic varieties. There also seems to have been a slight increase in the number of glyphosate treatments per ha of soybean treated over the last years. The total quantity of herbicides spread over soybean initially decreased from 1996 to 2001, but seemed to undergo two quite marked increases in 2002 and 2006. 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 2005 and overtaken in 2006 (Fig. 3). However, we 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 evolutions of herbicides used such as the development of conservation tillage and the drop in herbicide prices (see below).

Figure 3. Mean quantity of herbicides and in particular of glyphosate on total US soybean acreage, 1990-2006. Source: author's calculations based on USDA NASS (1991-2007); (Bonny, 2008).



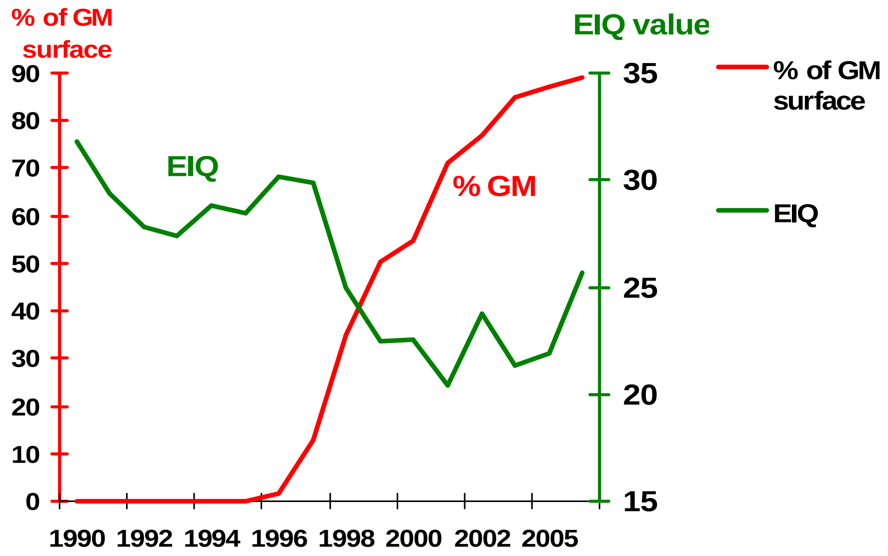
2.3 Environmental impacts

As indicated previously, it is necessary to balance each herbicide with indicators that take into account its environmental and toxicological impacts. Numerous parameters and indicators exist on the matter, assessing herbicide impacts on human health, animal health, various organisms (bees, mammals, etc.) and several environments (soil, water, etc.). The use of composite indicators elaborated using combinations of basic indicators is necessary in order to carry out global evaluations: they aggregate the various data on the toxicity and ecotoxicity of each pesticide. However, these composite indicators are numerous. Amongst them, the **EIQ, Environmental Impact Quotient**, perfected by Kovach (1992), 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 spread on soybean. Regarding its calculation method, the higher the EIQ, the higher the environmental impact, i.e. the more the herbicide is considered toxic.

In this study, updated Kovach's quotients for each given herbicide applied on soybean were used. Then we calculated the overall value of the EIQ for all herbicides applied annually by multiplying the amount of each herbicide used per ha by its EIQ, and by then adding the values. So for each year we assess the field EIQ value of all soybean herbicides. This impact indicator decreased from 1994-1996 to 2001, but tends to slightly increase in 2002 and 2006 (fig. 4). The toxicity of the herbicides used, considered overall, seems therefore to have decreased with the adoption of GM crops. But this diminution tends to subside after several years and particularly in 2006 as the quantities spread increase (fig. 4). Other works using another indicator or analysing different HT crops over less than 10 years also obtain a decrease in the level of toxicity of the herbicides applied (Nelson, Bullock, 2003;

Gardner, Nelson, 2008; Brookes, Barfoot, 2008). It is necessary to continue the analysis to examine how the total quantities of herbicide evolve and the environmental impact indicator, especially since glyphosate resistant weeds have appeared and other types of HT crops are likely to be placed on the market.

Fig. 4. Environmental Impact Quotient (EIQ) of all herbicides treatments on soybean, 1991-2006. EIQ is an index that measures the level of toxicity of the various herbicides used on soybean.



III Agro-economic impacts of HT soybean and prospects

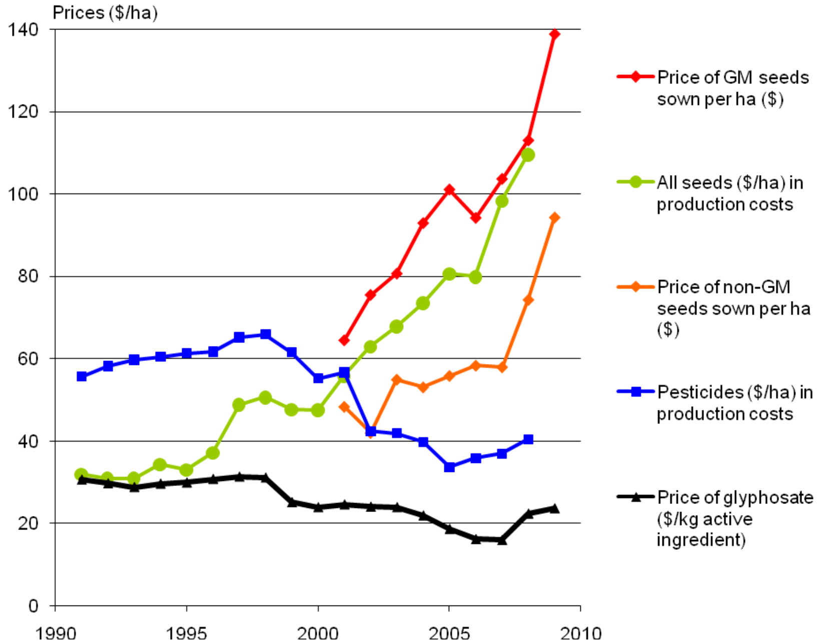
3.1 Agro-economic advantages that compensate for the drawbacks

At the farming level, there are many factors behind the rapid development of HT soybean (Alexander, 2006; Bonny, 2008). 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. Transgenic cultivation allows for easier weed management because only a single product is required. 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 (UIUC, 1999; Carpenter, Gianessi, 1999, 2000, 2001, 2002; Bullock, Nitsi, 2001; Nelson, 2001; Gianessi et al., 2002; Gianessi, 2008; Duke, Powles, 2008). However, there are also several disadvantages such as the use of a sole herbicide on a wide area without sufficiently alternating weedkillers and potential difficulties in controlling volunteers of the previous crop if it was also tolerant to the same herbicide. In addition there is a greater dependence on the input-supplier firms because of the contract stipulating not to save seeds and because of the high consolidation of the GM seed industry. Some other drawbacks can also be the potential difficulty in selling or exporting to some markets which want GM-free products; however, this was generally not the case for HT soybeans (Bonny, 2008).

For farmers, the economic advantage of HT soybean in relation to conventional soybean depends among other things on the difference in margin. The higher cost of transgenic seed – the "technology fee" – is generally balanced out by the reduced cost of herbicides. A comparison of conventional and transgenic soybean shows that they have broadly similar margins, sometimes slightly higher for transgenic soybean. However, soybean production costs vary greatly between farms (Foreman, Livezey, 2002). In addition, various other aspects reinforce the agro-economic advantages of HT soybean for the farmer. Indeed it is important to remember an important point: the farm must be considered as a system and the analysis of one production in isolation should be avoided. In particular, establishing the production costs of one crop independently of other possible productions and its interaction with the functioning of the whole farm can give a distorted picture as it ignores various opportunity costs. So HT soybean may have other advantages for the producer: simplification of weed control freeing up time for other activities or areas of production, a fair correlation with conservation tillage and hence development of this (synergy effect), non-persistence of herbicides, etc. (Fernandez-Cornejo et al., 2005; Gardner, Nelson, 2007; Marra et al., 2008; Givens et al., 2009)

It is necessary, however, to examine margin in a dynamic way because relative prices change frequently: it is thus useful to analyze the evolution of the cost of seeds and herbicides as their cost difference is the main factor in the differential of margin between conventional and transgenic soybeans (fig. 5). The diffusion of HT soybean having brought about the replacement of certain formerly used weedkillers by glyphosate, the agro-chemical firms that produced them markedly decreased their prices after 1996 to limit market losses and stay competitive. In addition the price of glyphosate decreased as its patent expired in 2000 and generics developed. This induced a global reduction in herbicide treatment costs for all soybean producers whether they use transgenic varieties or not (Lemarié, 2000; Bullock, Nitsi, 2001, Gianessi, 2008). This drop in herbicide prices may have contributed to a certain increase in the quantities used. As for seeds, their price has increased over the years (fig. 5). However, after 2005-2007, herbicide prices increased again and the price of seeds also rose as well as the prices of agricultural products, notably in 2008. Therefore the economic interest of GM soy might have recently experienced some changes: a follow up is necessary. However, the biotech companies set the seed price to ensure that the majority of farmers are interested in them...

Fig. 5. Price of glyphosate ($/kg of active ingredient), price of GM seeds and non GM seeds sown per ha ($), and costs of pesticides and seeds in soybean production costs per ha, 1991-2009 (the seed price is the price for the mean seed dose used for soybean). Source: author's calculations from USDA NASS (1992-2009) and from USDA ERS (2009).



3.2 Appearance of glyphosate resistant weeds

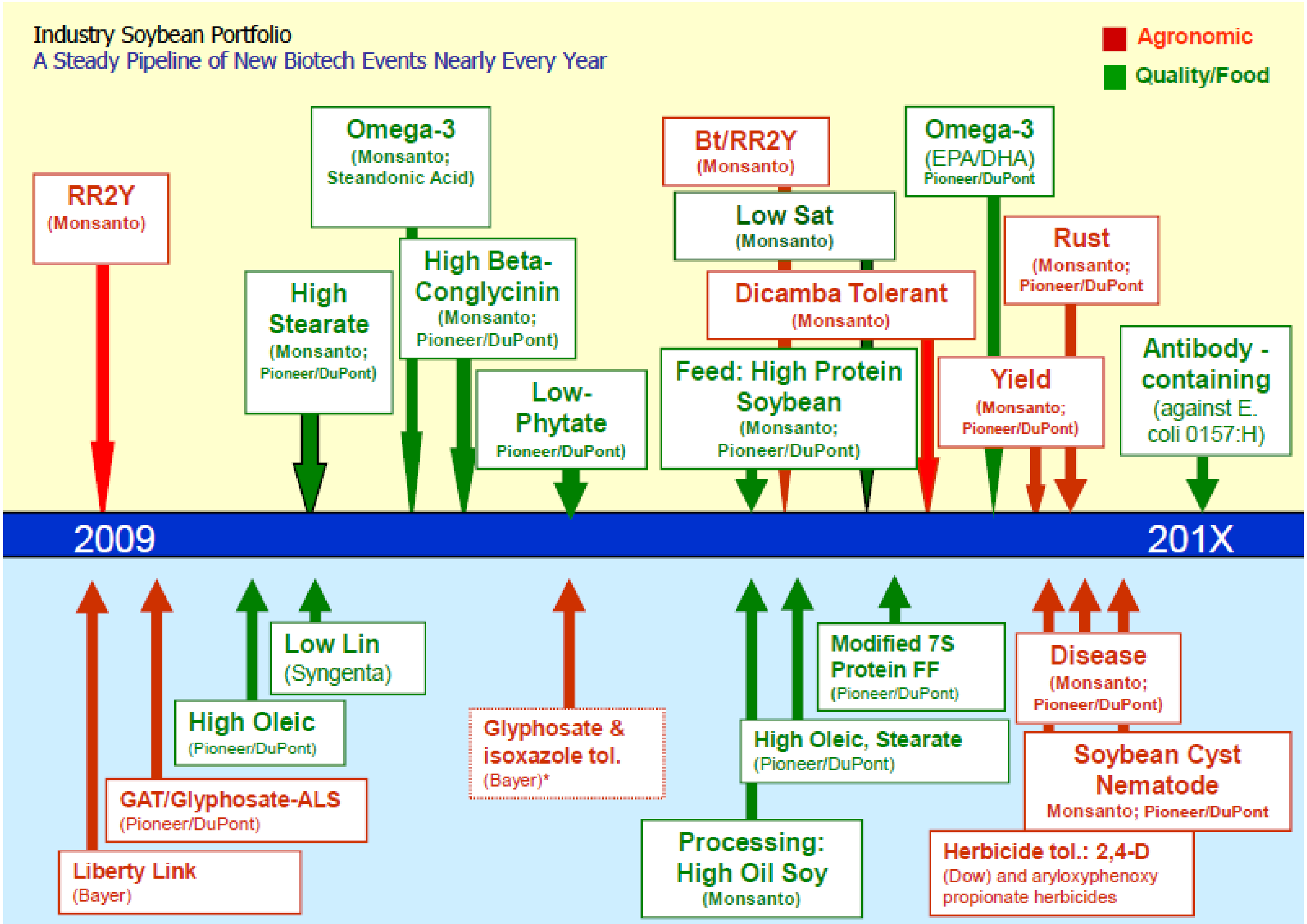
The significant increase in the use of glyphosate has diverse causes in addition to the rapid progression of herbicide-tolerant crops. Its price trends due to the expiration of its patent play an important role. The increased use of glyphosate, whether Monsanto's Roundup or generic versions, notably took place through HT plants, non-agricultural consumption, or conservation tillage. Some US estimates show that in the USA, the annual use of glyphosate in thousands of tonnes of active ingredient increased from 3.2 in 1987, to 16.3 in 1997, to 32 in 1999, and nearly 50 in 2001, taking into account all uses, including agricultural and others (Aspelin, Grube, 1999; Donaldson et al., 2002; Kiely et al., 2004).
This high increase in the use of glyphosate – formerly spread on much smaller areas – has led to the appearance of weeds resistant to this herbicide (Heap, 2009; Owen, Zelaya, 2005; Cerdeira, Duke, 2006; Duke, Powles, 2008; Shaw et al., 2009)**. Glyphosate resistant weeds have already appeared in the USA in different states** (nine weeds at the end of 2008), as well as elsewhere in the world (sixteen weeds in total at the end of 2008). This emergence was very predictable because of the high selective pressure for weeds, even if certain properties of glyphosate have slowed this in comparison with other herbicides that have known a similar phenomenon (Service, 2007). This partial loss in glyphosate's efficiency is considered prejudicial, as it will have to be supplemented or replaced by other herbicides that are generally more noxious and difficult to use compared to glyphosate: hence there is a risk of loss on a global environmental level (Service, 2007; Marsch et al., 2006). In this way, the present substantial expansion in the use of glyphosate may prove to be disadvantageous in the medium term, not so much for Monsanto, whose main sales are now transgenics and genomics, but above all globally.

3.3 Some technological prospects of transgenic soybean over the next few years

For 13 years, one trait introduced by transgenesis was dominant in GM soybean, and among all transgenics: Monsanto's herbicide tolerance. Will new traits be diffused over the years to come? This seems probable. Indeed, the big companies, Monsanto, Syngenta, Dupont/Pioneer, Bayer, BASF and Dow, that have actively invested in transgenics, continue their research while being engaged in fierce competition (fig. 6). On the one hand, other glyphosate-tolerant crops, in addition to soybean, corn, cotton, canola, and sugarbeet will most certainly be marketed in the USA, even though this is sometimes the subject of heated debate due to fears of losing a share of the export market. Indeed, HT wheat which was on the point of being commercialised in 2004, was not in the end to avoid a decrease in purchases by different countries. However, in 2009, the majority of US wheat growers declared themselves interested in GM wheat. On the other hand, concerning soybean, Monsanto has just launched a new generation of HT soybean: the "Roundup Ready 2 Yield" soybean, which should have a better yield as well as being glyphosate-tolerant; and is also preparing a new type of soybean tolerant to another herbicide, Dicamba (fig. 6) (Service, 2007; ASA, 2008; Monsanto, Basf, 2008; Monsanto, 2009a, 2009b, 2009c; Stein, Rodríguez-Cerezo, 2009).
Firms other than Monsanto envisage commercialising other glyphosate tolerance traits, notably the GAT system, Glyphosate ALS (acetolactate synthase) Tolerance, by Pioneer/DuPont, and for corn Agrisure Glyphosate Tolerance by Syngenta (IPTS, 2008; Green, 2009). In addition, since 2009 another GM soybean tolerant to a broad-spectrum weedkiller, glufosinate, has been commercialized: it goes by the name of "Liberty Link" soybean from Bayer (IPTS, 2008). In Brazil, tolerance to another herbicide, imidazolinone, has also been developed in soybean by BASF and EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária) and should be commercialized within a few years. So, if glyphosate tolerant soybean encounters some limiting factors such as the appearance of glyphosate-

resistant weeds, they might be avoided by other types of herbicide-tolerant soybeans instead of by more integrated weed management... (Benimelis, Pengue, Monterroso, 2009).
However, other types of transgenic soybeans are underway. The companies involved are working on different composition modifications that may concern human or animal foodstuffs or processing, particularly fatty acid composition. They are also working on perfecting varieties tolerant to soybean cyst nematode or rust. Other new traits in the soybean pipeline deal with taste and texture (ASA, 2008; Monsanto, Basf, 2008). Work is also in progress on soybean for energetic usage and its transformation to biodiesel. Transgenics with two or three traits introduced simultaneously for different objectives ("stacked traits") will certainly be marketed. However, this should lead to even higher seed prices.

Fig. 6. New traits planned for soybeans in the coming years by major biotech companies (from ASA, 2008).



Conclusion

GMOs continue to be the subject of lively controversy throughout the world, and even in the USA (Cowan, Becker, 2009). Does the HT soybean studied here contribute to more sustainable agriculture or not? Although all the dimensions of sustainability have not been addressed here, certain elements can be analysed.
At the environmental level, the results of HT soybean are mixed. Indeed, its expansion, with little integrated management of weeding has led to a very high and widespread use of glyphosate without enough diversity of weeding methods and herbicide active ingredients, leading to the appearance of glyphosate-resistant weeds and so the risk of losing this herbicide (Powles, 2008). This seems

detrimental as glyphosate had the advantage of being less harmful than many other herbicides, even if the impact of its degradation products is more mixed. However, on the other hand, the expansion of HT soybean has contributed to the development of soil conservation practices whose environmental effects are undeniably very positive.

At the agro-economic level, the results of HT soybean are also mixed. It certainly has advantages for farmers, particularly the greater ease of work and time saved enabling other activities. But the production of transgenic seeds is extremely concentrated in the hands of a restricted number of firms; furthermore, the number of non HT soybean varieties tends to diminish. There is therefore a high risk of monopoly or oligopoly for transgenic seeds, particularly soybean.

At the commercial level, the importation of GM soybean in some countries like France is criticized by many NGOs. They criticize the dependence in terms of plant proteins, when most of the animals could be fed by local resources, especially since a growing fraction of soybean comes from Brazil where its extension can contribute to the deforestation of the Amazon. On the other hand, the soybean exporters and the animal feed industry worry about the difficulties of access to certain markets like Europe because of asynchronous authorizations. Indeed, some GMOs, authorized for production in an exporting country, are not allowed to be imported the same year in some importing countries, which is a source of conflicts and tensions on the marketplace. In this respect, the concepts of sustainability strongly differ depending on the players.

At the social level, the first type of GMO widely diffused seemed to a part of the general public to be of little benefit or interest, but above all a source of risks given the type of new trait introduced which went hand in hand with the use of certain herbicides. Thus, this first type of GMO (if we exclude the *Flavr Savr* tomato whose diffusion was greatly limited) has disappointed compared to the expectations towards biotechnology in the 1980s and the beginning of the 1990s. It was therefore at the origin of a certain opposition to GMOs which has progressively increased in a certain number of countries, particularly in Europe.

More generally, the issue of GM crop impacts is often raised. However, what is called GM crop “impacts” is often not a consequence, an effect of genetic engineering in itself. It is mainly more an effect of how GMOs are designed, directed, implemented, regulated, and used in practice. In other words, the overall economic system orients the use of GMOs. Undoubtedly, the direction the economy is going in plays a role in whether or not GMOs and biotechnology applications contribute to a more sustainable agriculture.

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