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Economic Impact of Dominant GM Crops Worldwide: a Review

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Institute for Prospective Technological Studies

Economic Impact of Dominant GM Crops Worldwide: a Review

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Foreword

JRC-IPTS is a partner in the research project "Sustainable Introduction of GMOs into European Agriculture" (SIGMEA)[1] funded by the Sixth Framework Programme of the European Commission for 2004-2007. The objective of SIGMEA is to set up a science-based framework, strategies, methods and tools for assessing ecological and economic impacts of GM crops and for effective management of their development within European cropping systems. JRC-IPTS is the lead body for a work package dealing with the socioeconomic dimension of GM crops in Europe.

On 28 October 2004, within this framework of research activities, JRC-IPTS organised the scientific meeting "Economic Impact of Available GM crops: Methodologies and Results". The meeting brought together scientists from Europe, America and Asia to review the existing evidence on the economic impacts of GM crops in developed and developing countries. Another goal of the meeting was to discuss the variability of theoretical economic frameworks, methodologies, variables and hypothesis used in current studies.

Participants in this event were provided with a background document drafted by JRC-IPTS reviewing scientific literature in the subject to animate the discussion. Further review of this literature during the past two years has resulted in this comprehensive report on the scientific evidence available on the economic impacts of GM crops. This is a valuable addition to a scientific debate that has focused often on the impact on human health and the environment, and rarely on the agronomic and economic performance of GM crops.

Seville, December 2006

Per Sørup

Head of SAFH Unit
EUROPEAN COMMISSION
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1 SIGMEA gathers 44 parnerts and is coordinated by INRA (France) and NIAB (UK).

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1. Introduction

It is now more than ten years since the first genetically modified (GM) crops were introduced into agriculture. During the decade 1996-2005, GM varieties with novel agronomic traits (commonly known as "first generation GM crops") have quickly been taken up in many areas of the world.

Reports on the economic impact of GM crops often appear outside the scientific literature and with little chance of assessing their validity. However, the body of evidence accumulated during this decade by many research institutions and published in scientific journals has grown to the point where a picture of the effects of dominant GM crops worldwide can now reasonably be obtained, and this is the purpose of this review. Results from this research will also help identify the factors determining the adoption of GM crops by farmers, and shed light on the changes in the use of agricultural inputs induced by GM crops, therefore providing indirect evidence of their environmental impacts.

The report starts with a brief description of the dominant "first generation" GM crops worldwide and rates of adoption by farmers (Chapter 2).

Next, it presents (Chapter 3) the **economic effects of crops already adopted (*ex post* studies)**. Studies analysing *ex post* the effects derived from the adoption and diffusion of GM crops are of two types. The first type deals with the farm-level economic impacts. Farm-level analyses are largely based on surveying samples of commercial farmers, and provide data on the economic and agronomic performance of the crop and on the use of agricultural inputs. Results produced by farm-level studies constitute the bases for aggregate studies. These studies estimate the global economic welfare generated by adoption of GM crops, and its distribution among the economic agents (biotech research companies, seed suppliers, farmers, the food/feed industry, and consumers) or geographical regions. Chapter 3 reviews farm-level and aggregate research performed *ex post* for the four main dominant GM crops adopted worldwide, including the only case of *ex post* economic impact analysis available for the European Union (the case of GM maize grown in Spain).

Chapter 4 is particularly relevant for the European Union, where GM crops have not been adopted to any significant commercial extent (except for GM maize in Spain). Chapter 4 reviews research on the **potential adoption of GM varieties and potential economic impact (*ex ante* studies)**. *Ex ante* studies have a strong modelling component and sensitivity analysis of the main parameters is always fundamental to the correct interpretation of the results.

Finally, in Chapter 5 the impact on the economic balance of GM crops of issues such as market segmentation, **identity preservation and measures to ensure coexistence** with non-GM crops is reviewed.

This review has been compiled by surveying peer-reviewed articles on the economic impact of dominant GM crops. Where other sources are used, this is indicated in the text. For ease of comparison, all original data has been converted to euros and hectares[2].

2 Nominal exchange rates used: €1= $1.2; €1= CAD 1.56.

2. GM Crops: Evolution and Current Status of Adoption Worldwide

2.1 Global areas of GM crops in industrialised and developing countries

The first significant sowings of GM crops took place in 1996 when two agronomic input traits (herbicide tolerance and insect resistance) became available for a few major crops. Some 1.7 to 2.8 million hectares of GM crops were grown in 1996, almost exclusively in the United States (US). Since 1996, the adoption of GM crops has been progressing at a fast pace, compared with past innovations in plant varieties. Ten years later (2005), the area under GM crops has grown to 90 million hectares in 21 countries, of which 7 are high-income economies, and 14 are developing countries[3] (James, 2005). The global area under GM crops has increased every year, at an average rate of 15% since 2000 (see Table 1).

The distribution of the area between countries has been always very asymmetrical. In 2005, eight countries accounted for 99% of the global GM crop area. This year the US alone accounted for 55% of total area, followed by Argentina (19%), Brazil (10%), Canada (6%), China (4%), Paraguay (2%), India (1%) and South Africa (1%). The remaining 2% was shared by the other 13 countries.

Currently, Spain is the only country in the European Union farming a GM crop for commercial purposes at a significant rate. Spanish farmers started in 1998 to grow a type of GM maize (called Bt maize[4]), accounting for 53 225 hectares in 2005 (MAPA, 2005). France, Germany, Portugal and the Czech Republic also grew Bt maize in 2005 but report very small areas, in any case under 1000 hectares (James, 2005).

Table 1: Global area under GM crops and grower countries

Year	Area (million hectares)	Countries
1996	2.8	US, China, Canada, Argentina, Australia and Mexico
1997	12.0	US, China, Canada, Argentina, Australia and Mexico
1998	27.8	US, China, Argentina, Canada, Australia, Mexico, Spain, France and South Africa
1999	39.9	US, Argentina, Canada, China, Australia, South Africa, Spain, France, Portugal, Romania and Ukraine
2000	44.2	US, Argentina, Canada, China, South Africa, Australia, Romania, Mexico, Bulgaria, Spain, Germany, France, Portugal, Ukraine and Uruguay
2001	52.6	US, Argentina, Canada, China, South Africa, Australia, Mexico, Bulgaria, Uruguay, Romania, Spain, Indonesia and Germany
2002	58.7	US, Argentina, Canada, China, South Africa, Australia, India, Colombia, Honduras, Mexico, Bulgaria, Uruguay, Romania, Spain, Indonesia and Germany
2003	67.7	US, Argentina, Canada, Brazil, China, South Africa, Australia, India, Colombia, Honduras, Mexico, Bulgaria, Uruguay, Romania, Spain, Indonesia, Germany and Philippines
2004	81.0	US, Argentina, Canada, Brazil, China, South Africa, Australia, India, Colombia, Honduras, Mexico, Paraguay, Uruguay, Romania, Spain, Germany and Philippines
2005	90.0	US, Argentina, Canada, Brazil, China, South Africa, Australia, India, Colombia, Honduras, Mexico, Paraguay, Uruguay, Romania, Spain, Germany, Philippines, Iran, Portugal, France and Czech Republic

Sources: For the years 1996 and 1997 adapted from James (1997), for 1998 James (1998), for 1999 James (1999), for 2000 James (2000), for 2001 James (2001), for 2002 James (2002), for 2003 James (2003), for 2004 James (2004) and for 2005 James (2005)

3 According to the World Bank classification (high-income economies: GNI per capita= $10 666 or more; developing countries: the rest).

4 Bt maize is a GM crop that contains a gene derived from a soil bacterium (Bacillus thuringiensis), which produces a protein toxic for the European Corn Borer (ECB) and related maize pests.

2.2 Dominant GM crops and traits

During the first decade of commercial GM crops (1996-2005), two agronomic traits introduced by genetic engineering have been dominant. These traits are **H**erbicide **T**olerance[5] (referred to as **HT crops** in this paper) and insect resistance (referred to as **Bt crops** since the gene conferring resistance comes from the soil bacterium Bacillus thuringiensis).

Table 2 summarises the evolution of the agricultural area under dominant GM crop-trait combinations.

By 2005, the HT trait had been introduced into major crops and commercial HT varieties were grown for soybean, maize, cotton and canola (a type of oilseed rape). About 71% of the global GM crop area in 2005 was planted with HT crops (Table 2).

Insect resistant (Bt) crops were second after HT crops, with an estimated global share of 18%. By 2005, insect resistance Bt genes[6] were commercially used in varieties of maize and cotton.

Finally, the combination ("stacking") of the two traits, HT and Bt, in the same crop is growing rapidly and available "stacked" **Bt/HT crops** (cotton and maize) now account for 11% of the total GM crop area.

While "stacked" trait crops are rapidly growing in importance, they have shorter historical series of adoption than non-stacked crops, and it is hard to identify their economic impact (it is often unclear in studies looking at Bt crop economic impact whether stacked Bt/HT varieties have been considered or not).

2.3 Adoption rates for the main GM crops

In 2005, GM soybean accounted for **60% of the world's soybean** harvested area (Figure 1). All GM soybean varieties cultivated in the world are modified to tolerate herbicides (herbicide tolerant or HT soybean). HT soybean varieties accounted for 87% of the soybean grown in the US (James, 2005), the main producer of soybean in the world. The other major producers of soybean are Brazil, Argentina, China and India (FAOSTAT, 2006). Argentina (99% adoption rate) and Brazil are also significant growers of HT soybeans. China is testing the crop in field trials.

Table 2: Evolution of dominant GM crops and traits

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2005
	(million hectares)										% total
HT soybean	0.5	5.1	15.0	21.6	25.8	33.3	36.5	41.4	48.4	54.4	60.44
Bt Maize	0.3	3.0	7.0	7.5	6.8	5.9	7.7	9.1	11.2	11.3	12.56
HT Maize	0.0	0.2	2.0	1.5	2.1	2.4	2.5	3.2	4.3	3.4	3.78
Bt/HT Maize	--	--	--	2.1	1.4	2.5	2.2	3.2	3.8	6.5	7.22
Bt Cotton	0.8	1.1	1.0	1.3	1.5	2.1	2.4	3.1	4.5	4.9	5.44
Bt/HT Cotton	0.0	<0.1	--	0.8	1.7	1.9	2.2	2.6	3.0	3.6	4.00
HT Cotton	<0.1	0.4	--	1.6	2.1	1.8	2.2	1.5	1.5	1.3	1.44
HT Canola (oilseed rape)	0.1	1.2	2.0	3.5	2.8	2.7	3.0	3.6	4.3	4.6	5.11
Total	**1.7**	**11.0**	**27.0**	**39.9**	**44.2**	**52.6**	**58.7**	**67.7**	**81.0**	**90.0**	**100**

Source: For the period 1996-2003 adapted from ISAAA (2004); for 2004 James (2004) and for 2005 James (2005)

5 Herbicide Tolerance refers here to so-called total herbicides (glyphosate and gluphosinate) obtained by transgenesis (Genetic Modification, GM). Crop varieties tolerant to herbicides have also been generated by mutagenesis and/or selection.

6 Bt genes for insect resistance are a large family; several are used commercially for different pests; more than one Bt trait for different pests can be introduced into the same crop.

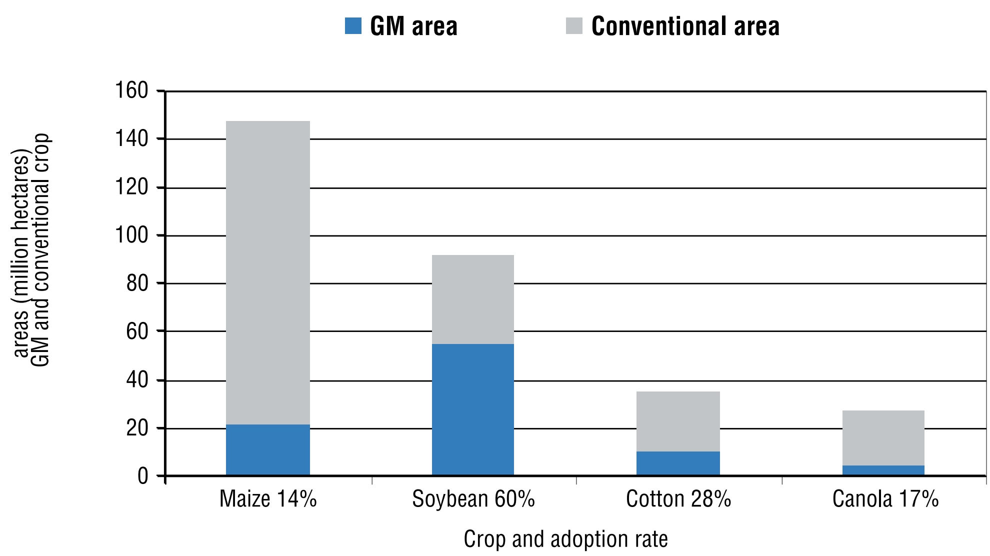
In 2005, **14% of maize** harvested area in the world was under GM varieties. The US, the main maize producer worldwide, grew about 50% of its maize area with GM varieties (either Bt, HT or "stacked" Bt/HT) (James, 2005). Other main maize producing countries such as China, Brazil, Mexico and India have not licensed any GM maize for cultivation.

The global adoption rate for **GM cotton was 28% of the total cotton area** in 2005. Major cotton producers are China, the US and Pakistan. The US grew about 79% of its cotton area with GM varieties (either Bt, HT or Bt/HT) in 2005 (FAOSTAT, 2006, Fernandez-Cornejo, 2005, James, 2005). China cultivated Bt cotton in nearly 66% of its cotton land area (3.3 million hectares) (James, 2005).

Finally, **17% of the global area devoted to canola (oilseed rape)** is sown with GM (HT) varieties. GM (HT) canola is grown exclusively in Canada and the US. China and India are also main growers of canola but there are no GM varieties authorised.

Taking these data together, it is not surprising that most literature on the economic impacts of GM crops focuses on the four arable crops mentioned above. Other GM crops have been cultivated but their adoption is insignificant. The present report concentrates, therefore, on reviewing the results on those dominant combinations of crop/traits.

Figure 1: Global adoption rates for major GM crops in 2005



Source: FAOSTAT (2006) and James (2005)

3. Economic Impact of Dominant GM Crops: *Ex post* Analyses after Adoption

3.1 Sources of farm-level economic impact

The adoption of a GM crop involves potential on-farm effects both on the revenue side and on the cost side compared with the conventional counterpart. The farm-level profitability of dominant GM crops is a function of some key variables such as:

- differences in yield (Bt crops are expected to reduce yield losses attributed to pests);
- reductions in insecticide costs (some Bt crops are expected to reduce insecticide use);
- reductions in weed management costs (HT crops are expected to save costs through simpler and more flexible weed management regimes based on a single or few herbicides);
- differences in seed prices (GM seeds are more expensive than conventional counterparts);
- differences in price received by the farmer between the GM crop and its conventional counterpart.

The adoption of GM crops may also have an effect for farmers on the income generated by off-farm activities, since some of the genetic modifications (herbicide tolerance) are designed to simplify crop management, eventually allowing farmers to use more time in off-farm activities (Fernandez-Cornejo, et al., 2005).

Novel operating costs may be linked to the introduction of GM varieties. For example, the planting of refuges of non-GM plants in the case of Bt crops (to prevent the appearance of resistance in pest populations). Also, novel potential costs incurred by GM farmers are mandatory farm measures to ensure coexistence with non-GM crops (these measures are being discussed by Member States of the European Union).

3.2 Herbicide Tolerant soybean (HT soybean)

3.2.1 The crop

Soybean is one of the world's most important and fastest expanding crops and it contributes considerably to overall human nutrition. In 2005, the crop occupied an area of about 91 million hectares in the world (FAOSTAT, 2006). In some agro-climatic conditions soybean is a poor competitor with weeds and therefore weed control becomes a critical component of profitable soybean production. Although there are many conventional weed control options for soybean growers, these are subject to some limitations in efficiency and cost (Carpenter and Gianessi, 1999).

The introduction of HT soybeans resulted in a novel way of weed control in this crop. The plants are genetically-engineered to tolerate the broad-spectrum herbicide glyphosate. The technology is known as HT soybean or "RoundupReady" soybean. It allows the replacement of an array of herbicides by a single broad-spectrum herbicide that usually is less expensive and simplifies weed management. Since its introduction in the US and Argentina in 1996, genetically modified HT soybean has been adopted at a very rapid rate. In 2005, HT soybean[7] was grown on 54.4 million hectares, accounting for some 60% of both total soybean harvested and global GM areas. The adoption of HT soybean in the US, which is the main world producer, is widespread in soybean-producing states accounting for up to 80% of the soybean crop. In Argentina, the rate of adoption

7 HT soybean is not a single variety. The transgene has been introduced into many previously existing soybean varieties adapted to local markets.

is even higher, up to 98%-99% of total soybean area. In 2005, Brazil approved a bill allowing the sale of commercial HT soybean seeds. This year, Brazil cultivated 9.4 million hectares of HT soybeans covering 41% of the crop area. Other countries growing HT soybeans in 2005 were Paraguay, Canada, Uruguay, South Africa, Romania and Mexico (James, 2005).

3.2.2 Farm-level economic impacts of HT soybean: The US, Argentina and Romania

Yields

Scientists do not find statistically significant differences in yield between HT and conventional soybean in the US or Argentina (Gianessi, 2005, Qaim and Traxler, 2005). Several arguments are given to explain the fact that HT soybean introduction is yield-neutral. The crop is not specifically designed to provide better yields, but to cut costs and simplify weed management procedures. Also, in the case of Argentina, the gene for herbicide tolerance had not yet been introduced into all top-yielding varieties of soybean therefore some HT soybean varieties being used may not be the best adapted to local conditions where they are grown.

Fernandez-Cornejo et al. (2002) argue that many factors other than the "herbicide treatment regime" vary widely among surveyed farmers and therefore yield differences may also be attributed to them (soil, weather, irrigation, farm practices, pest pressures, farmer education, etc.). To discern the portion of yield variability that can be attributed specifically to the use of HT soybean, the authors used econometric models to analyse the US case. The models use data from the Agricultural Resource Management Study (ARMS) survey conducted in 1997. The results showed a small but positive correlation between yields and the use of HT soybean in the US. Using survey data from Delaware farmers (116 individuals) in the 2000 season, Bernad et al. (2004) conducted a similar analysis. Most farmers cultivated both GM and conventional soybeans at the same time. They found higher yields for HT soybean adopters but the difference was almost negligible.

An exception is Romania, where soybean farmers had a relatively poor weed control situation (because of limited access to herbicides) and the introduction of HT soybean has resulted in yield increases of 31% on average compared with conventional soybean (Brookes, 2005).

Crop price

No price differences between the prices received by US farmers for HT or conventional soybean are reported in the scientific literature (Bullock and Nitsi, 2001, Fernandez-Cornejo, et al., 2002, Gianessi, 2005). The same situation is reported for Argentina although in this country and in Romania there are reports of small price premia for HT soybean producers due to lower contamination of the soybean grain with weed seeds (Brookes, 2005, Qaim and Traxler, 2005).

Seed price

In the US, seed prices for HT soybean are higher than for conventional soybean seeds (the "technology fee"). The sale and use of HT soybean seeds is protected in the US by patents and a sales contract with farmers, not allowing the use of farm-saved HT soybean seed. Fernandez-Cornejo and McBride (2000) found large price premia for HT soybean seeds in the US, ranging between €24-€28 per hectare (for 1997). Bullock and Nitsi (2001) analyzed a sample of US farmers growing HT soybean and reported an average additional seed cost of €13 per hectare in 1999.

The situation is quite different in Argentina (Qaim and Traxler, 2005), where under national law plant varieties cannot be patented and farmers are allowed to use farm-saved seed of HT soybean (estimated at 30% of all soybean planted). Also, some local seed companies received royalty-free access to the technology in the late 1980's from Monsanto and since then are exploiting their own HT varieties. The consequence of this situation is that the price difference between HT and conventional soybean seed in Argentina is very small (less than €3 per hectare in 2001) and this is an essential factor accounting for the adoption rate (99%) and economic impact of HT soybean for Argentinean farmers (see below).

Weed management costs

Savings in weed management costs are reported for HT soybean growers when compared with conventional soybean weed control programmes based on herbicides (Bernard, et al., 2004, Carpenter, 2001, Fernandez-Cornejo, et al., 2002, Qaim and Traxler, 2005). HT soybeans are tolerant to glyphosate, an herbicide effective for a broad range of weeds. It is usually cheaper than other herbicides and it replaces the use of a combination of 3-4 different products (Carpenter, 2001, Fernandez-Cornejo, et al., 2002). The combination HT soybean/glyphosate results in fewer tillage operations, and reduces the time needed for harvesting. Therefore it has reduced labour and machinery costs (Qaim and Traxler, 2005).

Economic balance at farm level

The question therefore is whether these lower costs on weed control and tillage currently outweigh higher seed costs and the fairly small or no differences in yield. Bullock and Nitsi (2001) reported, for a sample of US farmers using HT soybean, that in most cases the cost of the technology was higher than the cost savings, therefore negative net gains were derived from the adoption of HT soybean (compared to the use of conventional seeds). Fernandez-Cornejo et al. (2002) did not find statistically significant effects of the adoption of HT soybean in the US on profits on-farm, using a large US national survey data.

In contrast, Qaim and Traxler found that the technology increased farmers' profitability on average by €19 per hectare in Argentina, representing an increase of 8.5% over the gross margin obtained by conventional soybean farmers (Qaim and Traxler, 2005). The increase in gross margin was higher for the group of smaller farmers (less than 100 ha) than for larger farms in Argentina. The difference with the US is explained by the low seed price of HT soybeans in Argentina.

In Romania, characterised by the impact of HT soybean on yields (up 31%), increases of gross margin of 130-180% have been reported (Brookes, 2005).

Explaining adoption in the US: Off-farm income and simplicity of use

The economic results at farm level for the US results seem at odd with the rate of adoption of HT soybean (at 80% of total US soybean area). Why are US farmers cultivating HT soybean and increasing the HT soybean area? Answers to this question can be found in several studies (Carpenter, 2001, Carpenter and Gianessi, 1999, Fernandez-Cornejo, et al., 2003, Gianessi, 2005, Weick and Walchli, 2002). Farmers may be attracted by certain HT soybean advantages such as easier weed control, greater flexibility, and increased free time for other activities. These advantages are not easily converted into monetary units and are often absent in calculations due to methodological complexities.

Increased free time can be devoted to off-farm activities which result in earnings of increasing importance in the overall economic balance of the farm (Nehring, et al., 2005). In fact, recent US research, using a nationwide survey of soybean farms, showed that the adoption of HT soybean is associated with a significant increase in off-farm household income, averaging €11 310 a year for adopters of HT soybean (Fernandez-Cornejo, et al., 2005).

3.2.3 Aggregated economic welfare produced by HT soybean and its distribution

A few aggregated studies have been conducted with the objective of calculating how the introduction of GM crops changes economic welfare and its distribution between regions and/or stakeholders. Aggregate analyses take into account effects such as the impacts of GM crop introduction on global supply and market prices, the benefits for consumers (if prices are pushed down), the effects on prices of agricultural inputs (seeds, pesticides). Published studies show methodological variations regarding data sources, model assumptions, levels of regional aggregation, assumed price elasticities and developments over time.

Falck-Zepeda et al. (2000) did an early attempt to estimate the economic surplus generated by HT soybean the year after its introduction in the US (1997). A two-region model was used (US and Rest of the World, ROW) to estimate economic surplus generated for the 1997 season. Data source was limited to a small area representing about 15% of the total US soybean production. Total world surplus varies between €884 million and €364 million, depending on the assumptions used for US supply elasticity. In all cases, US farmers adopting the HT technology captured the highest share of total welfare created (76% of €884 million and 29% of €364 million).

More recently, and benefiting from the availability of additional data on farm-level impacts, Qaim and Traxler (2005) have carried out a large analysis computing the aggregated effects of HT soybean over the 1996-2001 period, with a 3-region partial equilibrium model comprising the two main growers (Argentina and the US) and the Rest of the World. Most of the parameters used in the model were fed with 2001 figures, therefore HT soybean adoption rates for Argentina, US and ROW were set at 90%, 68% and 0% respectively. For 2001, aggregating the three regions, the total welfare gain was about €1 000 million. On average, at global level, soybean consumers gained the highest share of the total surplus (53%) as a result of lower prices of the crop in world markets. Biotechnology and seed companies were next (34%) and soybean farmers, as a global group, captured the rest (13%). This average distribution pattern differs in Argentina, where HT soybean farmers capture 90% of the economic surplus created (as explained in the previous section, this is due to the low price premium for HT soybean seeds). The relatively small share obtained by soybean farmers at global level (13%) is due to the fact that farmers in the ROW, who are not adopters of HT soybean technology, suffer a negative change in economic surplus that has to be deducted from the gains obtained by the farmers adopting the technology.

3.2.4 Impact on the use of agricultural inputs

The use of inputs in agriculture is part of the economic balance but is also regarded as an indirect evidence for the environmental impact of crops. The main impact of the introduction of HT soybean in input use has been the change in the patterns of use of chemical herbicides. HT soybean adoption has led to the reduction of herbicides use (other than glyphosate) in the US and Argentina (Fernandez-Cornejo, et al., 2002, Qaim and Traxler, 2005). Glyphosate is classified internationally as a toxicity class IV pesticide, the lowest class for toxicity (WHO, 1988). The herbicides that glyphosate has replaced in soybean cultivation belonged to toxicity classes II and III (Qaim and Traxler, 2005, Fernandez-Cornejo, et al., 2002). The economic consequences of this substitution (a reduction in weed control costs) have been discussed above.

In aggregate terms, without considering toxicity classes, the total amount of herbicides used was reduced slightly in the US (Fernandez-Cornejo, et al., 2002, Nelson and Bullock, 2003). In Argentina, in contrast, aggregate herbicide use in soybean cultivation has increased from 2.6 to 5.5 litres per hectare. One reason according to Qaim and Traxler (2005) is that up to 80% of HT soybean farmers in Argentina have adopted no-tillage practices, using glyphosate instead of tillage for pre-sowing weed control.

Regarding the use of fuels, farmers cultivating HT soybeans in Argentina reduced its machinery use by 20% allowing to save 10 litres of fuel per ha (from 53 litres per ha used by conventional soybean farmers to 43 litres per hectare used by HT soybean farmers). This is again due to the fact that 80 % of HT soybean farmers have adopted also "conservation agriculture" or "no tillage" strategies *vs* 42% of conventional soybean farmers. This reduces the number of tillage operations and the fuel consumption. No tillage is also adopted because of its effect in preserving soil from erosion and degradation.

Regarding land use, the introduction of HT soybean varieties has coincided in time with a sizeable expansion of the land used for soybean production in Argentina (Qaim and Traxler, 2005), a situation that has not occurred in the US. There is no research on how much this effect can be attributed specifically to the availability of HT soybeans and/or to the global increase in demand, but it has been suggested that the tolerance to herbicides has made it possible to introduce soybean cultivation in Argentina in land previously dedicated to pasture, where past attempts to cultivate had been hampered by weed infestations.

3.3 Insect-resistant cotton (Bt cotton)

3.3.1 The crop

Cotton is a very important industrial crop for many countries in the world. It is the world's leading non-food crop both in terms of the amount of land cultivated and the economic turnover it generates. Cotton is grown in warm areas with a rainy season or under irrigation, the main producers being China, the US, India and Pakistan. Thirty-five million hectares were cultivated in 2005 and international cotton trade is forecast to reach 7.9 million tons in 2005/06 (FAOSTAT, 2006, ICAC, 2004). Cotton is mainly grown for fibre production. In addition, cotton seed is a by-product used to produce edible oils and cosmetics, and is also processed into meal cakes for animal feed.

Cotton is attacked by a number of insect pests, which constitute a major problem in most cotton producing areas. Conventional cotton production relies heavily on chemical insecticide use to such an extent that it is estimated that 25% of world use of agricultural pesticides is consumed in cotton production. This has also led to the appearance of pest populations resistant to the most commonly used insecticides.

Bt cotton is the name for transgenic cotton varieties that are resistant to a number of pests affecting this crop. Bt cotton was initially introduced in the US on 730 000 hectares and in small areas of Mexico and Australia in 1996. By 2005, eight countries were growing Bt cotton on 9.8 million hectares of land, accounting for 11% of global GM crop area. These countries are the US, Argentina, South Africa, Mexico, Colombia, India, China and Australia. Pakistan started to cultivate Bt cotton after the entry into force of its biosafety rules in 2005, and expects to cultivate at least 34 000 hectares in the year 2006-2007 (Rao, 2006).

Peer-reviewed literature on Bt cotton performance has been conducted in many countries and time series, making it the GM crop for which the most solid evidence is available regarding economic performance and impacts.

3.3.2 Farm-level impacts of Bt cotton in China, India, South Africa, Argentina, the US and Australia

China

In 1997, the Chinese Ministry of Agriculture approved Bt cotton varieties to fight against pests and the rising use of insecticides by farmers. In 2005, China grew 3.3 million hectares of Bt cotton occupying about 66% of the national cotton area. A particularity of China is the availability of Bt cotton varieties developed by the public research sector (CAAS[8]) that compete in the market with the Bt cotton varieties sold by private multi-national seed companies world-wide.

Huang et al. (2002) surveyed a sample of 282 cotton farmers in two different Chinese provinces in 1999 to assess the economic impact of adoption (see also Huang, et al., 2003). Several varieties of Bt cotton (either from Monsanto or CAAS) were compared with a conventional variety. The analysis found that, on average, the yield of Bt cotton was higher than that of non-Bt cotton (by between 7 and 10%). Yield increases where highest for smallest farms. Bt cotton farmers benefited from cost savings due to the reduced cost of pesticide use (€27 per hectare for Bt cotton growers against €148 per hectare for non-Bt growers). These results are confirmed in subsequent surveys in 2000 and 2001, carried out over the same and additional provinces (Huang, et al., 2004). The main economic impact of Bt cotton was to reduce the cost of production by 20% to 33% depending on the Bt cotton variety and the location, mostly due to reduced pesticide expenditure. The net income and returns to labour of all Bt varieties were superior to the non-Bt varieties. Among farmers growing Bt cotton, a relevant result is that smaller farms and farms which had lower incomes consistently obtained larger increases in net income than larger farmers and those with higher incomes.

The impact of Bt cotton introduction in reducing the use of insecticides by Chinese farmers is well documented. Bt cotton farmers reported fewer applications of insecticides (6.6 applications per crop on average) than conventional farmers (20 applications on average). Bt cotton farmers used 5 times less quantity of insecticide per hectare (see also Huang, et al., 2003, Pray, et al., 2001). Moreover, farmers using Bt cotton reported fewer incidence of pesticide poisonings (5-8%) than those using conventional cotton (12-29%) (Huang, et al., 2003).

India

India has the world's largest area devoted to cotton cultivation (about 9 million hectares in 2005) (FAOSTAT, 2006). However, severe insect pests problems had relegated India to third position among the world's cotton producers (Beyers and Thirtle, 2003). The Indian government considered biotechnology as part of the solution and in March 2002 approved the commercial release of Bt cotton. In 2005, about 1.3 million hectares were sown with Bt cotton with an adoption rate of 14% of the total cotton area.

Before data based on farmers' commercial practices became available, Qaim (2003) and Qaim and Zilberman (2003) carried out an analysis based on field trial results of Bt cotton in India. A sample of 157 farmers from three Indian states (Maharashtra and Madhya Pradesh in Central India and Tamil Nadu in the South) participating in field trials were surveyed in 2001. The average yield gains of Bt cotton were up to 80% and 87% over the non-Bt counterpart and the "popular check" (the most commonly used local variety), respectively. These large yield gains were partly due to high pest pressure in 2001. On average, less use of pesticide was reported for Bt cotton (three applications less) corresponding to savings of about €25 per hectare, and gross margins on Bt cotton plots were more than five times higher than on conventional plots.

Two seasons after the commercial release of Bt cotton, Morse et al. (2005) studied the economic impact on-farm based on data collected for a total of 7 793 cotton plots in 2002 and 1 577 plots in 2003. All these plots are located in three sub-regions of Maharashtra State. A higher average gross margin is reported for Bt cotton farmers compared with conventional cotton farmers (43% higher in 2002 and 73% higher in 2003). Although Bt cotton provided clearly better average economic performance, the figures show some local variability. For example in 2002, in

8 China Academy of Agricultural Sciences. In 1999, the Biotechnology Research Centre of the CAAS initiated an important research programme to develop Bt cotton.

the Marathwada sub-region, the gross margin for Bt cotton was just 4% higher than that of non-Bt cotton (see also Bennett, et al., 2006 for the same research).

This regional variability in agronomic and economic performances has been studied in detail recently by Qaim et al. (2006). Variations between regions (pest pressure, agro-ecological conditions) and farmers (pest control patterns) influence spatial differences in performance. The authors also point out that the current regulatory procedure in India, under which every single Bt hybrid needs its own approval, delays the authorisation of additional varieties and therefore the Bt technology has not been introduced yet in the cotton varieties best suited for each region (the "germplasm" effect on yields).

In India, the Genetic Engineering Approval Committee (GEAC) authorised the commercialisation of Bt cotton on condition that seed companies[9] ensured the planting of a refuge (of conventional cotton) around Bt-cotton fields, as a barrier to pollen flow, and to prevent the build-up of resistance among insects. At least 20% of the farmer's field must be planted with conventional cotton and a minimum of five rows of conventional cotton have to be sown along the border of every field irrespective of the size of the plot (Raghuram, 2003). These are important measures to prevent insect resistance and to maintain the Bt cotton yield advantage (Morse, et al., 2005). However, Raghuram (2003) points to difficulties for smallholders in applying these measures due to their small field sizes, which could present a barrier to adopting the technology.

South Africa

In South Africa, Bt cotton was introduced in 1998 and became the first GM crop cultivated in Africa. In 2005, about 30 000 hectares of GM cotton were grown in this country (James, 2005). Thirtle et al. (2003) surveyed a sample of 100 South African smallholders in two consecutive seasons to assess the on-farm impacts of Bt cotton. On average, during the first season, 1998-1999, Bt cotton adopters did not experience any yield increase. The authors showed that this fact could be partly explained by the sowing rate used for Bt cotton (seed sown per hectare). The sowing rate was 22% lower for Bt cotton adopters than for non-adopters due to the high price of Bt cotton seeds (twice the cost of conventional varieties). Pesticide costs were reported to be lower for the Bt cotton adopter. However, these savings were not enough to achieve better gross margins compared with conventional cotton. In the second season (1999), intense rains resulted in a generally poor crop yield. Yet, on average, Bt cotton adopters (second and first year adopters) achieved 40% higher yield per hectare. Despite Bt cotton seed costs per hectare were 68% higher for adopters, higher yields combined with savings on pesticide costs allowed Bt cotton adopters to obtain a economic advantage of 58% over non-adopters' gross margins.

Argentina

Argentina grew Bt cotton for the first time in 1998. In 2005, about 30% of the national cotton area was cultivated with either Bt or HT cotton (75 000 ha) (FAOSTAT, 2006, James, 2005). Contrary to the situation described for HT soybeans in Argentina, local and global seed companies have been able to enforce the intellectual protection rights of Bt cotton seeds, and purchase of Bt cotton seeds in Argentina is accompanied by a contract prohibiting the use of farm saved seeds.

Qaim and de Janvry (2003) surveyed 299 cotton farmers in 1999-2000 and 2000-2001. In 2001 the adoption of Bt cotton was still limited to 5% of national cotton area. The objective was to analyse the corporate pricing strategy for Bt cotton seeds and its effect on adoption by farmers. At the same time, the on-farm impact of the adoption of Bt cotton was studied.

9 In India, the Bt cotton varieties are the result of a joint venture between Monsanto and the national firm Mahyco.

On average, Bt cotton yields were 32% to 34% higher than those of conventional cotton for the two seasons studied. Bt cotton also reduced expenditure on insecticides by more than 50% in both seasons. The number of insecticide applications needed for Bt cotton was reduced (2.3 and 2.4 fewer applications for each season). Despite the better performance, the average Bt cotton seed price of €83 per hectare found in the survey (four times the price of conventional varieties) resulted in small net benefits to farmers, and at the same time did not maximise the profit of the seed supplier. In Argentina, the main constraint on higher adoption rates for Bt cotton seems to be the price of Bt cotton seeds (farmers´ average willingness to pay for Bt cotton seed was estimated to be less than half the actual market price). Another finding was that the Bt cotton seed price was almost 80% higher than the level that would maximise the monopolist's profits.

Mexico

Mexico grew Bt cotton for first time in 1996. In 2005, Mexico cultivated about 120 000 hectares of this crop (James, 2005). Adoption rates of the crop vary widely between regions, with regions reaching almost full adoption (Comarca Lagunera) and others insignificant adoption. This pattern reflects variability in pests attacking cotton, and regions where major pests are those best controlled by Bt cotton (for example pink bollworm) show high adoption rates.

Our survey found no peer-reviewed papers dealing with the impacts of Bt cotton in Mexico, but a book chapter by Traxler et al. (2003) studying the adoption of Bt cotton in Comarca Lagunera (96% adoption of Bt cotton by the year 2000). To calculate yields and cost reductions due to the adoption of Bt cotton, Traxler et al. (2003) surveyed two types of farmers, larger farms (30-120 hectares) and *ejidos* (2-10 hectares) for the first two years that Bt cotton was grown in Mexico (1997 and 1998). In the first year, with very low pest infestation, yields were similar. In 1998, Bt cotton had 20 % higher average yields, and higher average market prices. Total costs, were significantly lower for Bt cotton producers due to reduced insecticide costs, offsetting the higher seed prices. An average of two fewer pesticide applications was used on Bt cotton than on conventional cotton. Finally, Bt cotton farmers' profit advantage over conventional farmers' amounted to €236 per hectare on average over the two growing seasons.

US

Bt cotton was first introduced in the US on 730 000 hectares in 1996 (ISAAA, 2004). The US grew about 2 770 000 hectares of either Bt, HT or HT/Bt cotton in 2005 (James, 2005, Meyer, et al., 2005). This is slightly above 50% of the national cotton area. Despite this considerable importance, there is a lack of peer-reviewed articles studying performance of GM cotton in the country. There are a couple of governmental peer-reviewed reports which give figures on agronomic and economic performance of Bt cotton (Fernandez-Cornejo and McBride, 2000, K. Price, et al., 2003). Although the two reports apply different approaches to calculating the impact of adopting Bt cotton, both used data from the Agricultural Research Management Nationwide Survey (ARMS) for the year 1997. For the relevant regions, both reports found yield advantages for Bt cotton growers or derived from the adoption of Bt cotton. Fernandez-Cornejo and McBride (2002) reported that an increase of 10% in the adoption of Bt cotton in the Southeast increased yields by 2.1% and Price et al. (2003) found that, on average in the Southern Seaboard[10], Bt cotton growers enjoyed a yield advantage of 21% over non-adopters. Using ARMS, the two studies also

10 The Southern Seaboard is the name given to an area spanning the States of Virginia, North Carolina, South Carolina, Georgia, Mississippi, Alabama and Louisiana.

found economic advantages for Bt cotton over the conventional crop. Fernandez-Cornejo reported a positive and statistically significant effect on farm-level benefits of adopting Bt cotton (+2.2%) and Price et al. showed that on average adopters' pest control costs fell by 7% as a consequence of using Bt cotton.

Wossink and Denaux (2006) surveyed a sample of 208 North Carolina cotton farms to quantify the environmental and economic efficiency of HT and "stacked" Bt/HT cotton compared to conventional cotton. Data envelopment analysis (DEA) is used for quantification and pesticide leaching potential for the assessment of the external effects of pesticide. A Tobit regression is used as a further step to identify common characteristics in the most efficient cotton growers found using DEA analysis. Results show that the Bt/HT cotton contributes positively and significantly to both agronomic and environmental efficiency. However, the advantage of fewer applications of pesticides is offset by the high price of GM cotton seeds, which means that the use of GM varieties does not show a clear economic advantage. The authors, however, recognise that they do not include labour cost in their analysis, and that labour costs might be reduced as a consequence of reduced spraying.

Australia

In Australia, the Australian National Registration Authority approved a very limited commercial release of Bt cotton in 1996. About 90% of the total cotton area is now GM cotton, 300 000 hectares (Bt, HT and HT/Bt). Since then, there has been a drastic reduction in insecticide use against the major cotton pests (Fitt, 2003). According to this author, as confirmed in our survey, no full, relevant economic analysis has yet been carried out on the performance of Bt cotton in Australia.

3.3.3 Aggregate economic welfare produced by Bt cotton and its distribution

There is no recent and comprehensive multi-regional analysis on the aggregate economic impacts generated by Bt cotton. Qaim (2003) made medium-term economic projections showing welfare gains derived from the adoption of Bt cotton in India (for the period 2002-2005). Indian farmers adopting Bt cotton were the main beneficiaries of adoption (capturing 67% of generated welfare), followed by seed companies (33%).

An aggregate study (Falck-Zepeda, et al., 2000) calculated the total increase in world surplus and its distribution from the introduction of Bt cotton in the US in 1996, the first year of adoption. They modelled the introduction of Bt cotton as occurring in a large, open economy with no technology spillovers and influencing world market prices. Bt cotton decreased world trade cotton prices by €0.81 per kilogram, a small effect due to the minimal proportion of world cotton area occupied by Bt cotton at that time. Total surplus created was €192 million, of which 59% went to US farmers that adopted Bt cotton, 26% to the two main seed companies owning the Bt cotton technology and US consumers gained €18 million (9%). Consumers in the rest of the world achieved €30.2 million while non-adopting farmers in the rest of the world lost €14.93 million due to downward pressure on prices. The same analysis was made for 1997, the second year of planting of Bt cotton in the US. For this year total increase in world surplus was estimated by the model at €152 million, compared to €192 million in 1996. The 1997 welfare gains went mostly to US farmers growing Bt cotton (42%) and seed companies (44%).

Traxler et al. (2003) estimated the increase in welfare due to adoption of Bt cotton and its distribution in Comarca Lagunera (Mexico). For the two years studied (1997 and 1998), a total surplus of €5 million was produced, of which about 86% went to farmers and 14% to the seed companies.

3.4 Insect-resistant maize (Bt maize)

3.4.1 The crop

Maize insect pests are a major problem worldwide. The European Corn Borer (ECB), the Mediterranean corn borer and the South Western corn borer damage maize production, resulting in significant yield and economic losses. These losses are difficult to manage because insecticide sprays are effective only in the narrow time span between egg hatch and larvae boring into stems. The lack of effectiveness and additional cost is the reason why many maize farmers do not spray insecticides specifically for controlling corn borers and tend to assume the yield losses.

Bt maize contains a gene that confers protection from corn borers. Bt maize is the second GM crop in terms of area sown (11.3 million hectares or 12.56% of the global GM crop area in 2005) (James, 2005). Twelve countries were commercial growers of Bt maize in 2005, namely the US, Canada, Argentina, Honduras, South Africa, Uruguay, the Philippines, Spain, Germany, the Czech Republic, Portugal, and France.

The value of Bt maize is the expected reduction in yield losses due to pest attacks. Yet the levels of infestation in a given area vary greatly between crop seasons, depending on many factors, some of them not under farmers' control. Farmers would benefit from forecasting infestation levels before planting, but this is not easy. In low infestation years, the value of the protection derived from Bt maize may not cover the extra seed price paid for the technology, while in heavy infestation years Bt maize growers could obtain substantial yield increases translated into economic benefits.

3.4.2 Farm-level economic impacts of Bt maize in the US, South Africa and Spain

Bt maize economic performance at farm level has not been studied in detail (compared with HT soybeans or Bt cotton) despite its importance in terms of area and the numerous countries in which Bt maize is grown.

US

No peer-reviewed articles and only a few reports from governmental agencies have been found in our literature survey for the main Bt maize growing country, the US. In 2005, 50% of maize cultivated in the US was GM maize, equivalent to 16.5 million hectares (either Bt, HT or "stacked" HT/Bt maize) (James, 2005). Carpenter and Gianessi (2001) reported that, on average, Bt maize yields were higher than those of conventional maize in 1997, 1998 and 1999. However, for 1998-99 Bt maize farmers reported lower income per hectare than conventional maize farmers. These results are in line with those of Fernandez-Cornejo and McBride (2002), reporting that the adoption of Bt maize in US had a negative economic impact in 1998. Hyde et. al. (1999) (based on data from expert opinions) found that the mean profitability of Bt maize varied systematically with ECB pressure in Indiana (US).

As in the case of HT soybean, the question arises of how then to explain the adoption of Bt maize by US farmers. Marra et al. (2003) have reviewed the role of risk, uncertainty and learning in the adoption of new agricultural technologies. They use the example of GM insect-resistant crops (Bt crops), where uncertainty comes primarily from variable seasonal levels of pest infestations. This work concludes that farmers with "*high levels of absolute risk aversion*" contemplate Bt maize as an attractive technology. Farmer advisers, extension educators and academic researchers suggested that farmers use Bt maize as "insurance" against crop losses in the long term. On the other hand, market uncertainties, maize output prices, the price paid for the technology (GM seeds) and seasons with low level infestations are economic risk factors when deciding to adopt Bt maize.

South Africa

In 1998, the government of South Africa authorised the cultivation of yellow-grained Bt maize which is mainly used as animal feed and as an input in the food industry. Three years later, in 2001, white-grained Bt maize hybrids were also commercialised. White maize is the basic staple food in South Africa. Both Bt maize crops had been developed to resist the African maize stem borer (*Busseola fusca*) which causes harvest losses of an average of 10%. In 2005, South Africa cultivated about 85 000 hectares of white GM maize and 195 000 hectares of yellow GM maize (James, 2005). Gouse et al. (2005) surveyed 33 large-scale yellow maize producers to gather data for the 1999/2000 and 2000/2001 production seasons. Four South African provinces were analysed, two of them growing irrigated maize and two in dry land conditions. Those cultivating Bt maize achieved yield advantages ranging from 7% to 12%. At first glance, irrigation or dry conditions do not seem to have an impact on the effect of Bt maize on yields. The yield advantages together with reduced pesticide costs resulted in income advantages ranging from €20 per hectare to €124 per hectare. Gouse et al. (2005) also surveyed 368 small farmers growing Bt and conventional white maize at the same time, using seeds distributed by seed companies as field trials. Six areas were analysed in the 2001/2002 season. Each farmer cultivated their own traditional maize ("popular check"), the conventional counterpart of Bt maize and Bt maize. On average, the survey results show that Bt maize had a large yield advantage over the two conventional seeds. Another outcome of the research is that farmers were able to reduce pesticide costs except in one of the areas where little pesticide was used in the 2001/2002 season. The authors could not carry out an estimation of economic performance since the seeds were distributed free by companies.

Spain

Bt maize is the only commercial GM crop grown in the European Union (EU), and Spain is the only EU Member State where adoption of the crop has taken place to a significant extent. In 1998, Spanish farmers started the commercial cultivation of Bt maize growing some 20 000 to 25 000 hectares. Adoption and diffusion was voluntarily limited by seed companies by limiting seed distribution until new events and varieties of Bt maize were authorised by the EU in 2004.

Data from the Spanish Ministry of Agriculture show that Spanish farmers grew about 53 225 hectares of Bt maize in 2005, representing 12% of the national maize area. Regional rates of Bt maize adoption are quite variable, probably reflecting variability in maize borer pest pressure. In some regions such as Catalonia, Bt maize now represents 43% of the maize area. Bt maize is grown mainly in the Ebro Valley (Aragon and Catalonia regions) and in Albacete (Castilla-La Mancha region). In Spain, all Bt maize is sold through normal marketing channels to animal feed producers.

The largest and most updated source of empirical data for on-farm performance of Bt maize in Spain comes from a survey conducted by Gómez-Barbero et al. (manuscript in preparation). The authors surveyed 400 Spanish maize farmers to compare the economic performance of Bt maize in commercial conditions versus its conventional counterpart, for the three-season period 2002-2004. The survey was carried out in the Catalonia, Aragon and Castilla-La Mancha regions, which together represent 85% of the Bt maize area.

For the 2002-2004 period studied, farmers using Bt maize obtained an increase in their gross margin compared with farmers growing conventional maize. Taking Spain as a whole, the gross margin difference averages €85 per hectare per growing season. This represents an increase of 13% over the average gross margin obtained by a maize farmer in Spain, including subsidies. These benefits, however, vary widely in the three regions studied, ranging from the high gross margin differences in Aragon (€125 per hectare) and Catalonia (€71 per hectare) to just €7 per hectare in Albacete (Castilla-La Mancha). No differences in the price received by Spanish farmers for the Bt or conventional maize crop were found in the survey. Adoption of the Bt maize technology by Spanish farmers was not correlated with farm size, according to the survey.

The survey found that on-farm economic gains are mainly due to the better agronomic yield of Bt maize compared with conventional maize. The average yield advantage of Bt over conventional maize in Spain for the three seasons (2002/04) was 4.7%, with clear regional variations. Yield gains are high in Aragon and Catalonia, but not in Castilla-La Mancha (probably reflecting differences in the frequency and intensity of attacks of the ECB pest that causes yield reductions). The survey also found reduced use of insecticides for Bt maize growers. Fifty-eight per cent of conventional maize farmers sprayed insecticides to control the corn borer, a figure that is reduced to 30% among farmers using Bt maize. On average, conventional maize growers in Spain applied 0.86 insecticide treatments a year to control corn borers, as against 0.32 treatments a year for Bt maize growers.

The surplus economic welfare created by Bt maize introduction in Spain was captured mainly by Spanish Bt maize farmers (roughly 75%) followed by seed companies (about 25%). Other sectors such as industry or consumers do not capture economic benefits associated to Bt maize introduction in Spain because there has been no impacts on prices.

A previous study tried to estimate the impact of Bt maize cultivation in Spain. Demont and Tollens (2004) looked at the total welfare increase in Spain for each of the years from 1998 to 2003. The study, however, uses secondary data and data from a survey performed in 2002 by Brookes (2002) to estimate on-farm effects. The study estimates that on average and annually, Bt maize adopters captured €1.2 million (63% of the increase in welfare) and the seed industry €0.6 million (37%).

3.5 Herbicide Tolerant rapeseed/canola (HT rapeseed/canola)

Oilseed rape is an important crop worldwide. Breeding developments led to the production of rapeseed low in both erucic acid in the oil and glucosinolates in the meal (double-low varieties). The name canola was established with the licensing of the first double-low variety of rapeseed in Canada in 1974. Although, once established, canola is a good competitor with most weeds, young canola seedlings are very sensitive to early weed competition. GM herbicide-tolerant canola[11] (HT canola) aims at more efficient weed control and easier prevention of weed resistance to herbicides. It has been on the market since 1995. In 2005, Canada grew 4.2 million hectares of HT canola with an adoption rate of 82% over the total canola acreage (James, 2005).

Despite the substantial area cultivated and high rate of adoption of HT canola in Canada, the peer-reviewed literature on the economic impact of this crop is limited. Carew and Smith (2006) used a model to estimate that the contribution of HT canola varieties to increased yields of the crop is about 6.8% at national level. Mayer and Furtan (1999) looked at the increase in welfare from adoption. However, the economic consequences of reduced herbicide use and possible increased yields are not based on direct data from surveys but on the authors' estimates.

A book chapter by Phillips (2003) looks at the economic welfare effects of the introduction of HT canola in Canada by examining the aggregate direct impact and its distribution among farmers, seed companies and markets (processors and consumers). Using several sources of secondary data, farmers' net aggregate benefits (farmer's gross benefits minus negative change in producer's

11 Although herbicide tolerant canola (triazine tolerant canola) varieties obtained by "non-GM" (no transgenesis) breeding have been available since 1982, in the text we refer to GM herbicide tolerant canola.

price for canola due to increase production) was estimated at €44.8 million (€11.98 per hectare) for the year 2000. As for the distribution of the aggregate economic surplus generated, technology providers (seed companies) captured the highest share of total welfare every year in the period studied. However, their share dropped to about 58% in 2000 (from 94% in 1997). Phillips (2003) explained that this might be because when proprietary technologies lost their patent protection, more benefits should have flowed to farmers. The farmers' share of generated welfare rose from 6% in 1997 to 29% in 2000. Consumers have captured little from HT canola adoption by lower prices due to the structure of demand and supply. Strong concentration in the supply chain and the fact that 80% of Canadian canola production is exported seem to be major factors explaining this.

4. Assessing the Economic Impact of GM Crops before Adoption: *Ex ante* Studies

Ex ante evaluations deal with forecasting the economic impact of GM crops, at farm or aggregate level, before they are actually adopted. Evaluations of this kind have a strong modelling component and a number of parameters have to be estimated in *ex ante* studies. In particular, yield effects and cost reductions at farm level have to be estimated from experiences in field trials and/or other countries. This research is particularly relevant for the European Union, where GM crops have not yet been adopted (except for Bt maize in Spain). Sensitivity analysis of the main parameters is always fundamental to the soundness of this type of evaluation.

4.1 *Ex ante* analyses for the EU: Estimating the benefits of potential adoption

There is a small but growing number of *ex ante* studies addressing the potential economic impacts of GM crops not yet approved for commercial cultivation by EU farmers, but cultivated elsewhere in the world.

Desquilbet et al. (2001) evaluated the benefits derived from the potential adoption of HT rapeseed in France. A survey was done to estimate weed control costs of individual farms growing conventional rapeseed. For the HT rapeseed counterpart, the estimation of weeding costs was built using data from HT rapeseed field trials carried out in France. For the baseline scenario the estimated rate of adoption of HT rapeseed by French farmers was 75% of farmers. With this adoption rate, French farmers would save €24 million in weeding costs per season. The total gains from moving from the no adoption situation to 75% adoption of HT rapeseed in France were estimated at €38 million per season.

May (2003) analysed ex ante the economic consequences for UK farmers of potential adoption of HT sugar beet. Assuming that all UK sugar beet growers adopted HT sugar beet, average savings in weeding costs were estimated at €217 per hectare and year or €33.5 million a year nationally. Estimations were based on a complete cost analysis, using data mainly from different published sources such as the British Sugar annual national surveys.

In a book chapter, Demont and Tollens (2004) studied *ex ante* the aggregate economic welfare derived from introducing HT sugar beet in the EU and its distribution between different economic agents/regions. An equilibrium model was used in which the rate of adoption of HT sugar beet in the EU was assumed to be half the observed rate of HT soybean adoption in the US. This adoption rate was then applied to the producer regions covered in the study (EU and ROW). The global accumulated welfare created was €1 150 million after five years of adoption. Welfare created was shared by ROW (53%), the EU sugar beet growers (30%) and technology developers/seed suppliers (17%). Consumers do not capture gains in the form of lower market prices as a result of the EU Common Agricultural Policy which establishes intervention prices. EU sugar beet domestic prices do not decline as a consequence of the HT technology.

Gómez-Barbero and Rodríguez-Cerezo (2005) analysed the potential adoption and economic impact at farm level of Bt cotton in Southern Spain. A survey of 830 farmers across all cotton production areas in Andalusia (9% of all cotton farmers) showed that 58% of the responding farmers knew about GM Bt cotton. Within this group, 95% were willing to grow Bt cotton. Regarding the on-farm economic impact resulting from potential adoption, the assessment is that savings on direct pest control costs would be achieved by reducing the number of insecticide treatments. This analysis was applied to a representative Andalusian cotton farm, where a reduction of 2.6 insecticide treatments is assumed. This would result in a cost saving of €148.2 per hectare.

Flannery et al. (2004) carried out a cost-benefit analysis of the hypothetical cultivation of four GM crops in Ireland (sugar beet, winter wheat, spring barley and potato) including a cost which is estimated as a levy of up to €25 per hectare of GM crop cultivated[12]. Findings show a higher gross margin per hectare for all the GM crops than for their conventional counterparts (reaching €223 per hectare for GM HT sugar beet).

4.2 *Ex ante* analyses in developing countries

Elbehri and Macdonald (2004) used a multiregional general equilibrium model to estimate the potential economic impact of Bt cotton if introduced in West and Central Africa (WCA). Cotton is a major source of export revenue in the region and a cash crop for many farmers. The model is run under different adoption scenarios and the *status quo* scenario (where transgenic cotton is used in other regions but not in WCA). Findings show that the *status quo* scenario reduces WCA economic welfare substantially (about €70 million annually). Other scenarios in which WCA adopts Bt cotton show significant welfare gains ranging from €56 to €66 million.

Although no GM rice has yet been released on the market, China is considering the release of four varieties of insect-resistant GM rice. Huang et al. (2005) compared the performance of GM and conventional rice in China in 2002-2003 by using data obtained from GM rice preproduction field trials. Two GM rice varieties were analysed, GM Bt Xianyou and GM CPTI II-Youming 86[13]. Farmers were randomly selected (347 plots in total) and left free to cultivate under their common practices, without monitoring by technicians. Findings show that farm households adopting GM rice produced higher yields (between 3.5% and 9% depending on the methodology used and the GM variety) and reduced pesticide use. The same pesticide types are applied both by GM and non-GM rice farmers, but the former reported fewer applications and less quantity (0.5 times per season compared with 3.7 times and 80% less in terms of kilograms per hectare). The knock-on effects of fewer insecticide applications are lower expenditure on pesticide, less labour use and health benefits for adopters, documented by the reduction in the number of doctor's visits for pesticide poisoning. The question whether this increase in revenues and decrease in costs will be converted into profit gains cannot be answered without knowing the seed pricing policies to be applied by the GM seed developers. Even if GM rice in China, as it appears, proves profitable at farm level, the fact that rice is a food for direct human consumption raises the issue of market risks when analysing ex ante the impacts of adoption. This issue and the consequences of market segmentation, identity preservation and coexistence between GM and non-GM crops will influence estimations of the economic balance of GM crops, as discussed in the following Chapter.

12 Some EU member States are introducing a "Coexistence" fee in the form of a fixed levy per hectare of GM crop planted (see section 5)

13 Both varieties are resistant to rice stem borer. In the CpTI variety a modified *cowpea trypsin* inhibitor gene is introduced into rice.

5. Market Segmentation, Identity Preservation and Coexistence: Impacts on Economic Balance of GM Crops

Most of the research done so far on the global economic impacts of GM crop introduction has considered a global market with no significant segmentation and has not looked at costs incurred to preserve identity between GM and non-GM harvests and supply chains. These seem to be reasonable assumptions for the crops and periods of time studied. Domestic markets for these crops in producing countries are not segmented and the export markets for identity-preserved non-GM varieties of these crops remain fairly small at global level. Price differences at the farm gate for the non-GM counterparts of maize, soybean, cotton or rapeseed have not been common, or have not been enough to compensate farmers for switching to non-GM varieties, and the global share of GM varieties area cultivated with these major crops has increased every year (as reviewed in Chapter 2). Finally, dominant GM crops are largely used for animal feed and not directly for human consumption.

5.1 Introducing market segmentation and identity preservation costs in impact studies

Recent research describes how these assumptions may change with the introduction of GM crops directly used for human consumption such as GM wheat or GM rice. In 2002, an application for genetically modified HT wheat was submitted to the US and Canadian authorities for approval for commercial cultivation. In 2004, the applicant dropped plans for release of this GM wheat due to strong consumer resistance. Johnson et al. (2005) tried to estimate *ex ante* the aggregate economic welfare generated by HT wheat introduction in the US and economic costs derived. They assumed that introduction of HT wheat will be accompanied by an identity preservation system[14] and will create two significant market segments: one composed of non-GM wheat consumers and another of consumers who are indifferent to whether the commodity is of GM origin or not. Many crucial parameters of the wheat sector model run by Johnson et al. (2005) have been assumed due to the lack of experience with commercial HT wheat cultivation. For example, expected yield increase and potential savings for HT wheat adopters are estimated using data on the HT soybean growers. The authors also assume a 1% tolerance threshold for the presence of HT wheat in conventional wheat. Two scenarios for wheat price are considered.

The results show that producers and consumers of non-GM wheat bear the extra costs of segregation and identity preservation. These costs are substantial and depend mainly on the tolerance threshold considered. For the base case assumption, these costs outweigh the economic benefits derived from the introduction of GM wheat, resulting in a small net welfare loss at global level. The distribution of the welfare effect is highly dependent of wheat prices, but in all price scenarios, consumers who are indifferent to the origin of the wheat benefit from introduction paying lower market prices. Consumers of non-GM wheat suffer losses because of the segregation costs. The authors estimate that the majority of non-GM wheat consumers will be outside the US, therefore losses will be essentially for foreign consumers. In the "low price" scenario the welfare loss is largely borne by US taxpayers and by

14 The company applying for HT wheat market release also recognised the need to introduce the innovation together with a manageable identity preservation system for producers and handlers.

non-GM consumers in foreign countries. Wheat producers have small net benefits. In the "high price" scenario, wheat producers bear net losses, absorbing part of the segregation cost together with consumers of non-GM wheat. Sensitivity analysis applied to the "low cost" scenario shows that US economic well-being is found to increase as long as the GM wheat adoption rate increases.

In summary, the authors conclude that given the impact of tolerance thresholds in global welfare gains, there is an economic rational for providing reasonable tolerances in commercial transactions. They also conclude that because of the different attitude of US consumers towards biotechnology, US welfare may improve with high rates of HT wheat adoption while foreign welfare declines.

A recent study has considered market segmentation and segregation costs when looking at the welfare created by HT soybean adoption. Sobolevsky, et al. (2005) developed a partial equilibrium model for the US, Argentina, Brazil and ROW soybean markets. HT soybean products are considered as weakly inferior substitutes for conventional products in ROW markets. Different segregation costs, agricultural policy and GM policy scenarios are used. This paper uses Lin et al's (2000) estimate of soybeans segregation costs which is between 3.4% and 10.3% of the average US producers' price for soybeans. The outcome of the model is that all regions gain from the adoption of HT soybean; although some economic agents within them may lose (e.g. US farmers lose from the introduction of HT soybean where there is no US domestic price support to farmers, except in the scenario where segregation costs are equal to zero).

Further down the agricultural production chain, Moschini et al. (2005) modelled the effects of introduction in the EU of GM foods for direct human consumption that would be compared by consumers with conventional or organic food. They consider the relatively recent EU regulatory developments on labelling and traceability of GMOs (a new framework that became operative in 2004). The authors build a partial equilibrium model of the EU agricultural food sector to look for the qualitative and quantitative economic impacts of possible large-scale adoption of GM foods in the EU. The model assumes that consumers consider GM foods as weakly inferior substitutes for conventional ones, and that segregation costs are borne by conventional and organic producers and labelling and traceability costs imposed on GM products. The main outcome is that total EU welfare might decrease as result of GM food introduction mostly due to segregation costs and labelling costs. Surplus losses are borne by both suppliers and consumers. Organic producers are likely to benefit from the introduction of GM crops as they receive higher prices in most scenarios. However, this benefit can be outweighed by segregation costs if the tolerance of the unintended presence of GM content in organic food is too low.

5.2 The concept of coexistence and its impact on the economic balance and adoption of GM crops

In the case of the EU, analyses of the possible economic impacts of introducing GM crops on agriculture should consider in addition to the recent regulatory developments on labelling and traceability, the novel concept of *coexistence* between GM and non-GM agriculture developed by the EU. The issue of coexistence relates to segregation measures taken at farm or regional level to ensure that farmers can provide EU consumers with a choice of GM or non-GM harvests that comply with EU labelling standards (allowing for a maximum of 0.9% adventitious presence of GM crops in non-GM harvests).

In 2003, the European Commission published a recommendation on guidelines for the development of national strategies and best practices to ensure coexistence (2003/556/EC)[15].

15 Commission Recommendation of 23 July 2003 on guidelines for the development of national strategies and best practices to ensure the coexistence of genetically modified crops with conventional and organic farming (notified under document number C(2003) 2624)

The guidelines recommend that those farmers bringing in the innovation into a region should be the ones taking measures and changing practices if needed to ensure coexistence. Following this, the majority of EU Member States have begun drafting coexistence rules and have targeted GM farmers as the ones taking the measures (if necessary) and incurring the costs. A similar framework does not exist for the moment in other areas of the world where GM crops are cultivated.

Since coexistence costs are a relatively recent concept, few studies have included them when looking at the on-farm economic balance of GM crops in Europe, and no study is yet available on how coexistence costs will influence future rates of adoption of GM crops by EU farmers. When coexistence costs have been analysed, the analysis is based on hypothetical measures since most EU Member States have yet to define their options in technical terms. Moreover, coexistence costs are not limited to those of additional farming practices: some EU Member States have introduced a fixed levy on each hectare of cultivated GM crop to create compensation funds.

A recent report by Messéan et al. (2006) quantifies coexistence costs for a number of GM crops in Europe. The authors first identify crop by crop whether coexistence measures are needed to achieve levels of adventitious GM presence in conventional harvests below legal thresholds (0.9%), and then discuss the economic consequences of such measures. Some crops such as sugar beet or cotton do not need adapted farming practices to ensure coexistence. The results for the only GM crop grown so far in the EU (maize) suggest that coexistence measures are needed and a number of technical possibilities are offered. The main measures considered are the cleaning of harvesting machinery, the introduction of isolation distances between GM and non-GM fields and the planting of buffer strips of non-GM maize plants around GM maize plots. The efficacy of these measures in ensuring coexistence between GM and non-GM maize production in real agricultural regional landscapes in the EU is described in the report.

The authors attempt to estimate the economic consequences of such measures for farmers wanting to grow GM maize. The economic consequences of mandatory isolation distances (and of mandatory buffer strips) will be the opportunity costs of not being able to grow GM maize in part of the farm. This cost is the difference in farmers' gross margin between GM maize and the alternative crop planted, which most likely will be conventional non-GM maize. Gómez-Barbero et al. (manuscript in preparation) have empirically estimated this difference for Spain (for the period 2002-2004) at an average of €84 per hectare at national level. In addition to this opportunity cost, mandatory isolation distances or buffer strips directly affect costs due to the need to source inputs (seeds) and organise plantings for two crops instead of one.

Non-technical coexistence measures are also being imposed by EU Member States on GM crop growers. One is a fixed levy per hectare charged to GM crop farmers to cover possible economic losses of non-GM farmers. Another measure is a requirement to notify neighbouring farmers and the competent authorities of the intention to plant GM crops in advance (typically 1-2 months). Some Member States are considering the possibility of introducing a publicly accessible register containing these notifications. These measures are likely to weigh against GM varieties when farmers are considering whether to cultivate them. In sum, although more details of specific coexistence measures are awaited, there is a new cost to be computed in the balance for GM crops in the EU and a new factor affecting the process of adoption.

6. Summary and conclusions

A decade after the first GM crop was commercially planted the GM crop landscape is dominated by four major crops (soybean, cotton, maize and canola) and two agronomic traits (herbicide tolerance and Bt insect resistance). The American continent (US, Argentina, Brazil, Paraguay and Canada) still accounts for the majority of the GM crop area in the world (over 90 %) with China and India following. Overall, more than 20 countries in all continents grow GM crops, of which 14 are considered developing countries.

Published research analysing *ex post* the impacts of GM crops adoption at farm level is now abundant and includes studies of HT soybeans in the US, Argentina and Romania; of Bt cotton in China, India, South Africa, Argentina, Mexico, US and Australia; of Bt maize in the US, South Africa and Spain; and of HT canola in Canada. Most studies are based on surveys of commercial farmers (adopters and non-adopters of the technology). The picture emerging is that adoption of GM crops has taken place at a rapid rate and driven by a number of reasons including on-farm and off-farm benefits. On-farm benefits are derived from reducing production costs (weed control costs for HT crops and pest control costs for Bt crops). For some crops there are also yield increases (particularly in the case of Bt cotton), affected in some regions by the fact that GM traits have not yet been introduced in all local varieties.

Net benefits for farmers due to GM crop adoption may also derive from off-farm income. For example, adoption of HT soybean in the US had no significant effect on on-farm income, but resulted in crop management simplification, increased free time, and larger off-farm incomes for adopting farmers resulting in net benefits for adopters. Finally, some crops are adopted by farmers as an "insurance" against seasonal variability in yields, even in the absence of significant increases in gross margin.

The net economic benefits for farmers are nevertheless variable in regional terms. One reason is that the crops are designed to solve pest and weed problems which vary greatly in their geographical distribution and impact on production. In fact, adoption rates of a given GM crop in different regions of the same country can be very variable. Second, all GM crops cultivated to date have originated in North America and the process of introducing the GM trait into varieties suitable for all regions has not been finalised (the "germplasm" effect).

Ex post analyses also show that adoption of dominant GM crops and on-farm economic gains have benefited both small and large farmers. Small farmers have shown no difficulty in adopting the technology and adoption rates are not related to farm size. Moreover, detailed analyses (for example of Bt cotton in China) show that increases in gross margin are comparatively larger for smaller and lower income farmers than for larger and higher income farmers.

Ex post analyses provide data on the effects of GM crop adoption on the use of agricultural inputs. Bt cotton adoption has resulted in a significant decrease in the use of insecticides in all cases studied (25% of all insecticide used in agriculture world wide is for cotton cultivation). Bt maize adoption has induced only a little decrease in insecticide use since the pests Bt maize is designed to resist were not usually controlled by insecticide applications. The adoption of HT soybean has resulted in the displacement of several herbicides by one single product that is considered to be less toxic than the herbicides it replaces. Use of this herbicide has increased. HT soybean adoption has been associated with reduced fuel consumption per hectare and with the adoption of reduced soil tillage practices.

The adoption of HT soybean has been linked to increased use of land (normally from pasture crops) for soybean production in Argentina.

The aggregate economic effects of GM crop adoption (welfare creation and distribution) have also been studied *ex post*, although the number of studies published and their coverage is less comprehensive than analyses of on-farm effects. Aggregate studies show positive changes in economic welfare for countries adopting GM crops. The absolute value of these gains varies widely depending on the assumptions made for the aggregate models. In most cases farmers (adopters of the GM crop) are the main beneficiaries, followed by seed suppliers (the biotech industry) and consumers (due to lower market prices). The welfare distribution ratio between adopting farmers and seed suppliers is strongly affected by the price premium paid by farmers for GM seeds. Variations in price premium depend on the intellectual property regime affecting GM seeds in each particular country, on the market availability of GM varieties developed by the public sector and on company pricing policies.

Due to the scant adoption of GM crops in EU agriculture, *ex post* impacts have only been analysed for the case of Bt maize cultivation in Spain. Adoption has resulted on average in larger gross margins for adopting farmers (12% increase over the average gross margin per hectare of maize production) yet with large regional variations. The welfare created by Bt maize adoption in Spain is shared by adopting farmers and seed industry (roughly 75%/25%). In recent years, a number of *ex ante* analyses of the possible economic impacts of GM crops if introduced into EU agriculture have been published. *Ex ante* evaluations have a strong modelling component and a number of parameters, such as yield effects and cost reductions at farm level, have to be estimated from experiences in field trials and/or other countries. Several GM crops have been covered (HT rapeseed, HT sugar beet, Bt maize, Bt cotton) in various Member States. The studies range from on-farm impacts to more aggregate levels. Positive on-farm economic benefits are predicted by these studies, derived from a reduction of production costs for farmers.

Most of the research published on the economic impacts of GM crop introduction has considered a global market with no significant segmentation and has not looked at costs incurred to preserve identity of GM and non-GM harvests and supply chains. The domestic markets of GM crop producing countries are not segmented (no distinction is made between commodities of GM and non-GM origin) and the export markets for identity-preserved non-GM varieties of these crops remain niche markets at global level. Price differences at the farm gate for the non-GM counterparts of dominant GM crops have not been common.

Several developments suggest that these assumptions may have to be changed. One is the potential introduction in the main GM-producing countries of GM crops for direct human food use, such as wheat or rice. Even in a country with no GM labelling regulations, such as the US, it has been suggested that the introduction of a crop like wheat might be accompanied by identity preservation and segregation systems, and thus creating differentiated market segments and price differentials. Also, regulatory developments worldwide are taking place in this field at national and multi-national level. Many world regions are adopting specific legislation on labelling and traceability for all GMOs, produced domestically or imported.

Some studies have recently tried to model GM crop introduction including segmentation of markets and identity preservation costs. The results show that these costs can be substantial and depend mainly on the tolerance threshold considered for segregation. In some scenarios, these costs outweigh the economic benefits derived from the introduction of GM crop, resulting in a net welfare loss at global level. It is very difficult to model how these costs will be shared by different actors (price scenarios and regulatory frameworks may influence this aspect).

Finally, in the case of the EU, analyses of the economic impacts of introducing GM crops in agriculture should now consider the novel concept of *coexistence* between GM and non-GM agriculture developed by the EU, i.e. the segregation measures that should be taken at farm or regional level to ensure that farmers can provide EU consumers with a choice of GM or non-GM harvests that comply with EU labelling standards. EU Member States have begun drafting coexistence rules and have targeted GM farmers as the ones taking the measures (if necessary) and incurring the costs. Measures being established include technical measures (respecting isolation distances from non-GM crop fields), organisational measures (communication in advance of the decision to plant GM crops) and in some UE Member states a fixed levy per hectare of GM crop cultivated. A similar framework does not exist currently in other areas of the world where GM crops are cultivated. The impact of these recent developments in the GM crop adoption process and economic balance of GM crops on-farm needs further study.

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