Modelling ex-ante the economic and environmental impacts of Genetically Modified Herbicide Tolerant maize cultivation in Europe

Pascal Tillie *,1, Koen Dillen 1, Emilio Rodríguez-Cerezo

European Commission, Institute for Prospective Technological Studies (IPTS), Joint Research Center (JRC), Edificio Expo, c/Inca Garcilaso 3, E-41092 Sevilla, Spain

Abstract

Genetically Modified Herbicide Tolerant (GMHT) maize tolerant to the broad-spectrum herbicide glyphosate is a possible addition to the weed control toolbox of European farmers. We modelled ex-ante the economic and environmental changes associated with the adoption of GMHT maize in Europe. A dataset from a survey of maize farmers conducted in seven European countries was used to construct a baseline of current herbicide use and costs in maize cultivation. A stochastic partial budgeting model was used to simulate the impacts of adoption of GMHT maize on farmers’ gross margin. We built a first scenario representing the initial years of introduction of the technology (low, fixed technology fee and an herbicide program for GMHT maize based exclusively on glyphosate). Assuming that all farmers who benefit from the technology will adopt GMHT maize, the model predicts very high adoption rates for all seven countries (60–98% of maize farmers depending on the country). We also calculated the Environmental Impact Quotient Index (EIQ) associated with herbicide use when switching to GMHT maize. In ES, PT and CZ, countries with a high baseline of herbicide use in maize, the majority of adopting farmers (60–79%) will also experience reductions in EIQ, realising the economic and environmental potential of the technology. In contrast, for countries such as FR, DE and HU, only a fraction (19–28%) of adopting farmers experiences a decreased EIQ. In this situation, a purely economic-driven adoption may result in increased EIQ for many adopting farmers. We also explored the effects of additional scenarios introducing more complex herbicide programmes for delaying weed resistance and changes in the technology fee of GMHT seeds. In these scenarios adoption levels decrease but the technology is still economically attractive for a large share of farmers (14–86%), showing that a sustainable use of the technology to lower the risk of weed resistance development is not in contradiction with its economic attractiveness. These scenarios do not change significantly the proportion of adopting farmers for which the EIQ decreases. The pattern of two groups of countries in terms of potential environmental effects remains and calls for a better identification of the subset of farmers with economic and environmental potential for the technology. Finally, our results confirm that farmers are the main economic beneficiary of GMHT maize introduction while the technology provider is not able to capture all the benefits generated by the technology due to heterogeneity within the farmer population.

1. Introduction

Maize (Zea mays) was first domesticated in South-West Mexico about 6000 years ago. With more than 880 million tonnes produced in 2011, it is now the crop with the largest production and constitutes the third most important staple crop for human after rice and wheat. Within the European Union, it ranks second in terms of volume of production after wheat – but third in harvested area only to wheat and barley (FAOSTAT, 2013). However, while demand for maize is on the rise, driven both by increasing preference of consumers for meat products that require maize feedstuffs and by the growing biofuel production, maize producers in the EU are facing an increasingly complex challenge regarding the weed control in maize plots.

Weed control is crucial for the profitability of maize cultivation. Young maize plants have a shallow root structure that makes them particularly vulnerable to weed competition until they reach the...
eight-leaf growth stage, about two months after emergence (De- 
war, 2009; Johnson et al., 2000). Therefore achieving an optimal 
weedicidal control in the first stage of the maize growth is an important 
objective for farmers. Within the EU, this is becoming a challenging 
task, for diverse reasons: (i) Weed control in maize relies mainly on 
chemical control. However, the number of active ingredients (AI) 
that are authorized is declining through an environmental review 
program under Directive 91/414/EC and Regulation (EC) 1107/ 
2009; (ii) National policies aiming to rely on alternative – non 
chemical – weed control strategies or to reduce the use of herbi-
cides in agriculture are being set up in the EU, under the impulsion 
of the Directive on sustainable use of pesticides (Dir 2009/128/EC) 
or the current “greening” of the Common Agricultural Policy (CAP); 
(iii) Weed control options for maize growers are also hampered by 
the increasing number of weeds that have developed a resistance 
to one AI (Heap, 2013), while on the other hand no major AI with 
novel site-of-action has been developed during the last decades 
(Beckie and Tardif, 2012; Weersink et al., 2005).

For the EU maize growing sector, the challenge is thus to devel-
up new weed control strategies that have less negative effects to 
the environment but at the same time lead to no or minimum reduction in yield and farm profitability. The difficulty lies in find-
ing the complex equilibrium between the three dimensions – so-
cial, environmental and economic – of sustainable development 
(Sadok et al., 2009).

An element of maize weed control extensively used in other 
parts of the world but not yet in the EU is the use of genetically 
modified herbicide-tolerant (GMHT) maize varieties.

This technology consists in the genetic modification of a plant in 
order to make it tolerant to a given herbicide. If this herbicide is a 
broad-spectrum one (e.g. glyphosate or glufosinate) its use will re-
result in a more efficient control of all weed species in addition to an 
extended application window. Thereby, the use of the GMHT tech-
nology facilitates weed control and reduces the production risk in 
GMHT crop fields (Konduru et al., 2008; Qaim, 2009). Other agro-
nomic impacts are closely associated with the adoption GMHT 
crops. In North and South America, a clear synergy between the 
planting of glyphosate-tolerant crops and the adoption of reduced 
or non-tillage practices is observed: the application of glyphosate 
before planting and at the first stages of the plant growth solves 
the issues of weed control that arise when tillage is reduced or 
eliminated (Beckie et al., 2006; Konduru et al., 2008; Trigo and 
Cap, 2006). Adoption of conservation tillage in turn leads to re-
duced herbicide, labour and fuel costs. In some regions, notably 
South America, adoption of glyphosate-tolerant soybean has also 
facilitated the increased use of double cropping of soybean follow-
ing wheat in the same crop season, since the GMHT technology al-
lows for early planting and fastens the seeding preparation (Finger 
et al., 2009). Such changes in agricultural practices – timing, mode 
and frequency of herbicide application, combination of AI, tillage 
system and crop rotation – may lead to positive or negative im-
acts to the agro-ecosystem (Graef et al., 2007).

So far no GMHT varieties have been authorized for cultivation in 
the EU, although favorable opinions have already been issued by 
the European Food Safety Authority (EFSA) for three glyphosate-
tolerant maize varieties, opening the door for authorization (EFSA, 
2009). Several GMHT crops, namely soybean, maize, rapeseed, cot-
ton, alfalfa and sugar beet, have been largely adopted by farmers in 
other parts of the world. Overall, this high adoption is mainly driven 
by the non-pecuniary benefits described above, such as the 
facilitated weed control and the increased management flexibility 
(Qaim, 2009).

However, in the past years, farmers using GMHT crops (partic-
ularly glyphosate-tolerant soybean in North America) have faced 
increasing problems with weed populations resistant to the ap-
plied broad-spectrum herbicide. Weed resistance occurs when a 
biotype resistant to an AI, already present in a weed population 
but in a very small proportion, is selected under the pressure of 
recurrent applications of this AI (Beckie and Tardif, 2012). When 
the resistant biotype reaches a high frequency in the weed popula-
tion, the efficiency of this weed control strategy decreases. Among 
factors that increase the risk of weed resistance development are: 
excessive reliance on a single mode of action herbicide in the 
whole crop rotation, non-diversified crop rotation, exclusive use 
of chemical solutions for weed control, high weed infestation, im-
proper application rate or timing (Dewar, 2009; Vencill et al., 
2012). Conversely, the best long term strategies to mitigate the 
evolution and the spread of herbicide resistance rely on a greater 
diversity in weed control practices, such as the combination of 
non-chemical weed management with non-selective herbicide, 
and the adoption of more diversified cropping systems (Beckie, 
2006). The combined use of herbicides whose mode of action is 
the most diverse also allows for a significant reduction of the risk 
of resistant weeds (Neve et al., 2011). The availability on the mar-
ket of crop cultivars with multiple herbicide-tolerant traits might 
provide farmers with an additional option for weed management 
(Beckie and Tardif, 2012).

The appearance of resistance in weed populations negatively af-
flicts the benefits from the GMHT technology, because farmers 
either face a partial yield loss due to the decreased efficiency of 
the broad spectrum herbicide or they bear the costs of additional 
weed control practices. As pre-emptive action to prevent the out-
break of resistance also entails a cost, farmers are faced with a 
complex dynamic problem involving a temporal trade-off when 
deciding about their optimal weed control strategy (Pannell and 
Zilberman, 2000; Weersink et al., 2005). The threat of weed resis-
tance development will affect the adoption of GMHT maize as well as the potential economic and environmental impacts of this technology. 

So far knowledge about the economic potential of glyphosate-
tolerant maize for European farmers is limited (Areal et al., 2012, 
2011; Demont et al., 2008a; Wesseler et al., 2007). None of the 
available studies incorporates the possible development of resis-
tant weeds or the need for more complex weed control strategies 
over time. This paper attempts to add to this knowledge by provid-
ing an ex-ante assessment of the socio-economic and environmen-
tal impacts of glyphosate-tolerant maize as an alternative to the 
chemical weed control strategy in Europe. Different scenarios are 
developed to better understand how strategies to delay weed resis-
tance impact the economic and environmental potential of gly-
phosate-tolerant maize for Europe. The economic framework 
which incorporates farmer heterogeneity and the strategic pricing 
decision by the technology provider is fed with data from a farm 
level survey conducted in 7 EU countries.

2. Methodology

2.1. Model specifications

The paper relies on a simulation approach initially developed by 
(Demont et al., 2008a; Dillen et al., 2009) and applied in a variety of 
studies assessing ex-ante the economic impact of novel technolo-
gies in agriculture (Demont and Dillen, 2008; Demont et al., 
2009; Dillen et al., 2008, 2010a,b). Starting from a traditional par-
tial budgeting model, this stochastic simulation approach reduces 
two types of bias typically present in the former; homogeneity bias 
and pricing bias. For more details on the model the reader is re-
ferrred to the aforementioned papers; however, the present con-
tribution goes beyond the previous studies by relying on original 
survey data, by using an endogenous calculation rather than expert 
options to determine the GMHT technology fee, by taking into 
account the possibility that farmers could use diversified herbicide
programs associated to GMHT maize in order to address the development of weed resistance, and finally by linking the adoption of GMHT maize with an indicator for environmental impact. In the remainder of this subsection we guide the reader through the general reasoning behind the model in order to understand the results presented in Section 4.

The concept of farmer heterogeneity has a central place in the modelling framework. It is assumed that no such thing as an average farmer exists. Farmers differ in social, physical, natural and human capital endowment. The unique combination of these factors results in a unique farmer profile and in turn a unique valuation for a certain agricultural technology. The range of individual valuations for a GMHT technology has been identified as depending on different factors: herbicide management practices, labour resources, soil conditions, climate and market access but also on personal factors such as risk aversion, beliefs and education level. Depending on its individual technology valuation, \( v \), any farmer will decide whether or not to adopt the technology at a given price, \( \theta \). Under the assumption of rational agents, a farmer will adopt a technology when \( v > \theta \), while the same farmer will not adopt the technology if \( v < \theta \). With \( f(v) \) the probability density function (PDF) of \( v \) in the population of potential adopters, i.e. farmers, the adoption rate, \( \rho \), can be estimated as,

\[
\rho = \int_0^\infty f(v) \, dv
\]  

If we normalize \( f(v) \) to the adopting part of the population, \( f_\theta(v) \) the average profit for adopters can be represented as followed,

\[
\pi = \int_0^{\theta} (v - \theta) f_\theta(v) \, dv
\]  

This construction of \( \pi \) eliminates the homogeneity bias as it takes in consideration the effects of the novel technology for all farmers instead of a representative average farmer (Demont et al., 2008a). Eq. (2) demonstrates that the characteristics of both \( f(v) \) and \( \theta \) determine the final value of \( \pi \). Alterations in these parameters will therefore result in different economic effects of the novel technology. Although \( f(v) \) might be altered indirectly through external changes such as information provision, familiarity with the technology and market developments, \( \theta \) is the only choice variable in the model. In addition, assuming a drastic innovation or a (temporary) monopoly, the technology provider will set a price for its technology which maximizes his gross margin. For GM crops the price for the technology is commonly defined as the premium an adopter has to pay compared to the price of the isogenic conventional counterpart, the so-called technology fee. Hence the function to be maximized by the technology provider can be represented as:

\[
\pi_{\text{in}}(\theta) = (\theta - c) \lambda_{\text{adopt}} + (\theta - c)(1 - F(\theta)) \lambda_{\text{out}}
\]  

where \( c \) represents the long term marginal costs, \( \lambda \) the area of land cultivated and \( F(\theta) \) the cumulative probability distribution of \( f(\theta) \). The use of this endogenous calculated technology fee, \( \theta \), instead of an average break-even price or expert opinions eliminates the pricing bias. The technology provider can optimize \( \theta \) either in a global market or segment the market in different subgroups of consumers. In the latter, the technology provider can apply a price discrimination between the segments based on the specific valuation of the technology \( v \) by farmers in each of them. This choice gives the pricing of the technology a clear strategic dimension for the technology provider with important consequences for value creation and distribution (Dillen et al., 2009). Shi et al. (2012) reach a similar conclusion based on a different framework. The authors theoretically demonstrate how technology providers decide a price for GM crops depending on the typology of the farmer population and empirically show the importance of the different marketing strategies in the US maize market. Other empirical evidences of third degree price discrimination have been found in Mexico, South Africa or Spain (Gómez-Barbero et al., 2008; Gouse et al., 2004; Traxler et al., 2003).

The crucial issue associated with this methodological framework is to gather appropriate data in order to construct \( f(v) \). The methodology for the data collection depends on the characteristics of the technology under research. Possible options include stated preferences, partial budgeting, conjoint analysis, etc. In this study we opt for a partial budgeting approach. A shortcoming of this approach is that it only considers the pecuniary aspects of the technology, not the non-pecuniary benefits such as flexibility and easiness of management which have been shown to be important determinants of the adoption of GMHT crops to a high extent (Marra and Piggott, 2006; Qaim, 2009). The advantage is that a partial budgeting approach is less data intensive. Hence the assumption of pure profit maximizing farmers allows for a bigger geographical coverage than would have been possible with the other methodologies.

Under these assumptions, the individual technology valuation can be presented by the difference in profit for the counterfactual conventional herbicide program and the potential GMHT replacement program,

\[
v = [(p_c y_c) - h_c - k_c] - [(p_c y_g) - h_g - k_g]
\]  

where \( p \) is the selling price for the maize crop, \( y \) the yield of the maize crop, \( h \) the price of the herbicide program and \( k \) the other input costs. \( c \) and \( g \) subscripts respectively indicate conventional and GMHT production. For a complete description of the behaviour of \( v \), the reader is referred to Dillen et al. (2009).

Eq. (4) details the data needs of the model to assess the value of GMHT crops. In the case of GMHT maize in the EU the equation can be reduced. Areal et al. (2013) and Nolan and Santos (2012) conclude, based on a meta-analysis of the literature and on an extensive yield database, that the yield effect of GMHT crops is not significant in developed countries. This can be explained by the fact that weeds were managed equally well with conventional herbicides. Secondly, European maize is primarily used on-farm for feed or sold to the compound feed industry. The available data suggest that no price premium exists in the EU for non-GM identity preserved maize for feed use (Gomez-Barbero et al., 2008). It has to be noted that this situation could change once more farmers adopt the GM technology, reducing the supply of non-GM maize. Finally, we assume a ceteris paribus for the costs that are not directly related to the change in herbicide program (i.e. \( k = k_g \)). These assumptions reduce the analysis to a study of the change in input costs between a conventional maize herbicide programs and the replacing glyphosate based programs. The consequences of this approach will be discussed in Section 5.

2.2 Methodology for the environmental assessment of changes in herbicide use

Besides the economic assessment of GMHT maize cultivation, the second objective of this paper is to investigate the potential environmental impacts of switching from conventional maize cultivation to GMHT maize, focusing only on the changes in herbicide use. Some authors estimate the impact of changes in herbicides use by just relying on the quantity of AI used per area (Benbrook, 2012). However, as the environmental and health impact of herbicides vary from one to another, a linear relation between the amount of AI and its toxicity to target and non-target organisms is a weak assumption (Kleter and Kuiper, 2004). To overcome this limitation, indicators have been developed that take into account the inherent properties of each AI, including its toxicity towards living organisms and some determinants of the probability of
exposure of organisms to it (e.g. plant and soil half-life, leaching potential, etc.). The most widely used indicator is the Environmental Impact Quotient (EIQ) developed by researchers at Cornell University (Kovach et al., 1992). The main advantage of EIQ is that it considers the interactions between toxicity and rate of exposure and that it is a rather easy-to-implement framework (Nillesen et al., 2006). However, it does not take into consideration any element related to the conditions of pesticide application (soil type, crop, waterfall, etc.) or the ratio between concentration and toxicity, unlike exposure-toxicity ratio (ETR) indicators. The latter, though, require a much more detailed set of data about the actual context of the pesticide application and therefore are more adapted to ex-post evaluations (Feola et al., 2011; Reus et al., 2002).

The EIQ calculation consists of two stages. The first is the calculation of the EIQ associated to a particular AI, following a given formula that incorporates three dimensions: impacts on farm workers, on consumers and on the ecology (fish, birds, honeybees and other beneficial arthropods). The average of the separate components returns one single figure which constitutes the specific EIQ value for a given AI, the highest its value meaning the most harmful its impact. For instance, the EIQ value for glyphosate is 15.33 and the scores for its impact on farm workers, consumers and the ecology are 8, 3 and 35, respectively (see Table 1). The low impact on consumers reflects the fact that this AI has a rather short soil half-life, low leaching potential and little adverse chronic health effects, while its reduced impact on farm workers is due to its low dermal toxicity. The comparison of the EIQ of glyphosate with other AI commonly used for maize weed control in Europe is displayed in Table 1, showing that overall it has one of the lowest EIQ.

The second stage of the calculation involves multiplying the quantity of each active ingredient applied on a given field by unit of area with its corresponding EIQ value, and, in case of various AI applied on the same field, summing these figures. The result is an abstract value that represents the “field-use rating” EIQ/ha of the AI applied and allows for comparisons between different herbicide regimes. More details about the EIQ calculation, including formulas and EIQ values for the main AI used in agriculture, can be found online at the Cornell University dedicated website (Kovach et al., 2013).

2.3. Data

The data for this study originates from a 2009 telephone-based farmer survey in 7 EU countries that together cover 77% of the EU-27 grain maize area and 70% of the silage maize area (Eurostat, 2012). A random sampling was used stratified by the size of the different maize growing regions. The general characteristics of the sample are presented in Table 2. The questionnaire included questions about the farm structure, farm management practices – including the maize cultivation practices, costs and benefits – and the usual socio-demographic variables regarding the farmer.

A crosscheck was performed with the Farm Structure Survey (FSS) data from Eurostat (2013). As shown in Table 2, this comparison reveals an overrepresentation of the data on big (commercial) farms. Conceptually this bias in the data does not cause significant problems as the economic framework described in Section 2.1 assumes profit maximizing farmers. The Eurostat database on the other hand includes all types of farming operations, including small holdings used as a secondary source of income for the farmer. The bias towards big commercial farms should however be kept in mind when discussing the results in Section 5.

3. Scenarios for adoption of GMHT maize with different herbicide programs and technology fees

Based on literature and expert opinion, we designed four possible herbicide replacement programs for farmers adopting GMHT maize. Program’s characteristics are summarised in Table 3. Program A assumes farmers will replace their conventional herbicide programme by relying solely on glyphosate. The cost of this program is low due to the very low price of glyphosate since the patent expired (Duke, 2012). Furthermore, research has shown that such a strategy provides good weed control, in some situations superior to the conventional programs (Parker et al., 2006). We can then consider this to be the first choice of farmers when thinking about adopting GMHT maize. However, overreliance on a single AI could lead to the development of resistance in weed populations (Beckie, 2006). Hence programs using herbicides with different modes of action have been proposed in the literature in order to delay or avoid the possible development of herbicide resistance (Beckie and Tardif, 2012; Dewar, 2009). Three programs (B, C and D) of this type are described in Table 3. Farmers could adopt them proactively as part of good agricultural practices or adopt them once herbicide-resistant weeds appear. Experience from the US shows that farmers usually adopt these combination programmes only when they have experienced weed resistance problems (Wilson et al., 2008). We therefore assume that farmers will switch to herbicide programs B, C & D described in Table 3 in the longer term, after GMHT maize adoption in combination with program A is well established. This change in herbicide program affects the economic and environmental potential of GMHT maize over time and should be assessed explicitly.

By combining the alternatives on herbicide programmes with alternatives on the pricing of the technology we constructed the following three scenarios to be used in the model simulation:

1. Scenario 1: represents the initial years of introduction of GMHT maize varieties in which; (i) farmers rely exclusively on the glyphosate based herbicide program A (see Table 3); (ii) the technology provider prices the technology uniformly over the different countries at a rather low price level. Demont et al. (2008a) assume a technology fee of €15/ha for Hungary and Czech Republic which we extrapolate to the other countries under research. This scenario represents the technology provider’s strategy to quickly penetrate the market and promote the adoption of the technology by leaving technology rents with the farmer. The technology fee can be changed at a later stage depending on the market power of the technology provider and the competition with other technologies. This is in line with

| Table 1 Components of EIQ of main active ingredients used for weed control in maize in Europe. Source: New York State Integrated Pest Management Program (Kovach et al., 2013). |
|---------------------------------|-----------------|-----------------|-----------------|
| Farm workers (A) | Consumer and leaching (B) | Ecology (C) | EIQ (A + B + C)/3 |
| Acetochlor | 10.65 | 5.33 | 43.59 | 19.86 |
| Dicamba | 12 | 8 | 59 | 26.33 |
| Glyphosate | 8 | 3 | 35 | 15.33 |
| Mesotrione | 16 | 7 | 33 | 18.67 |
| Nicosulfuron | 15 | 6.25 | 13.7 | 11.65 |
| S-metachlor | 12 | 9 | 45 | 22 |
| TBA | 8 | 7 | 111 | 42 |
earlier literature stating that pricing of GM technologies is a strategic dynamic issue (Fulton and Giannakas, 2001; Shi et al., 2012).

2. Scenario 2: represents a mid-term scenario in which we assume that the technology provider is maintaining the same uniform technology fee. However, in this scenario farmers switch from herbicide program A to a diversified chemical weed management strategy (programs B, C & D) as part of good agricultural practices or because weed resistance has been observed. Farmers are assigned one of the three programs B, C or D randomly but it is assumed that farmers with a higher herbicide spending pattern for conventional maize, within a given country, have the most acute weed problems and are therefore more likely to turn towards programs B–C–D. This is introduced in the model through a correlation of 0.8 between the herbicide expenditure before and after adoption of GMHT maize.

3. Scenario 3 represents a longer term scenario in which farmers continue to use the same diversified herbicide programs of scenario 2 but the technology provider will attempt to extract more of the created value through the practice of third-degree price discrimination, i.e. he will set a different price in each country depending of the willingness-to-pay of local farmers. It is assumed that the technology provider can do this by analysing the observed adoption patterns in the earlier stages of commercialization. Depending on the difference between the uniform initial price scheme and the third-degree price discrimination, the effect on GMHT maize cultivation will vary.

The set of equations presented in Section 2.1 are solved through a Monte Carlo simulation, 10,000 iterations for each scenario. This approach requires a probability distribution function for the heterogeneous input variables. For \( h_t \), a lognormal distribution is used, calibrated on the mean and standard deviation depicted in Table 4. The choice for the lognormal distribution is based on the need for transparency and theoretical constraints. Indeed, the lognormal distribution is well known and assures that herbicide costs are never negative while in the tail of the distribution allowing for extreme cases of weed pressure. For the GMHT herbicide program costs the uniform distribution was preferred as little information was available and heterogeneity mainly stems from the variety of programs and not from the variation within a certain program (the ranges of cost used to fit the uniform distributions are displayed in Table 3).

### Table 2
Characteristics of maize farmers surveyed in seven EU countries. Source: Own survey performed in 2009.

| Country | Number of interviews | Utilised agricultural area (per farm in survey) ha | Utilised agricultural area (per farm in country) ha | Area cultivated with maize per farm in 2009 ha | Grain maize yield tonnes/ha | Std dev |
|---------|----------------------|---------------------------------|-----------------------|-----------------------------|--------------------------|--------|
| CZ      | 55                   | 1687                           | 236                   | 9.9                         | 4.3                      |
| DE      | 100                  | 155                            | 122                   | 10.4                        | 2.1                      |
| ES      | 249                  | 91                             | 83                    | 10.6                        | 2.7                      |
| FR      | 101                  | 140                            | 83                    | 9.6                         | 2.8                      |
| HU      | 104                  | 373                            | 813                   | 11.7                        | 4.2                      |
| PT      | 54                   | 373                            | 67                    | 11.7                        | 4.6                      |
| RO      | 102                  | 428                            | 661                   | 11.7                        | 4.3                      |

* Note: data source is Eurostat (2012).

### Table 3
Potential herbicide programs for GMHT maize in Europe. Source: Own elaboration based on Dewar (2009) and expert opinions.

| Program name | Description | Active ingredient | Rate of application (g of AI/ha) | EIQ of AI | Field-use rating per AI | Total EIQ field-use rating of program | Estimated cost of the herbicide program (€/ha) |
|--------------|-------------|------------------|---------------------------------|-----------|------------------------|----------------------------------------|-----------------------------------------------|
| Program A    | All glyphosate | Two glyphosate applications | Glyphosate | 2160                   | 15.33                   | 33.11                                  | 33.11                                   | 18–22                          |
| Program B    | Pre + Gly   | Pre-emergence residual (low rate) and glyphosate | S-metachlor | 375                    | 42                      | 15.75                                  | 46.06                                   | 48–52                          |
|              |             |                  | Glyphosate | 625                    | 22                      | 13.75                                  |                                         |                                |
|              |             |                  | Glyphosate | 1080                   | 15.33                   | 16.56                                  |                                         |                                |
| Program C    | EarlyPost + Gly | Tank mix of post-emergence residual and glyphosate | Mesotrione | 100                    | 18.67                   | 1.87                                   | 34.98                                   | 53–57                          |
|              |             |                  | Glyphosate | 2160                   | 15.33                   | 33.11                                  |                                         |                                |
| Program D    | Gly + Post  | Glyphosate + tank mix of glyphosate and dicamba   | Glyphosate | 240                    | 26.33                   | 6.32                                   | 39.43                                   | 43–47                          |

Abbreviations used in this table: Pre (pre-emergence), Post (post-emergence), Gly (glyphosate), AI (active ingredient).

### Table 4
Baseline of herbicide use and costs and field rate EIQ for maize farmers surveyed in seven EU countries. Source: Calculations from own survey performed in 2009.

| Country | Rate of herbicide application (g of active ingredient/ha) | Cost of herbicide treatment (€/ha) | Field-use rating EIQ/ha |
|---------|----------------------------------------------------------|-----------------------------------|------------------------|
|         | Pre-emergence                                           | Post-emergence                    | Average                |
| CZ      | 2531                                                     | 614                               | 45                     |
| DE      | 1166                                                     | 795                               | 44                     |
| ES      | 3273                                                     | 1074                              | 57                     |
| FR      | 1331                                                     | 396                               | 54                     |
| HU      | 1462                                                     | 511                               | 51                     |
| PT      | 1505                                                     | 470                               | 51                     |
| RO      | 1534                                                     | 792                               | 71                     |
|         | Std dev                                                  |                                   | Std dev                |
| CZ      | 150                                                      |                                    | 24                     |
| DE      | 75                                                       |                                    | 49                     |
| ES      | 57                                                       |                                    | 34                     |
| FR      | 57                                                       |                                    | 34                     |
| HU      | 51                                                       |                                    | 31                     |
| PT      | 71                                                       |                                    | 31                     |
| RO      | 21                                                       |                                    | 31                     |
4. Results of the simulations

4.1. The baseline

To construct the baseline that is needed to assess the different scenarios of weed control with GMHT maize, farmers were asked in the survey to provide details on their herbicide-based weed management practices including number of applications, products and rates of application chosen and price of the different treatments. The main results of this exercise can be found in Table 4. The data show the large variability of herbicide use practices in the cultivation of maize in EU. On average, farmers apply 2.15 kg/ha of AI for pre-emergence treatment and 0.72 kg/ha for post-emergence treatment. The variations across countries arise from different agro-climatic conditions, type of AI registered and maximum rate of application authorized, and use of Integrated Pest Management (IPM) or other non-chemical solution for weed control. In regions where the summer is dryer and maize is grown under rainfed systems, farmers tend to apply much less post-emergence herbicide. The very high rates of application in Spain are due to the hot and humid cropping conditions created by irrigation that are favourable to the development of weeds. The average field-use rating EIQ amounts to 37.7 EIQ/ha and values ranged from 20 for Hungary to 62 for Czech Republic. Besides this inter-country variability there is also intra-country variability as shown by the standard deviation which is most pronounced in Hungary. Despite the use of different AI across countries, EIQ field-use ratings are strongly correlated with the rates of application. Given the hypothesis of our model, the average expenditure on herbicide treatments is a critical determinant of the adoption patterns of GMHT maize. Results from our survey show that it is highest in Romania and lowest in the Czech Republic, while the rest of countries ranges between 19% and 28%. This is due to the low average field-use rate/ha of the conventional herbicide programs used in the latter countries and will be explained in more details in Section 5.

The data show the large variability of herbicide use practices in the cultivation of maize in EU. On average, farmers apply 2.15 kg/ha of AI for pre-emergence treatment and 0.72 kg/ha for post-emergence treatment. The variations across countries arise from different agro-climatic conditions, type of AI registered and maximum rate of application authorized, and use of Integrated Pest Management (IPM) or other non-chemical solution for weed control. In regions where the summer is dryer and maize is grown under rainfed systems, farmers tend to apply much less post-emergence herbicide. The very high rates of application in Spain are due to the hot and humid cropping conditions created by irrigation that are favourable to the development of weeds. The average field-use rating EIQ amounts to 37.7 EIQ/ha and values ranged from 20 for Hungary to 62 for Czech Republic. Besides this inter-country variability there is also intra-country variability as shown by the standard deviation which is most pronounced in Hungary. Despite the use of different AI across countries, EIQ field-use ratings are strongly correlated with the rates of application. Given the hypothesis of our model, the average expenditure on herbicide treatments is a critical determinant of the adoption patterns of GMHT maize. Results from our survey show that it is highest in Romania and lowest in the Czech Republic, while the rest of countries ranges between 19% and 28%. This is due to the low average field-use rate/ha of the conventional herbicide programs used in the latter countries and will be explained in more details in Section 5.

4.2. Scenario 1

Under this scenario farmers rely exclusively on Program A (the glyphosate strategy) trying to maximize immediate returns without taking into account the effect of their current decisions on the potential development of weed resistance. The replacement of conventional herbicide programs by glyphosate and the technology fee of €15/ha creates a potential high value for the adopting farmers. The estimated levels of adoption of glyphosate-tolerant maize and its economic impact for farmers in this first scenario are presented in Table 5.

In this scenario adoption of GMHT maize increase gross margin for the large majority of European maize farmers, ranging from 60% of Czech farmers to 98% of Romanian farmers. Typical average gross margin gains for adopters range from €41 to €51/ha for most countries (SP, FR, PT, DE and HU) with lower gains in the Czech Republic. The largest farmer’s gross margin increase associated to adoption of GMHT maize is predicted for Romania, a country where prices for conventional herbicide programmes are considerably higher. Moreover, as mentioned before, the sample contains mainly large commercial farms that rely intensively on chemical treatment compared to the tillage and manual weeding observed in smaller farms. Due to the framework which considers the distribution of technology valuation in the whole population, the adoption rate in one country does not necessarily translate to a high average profit per hectare for the adopters.

The EIQ variation due to changes in herbicide use (switch to program A) for farmers adopting GMHT maize is presented in Table 6. The shift to GMHT maize under scenario 1 generates a significant reduction in the average field-use EIQ/ha for CZ, ES and PT, ranging from –35 EIQ/ha in CZ to –7 EIQ/ha in PT. In these countries, the percentage of farmers for which the EIQ improves when adopting GMHT maize ranges between 60% and 79%. For Romania the average change is insignificant with the proportion of farmers for which the EIQ increases or decreases being close. For the remaining countries (FR, DE, HU) though, the average EIQ field-use rate/ha increases and the percentage of farmers for which the EIQ improves ranges between 19% and 28%. This is due to the low average field-use EIQ/ha of the conventional herbicide programs used in the latter countries and will be explained in more details in Section 5.

4.3. Scenario 2

Under this scenario the technology fee remains fixed at €15/ha but we assume that some of the farmers that had adopted GMHT combined with glyphosate-based programme A will over time shift to herbicide programs B–C–D that contain different AI. We assume that each program has the same probability of being chosen by the farmer, but as indicated before, the farmers with higher initial herbicide expenditure are assumed to have a higher probability to choose an expensive replacement program. Table 5 shows the effect of this simulation on the economic potential of GMHT maize. As expected, in this scenario of more expensive herbicide programmes for GMHT management, there are fewer farmers for which adoption of GMHT maize would result in increased gross margin compared to scenario 1. The decrease is on average by 33 percentage points (pp) and this effect is most pronounced in the

| Table 5 |
| --- |
| Estimated adoption of GMHT maize (% of farmers) and gross margin increase for adopters under different scenarios of herbicide programs and technology fee. |
| **CZ** | **DE** | **ES** | **FR** | **HU** | **PT** | **RO** |
| Scenario 1 | % of farmers adopting GMHT maize | 60% | 87% | 73% | 92% | 69% | 69% | 98% |
| Average gross margin increase for adopters of GMHT maize (€/ha) | 24 | 47 | 51 | 41 | 51 | 50 | 91 |
| Scenario 2 | % of farmers adopting GMHT maize | 14% | 49% | 39% | 51% | 40% | 36% | 86% |
| Average gross margin increase for adopters of GMHT maize (€/ha) | 22 | 39 | 50 | 29 | 45 | 50 | 71 |
| Scenario 3 | % of farmers adopting GMHT maize | 18% | 36% | 36% | 28% | 35% | 34% | 61% |
| Average gross margin increase for adopters of GMHT maize (€/ha) | 22 | 39 | 52 | 28 | 45 | 52 | 65 |
| Endogenous technology fee (€/ha) | 12 | 27 | 19 | 33 | 20 | 17 | 44 |

Note: Scenario 1: the technology fee is fixed for all countries (€15/ha) and weed control in GMHT maize is performed with glyphosate only (Program A, Table 3).
Scenario 2: the technology fee is fixed for all countries (€15/ha) and weed control in GMHT maize is performed with diversified herbicide programmes (Programs B-C-D, Table 3).
Scenario 3: same as Scenario 2 except for the technology fee that is an endogenous variable with different value for each country.
Czech Republic where the proportion of farmers with increased gross margin drops to 14%, a reduction of 46 percentage points (pp). In contrast, the average change in gross margin increase for those farmers adopting the technology compared to scenario 1 is rather small, since it is reduced by just €7/ha on average. This can be explained by the fact that those farmers abandoning the technology after the need for programs B–C–D are those that had experienced small gross margin increases from adopting the GMHT technology under scenario 1.

Table 6 shows the changes of the EIQ for scenario 2. The significant reduction in the average field-use EIQ/ha compared with conventional maize cultivation is maintained for two countries (CZ and ES) with as many as 72% of potential adopters benefiting from a decrease of their field-use rating EIQ. Farmers in RO and PT are in an intermediate position, with 45% of farmers for which the model predicts lower EIQ. In contrast, for FR, DE and HU, only about 20% of potential adopters would actually experience a lower EIQ/ha. In fact for these countries the simulation predicts that the field-use EIQ/ha of adopting farmers would increasing by approximately 15–22 EIQ/ha on average. It has to be pointed out that, even for farmers currently using herbicides at low rate and with a low EIQ, the model assumes that once they adopt GMHT maize, they will protect their investment in the technology by applying the replacement herbicide program at full rate. This scenario that results in higher EIQ for some farmers has not been considered in earlier literature on GMHT maize impacts (see Devos et al., 2008 for an overview).

4.4. Scenario 3

This scenario differs from Scenario 2 simply in the price of the technology. It can be considered representative of the long term situation in which both farmers and the technology provider value the technology based on the experienced gained from adopting or commercializing GMHT maize. The technology provider is assumed to use all the available information on the distribution of the technology valuation to maximize the part of the innovation

| Scenarios | % of farmers adopting GMHT maize | % of adopting farmers for whom the EIQ field-use rating decreases | Mean change in EIQ for all adopters | Mean change in EIQ for all adopters |
|-----------|----------------------------------|---------------------------------------------------------------|----------------------------------|----------------------------------|
| Scenario 1 (only glyphosate) | 60% | 79% | 21% | 65% |
| - Mean decrease of EIQ field-use rating | -46.4 | -28.7 | -24.2 | -23.6 |
| Scenario 2 & 3 (diversified herbicide programs) | 14% | 15% | 28% | -35.4 |
| - Mean decrease of EIQ field-use rating | -45.7 | -26.6 | -29.3 | -23.0 |

Table 6 Estimated changes in EIQ field-use rating for farmers adopting GMHT maize under different scenarios of herbicide programs and technology fee.

4.5. Distributional effects of the generated value

From the results of the different scenarios it is clear that besides the initial farm characteristics, the chosen strategies of pricing and weed management affect the final economic impacts of GMHT maize at national level. From a societal and scientific point of view, there has been a long lasting interest in understanding how the value generated by a novel technology is distributed among the different actors in the supply chain (e.g. Alston et al., 1997; Demont et al., 2007; Falck-Zepeda et al., 2000). Fig. 1 presents the share of the generated value accruing to farmers and technology providers under the different scenarios. When the technology provider uses the low and uniform technology fee with the idea of penetrating the market, the value share accruing to farmers is 76–73%, for scenario 1 and 2 respectively. The technology provider is able to extract a larger value share in scenario 3 (country-specific technology fees) but still remains at 36%, leaving 64% for the adopting farmers. These results are in line with previous estimates based on a meta-analysis on benefit sharing (Demont et al., 2007), on a stochastic simulation (Hareau et al., 2006) or from economic surplus model with monopoly profit (Falck-Zepeda et al., 2000; Trigo and Cap, 2006). They confirm that farmers are the main beneficiary of GMHT maize introduction and that the technology provider is never able to capture all the benefits generated by the technology due to the heterogeneous population of potential adopters (Demont et al., 2007; Dillen et al., 2009) even when a country-based...
price discrimination strategy is followed by the technology provider.

5. Discussion

The results presented in this paper suggest that GMHT maize technology could be profitable for a large share of European maize farmers. This share is particular high in the early stages of the introduction of the technology, and decreases to different extents, depending on the country, in scenarios reflecting the need to accommodate practices to avoid the development of herbicide resistance in weeds and possible increases in the technology fees. But overall, even in these scenarios there are large proportions of farmers for which the technology has economic interest.

This paper fills a gap in the literature by estimating the impacts of the introduction of GMHT maize on European agriculture based on a unique set of data for actual herbicide used. However, as in any other modelling exercise, the results should not be over-interpreted. The first limitation relates to the assumption of a ceteris paribus for outcome and farming practices other than those related to weed management. Assuming that economic savings are the only driver for the adoption of the GMHT maize, our results predict very high levels of uptake of the technology by maize farmers in the EU. In our adoption model, if savings in herbicide costs for a particular farmer are above the technology fee for GM seeds, the farmer is assumed to switch to GMHT maize. However, farming practices such as tillage, crop rotation, different scouting practices, labour requirements etc. could be altered by the adoption of GMHT maize (Devos et al., 2008). Similar observations have been made for other GMHT crops such as soybean in the US (Bonny, 2011) and Argentina (Bindraban et al., 2009). Depending on these changes the economic impact could change, and therefore the adoption levels predicted could vary. Furthermore, the model does not account for the possible impacts of coexistence requirements for the cultivation of GM varieties in the EU (Devos et al., 2009). Implementing ex ante and ex post coexistence measures has a certain cost to farmers adopting GM crops and may function as a hurdle for adoption (Areal et al., 2011; Beckmann et al., 2010; Demont et al., 2008b). Incorporating these costs might decrease both adoption and the gross margin from the technology compared to this analysis.

The ceteris paribus hypothesis used in the model also implies a yield neutrality assumption. Very few surveys have been conducted to compare the yield performance of GMHT maize with conventional maize in countries where it is actually grown (Díaz Osorio et al., 2004; Gouse et al., 2009) and they do not permit to conclude. However, it is usually admitted in literature that GMHT crops are neutral with respect to yield in developed countries but more research and surveys are required to improve the robustness of this conclusion (Areal et al., 2013).

Another variable not considered in the model and that could decrease the adoption rate of the technology is the farmers' personal negative attitude toward GMHT crops. Farmers' own concerns about biotechnology as well as their negative social perception of adopting GM crops were described as important factors influencing the decision to adopt GMHT crops in Europe (Areal et al., 2012, 2011).

On the other hand, non-pecuniary effects of this technology, such as simplification of weed management, are important drivers of its quick adoption in other parts of the world. Therefore a model based solely on economic drivers may lead to an underestimation of the valuation for the technology by farmers and therefore an underestimation of the potential adoption rate (Piggott and Marra, 2008).

With all the limitations discussed above, the model predicts very high adoption rates for GMHT maize, if based on economic profits, in all seven countries and high gross margin gains from about €24/ha in CZ to €91/ha in RO for adopting farmers in the short run. In ES, PT and CZ, countries currently with a high baseline of herbicide use in maize, the majority of adopting farmers (60–79%) will also experience reductions in EIQ under a scenario of glyphosate-based weed control, realising both the economic and environmental potentials of the technology. This holds true even for late stage scenarios introducing herbicide programmes for delaying weed resistance (scenarios 2 and 3).

In contrast, for a second group of countries (FR, DE and HU), simulations predict that only a fraction of potentially adopting farmers will experience a decreased EIQ. In this situation, a purely economic-driven adoption may result in increased EIQ for many adopting farmers. This is explained by current low rates of application of herbicide or the use of less harmful AI for the weed control in conventional maize in these countries, and by the fact that the model assumes that farmers relying on mechanical control options and using low herbicide rates will adopt a full herbicide control program in order to protect their investment in the GMHT maize technology. We conclude that in this group of countries a purely economic-driven adoption may actually result in increased EIQ for many adopting farmers. Therefore to fully realise the potential of the technology and manage impacts, the characteristics of the subset of farmers with potential for economic and environmental benefits has to be identified.

Although changes in the toxicity and amounts of herbicide use is one of the main environmental effect associated to GMHT adoption, the technology may also be associated to savings in fuel consumption (Wesseler et al., 2011) or adoption of conservation tillage practices (Qaim and Traxler, 2005). Our survey/model did not address these changes, therefore the EIQ decrease is the only indicator used here for potential environmental impacts.

In Romania, the model displays high economic benefits for maize farmers that can be partially explained by the high cost of herbicide products for conventional weed control in this country.
while in Czech Republic the reverse situation occurs. It is worth noting that both countries are subject to the bias towards the inclusion in the survey sample of farms larger than the average already noted before. It is likely that in these countries, smaller farms tend to rely more on labour or non-chemical solutions to control weeds in maize fields. Eventually, whether this bias under- or overestimate the adoption rate of the GMHT technology depends on the cost of these alternative weed control strategies for which we were not able to collect detailed information.

Our results expand considerably previous attempts to evaluate ex-ante the economic impact of GMHT maize in Europe (Demont et al., 2008a), by incorporating scenarios of GMHT maize cultivation with diversified herbicide programmes (in addition to only glyphosate-based programmes). These diversified programs are in line with the stewardship measures recommended by technology providers to avoid the development of weed resistance to glyphosate and maintain the benefits of the technology in the long run (Dewar, 2009). The main effect of the introduction of these scenarios is a drop in possible adopters, since the share of farmers for which GMHT would be economically profitable decreases, although the average profit per adopting farmer is largely unchanged. The drop in adoption is only pronounced for Czech Republic. For the rest of the countries, positive additional gross margin is predicted for 36–86% of farmers, showing that the use of strategies to lower the risk of development of weed resistance is not in contradiction with economic attractiveness of the technology and therefore with predicted adoption. In terms of environmental effect, the introduction of these scenarios does not change significantly the proportion of adopting farmers for which the EIQ decreases. The clear pattern of two groups of countries in terms of potential environmental effects is not changed.

Our short-term scenario (glyphosate-based strategy) is very likely since farmers generally tend to find necessary to control a specific weed species only if it results in yield loss, lower yield quality, or hampers agricultural operations. Through a farmer survey, Wilson et al. (2008) demonstrated that farmers place greater importance on coping with existing weed populations than on the prevention of weed shifts and resistance development. The discrepancy between the short-term goals of farmers and the longer term goal of delaying resistance development indicates a need for clear guidelines on how to manage GMHT maize introduction in Europe.

Another crucial parameter not covered in earlier research is the role of the technology provider in the spreading of GMHT maize through the choice of the technology fee. A low fee will lead to a high penetration in the seed market, leading to high adoption levels. However, by optimizing the technology fee under price discrimination, more value accrues to the technology provider, both in absolute and relative value. Hence after initial market penetration and with increased market information, the price of the technology might increase, as has been observed in the case of the introduction of GMHT sugar beet in the US. However, an important consideration should be made when interpreting the decreased adoption rates due to increased technology fees. Scenario 3 assumes the technology valuation by farmers has not changed over the course of time. But the increased knowledge of the technology and the familiarity with the non-pecuniary benefits could make the farmers rather price inelastic and thus the reduction in adoption rates should not be seen as an immediate effect.

Finally the issue of time dependence of the model used in the paper has to be further explored. This study tries to introduce a time dimension through the use of scenarios. However there is no direct linkage between the scenarios as no information is provided on when farmers will shift away from glyphosate-only practices or how technology providers will price the technology. These decisions among others depend on policies, market signals and the development of weed resistance. A more dynamic framework starting from the farmer’s choice in each growing season might offer a first step towards a better understanding of adoption and its effects through time.

6. Conclusions

The paper models ex-ante the impacts of cultivating GMHT maize, an addition to the European toolbox for weed control, on agricultural profitability and the environment. Similar to earlier papers, the results show that GMHT maize has indeed the potential to create economic value for a very large proportion of European maize farmers. However, taking into account the possibility of weed resistance development over time shows that the outcome is not straightforward positive as often described in earlier papers. Depending on the decisions taken by both farmers and the technology provider, the economic and environmental effects can change.

Because it is based on a unique dataset of weed control strategy of European maize farmers, including not only cost but also sufficient details on active matters and rates of application to make calculation of EIQ possible, this paper is the first to highlight the differences across EU countries regarding the economic and environmental effects of the introduction of the GMHT maize technology. In view of the variability of the environmental results across countries, this paper show that the environmental relevance of GMHT maize needs to be assessed on a case-by-case basis, and also depends on the use of the technology by farmers in the short and longer term.

The threat – or eventually development – of weed resistance will likely shift farmers to more complex weed control strategies in combination with GMHT maize, replacing the commonly assumed overreliance on a single broad-spectrum herbicide. Our results show that this shift reduces the potential adoption level of GMHT maize. This shift from a broad-spectrum herbicide to a more complex herbicide strategy has however an important consequence for the environment. As the broad-spectrum herbicide is generally considered benign, adoption of GMHT maize is often introduced as an environmentally positive evolution. Our results show that over time a shift to more complex herbicide strategies generally erodes this positive environmental effect or could even increase the impact on the environment compared to the baseline. This indicates that both from an overall economic and environmental perspective, the long-term efficiency of broad-spectrum herbicides has to be safeguarded. This can be achieved through the use of appropriate non-chemical weed control options such as rotation or mechanical weeding, or by decreasing the reliance on the broad-spectrum herbicide after adoption through the use of alternative chemical programs.

These observations highlight the need for a dynamic assessment of GMHT crops. This paper presents a first approach through scenario analysis but further research will be needed to understand when and how farmers make specific herbicide choices. A better understanding of this aspect will not only ameliorate the ex-ante socio economic impact assessments of GMHT crops, but might help when designing a policy framework that assures that the potential benefits of GMHT maize are sustainably realised and not lost due to short-term goals of actors involved.

Disclaimer

The opinions expressed are those of the authors only and should not be considered as representative of the European Commission’s official position.
Acknowledgements

The authors are grateful to their colleagues Jonas Kathage and Mauro Vigani for their feedback on previous versions of this paper, as well as to the journal editor and two anonymous reviewers for their insightful comments that helped to improve this publication.

References

Alston, J.M., Sexton, R.J., Zhang, M., 1997. The effects of imperfect competition on the size and distribution of research benefits. Am. J. Agric. Econ. 79, 1252–1265.
Areal, F.J., Riesgo, L., Rodriguez-Cerezo, E., 2011. Attitudes of European farmers towards GM crop adoption. Plant Biotechnol. J. 9, 945–957.
Areal, F.J., Riesgo, L., Rodriguez-Cerezo, E., Gomez-Barbero, M., Rodriguez-Cerezo, E., 2012. Consequences of a coexistence policy on the adoption of GMHIT crops in the European Union. Food Policy 37, 401–411.
Banila, N., 2011. Suppliers double up as creditors to fund cash-strapped farmers. The Diplomat, March 2011.
Beckie, H.J., 2006. Herbicide-resistant weeds: management tactics and practices. Weed Technol. 20, 793–814.
Benbrook, C., 2012. Impacts of genetically engineered crops on pesticide use in the U.S. – the first sixteen years. Environ. Sci. Eur. 24, 1–13.
Bennett, J.P., Franke, A.C., Ferrar, D.O., Ghera, C.M., Lotz, L.P., Nepomuceno, A., Smulders, M.J.M., Van De Wiel, C.C.M., 2009. GM-related sustainability: agro-ecological risks, and opportunities of soy production in Argentina and Brazil, p. 56.
Bonny, S., 2011. Herbicide-tolerant transgenic soybean over 15 years of cultivation: pesticide use, weed resistance, and some economic issues. The case of the USA. Sustainability 3, 1302–1322.
Demont, M., Dillen, K., 2008. Herbicide tolerant sugar beet: the most promising first-generation GM crop? Int. Sugar J. 110, 613–617.
Demont, M., Dillen, K., Mathijs, E., Tollens, E., 2007. GM Crops in Europe: how much value and for whom? EcoChoices 6, 46–53.
Demont, M., Cerovska, M., Daems, W., Dillen, K., Fogarasi, J.Z., Mathijs, E., Muska, F., Soukup, J., Tollens, E., 2008a. Ex ante impact assessment under imperfect information: biotechnology in New Member States of the EU. J. Agric. Econ. 59, 463–486.
Demont, M., Daems, W., Dillen, K., Mathijs, E., Sausse, C., Tollens, E., 2008b. Regulating coexistence in Europe: beware of the doom-effect! Ecol. Econ. 64, 683–689.
Demont, M., Rodenburg, J., Diagne, M., Dillio, S., 2009. Ex ante impact assessment of herbicide resistant rice in the Sahel. Crop. Prod. 28, 728–736.
Devis, Y., Couignon, M., Veguecht, S., Bulcke, R., Haesaert, G., Steurbaut, W., Reheul, D., 2008. Environmental impact of herbicide regimes used with genetically modified herbicide-resistant maize. Transgenic Res. 17, 1059–1077.
Devis, Y., Demont, M., Dillen, K., Reheul, D., Kaiser, M., Sanvido, D., 2009. Coexistence of genetically modified (GM) and non-GM crops in the European Union. A review. Agron. Sust. Dev. 29, 11–30.
Dewar, A.M., 2009. Weed control in glyphosate-tolerant maize in Europe. Pest Manag. Sci. 65, 1047–1058.
Díaz Oorio, J., Herrera, R., Valderrama, J., Llanos Ascencio, J.L., 2004. Potential changes in the competitiveness of maize growers in Central Chile through the use of transgenic seed (Bt and RR). Spanish J. Agric. Res. 2, 145–156.
Dillen, K., Demont, M., Tollens, E., 2008. European sugar policy reform and agricultural innovation. Can. J. Agric. Econ. 56, 533–553.
Dillen, K., Demont, M., Tollens, E., 2009. Corporate pricing strategies with heterogeneous adopters: the case of herbicide-resistant sugar beet. AgEcon Papers 12, 334–345.
Dillen, K., Mitchell, P.D., Tollens, E., 2010a. On the competitiveness of different damage abatement strategies against Diabrotica virgifera virgifera: a bio-economic approach. J. Appl. Entomol. 134, 395–408.
Dillen, K., Mitchell, P.D., Van Looy, T., Tollens, E., 2010b. The Western Corn Rootworm, a new threat to European agriculture: opportunities for biotechnology? Pest Manag. Sci. 66, 956–966.
Duke, S.O., 2012. Why have no new herbicide modes of action appeared in recent years? Pest Manag. Sci. 68, 505–512.
EFSA, 2009. Scientific opinion of the panel on genetically modified organisms about NK603. EFSA J. 1137, 1–50.
Eurostat, 2012. Agricultural statistics. Eurostat, Luxembourg, <ec.europa.eu/ eurostat> (accessed on 15.12.12).
Eurostat, 2013. Farm Structure Survey 2007. European Commission, <http://epp.eurostat.ec.europa.eu/portal/page/portal/agriculture/farm_structure/ database> (accessed on 16.01.13).
Falck-Zepeda, J., Traxler, G., Nelson, R.C., 2000. Surplus distribution from the introduction of a biotechnology innovation. Am. J. Agric. Econ. 82, 360–369.
FAOSTAT, 2013. FAOSTAT Production database. Statistics Division of the Food and Agriculture Organization of the United Nations, <http://faostat3.fao.org/home/index.html> (accessed on 16.05.13).
Feola, G., Rahn, E., Binder, C.R., 2011. Suitability of pesticide risk indicators for less developed countries; a comparison. Agric. Ecosyst. Environ. 142, 238–245.
Finger, R., Hartmann, M., Feinberg, M., 2009. Adoption patterns of herbicide- tolerant soybeans in Argentina. AgBioForum 12, 404–411.
Fulton, M., Giannakas, K., 2001. Agricultural biotechnology and industry structure. AgBioForum 4, 137–151.
Gomez-Barbero, M., Berbel, J., Rodriguez-Cerezo, E., 2008. Bt corn in Spain: the performance of the EU’s first GM crop. Nat. Biotechnol. 26, 384–386.
Gousse, M., Pray, C.E., Schmollmugen, D., 2004. The distribution of benefits from BT crop adoption in South Africa. Agric. Econ. 30, 375–395.
Gousse, M., Pisse, J., Thurtle, C., Poulton, C., 2009. Assessing the performance of GM maize amongst smallholders in KwaZulu-Natal, South Africa. AgBioForum 12, 78–83.
Grab, F., Stachow, U., Werner, A., Schutte, G., 2007. Agricultural practice changes with cultivating genetically modified herbicide-tolerant oilseed rape. Agric. Syst. 94, 111–118.
Hareau, G.C., Mills, B.F., Norton, G.W., 2006. The potential benefits of herbicide- resistant transgenic rice in Uruguay: lessons for small developing countries. Food Policy 31, 162–179.
Heap, I., 2013. International survey of herbicide resistant weeds, <http://www.weedsscience.com/Summary/home.aspx> (accessed on 12.02.13).
Hijmans, R.J., van der Lijden, P., Ruisinger, B., Hart, S.E., van der Lijden, P., Ruisinger, B., Hart, S.E., 2011. Economic and agronomic impact of commercialized GM crops: a meta-analysis. J. Agric. Sci. 151, 73–33.
Hijmans, R.J., Tardif, F.J., 2012. Herbicide cross resistance in weeds. Crop Prod. 35, 15–28.
Hijmans, R.J., Harker, K.N., Hall, L.M., Lawrence, S.I., Legere, A., Sikkenka, P.H., Clayton, W.G., Thomas, A.G., Leeson, J.Y., Seguin-Szwartz, G., Simard, M.I., 2006. A decade of herbicide-resistant crops in Canada. J. Can. Plant Sci. 86, 1243–1264.
Beckie, H.J., Tardif, F.J., 2012. Herbicide cross resistance in weeds. Crop Prod. 35, 15–28.
Beckie, H.J., Harker, K.N., Hall, L.M., Lawrence, S.I., Legere, A., Sikkenka, P.H., Clayton, W.G., Thomas, A.G., Leeson, J.Y., Seguin-Szwartz, G., Simard, M.I., 2006. A decade of herbicide-resistant crops in Canada. J. Can. Plant Sci. 86, 1243–1264.
Beckie, H.J., Voregario, C., Wesseler, J., 2010. Ex-ante regulation and ex-post labelling under uncertainty and irreversible expropriation of the coexistence of GM crops. Economics: the open-access. Open Asses. E-J. 4.
Benbrook, C., 2012. Impacts of genetically engineered crops on pesticide use in the U.S. – the first sixteen years. Environ. Sci. Eur. 24, 1–13.
Bindo, L., J., S., Diff., H., J., P., 2003. Analysis of herbicide-tolerant crops in Hungary in 2009. J. Agric. Econ. 59, 463–486.
Bindo, L., J., S., Diff., H., J., P., 2003. Analysis of herbicide-tolerant crops in Hungary in 2009. J. Agric. Econ. 59, 463–486.
Bindo, L., J., S., Diff., H., J., P., 2003. Analysis of herbicide-tolerant crops in Hungary in 2009. J. Agric. Econ. 59, 463–486.
Bindo, L., J., S., Diff., H., J., P., 2003. Analysis of herbicide-tolerant crops in Hungary in 2009. J. Agric. Econ. 59, 463–486.
Trigo, E.J., Cap, E.J., 2006. Ten Years of Genetically Modified Crops in Argentine Agriculture. Argentine Council for Information and Development of Biotechnology, Buenos Aires.

Vencill, W.K., Nichols, R.L., Webster, T.M., Soteres, J.K., Mallory-Smith, C., Burgos, N.R., Johnson, W.G., McClelland, M.R., 2012. Herbicide resistance: toward an understanding of resistance development and the impact of herbicide-resistant crops. Weed Sci. 60, 2–30.

Weersink, A., Llewellyn, R.S., Pannell, D.J., 2005. Economics of pre-emptive management to avoid weed resistance to glyphosate in Australia. Crop Prot. 24, 659–665.

Wesseler, J., Scatasta, S., Nillesen, E., 2007. The Maximum Incremental Social Tolerable Irreversible Costs (MISTICs) and other benefits and costs of introducing transgenic maize in the EU-15. Pedobiologia 51, 261–269.

Wesseler, J., Scatasta, S., Fall, E.H., 2011. Chapter 7. The environmental benefits and costs of genetically modified (gm) crops. In: Carter, C.A., Moschini, G., Sheldon, I.M. (Eds.), Genetically Modified Food and Global Welfare (Frontiers of Economics and Globalization, Volume 10). Emerald Group Publishing Limited, pp. 173–199.

Wilson, R.S., Tucker, M.A., Hooker, N.H., Lejeune, J.T., Doohan, D., 2008. Perceptions and beliefs about weed management: perspectives of Ohio grain and produce farmers. Weed Technol. 22, 339–350.