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A Meta Analysis on Farm-Level Costs and Benefits of GM Crops

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Abstract: This paper reviews the evidence on the socio-economic impacts of GM crops and analyzes whether there are patterns across space and time. To this end, we investigate the effect of GM crops on farm-level costs and benefits using global data from more than one decade of field trials and surveys. More specifically, we analyze the effects of GM-crops on crop yields, seed costs, pesticide costs, and management and labor costs and finally gross margins. Based on collected data from studies on Bt cotton and Bt maize, statistical analyses are conducted to estimate the effect of GM crop adoption on these parameters. Our results show that, compared to conventional crops, GM crops can lead to yield increases and can lead to reductions in the costs of pesticide application, whereas seed costs are usually substantially higher. Thus, the results presented here do support the contention that the adoption of GM crops leads on average to a higher economic performance, which is also underlined by the high adoption rates for GM crops in a number of countries. However, the kind and magnitude of benefits from GM crops are very heterogeneous between countries and regions, particularly due to differences in pest pressure and pest management practices. Countries with poor pest management practices

benefited most from a reduction in yield losses, whereas other countries benefited from cost reductions. However, our study also reveals limitations for meta-analyses on farm-level costs and benefits of GM crops. In particular, published data are skewed towards some countries and the employed individual studies rely on different assumptions, purposes and methodologies (e.g., surveys and field trials). Furthermore, a summary of several (often) short-term individual studies may not necessarily capture long-term effects of GM crop adoption.

Keywords: biotechnology; GM crops; food security; technological change

1. Background and Goal

Green biotechnology, particularly the development of genetically modified crops, has been one of the major technological innovations in global agriculture of the last decades. Since its first commercial application in 1996, the global area under GM crops has increased to 148 million hectares in 2010 [1]. The major traits of GM crops are insect resistant Bt crops (made resistant against insect pests by incorporating a gene from the *Bacillus thuringiensis* (Bt) bacterium) and herbicide tolerant (HT) crops. In addition to these major traits, stacked traits that combine two or more characteristics (e.g., pest resistance and herbicide tolerance) are the major source for additional GM crop adoption [1]. Ever since its first application, the effect of a widespread application of GM crops on sustainable development has been the subject of controversial discussions ranging from food production and health issues to impacts on ecosystems and the environment. As a result, the literature on the impacts of GM crops is already substantial, especially in terms of the socio-economic impacts on farmers, their families and consumers. The voices on both sides of the debate (pro and anti-GM crops) have pointed to individual studies that support their view and clearly there is much contradiction. Therefore, it is timely to review the evidence on the socio-economic impacts of GM crops to see whether there are patterns across space and time. This paper focuses on the effects of GM crops on food production and farmers' costs and benefits from growing GM crops, which are highly relevant with regard to food security and poverty reduction especially in low income countries.

To this end, in this paper we investigate at the global and country level what effect GM crops have on crop yields and assess the effect of GM crops on farm-level costs and benefits. More specifically, we analyze the effects of GM crops on crop yields, seed costs, pesticide costs, and management and labor costs and finally gross margins. The review and meta-analysis presented here extends the existing literature by considering all countries and by focusing on a wide scope of literature. Moreover, the collection of observations from more than a decade of field trials and surveys allow for the analysis of temporal trends in the performance of GM crops. This analysis of trends over time is important to address concerns about the development of benefits over time. In particular, resistance, secondary pests and the growing market power of seed suppliers could conceivably increase adoption costs and reduce potential benefits of GM crops over time [2]. It is important to note that this study did not include evidence other than farm-level economic effects. Thus, more macro-effects of growing GM

crops on the environment and social welfare, as well as indirect effects of the cultivation of GM crops and its possible effects on health and biodiversity, are not considered.

2. Data and Methodology

In order to ensure that the analysis was based on a comprehensive set of evidence, the existing (peer-reviewed and grey) literature on GM crop performance at the field and farm level was reviewed, with especial emphasis on insect resistance (Bt cotton and Bt maize). Existing evidence from the literature derived in our review for HT soy and canola did not allow for statistical analysis due to insufficient amounts of available data. Other, emerging GM crop developments such as stacked traits and virus resistance plants have not been considered.

In order to collect the literature, a keyword search was conducted initially on specific literature databases such as the *Web of Science*, the *Web of Knowledge*, Research Papers in Economics (RePEc), Research in Agricultural & Applied Economics (AgEcon-Search) and others, while further sources were found through *Google-scholar* search. The keywords “gm crops” (bt cotton, bt maize, *etc.*), “economic performance”, “input costs”, “yield”, “income” or “revenue” *etc.* and combinations were used. The review of grey literature (consisting of conference contributions and institutional reports) was mainly based upon datasets available through the Internet. To ensure that the data had not been repeated or even misinterpreted in the source document, the screening of the publication often led to another source to track the primary data. Such an approach was considered to be necessary in order to avoid the duplication of data and possible bias derived from citation and re-interpretation of data by different authors. The literature search was focused on publications in English.

Based on a comprehensive reference list a database was set up that was used for the subsequently presented meta-analyses. A list of the references that were included in the database, either as a publication only or providing single study entries is available upon request from the authors. To guarantee comparability, data were entered in identical units and this often required the conversion of values. Values in various currencies were converted to US Dollars using the average exchange rate for the year of the study. All area values were entered in (and if necessary, converted to) hectares and weight figures were entered in kilograms.

In total, 203 publications based on field trials and surveys were reviewed, containing 721 single study entries for GM crops and control groups of conventional (non-GM) crops. Note that we used the mean values reported in each study (e.g., mean crop yield for a specific year) and only used values that had been reported in the source directly, *i.e.*, no additional calculations were made. To allow the estimation of GM crop effects on production and farmers’ income, all available observations on economic performance indicators were collected in a dataset, including data on crop yields, gross margins, seed costs, pesticide costs, and management and labor costs for both GM and conventional crops.

Asia and Europe were the most well represented continents in the dataset, with a significant number of studies from India (220) and China (70) for the former and Spain (65) for the latter. South Africa represents the African continent with 58 studies. The largest share of American studies included in the database was located in the USA (120) and Argentina (55). Table 1 shows that cotton followed by maize, especially Bt trait, are best represented in the database. Note that the relatively small number of

studies found for HT soy and canola did not allow for statistical analysis and are thus not considered further in this paper.

Table 1. Number of studies included in the database, according to crop type and trait.

Crop type/trait	Total	HT	BT	Conventional
Maize	177	7	105	65
Cotton	454	22	237	195

The remaining 90 studies (to the total number of 721) refer to soy and canola.

We employed a linear regression model to test for (a) a time trend in the economic performance indicators (Y), (b) an effect of GM crops (*i.e.*, a comparison between GM and conventional crops), and (c) a time trend in the effect of GM crops. The regression analysis had the following form:

$$\text{Log}(Y) = \beta_0 + \beta_1 \text{Year} + \beta_2 D_{GM} + \beta_3 D_{GM} \text{Year} + \beta_3 D_{Country} + \varepsilon \quad (1)$$

The dummy variable D_{GM} indicates observations for conventional ($D_{GM} = 0$) and GM crops ($D_{GM} = 1$). We used the logarithm of the various economic indicators (yield, costs of herbicides and pesticides per hectare, seed costs, labor and management costs and gross margin per hectare) because this leads to a less skewed distribution of dependent variables and thus improves the suitability of the regression models. The log transformation of dependent variables allows for interpretation of the parameters as relative (percentage) impact of the independent variables.

The regression coefficient β_1 measures the effect of technological change and development over time on the dependent variable chosen for measuring the economic performance (e.g., to capture generally increasing yield levels). β_2 measures the difference in the economic performance between GM and conventional crops in percentage points. β_3 shows how the difference in economic performance between the technologies changes over time (e.g., a yield benefit of GM crops relative to non-GM might decrease over time). In order to control for totally different levels of economic performance indicators across countries, and thus to make a comparison across all countries possible, we included country as a dummy variable (e.g., South Africa = 1, Argentina = 2, *etc.*). Thus, these dummy variables remove the average value of the economic performance indicators (e.g., yield) for each country from the observations. The country means are evaluated in the regression against an omitted reference dummy (*i.e.*, reference country). These coefficient estimates would indicate, for instance, differences of average cotton yields between India and the USA. Because these values are not of interest for our analysis and due to the lack of space, these coefficient estimates are not presented.

Finally, ε is the error term that captures all other factors which influence the economic performance variable other than the regressors. In order to assess the quality and the suitability of the regression model we used graphical regression diagnostic tools and associated tests. In order to avoid a potential omitted variable bias due to different climatic conditions, we also included a dummy variable climate zone (that might be correlated with dependent variables and the independent variable) in the regression analysis, which had, however, no effect and did not change the effect of the other independent variables and where thus not included in the regression model. We also expect the specific varieties used to have an influence on the GM effect and the economic performance parameter, which is not testable due to a lack of data on employed varieties.

In addition to the regression analysis, we conducted country specific analyses to test for GM crop effects within a specific country. To this end, mean values of the economic performance indicator for GM and conventional crops (as well as the percentage change and the number of observations) were presented for the countries with an acceptable minimum of observations. In order to test for differences between GM and conventional crops, we used the Mann-Whitney non-parametric test. Note that the presentation of country specific results is limited to those cases where enough data were available. Thus, this selection may not necessarily be representative of the global importance of specific countries [1].

3. Results

3.1. Cotton

Within the database, the majority of data for Bt cotton came from India, China, Australia, USA and South Africa. Only limited observations were available for Argentina, and Indonesia.

Figure 1 shows the economic performance indicators for Bt cotton (*i.e.*, yield, gross margin, seed costs, pesticide costs, as well as management and labor costs) by year, country and trait (GM and conventional crop). In general, the figures show a large amount of heterogeneity within each of the parameters. This heterogeneity is caused by country specific effects (e.g., yield levels in China generally seem to be higher than in the USA), variation over time (e.g., the yield levels seem to generally increase over time) and differences between Bt and conventional cotton. In order to explain the heterogeneity within the observations, the linear regression model is used.

Figure 1. Yields (top left panel), gross margins (top right), seed costs (middle left), pesticide costs (middle right) and management and labor costs (bottom) for cotton.

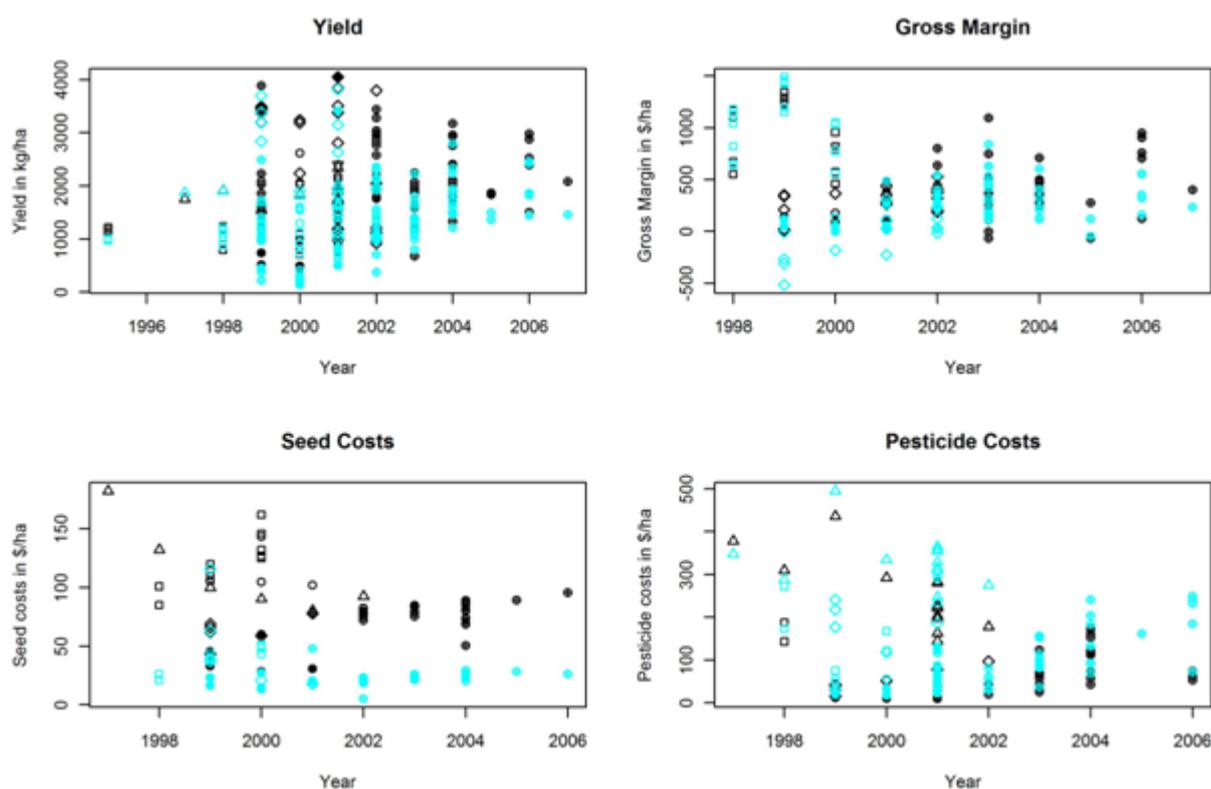


Figure 1. Cont.

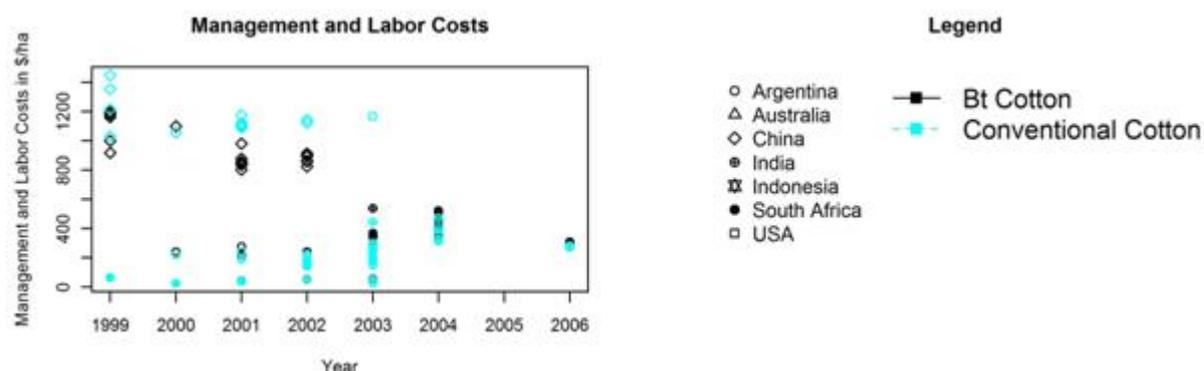


Table 2 shows the results of the regression model in which the dependent variable is the logarithm of the economic performance indicator. The coefficient estimates can be interpreted as a percentage effect on the economic performance indicator: For instance, the coefficient estimate for the Bt effect of 0.463 in the yield model shows that Bt yields are, on average, 46.3% higher than conventional yields. The 0.085 for the time effect show that, on average, cotton yields generally (*i.e.*, over all traits and countries) increase by 8.5% per year.

Table 2. Coefficient estimates from the regression models on different economic performance indicators for Bt cotton

Coefficient	Yield model	Gross margin model ¹	Seed costs model	Pesticide costs model	Management and labor costs model
Intercept (β_0)	6.400 (36.45) ***	5.641 (11.17) ***	2.863 (10.49) ***	3.776 (15.913) ***	4.970 (21.50) ***
Time Effect (β_1)	0.085 (3.97) ***	0.1629 (1.98) **	0.037 (0.95)	0.117 (3.30) ***	0.069 (1.50)
Bt Effect (β_2)	0.463 (2.31) **	0.863 (2.05) **	0.979 (5.41) ***	-0.482 (-2.29) **	-0.196 (-0.84)
Bt Effect *	-0.019	-0.109	0.028	-0.003	0.069
Time Effect (β_3)	(-0.73)	(-1.33)	(0.84)	(-0.09)	(1.34)
Adjusted R-squared	0.28	0.11	0.73	0.65	0.77
Degrees of freedom	292	172	105	164	98

¹ In order to allow for logarithmic regression, all gross margin observations are transformed so that all observations are above zero, with the lowest observation equal to 0.0001. *, **, and *** denote significance at the 10, 5, and 1% levels, respectively. Numbers in parentheses are t-values.

Time effect. We find significant increases over time (β_1) for cotton yields, gross margins and pesticide costs. Increasing yields and costs might reflect general technological advances in agriculture and input costs [3-5]. In addition, time effects are positive but statistically insignificant for seed costs and management and labor costs.

Bt effect. There are significant Bt-effects (β_2) for all of the considered dependent variables except for management and labor costs. The results suggest higher yields (of about 46%) for Bt cotton, but lower pesticide costs and management costs (albeit statistically insignificant) in the range of 48% and 20%, respectively. However, there is evidence for higher (up to twice as high) seed costs for Bt than

for conventional cotton. In total, these parameters suggest significantly higher gross margins (+86%) for Bt than for conventional cotton. However, please note that the exact values have to be interpreted with care, particularly because of the unbalanced dataset towards observations from India and some influential (leverage) observations that might determine the magnitude of coefficient estimates.

Bt effect over time. The interaction effect between Bt and time (β_3) is not significant for any of the economic performance indicators. Thus, the estimated Bt effects were stable over time.

Table 3 shows the results of country specific analyses. Please note that the low number of available observations for some countries requires careful interpretation.

Table 3. Economic performance indicators by country for Bt and conventional (conv) cotton.

Country	Trait	Economic performance indicator				
		Yield (kg/ha)	Gross margin (\$/ha)	Seed costs (\$/ha)	Pesticide costs (\$/ha)	Management and Labor costs (\$/ha)
India	Conv	1,315.31 (N = 96)	294.09 (N = 55)	24.13 (N = 27)	113.89 (N = 47)	221.69 (N = 38)
	Bt	1,982.77 *** (N = 76)	389.52 * (N = 42)	80.43 *** (N = 27)	79.73 *** (N = 37)	305.86 *** (N = 26)
	% Change	50.8	32.5	233.4	-30.0	38.0
China	Conv	2,277.27 (N = 15)	295.11 (N = 24)	49.08 (N = 6)	163.96 (N = 7)	1163.98 (N = 12)
	Bt	2,342.89 (N = 27)	-58.67 *** (N = 17)	62.93 (N = 7)	46.48 *** (N = 9)	939.94 *** (N = 19)
	% Change	2.9	-120.0	28.2	-71.7	-19.3
South Africa	Conv	879.57 (N = 7)	50.22 (N = 5)	20.09 (N = 5)	30.33 (N = 7)	43.34 (N = 3)
	Bt	1,133.00 (N = 7)	107.47* (N = 5)	39.53*** (N = 5)	14.66*** (N = 7)	43.19 (N = 3)
	% Change	28.8	114.0	96.8	-51.7	-0.3
Australia	Conv	1,764.31 (N = 13)	n.a.	n.a.	326.70 (N = 13)	n.a.
	Bt	1,788.59 (N = 13)	n.a.	112.96 (N = 6)	254.79 ** (N = 13)	n.a.
	% Change	1.4	n.a.	n.a.	-22.0	n.a.
USA	Conv	1,055.92 (N = 20)	1,047.20 (N = 17)	36.19 (N = 16)	138.39 (N = 17)	n.a.
	Bt	1,064.63 (N = 16)	938.46 (N = 13)	116.54 *** (N = 13)	116.23 (N = 13)	n.a.
	% Change	0.8	-10.4	222.0	-16.0	n.a.

Comparisons are made with the Mann-Whitney-U test. *, **, and *** denote significance at the 10, 5, and 1% level, respectively. N denotes the number of available observations.

Yields. A significantly higher cotton yield due to the adoption of Bt is indicated only for India, while this effect is positive but insignificant for the other countries. The estimated yield increase due to Bt cotton adoption ranges from almost zero (USA, Australia, China) to about 50% (India). These results are in line with those of Carpenter [6] showing that India provides the highest cotton yield increases due to Bt adoption. A discussion on large yield effects of Bt Cotton in India is provided by

Qaim *et al.* [7]. The increases in yield due to Bt adoption are typically related to reduced yield losses rather than to higher yields *per se*. Hence, countries with appropriate pest control mechanisms such as Australia or the USA, do not witness additional yield increases with Bt cotton. The results are consistent with findings from other authors in previous studies: For example, the absence of a yield advantages for Bt cotton or mixed effects on cotton yields were observed in Australia [8,9], and for the USA [10-14]. Table 3 shows, on average, lower yield advantages from Bt cotton adoption for South Africa and China than for India. However, Thirtle *et al.* [15] suggest that seeding rates of adopters and non-adopters should be compared rather than absolute yield differences because Bt cotton growers used less seed per hectare (perhaps because of the higher cost).

Pesticide costs. In Table 3 the reductions in pesticide costs range from 16% in the USA to about 70% in China. China showed the strongest effect of Bt cotton adoption on pesticide costs largely because cotton bollworms (*Helicoverpa armigera*) have been a major problem for cotton production in that country [16-19]. Indeed rising pest infestation has led to a sharp increase in pesticide use in China [17,18]. If pesticides were not used at all or were used only to a limited extent, then the adoption of Bt cotton would have less influence on pesticide costs, but could possibly benefit yields through more effective pest control. Also Qaim and Zilberman [20] show that yield effects of Bt cotton adoption in Argentina are higher than in other countries primarily because of the low level of insecticide use in conventional cotton production.

Seed costs. There were significantly higher seed costs for Bt than for conventional cotton in the cases of India, South Africa and the United States. A positive but statistically insignificant Bt effect on seed costs is indicated for China. The estimated mark-up of seed costs for Bt cotton ranges from 28% (China) to more than 200% (in India and the USA). Gómez-Barbero *et al.* [21,22] note that different price mark-ups are related with regional pest pressure. In addition, market structure is expected to play a major role in determining price mark-ups [23]. In general, price mark-ups for GM crops are expected to be the result of intellectual property rights that give seed companies some monopolistic power, which allows them (together with a higher willingness to pay from the farmers) to set higher prices for GM crop seeds than for conventional seeds [23].

Possible reasons for insignificant seed cost differences in China are given by Pray *et al.* [16] and Huang *et al.* [19] who observed a large difference between market prices and seed prices actually paid by farmers. As Bt farmers save seed and need less seed per hectare compared to conventional cotton growers, they can partly offset seed price differences. Note that due to governmental intervention in India, seed prices for Bt cotton strongly decreased in 2006/07 (price mark-up declined to 68%) resulting in prices being similar to those paid by Chinese farmers [2].

Management and labor costs. Compared with conventional cotton, management and labor costs for Bt cotton were higher in India and lower in China. In India, Qaim *et al.* [24] observed an increase in workload for crop maintenance and harvest of Bt adopters, mainly as a result of the higher yield. In contrast, Bt cotton adoption in China led to a sharp decline in pesticide applications from an average of 20-times to 8-times per crop season thereby reducing both pesticide and labor costs [19]. In general, these findings regarding management and labor costs are in agreement with the variation reported in Brookes and Barfoot [25].

Gross margins. Gross margins for Bt cotton compared to conventional cotton are slightly, although insignificantly (at the 5% level of significance) higher for all of the countries except for China and the

USA. Thus, the significant increase of gross margins indicated for the analysis over all countries hides the very heterogeneous effects within the countries. Note that these low gross margin effects of Bt cotton for China and the USA clearly contrast with high adoption rates in these countries [1]. This finding reflects the non-representativeness of available publications for production conditions in specific countries. However, the observed between-country heterogeneity can mainly be explained by different pesticide management practices in the respective countries. In India, increasing yields lead to higher revenues and lower pesticide costs offset higher costs for seed and labor. Furthermore, product quality increases with the adoption of Bt cotton, resulting in an additional net benefit for the farmer [26]. In China, where yield levels were already high, the main advantages of Bt cotton are cost reductions due to lower pesticide use. While yields of Bt and conventional cotton are similar, pesticide, management and labor costs are substantially reduced. However, on average, higher seed costs could not be offset in China, thereby resulting in lower average gross margins. Health benefits for farmers due to Bt cotton adoption in China are frequently mentioned [27,28], but are not addressed in this economic analysis.

In South Africa, yields were higher for Bt cotton adopters than non-adopters and pesticide costs were also significantly reduced [29-32]. Shankar and Thirtle [33] observed that smallholders are offsetting the higher seed cost of GM by lowering the seeding rate per hectare. In the USA, the advantages of Bt cotton adoption are not as clear as in other countries. The USA already has adequate pest control measures in place as well as wide range of conventional varieties that are perfectly adapted to local conditions. Studies conducted by Bryant *et al.* [34] and Jost *et al.* [35] found that the profitability of cotton production is associated with yield and not with technology. Therefore, they suggest that cultivar selection should be focused on the yield potential of the underlying variety and not the technology.

In conclusion, the published effects of Bt cotton are very heterogeneous between the countries. This heterogeneity increases even more when going from the national to regional scale within a country. For instance, results for the effects of Bt cotton in India show a huge within-country heterogeneity ranging from negative effects to very promising increases of yields and gross margins [6]. In general, Bt cotton has the highest potential to create an added value to conventional crops if the trait is introduced in locally adapted varieties and if pest pressure is high. Due to the differences in pest management practices and general yield levels, results differ strongly between countries. India, with low yield levels benefited most from a reduction in yield losses. In contrast, China, with a yield level that was already high, benefited most from reduced production costs. In countries where crops are well adapted to local conditions and pesticide control is efficient (e.g., Australia and the USA), Bt cotton shows the lowest benefit. There are potential benefits from Bt cotton that are not covered by our analysis of economic effects but that are frequently mentioned in the literature. These are related to health effects and reduced environmental pollution [15,29,30].

3.2. Maize

Most data for Bt maize are available for Spain, Germany, South Africa and Argentina. Only limited observations are available for the Czech Republic, France, Poland, Portugal, Romania, and Slovakia.

Note that the (commercial) cultivation of maize varieties that contain the MON810 trait has been banned in France and Germany in 2008 and 2009, respectively [36].

Figure 2 shows yields and seed costs for maize by year, country and trait (Bt and conventional crop). Other plots are omitted due to the lack of data. The most observations are available for yield and seed costs. For gross margins, the small number of observations does not allow for regression analysis. The plots indicate that the heterogeneity within the data is mainly caused by country specific effects. Results of the regression are presented in Table 4.

Figure 2. Yields (left panel) and seed costs (right panel) for maize.

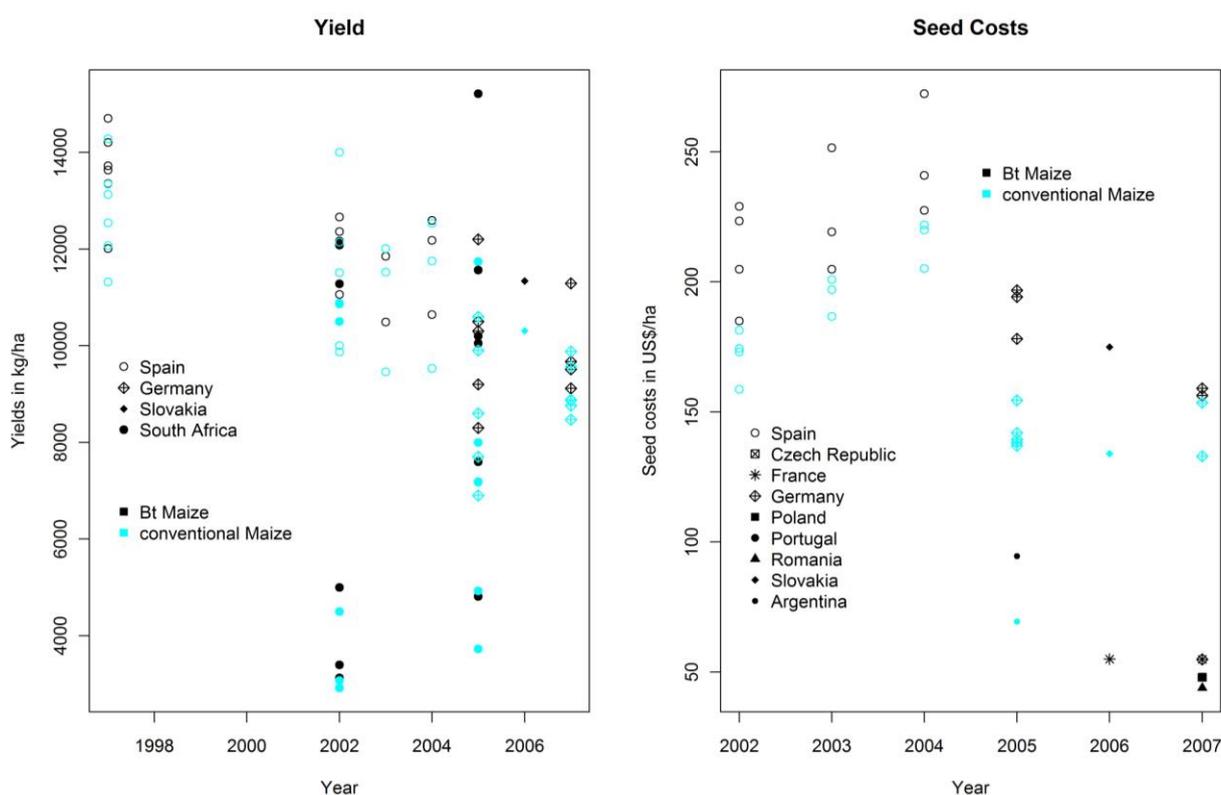


Table 4. Parameter estimates from the regression models on different economic performance indicator for maize.

Economic performance indicator	Yield model	Seed costs model	Pesticide costs model	Management and labor costs model
Intercept (β_0)	9.408 *** (72.96)	5.331 (37.77) ***	2.965 (3.86) ***	6.452 (41.35) ***
Time Effect (β_1)	-0.012 (-0.57)	-0.090 (-1.85)*	-0.086 (-0.28)	-0.013 (-0.17)
Bt Effect (β_2)	0.039 (0.22)	0.479 (2.56) **	-0.666 (-0.75)	0.051 (0.26)
Bt Effect *	0.0117 (0.51)	-0.109 (-2.27) **	-0.231 (-0.87)	-0.014 (-0.11)
Adjusted R-squared	0.33	0.77	0.54	0.96
Degrees of freedom	71	45	39	19

*, **, and *** denote significance at the 10, 5, and 1% level, respectively. Numbers in parentheses are t-values.

Time effect. Coefficient estimates for β_1 show that there is no significant change in all of the economic performance indicators over time (except for seed costs, showing a slight reduction over time). Increases over time in maize yields were expected, at least for most of the developed world [3,37]. However, such a trend was not indicated by the results because of the relatively short time period of observations for Bt maize (dataset covers the period 1997–2007).

Bt effect. Seed costs for Bt maize (β_2) were significantly higher than for conventional maize (in the range of 48%). Yields, pesticide costs and management and labor costs were not significantly affected by Bt maize adoption.

Bt effect over time. While no significant interaction (β_3) was found for yield or pesticide and management and labor costs, a significant interaction effect for seed cost indicates that the mark-up for Bt maize is fading over time. However, it should be noted that this particular result was caused by very low seed costs (*i.e.*, influential observations with a leverage effect) in the year 2007 for some European countries (see Figure 2). The relatively high values of goodness of fit, although most coefficients were insignificant, show that differences between countries (country dummies) explained the vast majority of heterogeneity within the data. Thus, more insight can be gained from country specific analyses, which are presented in Table 5. The lack of observations for most variables and countries requires a careful interpretation.

Table 5. Economic performance indicators by country for Bt and conventional maize.

Country	Trait	Economic performance indicator				
		Yield (kg/ha)	Gross margin (\$/ha)	Seed costs (\$/ha)	Pesticide costs (\$/ha)	Management & Labor costs (\$/ha)
Spain	Conv	11,840 (N = 19)	1,214 (N = 5)	186.3 (N = 12)	23.680 (N = 11)	na
	Bt	12,500 (N = 17)	1,333 (N = 5)	204.80 ** (N = 13)	10.380 ** (N = 10)	na
	% change	+5.6	+9.8	+9.9	-56.2	na
Germany	Conv	8,921 (N = 11)	36.50 (N = 2)	142.7 (N = 11)	117.50 (N = 9)	631.0 (N = 9)
	Bt	10,010 (N = 9)	88.50 (N = 2)	166.60 ** (N = 8)	88.63 ** (N = 7)	673.7 (N = 7)
	% change	+12.2	+142.5	+16.7	-24.6	+6.8
South Africa	Conv	7,124 (N = 12)	na	na	19.35 (N=5)	na
	Bt	8,874 (N = 12)	na	na	8.485 (N = 4)	na
	% change	+24.6	na	na	-62.4	na
Argentina	Conv	na	62.8 (N = 4)	69.3 (N = 4)	na	46.2 (N = 4)
	Bt	na	73.4 (N = 4)	94.5 ** (N = 4)	na	46.0 (N = 4)
	% change	na	+16.9	+36.4	na	0%

Comparisons are made with the Mann-Whitney-U test. *, **, and *** denote significance at the 10, 5, and 1% level, respectively. N denotes the number of available observations. na denotes non-availability of data.

Yields. As indicated by the regression model applied over all countries, there were higher yield levels for Bt than for conventional maize. For Spain, average observed yield increases due to Bt maize adoption were approximately 6%, for Germany around 12% and for South Africa about 25%. The result for Spain is in line with Brookes [38] who estimated an average yield advantage of 6.3% between 1998 and 2003 and of 10% from 2004 onwards. However, yield advantages reveal large heterogeneity over regions and time. For instance, a survey conducted by Gómez-Barbero *et al.* [21,22] in Spain showed yield effects of Bt maize adoption that ranged from -1.3% in Albacete to +12.1% in Zaragoza. Highly heterogeneous results depending on region, infestation level and the effectiveness of common pest management practices were also observed in Germany: Whereas most studies show yield increases due to Bt maize adoption [39-41] others did not find significant yield differences [41]. In Germany, Bt maize seems to be most beneficial in the Oderbruch region [42] due to high pest infestation levels. Moreover, large scale farm structures in the Oderbruch region particularly facilitated the adoption of BT maize due to low costs for compliance with co-existence rules in Germany [43].

In South Africa, yield advantages for Bt maize seem to be more consistent over time and across regions as compared to Spain and Germany. Gouse *et al.* [44,45] showed high yield advantages from Bt maize for smallholders as well as large commercial farmers during the growing seasons 2000/01 to 2003/04, even if farmers did not report high stem borer infestation levels [44]. However, after three years of dry conditions, low stem borer infestation levels reduced the benefits of Bt maize [45].

Pesticide costs. The results indicate lower pesticide costs for Bt maize in all of the countries included in the dataset, but statistically significant effects were only observed in Spain and Germany. As for yields, pesticide reductions in Spain varied widely between regions of that country. For instance, Bt maize farmers in Albacete and Zaragoza had 33% and 37% of the pesticide costs of conventional maize growers, whereas in Lleida no difference in pesticide cost was observed [21,22]. Indeed, the ability to significantly reduce pesticide costs is the main reason for the adoption of Bt maize for German maize farmers [40,41,43]. In particular, farmers adopted Bt maize because other available pest control measures did not effectively control pests. This is supported by the observation that the reduction of pesticide costs in South Africa was highest in irrigated areas where the moist conditions particularly favor insect growth and reproduction [44].

Seed costs. There were significantly higher seed costs for Bt than for conventional maize in Spain, Germany and Argentina. Bt mark-ups in seed cost ranged from 10% (Spain) to 36% (Argentina). In Spain, seed costs varied between regions because of the divergent pricing policies of seed suppliers [46,47], the bargaining power of farmers [48] and the potential for price discrimination between farmers [21,22]. In general, seed prices were lower in regions where yield benefits from GM crops were low [21,22,47]. The data for Germany showed almost 17% higher seed costs for Bt than for conventional maize. However, as in Spain, seed prices vary with region and infestation level (*i.e.*, potential demand). A study conducted in Saxony [41] showed that seed costs for Bt seed were low, due to discounts on Bt seed and reduced planting densities for Bt maize. For Argentina, seed cost increases due to Bt maize of about 36% have been reported by Paredes and Martin [49]. For South Africa, no seed cost data are available, but Gouse *et al.* [44] mention seed cost differentials being dependent on the seed company. Whereas some studies show Bt seeds being offered free of charge by a seed company [44], other studies state that when farmers have to pay mark-ups for Bt seed, in particular smallholders were not able to do so due to financial constraints [44].

Management and labor costs. For Germany, increased management and labor costs were indicated due to the adoption of Bt maize. This result represented the additional labor needed to clean the machinery used for Bt maize (due to legal restrictions on GM crops) [41]. In Spain, increased management flexibility and convenience, reductions in contractor costs for spraying and reduced production risk were observed by Brookes [50]. In South Africa, reduced labor and fuel costs were observed for large commercial farmers because less pesticide applications were needed and less time was spent scouting fields for pests [44].

Gross margins. The few observations of gross margins in the dataset showed advantages of Bt over conventional maize, indicating that, on average, higher seed costs could be offset by higher yields and/or lower pesticide costs. In Spain, the main reason for gross margin differences have been attributed to different yield effects [21,22]. German farmers have benefited from higher yields (where commonly used pest control measures were not effective) leading to increases in income [43]. Schiefer *et al.* [41] have mentioned pest pressure as an important determinant in the advantage of Bt maize, and this is affected by weather. Paredes and Martin [49] report higher gross margins due to Bt maize adoption in Argentina but point out that the adoption of Bt maize on smaller farms with low current input use might reduce gross margins as a result of increases in input use (e.g., fertilizer and herbicides). In South Africa, the main advantage of Bt maize for some farmers was higher yields, while for others it was higher quality of the produce [44]. However, in growing seasons with low pest pressure, Bt maize growers were worse off than conventional farmers as Bt does not provide yield benefits *per se* and the seed costs are higher [44,45]. Quality advantages of Bt maize have also been observed in Germany because of reduced mycotoxin content [40,41,43]. Less pest damage in Bt maize resulted in less fungal infection and hence reduced mycotoxin. Another benefit mentioned by German farmers was related to a positive impact of Bt maize on the environment [43]. See Brookes and Barfoot [51] for a global review on environmental effects of GM crops.

In summary, the country specific analyses as well as the regression analysis support the existence of higher seed costs for Bt than for conventional maize. Moreover, some evidence is provided that pesticide costs are lower for Bt maize, whereas yield levels are only slightly higher. In contrast to Bt cotton, the lack of sufficient observations does not allow for an in-depth analysis of the effects of Bt maize on economic performance indicators. However, the results suggest a large regional heterogeneity of the effects of Bt maize within countries, primarily as a result of different infestation levels and commonly used pest control measures. Hence, the (on average) lower effects of Bt maize compared to Bt cotton might be explained by the already well adapted varieties and pest measures available for maize, that do not compensate for higher seed costs. Regional and seasonal variation also appears to be prevalent for Bt maize performance.

4. Discussion

As shown in Table 1, Bt Cotton was the most represented GM crop in the database. In agreement with the findings of Smale *et al.* [52], it appears that most of the available literature on farm-level impacts of GM crops in developing countries is related to Bt Cotton in China, India and South Africa. There is a lack of available publications for other developing countries and crops. In particular, Brazil and Argentina (as well as Mexico) are relatively under-represented (given the large area under GM

crops in these countries) in the database suggesting that there are few published accounts for GM performance in those countries. This point has also been made by Contini *et al.* [53], Paredes and Amrtin [49] and Smale *et al.* [52]. One possible reason for the relative lack of studies from Latin America in the database might be the focus upon publications written in English. However, there are other explanations for different parts of the world. For example, in agreement with the findings of this study, Maciejczak [54] has reported a lack of publications on farm-level GM crop benefits in Europe—except for Spain. This lack of available information is primarily a result of the small adoption rates of GM crops in Europe. Moreover, the focus of European research related to GM crops is rather on coexistence, public acceptance, or environmental impacts than farm-level socio-economic benefits. The studies of Brookes *et al.* [46,47,50,55-57] are the most comprehensive sources for farm-level GM crop benefits in Europe at large [54]. There is also a problem in the sense that most European work on GM crops has been published in form of reports and conference papers, and these are not so readily accessible. A similar problem of data availability was encountered for Bt Cotton in developed countries, where the most important communication channels of farm-level effects of Bt Cotton have been conference proceedings (e.g., the Beltwide Cotton Conference). Conference proceedings can be sporadic in terms of their availability via online databases and search engines. Therefore, numerous data sources for GM cotton may not be included in the database, even though they may be frequently cited in the literature. Moreover, we found a general lack of available sources for farm-level benefits of Bt Maize for developed countries. In agreement with Gómez-Barbero and Rodríguez-Cerezo [58], a particular lack of available observations was found for the USA, although ironically it is the main adoption country of Bt Maize.

It also has to be noted that the results presented here are limited due to unobserved costs that may arise with the adoption of GM crops. For instance, Finger *et al.* [59] indicate that land rents might rise with increasing rates of GM crop adoption. Thus, economic rents of GM crops might increase the welfare of landowner and not necessarily those of the farmers. Moreover, longer-term market responses to the introduction of GM crops are not reflected in the analysis. For instance, an increasing demand for genetically modified seeds could conceivably increase seed costs for farmers and an increased production due to widespread GM adoption might reduce output prices. Furthermore, farm-level costs and benefits of GM crops might be highly influenced by governmental regulation and societal acceptance as in many parts of Europe [60,61]. In general, benefits have to be balanced with local public concerns (see Azadi and Ho [62] for a review), as public opinion can influence individual farmers adoption choices [43]. In addition, the risk of resistance of insects and weeds to GM traits and herbicides [63] should be addressed in further research.

The analysis of trends of GM crop effects over time did not reveal significant changes, but it should be noted that most studies and surveys capture information only over one or perhaps a few growing seasons. These are relatively short periods of time to assess the long-term impact of the introduction of a new technology [6]. Thus, long-term effects, particularly with respect to infestation levels, pesticide costs and crop yields, might not be adequately addressed by combining several short-term studies as has been done here.

The use of individual studies in a meta-analysis is furthermore hampered by the fact that these studies might use totally different methodologies (and motivations) to assess the economic effects of GM crops. For instance, such assessment might be based on impact studies using field trials or surveys

that have been conducted by public research institutions or private companies. Smale *et al.* [52,64] provide a description of potential biases that can occur with different methodologies. A sensitivity analysis on the general study type (comparing for instance field trials and surveys) and the study conductor using the database revealed differences within these items, but the problem is that this factor is often confounded with others such as the crop and country. It is rare to find a situation where a GM crop grown in one country has been the subject of a range of different yet replicated methodologies. Hence this issue is beyond the scope of the paper. Moreover, results are potentially biased because studies might differ in their focus on potential or realized yield levels, their use of different baselines for comparisons and other background conditions. Thus, we are aware that the comparability among individual studies is restricted.

As a result of all the above points the conclusions presented in the paper have to be treated with caution and it is not possible to generalize to a global scale. However, some interesting points do emerge that shed light on the diversity that can be observed in the literature and which helps fuel the divergent viewpoints held in the GM debate. The analyses presented here do broadly support the pattern set out in much of the literature for the economic performance of GM crops: Compared to conventional crops, GM crops can lead to yield increases and can lead to reductions in the costs of pesticide application, whereas seed costs are usually substantially higher [6,25]. On a global level, no overall large yield effect of Bt crops (resulting from reduced yield losses) was indicated. In cases where yield increases and the reduction of pesticide inputs outweigh the higher seed costs, farmers receive a higher gross margin by growing GM crops. However, the results also show a heterogeneous pattern with benefits of GM crop adoption being manifested in various ways, depending upon the extant pest management practices in the specific country. Note that heterogeneous impact patterns (depending on local production conditions) are not exclusively a GM crop specific result, but are rather the rule for agricultural technologies in general. The same mechanisms are at play when progressing from the country to the regional level. Indeed the heterogeneity of study results can be even larger at the regional level (see for example the results of Gómez-Barbero *et al.* [21,22], for Spain). The observed economic impacts of GM crops in any 'place' will depend on the yield potential of crop varieties (GM as well as conventional varieties), the pest pressure and general and seasonal dependent climate and weather conditions, as well as government intervention. For example, if pest management was already well established before the adoption of Bt maize or cotton then any yield benefits which arise from growing such insect-resistant GM varieties may be rather low (e.g., the USA and Australia). These countries, however, benefit most from reduced pesticide costs. In countries with poorer pesticide or herbicide management (e.g., India for Bt cotton), yield advantages were the major benefit of GM crop adoption, as yield losses can substantially be reduced. An illustrative example for this argument is the case of HT soy in Romania, where significant yield increases have been reported for HT soy based on the very poor weed management prior to the adoption of HT soy [56,57], while yield effects in other countries with better weed management have been low [65]. However, benefits of GM crops might differ substantially between years, in particular due to large variability of infestation levels and/or weather [45]. Thus, farmers' advantages of GM crop adoption appear in various ways, depending on the pest management practices in the specific country. Hence results from different locally conducted studies often do not show clear and consistent trends, thereby allowing those at either end of the GM debate to select studies that support their own view.

5. Conclusions

The results presented here do support the contention that the adoption of GM crops leads on average to a higher economic performance, *i.e.*, benefits, for farmers than conventional (non-GM) crops. This is in agreement with other studies that analyze economic performance of GM crops and are also underlined by the high (and increasing) adoption rates for GM crops in a number of countries [1]. An important finding of the analysis is that the kind and magnitude of benefits are heterogeneous across crops, traits, countries and regions. By and large, the results suggest that the adoption of Bt cotton is particularly (economically) beneficial for the farmers in developing countries while positive effects are present but less significant for developed countries.

The analysis suggests that the overall assessment of farm-level costs and benefits of GM crops has severe limitations. Published data are skewed towards some developing countries, thereby increasing their representation compared to the globally more important agricultural producing countries in a combined analysis. Moreover, such overall (or general) assessment often combines data sources that rely on totally different methodologies and assumptions and are conducted with different purposes. Thus, by adding-up individual studies within a meta-analysis there is the risk of comparing apples and oranges. Furthermore, a summary of several (often) short-term individual studies may not necessarily capture long-term environmental and economic effects and trends.

Though yield increases are significant for specific countries, no general increases of crop yields for analyzed countries were observed due to the adoption of GM crops. This is due to the fact that insect and herbicide resistant traits are not designed to increase crop yield potential. Rather, they are designed to facilitate crop management and yields are indirectly affected through reducing the risk of losses via pest damage. These currently used traits will not allow GM crops to overcome other constraints such as poor soil fertility, salinization or lack of water, although of course the GM industry is working on addressing those characteristics amongst others. However, even then there are key issues of distribution and global market inequalities to consider and these are beyond the ability of GM technicians to address. Hence, GM crops by themselves cannot address poverty or resolve global food imbalances. Nonetheless, the analysis presented here shows that GM crops are a potential tool to increase farmers' income and thus might contribute to poverty reduction and rural economic development, especially in developing countries [2]. In this respect, GM crops can be one of many pieces of the puzzle necessary to enable sustainable social and economic development, and all of these aspects should be considered in the assessment of this technology. However, while the literature on the economic impact of GM crops has grown in recent years there is still a need for more comparative studies across space and time in order to pin down these impacts and allow for a better assessment of the contribution that this technology can make to sustainable development. In effect the jury is still out although the signs so far are positive.

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