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First impact of biotechnology in the EU: Bt maize adoption in Spain

By M DEMONT * and E TOLLENS

Katholieke Universiteit Leuven, de Croylaan 42, B-3001 Leuven, Belgium

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Summary

In the present paper a bio-economic model was constructed to estimate the impact of a biotechnology innovation in EU agriculture. Transgenic *Bt* maize offers the potential to efficiently control corn borers that cause economically important losses in maize growing in Spain. Since 1998, Syngenta has commercialised the variety Compa CB, equivalent to an annual maize area of about 25 000 ha. During the 6-year period 1998-2003, a total welfare gain of 15.5 million euros was estimated from the adoption of *Bt* maize, of which Spanish farmers captured two thirds, the rest accruing to the seed industry.

Key words: Biotechnology, impact, EU, *Bt* maize, corn, Spain

Introduction

Since the Second World War, the industrialisation of maize growing in Europe has essentially been driven by technological (genetics, mechanics and chemistry) and economic change. The innovation wave started with the commercialisation of hybrid maize in the fifties (Griliches, 1958). In the seventies, technical and economical constraints emerged due to a slowing down of growth in productivity (Gaillard, 1988). During the eighties, fixed costs increased, causing a sharp decline in maize profitability (Le Stum & Camaret, 1989). Today, the sector faces structural constraints, raising the demand for cost-reducing technological innovations such as biotechnology. In 1998, two transgenic maize varieties from Syngenta Seeds were approved for commercialisation in Spain. However, in 1999 the EU issued a *de facto* moratorium on new approvals of transgenic crops. Syngenta voluntarily agreed to limit its transgenic seed supply to the 1998 level for the variety Compa CB until the moratorium is lifted (Brookes, 2002). Hence, Spain is the only EU country where transgenic crops are currently grown by farmers.

The purpose of this paper is to estimate the first impact of a biotechnology innovation in the EU, i.e. transgenic maize in Spanish agriculture. The temporal variability of the impact estimates, uncertainty and the sensitivity of the model to the limited set of data and assumptions is also assessed. The paper is structured as follows; in the first two sections the importance of maize growing in the world and maize crop protection are assessed. In the third and fourth sections the model is constructed and data and assumptions are discussed. The fifth and sixth sections outline the results and conclude.

Economic Importance of Maize on a World-Wide Scale

Maize is the world's most ubiquitous cereal (Table 1). It is cultivated from the equator to roughly 50º north or south latitude, from sea level to more than 3000 m altitude. No other cereal is used in as many different ways; nearly every part of the maize plant has economic value. Moreover, growing incomes in developing countries have stimulated demand for meat and poultry consumption and, as a result, derived demand for maize as animal feed (Pingali, 2001). The present study concentrates on grain maize.

Table 1 shows that, while maize is important in all continents, yields vary greatly, ranging from 1.6 t ha^{-1} in Africa to 10.6 t ha^{-1} in Belgium. Three sub-continents (USA, South-America and Asia) produce three quarters and export 11% of global maize (Pingali, 2001). The three largest EU maize producers, together responsible for 77% of maize output, are France (40%), Italy (26%) and Spain (11%).

Economic Importance of Maize Crop Protection

The corn borer

The European Corn Borer ECB (*Ostrinia nubilalis* (Hübner)) and Mediterranean Corn Borer (MCB) [*Sesamia nonagrioides* (Lefebvre)] are economically important pests. In North-America and Central-Europe, losses are primarily caused by the ECB. On a continental level, the number of ECB generations increases progressively from north to south (Mason *et al.*, 1996). In contrast to the USA Corn Belt, where ECB occurs bivoltine, a single generation is observed

*Corresponding Author E-mail: matty.demont@agr.kuleuven.ac.be

in Central-Europe (Bohn *et al.*, 1999), while in southern Europe up to three generations occur (Kergoat, 1999).

The MCB is considered to be one of the most severe maize pests around the Mediterranean Sea and Morocco. Like the ECB, the number of generations increases according to latitude. Two generations prevail, but a single generation also occurs in some areas, like the Azores. In the north-east of Spain, the south of Portugal, Sardinia and Greece, three generations dominate, while four generations can be observed in Morocco (Cordero *et al.*, 1998).

Both insects cause severe crop losses in Spanish maize production. The degree of crop loss largely determines whether the adoption of a pest control strategy is economical. Corn borers cause severe physical damage to the plant. The borer penetrates the stalk and excavates large tunnels that result in important yield losses. This complicates the circulation of water and nutrients to the plant and the ear. The timing of corn borer attack is important and plants are most vulnerable before physical maturity.

Crop protection: insecticides, Bt and Bt maize

Larvae from corn borers are difficult to control with chemical insecticides (organophosphates and synthetic pyrethroids) because they are vulnerable to sprays or residues for only a short time before they bore into and are protected by the cob, sheath-collar, or stalk (Jansens *et al.*, 1997). Insecticides are effective when the larvae have just hatched or when they migrate to neighbouring plants (Velasco *et al.*, 1999). Therefore, proper timing of insecticide application is crucial for success and repeated applications are often necessary. However, actual practices are rarely optimal, such that the use of insecticides is limited in Spain (Brookes, 2002).

Bacillus thuringiensis (*Bt*) is a naturally-occurring soil borne bacterium that is found worldwide. A unique feature of this bacterium is its production of crystal-like (Cry) proteins that selectively kill specific groups of insects (Ostlie *et al.*, 1997). *Bt* incorporated into sprays provides organic farmers with a natural crop protection tool against corn borers.

Plant geneticists create *Bt* maize by inserting a gene of the bacterium, that causes the plant to produce the toxin. Depending on the gene, the proteins Cry1Ab, Cry1Ac, Cry1B or Cry9C are produced. Labatte *et al.* (1996) demonstrated that *Bt* maize has a higher efficacy and shorter time response than insecticides, regardless of the infestation date. Therefore, *Bt* maize has the potential to dramatically improve the control of corn borer, compared with current practices.

Adoption of Bt maize

Transgenic maize was first commercialised in the USA and in Canada in 1996 and two years later in Argentina, South-Africa and Spain. Since then, the adoption has increased up to 15.5 million ha in 2003 (Table 2). The majority of transgenic maize, i.e. 9.1 million ha, are insect resistant (IR) *Bt* varieties. The other varieties are herbicide tolerant (HT) or stacked IR and HT. Today, 8 yr after introduction, the experiences of *Bt* maize growers all over the world are well recorded (extensively reviewed by James 2003*a*). Yield gains due to *Bt* maize are estimated at 5% in the temperate growing areas and 10% in the tropical areas, where there are more and overlapping generations of pest leading to higher infestations and losses. Farmers assign *Bt* maize high value because it is a convenient and cost effective technology that allows them to manage risk in an uncertain environment and offers insurance against devastating crop losses in years when pest infestations are unusually high. Moreover, the technology offers safer feed and food products than conventional maize with lower levels of harmful mycotoxins.

On the 26 March 1998, Syngenta's *Bt* maize varieties Compa CB (Bt 176) and Jordi CB were registered in the Commercial Variety Register in Spain and approved for commercialisation, but only the first variety has been sold effectively. The main adopting regions were Catalunya (13%), Aragon (11%), Castilla-La Mancha (9%), Madrid (9%), Navarra (4%), Andalusia (3%) and Extremadura (2%) (Alcalde, 2003). Table 2 shows that during 1998-2002 *Bt* maize adoption in Spain stagnated at about 25 000 ha because of Syngenta's voluntary arrangement. In 2003 this constraint was lifted and the Ministry of Agriculture approved five new varieties, developed by Syngenta, Pioneer, Monsanto, Nickerson and Limagrain. In the same year, the area planted to *Bt* maize increased to 32 000 ha (James, 2003*b*).

Bio-Economic Model

Estimating the impact of *Bt* maize can be done through expensive on-farm surveys comparing *Bt* maize fields with conventional maize fields (Marra *et al.*, 2002), which is outside the scope of this research. Instead, we estimate the impact of *Bt* maize analogously to Ostlie *et al.* (1997).[1] It is assumed that maize borer infestation decreases yield proportionally to the damage incurred despite pest control technology k. The technology k can be: absent ($k = o$), conventional through insecticides ($k = c$) or biotechnological through *Bt* maize ($k = g$). The observed yield y_{jk} (t ha^{-1}) can be expressed as:

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[1] Hyde *et al.* (1999) use a more complex model, requiring data that are not available for our study.

Table 1. *Importance of grain maize growing in the world, average 1998-2003*

	Area (10^6 ha)	%	Yield (t ha^{-1})	Production (10^6 t)	%	% EU
Africa	26.0	18.7%	1.6	42.6	7.0%	
Asia	43.1	31.0%	3.8	163.8	26.8%	
Canada	1.2	0.9%	7.3	8.7	1.4%	
EU-15	4.3	3.1%	8.8	38.1	6.2%	100.0%
Austria	0.2	0.1%	9.4	1.7	0.3%	4.5%
Belgium-Lux.	0.0	0.0%	10.6	0.4	0.1%	1.1%
France	1.8	1.3%	8.6	15.2	2.5%	39.8%
Germany	0.4	0.3%	8.6	3.3	0.5%	8.8%
Greece	0.2	0.2%	9.3	2.0	0.3%	5.3%
Italy	1.1	0.8%	9.4	10.1	1.6%	26.4%
Netherlands	0.0	0.0%	8.6	0.2	0.0%	0.5%
Portugal	0.2	0.1%	5.8	0.9	0.1%	2.4%
Spain	0.5	0.3%	9.5	4.3	0.7%	11.3%
South-America	17.2	12.4%	3.4	59.0	9.6%	
USA	28.7	20.6%	8.5	244.4	40.0%	
Other	18.6	13.4%	3.0	55.2	9.0%	
World	139.0	100.0%	4.4	611.7	100.0%	

Anon. (2004*c*)

Table 2. *Adoption of transgenic and Bt maize in the world and in the EU, 1996-2003*

Area	1996	1997	1998	1999	2000	2001	2002	2003
World (10^6 ha)								
Transgenic maize	0.3	3.2	8.3	11.1	10.3	9.8	12.4	15.5
Bt maize	0.3	3.0	6.7	7.5	6.8	5.9	7.7	9.1
EU *Bt* maize								
Spain (ha)	0	0	22 000	30 000	20 000	25 000	25 000	32 000
Spain (%)	0	0	4.8%	7.6%	4.6%	5.0%	5.4%	6.8%
France (ha)	0	0	2000	< 2000	< 500	0	0	0
Germany (ha)	0	0	0	0	< 500	< 500	< 500	< 500
Portugal (ha)	0	0	0	1000	0	0	0	0

James (1997; 1998; 2000; 2001*a,b*; 2002*a,b*; 2003*a,b*)

$$y_{jk} = y_{jm}\,[1 - (1 - \alpha_k)\, s_j] \qquad (1)$$

with y_{jm} (t ha^{-1}) the theoretical maximum yield attained under hypothetical absence of corn borers in year *j* (j = 1998, 1999, ..., 2003), α_k the efficacy of technology *k*, measured by the proportion of larvae killed before affecting yield, and s_j the theoretical average proportional loss caused by corn borers in year *j* under absence of treatment. The profit per hectare π_{jk} (euros ha^{-1}) of the farmer using technology *k* in year *j* is:

$$\pi_{jk} = p_j\, y_{jk} - w_k - c_j = p_j\, y_{jm}\,[1 - (1 - \alpha_k)\, s_j] - w_k - c_j \quad (2)$$

with p_j (euros t^{-1}) the maize price in year *j*, w_k (euros ha^{-1}) the cost of technology *k* to combat corn borers and c_j (euros ha^{-1}) all other costs that are independent of the choice of technology *k*, including the cost of conventional seed. In the case of an insecticide treatment ($k = c$) w_k comprises the cost of the product and the spraying application. For biotechnological crop protection ($k = g$), w_k represents the technology fee. In case of no treatment ($k = o$), $w_k = 0$.

Before 2003 the adoption of *Bt* maize stagnated at an average of 5.5% (Table 2), while the adoption of insecticides reached 13% to 22% during 1999-2001 (*cfr. infra*). Brookes (2002) observed some *Bt* maize adopters who did not previously use insecticides. Since no data is available on the share of this category of adopters, it can be reasonably assumed that the actual *Bt* maize adopters were insecticide users before adoption. This provides a conservative impact estimate.[2] This assumption

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[2] Our null hypothesis assumes that farmers are not benefiting from *Bt* maize. Since no survey data is available about the share of *Bt* adopters who were non-insecticide users before, by making this assumption a type II error is avoided, in which the null hypothesis is rejected by overestimating farmer's benefits. Choosing conservative assumptions is very common in impact assessments of agricultural research since Griliches' (1958) seminal paper, stating: "*At almost every point at which there was a choice of assumptions to be made, I have purposely chosen those that would result in a lower estimate*".

implies that the benefits from adopting *Bt* maize are generated by two factors: the difference in efficacy of corn borer control and the cost difference between both technologies. Next, the innovation as a technology spill-in into Spain, mainly from the USA who started to adopt *Bt* maize first, was modelled. The low presence of Spain in global maize production (Table 1) and low degree of self-sufficiency (Table 3) suggest modelling Spain as a small open net importer of maize, i.e. not able to influence world prices significantly through the adoption of the new technology. Moreover, the EU's Common Market Policy guarantees a minimum price for maize, preventing any price decline below a certain threshold. Both arguments suggest modelling maize demand in Spain as infinitely elastic. These assumptions allowed the change in producer surplus ΔPS_j (euros) in year *j* to be modelled as (Alston *et al.*, 1995, p. 227):

$$\Delta PS_j = p_j\, Q_{0,j}\, K_j\, (1 + 0.5\, K_j\, \varepsilon) \qquad (3)$$

with ε the maize supply elasticity. The counterfactual maize production $Q_{0,j}$ (t) in year *j* is the production that would have been recorded if no *Bt* maize were available in that particular year and was calculated as:

$$Q_{0,j} = Q_{1,j} \,/\, (1 + K_j\, \varepsilon) \qquad (4)$$

with $Q_{1,j}$ (t) the observed national maize production in year *j*. The calculation of the proportionate vertical supply-shift K_j has been the subject of discussion in recent literature. Alston *et al.* (1995) suggested converting yield increases to the equivalent cost reduction by dividing the yield increase by the elasticity of supply. Falck-Zepeda *et al.* (2000) calculated the K-shift of *Bt* cotton in the USA by adding this cost reduction to the net pesticide cost change per ton. Oehmke & Crawford (2002) argued that this approach is very sensitive to the assumed value of the supply elasticity and recommended investing greater efforts to obtain data that can inform a direct measurement of the K-shift. According to Lekakis & Pantzios (1999), Spanish maize production is highly elastic, their econometric model yielding an elasticity of 2.5 for the period 1990-1994. Therefore, analogous to Qaim's (2003) impact assessment of *Bt* cotton in India, the gain in total factor productivity (TFP) was estimated at the farm level by calculating the proportionate per-unit cost reduction ΔC_j due to the conversion from insecticides ($k = c$) to *Bt* maize ($k = g$) in year *j*[3]:

$$\Delta C_j = \frac{(w_c + c_j) \,/\, y_{jc} - (w_g + c_j)\, y_{jg}}{(w_c + c_j) \,/\, y_{jc}} \qquad (5)$$

Next, the proportionate vertical supply-shift K_j is then simply:

$$K_j = \Delta C_j \rho_{jg} \qquad (6)$$

with ρ_{jg} the *Bt* maize adoption rate in year *j*. The present value *W* (euros) in 2004 of the aggregated producers' surpluses since 1998 was calculated as:

$$W = \sum_{j=1998}^{2003} \Delta PS_j\, (1 + i)^{2004-j} \qquad (7)$$

with *i* the interest rate as discount factor. The gross profit Π_j (euros) captured by the seed industry[4] in year *j* was:

$$\Pi_j = w_g\, L_j\, \rho_{jg} \qquad (8)$$

with L_j (ha) the total amount of land allocated to maize production. The present value Π (euros) in 2004 of the aggregated gross profits since 1998 is:

$$\Pi = \sum_{j=1998}^{2003} \Pi_j\, (1 + i)^{2004-j} \qquad (9)$$

Finally, the present value in 2004 of the total welfare increase W_{tot} (euros) in Spain is:

$$W_{tot} = W + \Pi \qquad (10)$$

It is important to note that the *ex post* welfare calculation only contains private reversible effects. In reality, technologies also engender non-private effects, the so-called externalities. A growing body of scientific literature about the non-private effects of *Bt* maize is available, reviewed by James (2003*a*). The major concerns include (1) effects on non-target organisms, (2) gene flow, (3) the impact of Cry1Ab proteins in soil and surface water, (4) the evolution of pest resistance, (5) the development of antibiotic resistance and (6) food and feed safety aspects of *Bt* maize. However, positive externalities are also reported, such as (1) lower contamination of aquifers with insecticides, (2) lower farmers' exposure to insecticides and (3) lower levels of the mycotoxin fumonisin in *Bt* maize. Some of these non-private effects are potentially irreversible. For a detailed review on irreversibility, how to include it into welfare analysis and the application of the concept on a concrete case study see Demont *et al.* (2004*a,b*).

Data

An important constraint for impact assessment is the scarcity and low accuracy of data. Therefore, analogous to Davis & Espinoza (1998), stochastic

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[3] Using the before-mentioned approach, which is also common in literature, the producer surplus estimates are on average 26% lower due to the high maize supply elasticity, but do not change the general statements presented.

[4] The "seed industry" includes the gene developers, i.e. Syngenta from 1998 to 2003 and Pioneer, Monsanto, Nickerson and Limagrain in 2003, and the seed suppliers.

Table 3. *Maize supply balance in Spain, 1998-2001*

	1998	1999	2000	2001	Average 1998-2001
Production (t)	4 349 070	3 731 000	3 991 752	4 956 600	4 257 106
Import (t)	3 500 000	3 524 000	3 657 000	3 578 000	3 564 750
Export (t)	691 000	535 000	603 000	648 000	619 250
Stocks (t)	1 210 000	800 000	960 000	910 000	970 000
Stock changes (t)	150 000	-410 000	160 000	-50 000	-37 500
Domestic supply (t)	7 008 070	7 130 000	6 885 752	7 936 600	7 240 106
Domestic uses (t)	7 008 000	7 130 000	6 621 000	7 937 000	7 174 000
Animal feed (t)	5 975 000	6 075 000	5 535 000	6 804 000	6 097 250
Industrial use (t)	954 000	975 000	1 000 000	1 050 000	994 750
Human consumption (t)	48 000	47 000	52 000	43 000	47 500
Seed (t)	15 000	19 000	20 000	20 000	18 500
Loss (t)	16 000	14 000	14 000	20 000	16 000
Degree of self-sufficiency (%)	62.1%	52.3%	58.0%	62.5%	58.7%

Anon. (2003*a*)

simulation techniques were used through the software @Risk of Palisade Corporation. For uncertain parameters prior stochastic distributions were introduced and through Monte Carlo simulation techniques, posterior distributions for the outcomes in the model were generated.

Insecticide use and cost

During 1999-2001, only 59 000 to 98 000 ha, i.e. 13% to 22% of total maize area was sprayed with insecticides against ECB and MCB (Brookes, 2002). The uncertainty around insecticide adoption ρ_c (%) was modelled through a triangular distribution with a minimum of 13%, a most likely value of 18% and a maximum of 22%:

$$\rho_{jc} \sim \text{Triangular}(13\%;\ 18\%;\ 22\%) \qquad (11)$$

This is higher than the reported 5% in the USA Corn Belt (Gianessi & Carpenter, 1999), 5% in Italy, 14% in France and 10% in Germany (Gianessi *et al.*, 2003).

Estimates for the insecticide cost for corn borer control are reported by Brookes (2002). Farmers apply one or two insecticide treatments for ECB control. The insecticide cost per hectare w_{irr} (euros ha^{-1}) in irrigated maize, including the cost of the product and the application, is 18-24 euros ha^{-1}. w_{irr} was modelled as:

$$w_{irr} \sim \text{Triangular}(18 \text{ euros ha}^{-1};\ 42 \text{ euros ha}^{-1};\ 66 \text{ euros ha}^{-1}) \qquad (12)$$

The minimum is based on one treatment at a cost of 18 euros ha^{-1}. The maximum is based on two treatments at the maximum cost of 24 euros ha^{-1} and including one treatment for control of spider mites[5] at a cost of 18 euros ha^{-1}. The most likely value is the average of both. The same rationale was applied for aerial spraying (36-42 euros ha^{-1}) and the insecticide cost per hectare w_{air} (euros ha^{-1}) was modelled as:

$$w_{air} \sim \text{Triangular}(36 \text{ euros ha}^{-1};\ 69 \text{ euros ha}^{-1};\ 102 \text{ euros ha}^{-1}) \qquad (13)$$

The average insecticide cost per hectare w_c (euros ha^{-1}) for both spraying techniques was weighted according to the share of irrigated land ϕ in maize cultivation:

$$w_c = w_{irr}\,\phi + w_{air}\,(1-\phi) \qquad (14)$$

Technology fee

The technology fee represents the difference between the seed cost of a *Bt* maize variety and the average seed cost of equivalent conventional varieties. For Syngenta's Compa CB, Brookes (2002) reported a technology fee of 29-31 euros ha^{-1} in Spain. This price is recommended by the seed industry but many farmers pay lower prices through local cooperatives, i.e. 18-19 euros ha^{-1}, capturing 70% of the Spanish maize seed market[6]. These data suggest modelling the technology fee w_g (euros ha^{-1}) as:

$$w_g \sim \text{Triangular}(18 \text{ euros ha}^{-1};\ 18 \text{ euros ha}^{-1};\ 31 \text{ euros ha}^{-1}) \qquad (15)$$

Theoretical loss due to corn borers

The annual loss due to corn borers varies

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[5] In some cases the *Bt* maize farmer no longer has to spray for spider mites due to the fact that the beneficial insects that control these mites have not been destroyed by the use of insecticides.

[6] As a comparison, the technology fee of *Bt* maize in the USA was estimated at 26 euros ha^{-1} in 1997, 22 euros ha^{-1} in 1998 and 1999 and 16-17 euros ha^{-1} in 2001 (Gianessi *et al.*, 2002), while Benbrook (2001) estimated this fee to be higher, i.e. 25 euros ha^{-1} during the same period.

considerably from year to year. Therefore, a bio-economic stochastic distribution was constructed for this parameter. For each year *j* such a distribution was incorporated and assumed to be mutually independent, since Hurley *et al.* (2004) found no statistically[7] insignificant time trends of ECB losses. While gamma as well as lognormal distributions were used to model insect damage, a better statistical fitting for the lognormal distribution was observed. Therefore, the proportional loss s_j by corn borers in year *j* in hypothetical absence of pest control was defined as:

$$s_j \sim \text{Lognormal}(\mu\,;\,\sigma) \tag{16}$$

Data on average annual losses caused by corn borers in Spain are scarce but Alcalde (1999) and Fernández-Anero *et al.* (1999) reported estimates for these losses s_j during the four-year period 1995-1998 (first row in Table 4). The loss was estimated by comparing the yield of *Bt* varieties with that of isogenic[8] varieties. This is the most accurate methodology to estimate the yield boost of transgenic insect resistant varieties (Demont & Tollens, 2001). Since only a small sample of four data points was disposed of, the median of 0.09 was used as the most likely value μ for the lognormal distribution. The median is more robust for outliers than the average in the case of such a small skewed sample. The standard deviation of 0.09 was used as an estimate for σ.

By dividing the annual loss s_j by an average loss of 6% per corn borer per plant (Bohn *et al.*, 1999), estimates of the population sizes were obtained, measured as the average number of borers *n* per plant (second row in Table 4). In the absence of pest control, on average two corn borers per Spanish maize plant can be found. Calculating the coefficient of variation (CV, last column) allowed a comparison of the parameters of the stochastic distribution of Spain with data from the USA. The Spanish situation is most comparable with data from Cumming County (Hurley *et al.*, 2004). The average was high, justifying the use of the median as the most likely value. The coefficient of variation was in the range of values (0.75-1) found in the USA. The occurrence of one severe loss every 4-8 yr has also been observed in the USA (Rice & Ostlie, 1997). Finally, since no negative losses or losses greater than 100% can be incurred, the lognormal distribution was truncated to the interval [0,1].

Efficacy of both technologies

Estimates of the efficacy of insecticides to control corn borers vary considerably. Ostlie *et al.* (1997) reported an efficacy of 80% against first generation borers and 67% against second generation. Labatte *et al.* (1996) observed an average efficacy of 72% in the case of suboptimal timing. Since timing plays a crucial role, a wide variation for the insecticide spraying efficacy α_c (%) was assumed:

$$\alpha_c \sim \text{Triangular}(70\%;\,80\%;\,90\%) \tag{17}$$

Low values capture the potential impact of the development of ECB resistance against insecticides while high values capture the emergence of technological innovations in conventional spraying techniques.

Regarding the efficacy of *Bt* maize in Spain, no data is available. Farmers report no loss of yield from using it (Brookes, 2002). Labatte *et al.* (1996) also observed no yield losses in France. We conservatively used the value of 95%. Uncertainty about the efficacy of *Bt* maize in Spain α_g (%) was modelled by assuming:

$$\alpha_g \sim \text{Triangular}(90\%;\,95\%;\,100\%) \tag{18}$$

Low values capture the potential development of ECB resistance against the *Bt* toxin.

The efficacy of the absence of a treatment is zero, i.e. $\alpha_o = 0\%$. Total average efficacy α_j of the observed mix of technologies in year *j* in Spain was weighted as follows:

$$\alpha_j = \alpha_c\,\rho_{jc} + \alpha_g\,\rho_{jg} + \alpha_o\,(1 - \rho_{jc} - \rho_{jg}) = \alpha_c\,\rho_{jc} + \alpha_g\,\rho_{jg} \tag{19}$$

The theoretical maximum yield y_{jm} (t ha^{-1}) in Eqn 1 can now be estimated as:

$$y_{jm} = y_j \,/\, [1 - (1 - \alpha_j)\,s_j] \tag{20}$$

with y_j (t ha^{-1}) the observed average national yield.

All other costs

In order to obtain an estimate for c_j (euros ha^{-1}), i.e. all other costs that are independent of the choice of technology *k*, an estimate for the average maize production costs *AC* (euros ha^{-1}) in Spain is required. A cost estimate from 2001 extracted from the European Commission's (Anon., 2004*a*) Farm Accountancy Data Network (FADN) was used. This estimate does not include family labour costs nor interest costs for own capital. Therefore, it consists of a lower estimate for the average maize production costs. As an upper estimate, the per hectare value of production was used. The most likely value is the average of both limits, i.e.:

$$AC \sim \text{Triangular}(916\text{ euros ha}^{-1};\,(916\text{ euros ha}^{-1} + P_j\,y_j)/2;\,P_j\,y_j) \tag{21}$$

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[7] with a degree of significance of 5%.

[8] varieties that have exactly the same genetic composition with the exception of the *Bt* gene.

An estimate for c_j (euros ha^{-1}) was reconstructed by taking into account national adoption and costs of insecticides, *Bt* maize and the absence of a treatment:

$$c_j = AC - w_c\,\rho_{jc} - w_g\,\rho_{jg} - 0(1 - \rho_{jc} - \rho_{jg}) \qquad (22)$$

Other parameters

Adoption rates (James, 1997, 1998, 2000, 2001a,b, 2002a,b, 2003a,b), yields, area harvested, prices (Anon., 2003*a*) and the share of irrigated land in maize cultivation[9] (Anon., 2003*b*, 2004*b*) were modelled as deterministic parameters, i.e. without assuming a stochastic distribution. A deterministic maize supply elasticity of 2.5 reported by Lekakis & Pantzios (1999) for the period 1990-1994 was used. All prices and costs were deflated using the GDP deflator (Anon., 2003*a*,*c*). For the interest rate *i* (%) a risk adjusted rate of return of 10.5% derived from the capital asset pricing model (CAPM) was used.

Results

Average impact results

In Table 5 the average values generated by the model are presented. In the eighth column the 6-yr average (1998-2003) is reported. Annually, Spanish *Bt* maize adopters gained 1.2 million euros or 47 euros ha^{-1}, taking into account an average loss by corn borers of 9% (Alcalde, 1999; Fernández-Anero *et al.*, 1999). The aggregated producer surplus accumulated during the six-year period and actualised to 2004 was 10.3 million euros (last column). During the same period, the seed industry extracted an annual gross profit of 0.6 million euros or an aggregated profit of 5.2 million euros from the new technology.[10] Average total annual welfare change was 1.8 million euros and accumulated to 15.5 euros million after six years of adoption. Farmers gained two thirds (64.5%) of the total benefits, while one third (35.5%) accrued to the seed industry. This benefit sharing is consistent with the majority of biotechnology impact distribution studies in literature. Price *et al.* (2003) reviewed eight published studies and added four own-calculated estimates. Adding Qaim (2003), we have a sample of 13 impact distribution estimates. On average, farmers and consumers extracted 60.7% of total domestic benefits, or with a 95% confidence interval between 50.5% and 70.9%, the rest accrued to the seed industry.

Uncertainty

To obtain detailed information regarding the uncertainty surrounding the average impact results, a posterior distribution was generated for the latter, given the assumed prior distributions for the uncertain parameters. Using @Risk a Monte Carlo

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[9] The Spanish climate necessitates irrigation. Some 92% of total maize area is irrigated (Anon., 2003*b*, 2004*b*). Only in the north can maize be grown without irrigation. Irrigated land is cultivated more intensively and plant density, investment per unit of land and yields are higher.

[10] This gain is distributed among the gene developers and the seed companies that pay a technology license to the former. Since we do not have any information about this contract, we can not calculate the share captured by the seed companies.

Table 4. *Data mining of the average theoretical loss by corn borers*

	1995	1996	1997	1998	Average	Median	St. Dev.	CV (%)
s Spain	0.09[a]	0.06[a]	0.26[a]	0.09[b]	0.13	0.09	0.09	0.74
n Spain	1.49	1.01	4.36	1.49	2.09	1.49	1.53	0.74
n Cumming County	-	-	-	-	1.84[c]	-	1.49	0.81[c]
s Cumming County	-	-	-	-	0.11	-	0.09	0.81
Loss per borer	-	-	-	-	0.06[d]	-	-	-

[a] Alcalde (1999)
[b] Fernández-Anero *et al.* (1999)
[c] Hurley *et al.* (2004)
[d] Bohn *et al.* (1999)

Table 5. *Economic impact of Bt maize on Spanish agriculture and the seed industry, 1998-2003*

Year	1998	1999	2000	2001	2002	2003	Average 1998-2003	Aggregated value 2004
Adoption (%)	4.8%	7.6%	4.6%	5.0%	5.4%	6.8%	5.7%	5.7%
Bt maize adopters (€ ha^{-1})	50.3	50.1	48.0	46.9	44.2	40.6	46.7	407.6
Agriculture (10^6 €)	1.1	1.5	1.0	1.2	1.1	1.3	1.2	10.3
Seed industry (10^6 €)	0.5	0.7	0.5	0.6	0.6	0.8	0.6	5.2
Total impact (10^6 €)	1.6	2.2	1.4	1.8	1.7	2.1	1.8	15.5
Agriculture (%)	64.5%	64.4%	63.5%	62.9%	61.7%	59.8%	62.8%	64.5%
Seed industry (%)	35.5%	35.6%	36.5%	37.1%	38.3%	40.2%	37.2%	35.5%

simulation was conducted and generated 100 000 iterations. The results are presented in Table 6. Total profit for Spanish agriculture lies within a 95% confidence interval of 4.1 million euros and 17.7 million euros (Fig. 1), while the seed industry's gross profit varied from 4.3 million euros to 6.8 million euros. Thus, with a probability of 95% agriculture captured between 41.4% and 78.9% of total profit and the seed industry between 21.1% and 58.6%. The idea of agriculture losing money on average by adopting *Bt* maize is very unlikely and only occurs in 0.006% of iterations. In 92.0% of the cases, more than half of total benefits accrued to farmers.

Sensitivity analysis

Since the model is fed by some uncertain parameters, defined by subjective distributions, it is important to assess the influence of our assumptions on the model results. Therefore, the data generated by the iterations in @Risk were analysed. Through a regression analysis, the influence of each individual parameter on the impact estimates was assessed. Table 7 illustrates these results for the most recent year, i.e. 2003, the sensitivity estimates for the other years (1998-2002) being essentially the same. In a given year, the theoretical loss by corn borers is the main factor (coefficient of 0.805) explaining the benefits of *Bt* maize. Temporal and geographic heterogeneity of corn borer infestations significantly influenced the payoff of this technology, limiting the input industry's monopolistic pricing behaviour and farmers' adoption of the new technology. In some regions and some years, the benefits of the technology simply do not compensate for the high technology fee. Because of this, Spain's *Bt* maize adoption potential is limited to 36% (Brookes, 2002). The cost of the conventional technology turns out to be the second most important factor (coefficient of 0.447), due to the wide assumed distribution. Insecticide prices would be expected to fall as a reaction on the adoption of *Bt* maize. As a result, these competition effects will erode the comparative advantage of the new technology. In the third place comes the efficacy of the conventional technology, which is negatively correlated with the impact results (coefficient of -0.223). Any technological innovation able to increase the insecticide efficacy, e.g. a new insecticide or a new managerial spraying or scouting

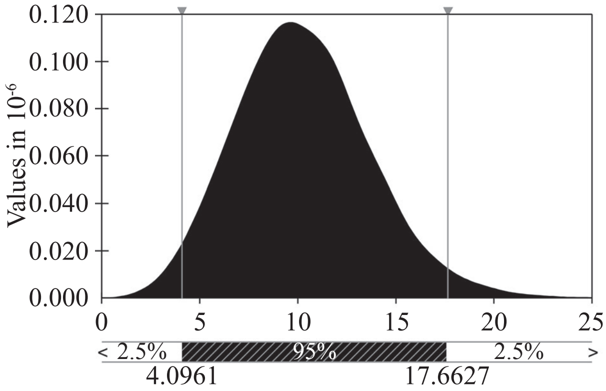

Fig. 1. *Posterior distribution of the aggregated impact of Bt maize on Spanish agriculture (values in million euros).*

Table 6. *Descriptive statistics of the posterior distribution of the aggregated impact of Bt maize on Spanish agriculture and the seed industry, 1998-2003*

	Minimum	5% confidence limit	Mean	95% confidence limit	Maximum
Agriculture (10^6 €)	-0.5	4.1	10.3	17.7	34.5
Seed industry (10^6 €)	4.2	4.3	5.2	6.8	7.3
Total (10^6 €)	5.8	9.6	15.5	22.7	39.6
Agriculture (%)	-8.3%	41.4%	64.5%	78.9%	88.4%
Seed industry (%)	11.6%	21.1%	35.5%	58.6%	108.3%

Table 7. *Regression results of the sensitivity analysis of the impact of Bt maize on Spanish agriculture and the seed industry in 2003*

Parameter	Agriculture	Seed industry	Total	Agriculture (%)	Seed industry (%)
Theoretical loss s_{2003}	0.805	0.000	0.816	0.558	-0.558
Irrigated insecticide cost w_{irr}	0.447	0.000	0.453	0.549	-0.549
Efficacy insecticides α_c	-0.223	0.000	-0.225	-0.198	0.198
Technology fee w_g	-0.154	1.000	0.000	-0.445	0.445
Efficacy *Bt* maize α_g	0.107	0.000	0.108	0.096	-0.096
Average production cost AC_j	-0.082	0.000	-0.083	-0.083	0.083
Aerial insecticide cost w_{air}	0.049	0.000	0.05	0.062	-0.062
Adoption of insecticides ρ_c	0.000	0.000	0.000	0.000	0.000
R^2	0.940	1.000	0.939	0.868	0.868

technique, will compete with *Bt* maize. Finally, the narrow distribution of assumed technology fees has a relatively small negative impact (coefficient of -0.154) on the model outcomes.

Due to the static character of the model through Eqn 8, the benefits for the seed industry are simply a function of the technology fee. The question is how this price will evolve now that other companies have recently entered the market for transgenic maize seed. Remarkably total benefits (column 4) are not affected by the technology fee, although benefit sharing is (columns 5 and 6). Three factors, i.e. the theoretical loss by corn borers (coefficient of 0.558), the cost of the conventional technology (coefficient of 0.549) and the license between the biotechnology industry and the farmer (coefficient of -0.445) essentially drive the welfare distribution of the new technology.

Discussion

Since plantings of transgenic seed have been limited to a small fraction of the Spanish maize area, i.e. 5.7% on average during 1998-2003, and an even smaller fraction of total Spanish maize supply, i.e. 3.2% on average during 1998-2001 (Anon., 2003*a*), the supply shift engendered by the new technology has been small so far. An average vertical and horizontal supply shift of $K = 0.18\%$, respectively $\varepsilon K = 0.44\%$ per year during 1998-2003 was found. This supply shift would be expected to increase now that Syngenta's voluntary agreement is lifted and *Bt* maize adoption is no longer constrained. The limited adoption so far was assumed to be primarily driven by insecticide users switching to *Bt* maize in search for a more efficient pest control tool. A rational farmer facing economically important ECB losses to the point that *Bt* maize pays, would also likely adopt insecticides. Because of this assumption, welfare estimates are conservatively biased downwards. As soon as *Bt* maize adoption levels increase beyond insecticide adoption levels, an important proportion of the adopters will consist of non-insecticide adopters.

Domestic maize demand was modelled as infinitely elastic in a small open economy. As a result, no price decline was generated by the model and no benefits accrued to Spanish consumers. Spanish maize production is highly elastic, meaning that if the maize sector faced a less elastic downward sloping domestic demand, the technology-induced supply-shift would quickly erode domestic prices. Any cost reduction translates to a 2.5-fold production response. Since the EU guarantees a minimum price for maize, Spanish maize farmers are largely protected against price declines and the main resulting effect is a sharp production boost. The latter yields an opportunity to increase the low degree of self-sufficiency of Spanish maize production, i.e. 58.7% on average during 1998-2001 (Table 3). The lion's share of Spanish maize supply, i.e. 84.9% on average, was used by the animal feed industry. Even in case price declines occurred, in the short run benefits would flow to the animal feed industry, cattle farmers, processors and distribution sectors and in the long run to consumers through lower animal product prices.

Conclusions

Maize is the most wide-spread cereal on earth and has a wide range of yields. Spain provides 11% of the EU's grain maize. Two types of corn borers cause severe losses in this sector. This opens up perspectives for transgenic *Bt* maize, providing a tool to control these insects more efficiently. Up to 2002, Syngenta voluntarily limited transgenic maize seed supply to an equivalent of 25 000 ha of the variety Compa CB. As a result, adoption rates stagnated to an average of 5.5% of Spanish maize area.

Conservatively assuming that this minority of *Bt* maize adopters previously used insecticides, the innovation for a small open net importer of maize was modelled. As a result, during the 6-yr period 1998-2003 Spanish maize growers captured 10.3 million euros while the seed industry gained 5.2 million euros. Two thirds of the benefits accrued to agriculture, while one third was extracted by the industry. This result is primarily sensitive to our assumptions about corn borer losses and insecticide costs.

Up to now, the Spanish situation has been artificial in a sense, since Syngenta voluntarily limited the supply of seed. The question remains as to what extent the observed technology fee was also artificial. The price of the seed was similar to the price in the USA. Due to the end of the voluntary agreement in 2003, five new varieties were approved. With this additional competition in mind it is likely that technology fees will fall. This has happened in all other countries where transgenic crops have been introduced (Gianessi *et al.*, 2002). It is unlikely that the biotechnology industry will be able to extract the lion's share of the benefits. American literature shows that farmers are generally the main beneficiaries of agricultural biotechnology innovations. In the long run, these benefits flow from farmers to downstream sectors, distribution and finally to the consumer.

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