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Economic and environmental impacts of stacked transgenic events on soybean and corn

Lorente, J.[1]; Vassallo, M.[1]; García Suárez, F.[1]

[1]Universidad de la República, Facultad de Agronomía, Departamento de Ciencias Sociales, Montevideo, Uruguay

Editor

Bruno Lanfranco
Instituto Nacional de Investigación Agropecuaria (INIA), Montevideo, Uruguay

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Correspondence

Juan Lorente
jlorente@fagro.edu.uy

Abstract

Between 1996 and 2020, the Uruguayan government authorized twenty-eight genetically modified varieties of corn and soybean. This study investigates if the transgenic seed with stacked events with more than one agronomic characteristic in soybean and corn (HT and Bt), compared to those of one event (HT or Bt), shows productive, economic and environmental advantages in the period between 2010 and 2020 in Uruguay. To achieve the proposed objectives, a partial budgeting method was developed for the economic analysis. In addition, the mean difference for soybean yields was estimated with the "Bootstrap" and "Anova" techniques. The consumption of herbicides and insecticides in trans-genic soybean and maize crops was estimated, comparing it with national imports. Toxicity indices for mammals, bees and chemical persistence in soil were constructed with the evolution of the main herbicides and insecticides according to toxicological category applied to soybean and corn crops. Finally, the number of insecticide applications entrances to field was also weighted and then validated through the Poisson technique. Results showed economic advantages, mainly for corn crops with three stacked events. While the soybean varieties with stacked events did not have differences in yield, a decrease in the entries to field due to insecticide applications was observed, which does not compensate for the higher cost of the seed. The results obtained showed a general improvement in the evolution of less toxic insecticides for mammals and bees, but with an increase in applications with non-glyphosate herbicides.

Keywords: transgenic events, costs, productivity, environmental impact, agrochemicals

Impactos económicos y ambientales de los eventos transgénicos apilados en soja y maíz

Resumen

El gobierno uruguayo, entre 1996 y 2020, autorizó 28 organismos genéticamente modificados (OGM) para maíz y soja. Este trabajo investiga si la semilla transgénica con eventos apilados con más de una característica agronómica en soja y maíz (HT y Bt), respecto a los de un evento (HT o Bt), evidencia ventajas productivas, económicas y ambientales en el período entre 2010 y 2020 en Uruguay. Para cumplir con los objetivos propuestos, se utilizó para el análisis económico el método de presupuestación parcial. Además, se estimó la diferencia de medias para los rendimientos de soja con la técnica Bootstrap y Anova. Los consumos de herbicidas e insecticidas en cultivos transgénicos fueron estimados comparándolos con las importaciones nacionales. Se construyeron índices de toxicidad para mamíferos y abejas y persistencia química en suelo con la evolución de los principales herbicidas e insecticidas de uso en chacras. Finalmente, se ponderó

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también la cantidad de ingresos a chacras por aplicaciones de insecticida, lo que fue validado mediante la técnica de Poisson. Los resultados evidenciaron ventajas económicas, principalmente para los cultivares de maíz con tres eventos apilados. Las variedades de soja con eventos apilados no tuvieron diferencias en rendimiento, pero se pudo constatar una disminución en el ingreso a chacras por aplicaciones de insecticidas, lo que no compensa el mayor costo de la semilla. Se constató una mejora general con el uso de insecticidas de menor toxicidad para mamíferos y abejas, pero con un aumento en las aplicaciones con herbicidas no glifosato.

Palabras clave: eventos transgénicos, costos, productividad, impacto ambiental, agroquímicos

Impactos econômicos e ambientais de eventos transgênicos empilhados em soja e milho

Resumo

Entre 1996 e 2020 o governo uruguaio autorizou vinte e oito eventos transgênicos para milho e soja. Este trabalho investiga no período entre 2010 e 2020 no Uruguai, se a semente transgênica com eventos empilhados com mais de uma característica agronômica em soja e milho (HT e Bt), em relação aos de um evento (HT ou Bt), apresentam vantagens produtivas, econômicas e ambientais. Para atender aos objetivos propostos, foi utilizado o método de orçamentação parcial para a análise econômica. Além disso, a diferenças médias nas produtividades da soja orami estimadas utilizando as técnicas “Bootstrap" e “Anova”. Estimou-se o consumo de herbicidas e inseticidas ao nível dos cultivos transgênicos, comparando-os com as importações nacionais. Foram construídos índices de toxicidade para mamíferos, abelhas e persistência química no solo com a evolução dos principais herbicidas e inseticidas importados. Finalmente, também foi ponderado o número de entradas em campo devido à aplicação de inseticida, validado pela técnica de Poisson. Os resultados mostraram vantagens econômicas, principalmente para cultivares de milho com três eventos empilhados. Enquanto as variedades de soja com eventos empilhados não tiveram diferenças no rendimento, mas foi possível verificar uma diminuição na pulverização da cultura devido às aplicações de inseticidas, o que não compensa o maior custo da semente transgênica. Houve uma melhora geral na importação e uso de inseticidas com menor toxicidade para mamíferos e abelhas, mas com aumento de aplicações com herbicidas não-glifosato.

Palavras-chave: eventos transgênicos, custos, produtividade, impacto ambiental, agroquímico

1. Introduction

In the world, the introduction of genetically modified organisms (GMOs) into agriculture has sparked significant socioeconomic and environmental controversies. In Uruguay, since the approval in 1996 of the first transgenic event in soybean cultivation, the debate about the adoption of this biotechnology has also been raised.

The supposed benefits of GMOs are questioned by a sector of the academic community that sees in the current model of production and agricultural management –with its associated technological package– negative effects on the economic, social and environmental aspects, including health risks for those exposed to agrochemicals and regulatory issues on proprietary use of seeds[(1)(2)(3)(4)]. Another group of academics has presented scientific evidence supporting the benefits of GMOs containing one or more transgenic events, demonstrating higher yields, lower use and costs of agrochemicals, and higher profits for farmers[(5)(6)(7)(8)].

This study evaluates some economic, productive and environmental impacts in Uruguay due to the use of soybean and corn seeds with stacked transgenic events compared to those with a single event, from 2010 to 2020. The main interest of this study is to show whether the transgenic events of soybeans and corn approved in 2011 and 2012 by the National Biosafety System with herbicide tolerance (HT) and pest resistance (Bt) are economically profitable, improve yields and reduce the use of insecticides.

2. Materials and Methods

To achieve the proposed objective, the main analysis consisted of making comparisons of costs that vary due to the introduction of soybean and corn seeds with stacked transgenic events in the country with those with a single event.

2.1 Quantitative approach

For estimating field costs and the net benefits of planting soybean and maize seeds with stacked events (incorporating more than one trait), the partial budgeting method proposed by the International Maize and Wheat Improvement Center[(9)] was used, which verifies cost savings from the reduced need for insecticide applications.

As a first step for the preparation of the partial budget, experimental yields were collected for eight soybean harvests (2013/14 to 2020/21) and seven corn ones (2013/14 to 2020/21), based on the National Cultivar Evaluation (ENC, *Evaluación Nacional de Cultivares*) conducted by INASE[(10)]. For maize, no experimental data were available for the 2017/18 season due to drought conditions.

In the case of soybean cultivation, yields were separated into two groups: one with all cultivars that had the RR1 transgenic event which confers glyphosate tolerance (HT), and another with cultivars that had the RR2 stacked transgenic event with "Intacta" technology, which combines glyphosate tolerance (HT) and resistance to lepidoptera (Bt).

In the case of maize cultivation, during the first two harvests (2013/14 to 2014/15) a comparison was made between cultivars of seeds with the Bt11 event, with two genes conferring resistance to lepidoptera by the Bt toxin and tolerance to the herbicide glufosinate-ammonium, and cultivars with the stacked Bt11 × GA21 events, which includes glyphosate tolerance as an additional trait.

Starting from the 2015/16 season, corn seeds with the stacked event Viptera 3 offering resistance to the three most important lepidopteran species, in addition to tolerance to both herbicides glufosinate ammonium and glyphosate, were surveyed and compared, in this case, to corn seed with the GA21 event, which provides glyphosate tolerance.

Experimental data from the evaluations conducted by INASE for each material included three repetitions in three different locations. The average experimental yield for eight soybean growing seasons and seven maize seasons was adjusted to reflect the actual yields achieved by producers (Ya). In soybeans, the estimated adjustment[(11)] of potential yield was used, which, in this case, were the average yields of the NCS limited only by water availability (Yw) versus actual producer yield (Ya), where the gap between the two (Yg) was determined to be 31%. For maize[(12)], the adjustment reflected a 41% gap (Yg) of 41% between the water-limited potential yield (Yw) and the adjusted yield (Ya).

The partial budgeting method proposed by CIMMYT is based on creating a partial budget that identifies only the varying costs and benefits of different treatments to make recommendations on new technologies.

In addition to harvest costs, transportation costs for soybean and maize were estimated according to an average distance from an agricultural field located in the south and north of the country to the port of Nueva Palmira. From the harvest costs, the gross field benefit (GFB) was obtained according to the southern and northern regions. The next step involved calculating the variable costs for each treatment, which is the sum of the costs of transgenic seeds, insecticides application and herbicides in the case of corn, and labor costs related to the application of these agrochemicals.

For the proposed technological management, which evaluated herbicide and insecticide applications and the number of applications required according to transgenic soybean and corn seeds, budgets were sourced from the technical departments of the Flores Rural Union, the Colonia Valdense Rural Development Society, the oilseed reports for the Mesa Tecnológica de Oleaginosos, data provided by Agr. Alfredo Silbermann from the company Procampo, and validation by Dr. Sebastián Mazzilli from the Agronomy College (Udelar) and Agr. Pablo Farina (private consultant).

The last step in partial budgeting was the calculation of net profits, obtained by subtracting the total variable costs from the GFB. Net benefits do not represent a farmer's profits, but rather the economic benefits or non-benefits from the introduction of a new technology.

For the comparison of transgenic soybean crop's yield, statistics were estimated: weighted averages by field area, standard deviation and coefficient of variation for the six seasons from 2015/16 to 2020/21. Yields were compared between the seed groups with a single event RR1, without Bt toxin, and stacked RR2, with Bt, according to first and second crops.

The unit of analysis, in this case, consisted of fields from the database of the Federación Uruguaya de Grupos CREA (FUCREA), as a primary source of information on the agricultural-livestock production systems of the six harvests, providing yield records between 2015/16 and 2020/21. The crop areas for soybean and corn in the 2020/21 harvest, which covers the FUCREA base, represented 9% of the national area for both crops. For maize, this analysis was not performed due to the lack of yields records for cultivars with a single transgenic event.

To determine whether there was a significant difference between the means of the two groups of transgenic soybeans, RR1 and RR2, the R software was used with the bootstrap resampling method, which allows for the creation of a large number of resampled datasets with replacement from the observed data in each soybean group, RR1 and RR2.

The resampling method consisted of a matrix of *n* records per harvest from 2015/16 to 2020/21 for soybean fields classified as first and second crops, according to the southern and northern coastal agricultural regions for producers who planted soybeans with the simple RR1 event compared to the stacked event RR2, with *B* number of repetitions previously defined. Then, a statistical significance test was performed using two approaches: the absolute mean difference and the absolute median difference.

At the end of the hypothesis test of the bootstrap test, the p-value was calculated under the null hypothesis of no difference in means and similar distributions, with Ho = equal yields between the RR1 and RR2 seed groups and Ha = different yields between both groups. On the other hand, an analysis of variance (Anova) was performed for the means of soybean yields based on the ENC (Evaluación Nacional de Cultivares) of INASE, according to genotype, year and the interaction between the two. However, due to the limited sample size for maize genotypes with single and stacked events, no statistical significance tests could be performed for maize (n = 19 vs. 1462 observations for soybeans).

The use of herbicides and insecticides in agricultural systems was estimated for the years 2010, 2015, and updated to 2020, based on a representative technological model package applied to transgenic soybean and maize crops. To this end, the economic budgets of the technical departments of the cooperatives and the validation by the qualified experts already mentioned were considered.

The selection of these agrochemicals represented the technological package (TP) used before 2010, prior to the approval of the last stacked transgenic events under study, and the TP after 2010. Validation of the selected herbicides and insecticides included recommendations from researchers of the Department of Plant Protection of the Agronomy College (Udelar), including Dr. Grisel Fernández, Agr. (MSc) Horacio Silva and Dr. Carlos Pérez.

Likewise, the imports of agrochemicals from the General Directorate of Agricultural Services (DGSA, in Spanish)[13] alongside the soybean and maize acreage for 2010 and 2020 were considered as a comparison of the use of herbicides and insecticides in soybeans and corn (2021 interview with a technician from an agricultural policy office; unreferenced). In Uruguay, over 80% of field-applied agrochemicals have been derived from imports since 2010, while national formulations have accounted for less than 10% (DGSA).

To estimate the thresholds of toxicity and chemical degradation in soil, herbicides and insecticides were taken as the unit of analysis according to the "model" management used in soybean and maize fields. A mammalian toxicity index was developed from 2010 to 2020 according to four hazard thresholds (I, II, III and IV) under the World Health Organization (WHO) criterion based on lethal dose 50 (LD50-mg/BW). The fungicide category was not considered for the study since there are no transgenic events with resistance to diseases.

A toxicity index for bees and chemical persistence in soil was also developed for the same selected agrochemicals, the most commonly used in agricultural fields, considering the British pesticide database Pesticides Properties Data Base (PPDB-IUPAC). The bee toxicity risk classification was based on LD 50 ug bee-1: low (L), medium (M) and high (H). Meanwhile, for chemical persistence in the soil, the typical DT50 was considered: non-persistent (No Persist), moderately persistent (Mod Persist), persistent (Persist) and very persistent (Very Persist).

Finally, to determine if there were fewer insecticide applications, the same FUCREA database covering five harvests, from 2015/16 to 2019/20, was considered, where the unit of analysis is the agricultural field. The variables used were: soybean and corn seeds with one or more transgenic events (RR1 and RR2 events for soybean and Bt11/MON 810 and Viptera3/VT3 PRO events for corn), and amount of field income from insecticide applications. On this basis, the average, median, minimum and maximum amount of income to fields was estimated. To validate the results of income from field applications, the Poisson test was applied, which is appropriate for discrete variables describing random phenomena such as insecticide applications occurring in the cycle of soybean and corn crops. The analysis was performed using R free software, the hypotheses being:

Null hypothesis: H_0 = the ratio of applications with one soybean event (RR1) to two soybean events (RR2) is equal to 1.

Alternate hypothesis: H_a = the ratio of applications with one event (RR1) to two events (RR2) is different from 1.

2.2 Qualitative approach

The semi-structured interview technique was employed as a research instrument, allowing the use of a flexible framework to explore the perceptions of the interviewed informants about the use of these technologies. The following actors were selected as the first unit of analysis:

- Uruguayan agricultural entrepreneurs.
- Agronomists hired as production managers for the management and administration of agricultural enterprises of national or foreign capital.
- Agronomists hired as technical managers, advising agricultural companies and cooperatives, including the purchase of transgenic soybean and corn seeds.

Given the challenge of encompassing the entire population under study for interviewee selection, a non-probabilistic snowball sampling technique was used. Snowball sampling identifies subjects to be included in the sample through referrals from the initial participants. A total of 26 actors were interviewed, covering 24% of the area planted with soybeans and corn in the 2020/21 season. After completing the first two stages of the qualitative research, preparatory and fieldwork, using the interview technique, the analytical stage followed. This third stage consisted of two tasks based on the interviews conducted: 1) transcription of the interviews and data reduction, with coding and categorization of the data obtained from the interviewees, and 2) disposition and transformation of the data.

The interpretations of results derived from the quantitative approach were supported and validated with textual fragments of the interviews that support the main topics raised in the research objective. At the end of the results of the quantitative approach, a descriptive synthesis is presented, summarizing the global perception of interviewees on each of the analyzed dimensions.

3. Results

3.1. Results obtained from the quantitative approach

3.1.1. Variation in costs and net profits of soybean production by transgenic event

The total average variable costs between 2013/14 and 2020/21 were US$120 for the RR1 group and US$153 for the RR2 group. The primary reason for this difference lies in the cost of seeds, which can be attributed to the differential cost of paying royalties on the sale of certified seed charged by the companies holding the patents for transgenic events. According to qualified informants who market soybean and corn seeds with GM events, the royalty for self-use was US$ 550/ton for the Intacta RR2 soybean stacked event in 2018-2019, while it was US$ 64/ton plus VAT for all soybean seed varieties with the RR1 event.

For most of the evaluated harvests, both in the northern and southern regions, the soybean alternative with the RR1 event showed superior benefits compared to the RR2 soybean seeds (**Table 1**). The three harvests in which the net benefits (NB) were higher for soybeans with an RR2 event saw yields greater than 0.140 t/ha compared to RR1 materials.

Table 1. Costs and net profits (US$/ha) by soybean seed planted with RR1 and RR2 events

Harvest year	2013-14		2014-15		2015-16		2016-17		2017-18		2018-19		2019-20		2020-21	
Transgenic event	**RR1**	**RR2**	**RR1**	**RR2**	**RR1**	**RR2**	**RR1**	**RR2**	**RR1**	**RR2**	**RR1**	**RR2**	**RR1**	**RR2**	**RR1**	**RR2**
Adjusted yield (tt/ha)	3.19	**3.22**	2.29	**2.30**	1.87	**1.94**	3.08	**3.13**	1.32	**1.28**	3.10	**3.29**	2.14	**2.28**	2.52	**2.91**
Gross benefit south U$S/ha	1359	1373	875	878	547	566	1014	1030	402	393	965	1024	589	628	844	975
Gross benefit north U$S/ha	1304	1318	838	841	526	545	971	986	384	375	931	987	577	615	824	952
Seed cost	88	**132**	103	**147**	92	**136**	106	**150**	78	**122**	98	**142**	74	**118**	60	**104**
Total costs that vary U$S/ha	126	**162**	139	**169**	121	**153**	134	**167**	117	**159**	129	**161**	104	**136**	89	**121**
Net benefit south U$S/ha	1232	**1212**	736	**709**	426	**414**	879	**863**	285	**234**	836	**863**	486	**492**	755	**854**
Net benefit north U$S/ha	1178	**1157**	699	**672**	406	**393**	836	**819**	267	**216**	802	**826**	473	**479**	735	**831**

Source: material gathered from an unpublished draft (private collection; unreferenced).

In two of these three harvests, 2018/19 and 2019/20, if the RR1 group from the southern zone is compared with RR2 from the northern zone, the advantage is favorable for RR1 in US$ 10 and US$ 7 per hectare, respectively, due to the distance from the port. In this regard, one of the interviewees mentioned: "If you have a very rainy year with a lot of pest pressure, I would probably adopt Intacta RR2 soybeans more massively if the costs were lower, because it means less risk. But, since the costs are significant, one has to speculate with the conditions, and when forecasts are dry or little pest pressure is expected for a year, I might not be able to assume the cost of Intacta soybeans because I will not see a return" (2021 interview with a country manager from an agricultural company in Mercedes; unreferenced).

3.1.2. Variation in field costs and net benefits in maize by transgenic event

Following the same partial budgeting methodology applied to maize seeds, the results indicated lower costs per hectare for materials with more than one event stacked compared to seeds with a single event in six of the seven analyzed harvests. For the first two harvests, there was no clear economic advantage for stacked events, as the costs were similar because both events had similar insecticide applications and smaller differences in seed costs compared to the last five harvests.

Net benefits in the case of corn stacked events were higher for all harvests except for 2013/14 (**Table 2**). Seeds with Bt protection against the three main pests offered cost savings in terms of reduced insecticide applications added to the cost of the insecticide, which outweighed the higher price of Viptera 3 seeds with three events compared to GA21 seed (its refuge) with one event. Bt protection also minimized yield loss.

Table 2. Costs and net benefits (US$/ha) according to corn seed sown with one event (Bt11 and GA21) compared to two or more events (Bt11xGA21 and Viptera 3)

Harvest year	**2013-14**		**2014-15**		**2015-16**		**2016-17**		**2018-19**		**2019-20**		**2020-21**	
Transgenic event	**Bt11**	**Bt11x GA21**	**Bt11**	**Bt11x GA21**	**GA21**	**VIP3**	**GA21**	**VIP3**	**GA21**	**VIP3**	**GA21**	**VIP3**	**GA21**	**VIP3**
Adjusted yield (tt/ha)	3,67	3,10	4,91	5,16	3,69	4,08	5,33	5,68	5,85	6,43	5,21	5,38	5,09	5,37
Gross benefit south U$S/ha	695	587	886	932	575	636	915	975	1.055	1.160	769	794	911	961
Gross benefit north U$S/ha	633	534	808	849	534	591	840	896	991	1.090	738	762	870	918
Seed cost	162	176	153	170	147	191	147	187	147	185	147	198	147	198
Total costs that vary U$S/ha	232	**231**	220	**220**	203	**191**	201	**187**	210	**185**	205	**198**	207	**198**
Net benefit south U$S/ha	463	**356**	666	**711**	371	**446**	713	**788**	845	**976**	564	**596**	704	**763**
Net benefit north U$S/ha	401	**303**	588	**629**	331	**401**	639	**708**	781	**905**	532	**564**	663	**720**

Source: material gathered from an unpublished draft (private collection; unreferenced).

This was supported by an interview with a technical advisor, who highlighted: "From the perspective of corn, there are savings especially with Viptera 3. Perhaps, in this case, you're saving two applications, depending on the comparison: if it is against the refuge, it is two to four applications, so in this case, it is not even questionable. There is a difference with a Bt11 material that takes at least three applications and you end up harvesting fewer kilos because you never managed to fully control the level of pests. It is true that Viptera 3 seeds are much more expensive than Bt11, but it is possible that what you pay for the bag covers those extra applications. I think the yield in Viptera 3 ends up being higher because the control of the pest was much higher" (2020 interview with a country manager from an agricultural company in Soriano, Río Negro and Paysandú; unreferenced).

When considering the grain transportation costs, single-event materials (Bt11 and GA21) in the southern region only surpassed the net benefit of stacked materials (Bt11 × GA21 and VIP3) in the northern region during the 2014/15 and 2016/17 harvests, with values of US$ 37 and US$ 5 per hectare, respectively.

3.1.3. Soybean yields with stacked events against a single event

On the southern coast, about 60% of the observations, regardless of whether it was a first (S1) or second (S2) crop soybean, showed higher average yields for the RR1 event compared to the stacked event RR2 (**Table 3**). Only two records out of twelve RR2 event records exceeded 10% of the yield differential claimed by the company Monsanto (now Bayer) for RR2 soybeans compared to RR1 soybeans.

Table 3. Soybean yields with stacked event RR2 and event RR1 southern region

Harvest year	2015-16				2016-17				2017-18				2018-19				2019-20				2020-21			
Southern region	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**
	S1	S1	S2	S2	S1	S1	S2	S2	S1	S1	S2	S2	S1	S1	S2	S2	S1	S1	S2	S2	S1	S1	S2	S2
Media	2225	**1723**	2051	**2322**	3274	**3250**	2973	**2716**	1189	**1073**	1168	**1370**	3710	**3701**	2876	**3113**	2472	**2662**	2153	**2131**	2045	**1922**	1787	**1864**
CV	26%	39%	29%	22%	16%	19%	22%	17%	48%	41%	50%	44%	14%	19%	27%	25%	23%	31%	19%	24%	32%	29%	35%	37%
n	318	49	190	28	231	71	166	96	241	58	101	68	167	54	161	33	195	82	167	138	260	92	319	184
P-value media	81%		51%		52%		50%		50%		58%		54%		51%		52%		67%		50%		50%	
P-value median	66%		41%		60%		48%		54%		75%		40%		64%		57%		87%		58%		58%	

Source: material gathered from an unpublished draft (private collection; unreferenced).

By means of the bootstrap technique and according to the statistical values observed, no significant differences were found according to the p-values estimated for the mean and median difference tests (**Table 3** and **Table 4**). That is, assuming a true null hypothesis, of equal means, in any case the probabilities of obtaining values equal to or above the statistical test observed for both regions were over 50%. This means that, out of the 10,000 replications defined by the R software, more than half of the statistical values of the *bootstrap* test exceeded the observed statistical value, confirming the null hypothesis as true: the means between the two groups of seeds do not have significant differences.

Table 4. Soybean yields with stacked event RR2 and event RR1 northern region

Harvest year	2015-16				2016-17				2017-18				2018-19				2019-20				2020-21			
North region	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**	RR1	**RR2**
	S1	S1	S2	S2	S1	S1	S2	S2	S1	S1	S2	S2	S1	S1	S2	S2	S1	S1	S2	S2	S1	S1	S2	S2
Media	1794	**1734**	1690	**1817**	2881	**3269**	2534	**2811**	1015	**1211**	954	**972**	3022	**3275**	2759	**2703**	2406	**2340**	2083	**2196**	2240	**2315**	1658	**2095**
CV	25%	23%	28%	17%	15%	11%	19%	14%	40%	41%	41%	41%	18%	15%	23%	22%	23%	30%	24%	25%	27%	21%	42%	33%
n	92	39	53	2	97	69	34	9	85	64	40	27	166	80	104	35	215	135	136	78	134	107	130	102
P-value media	99%		51%		50%		50%		50%		60%		50%		78%		55%		51%		57%		50%	
P-value median	44%		40%		50%		49%		39%		63%		51%		71%		39%		60%		49%		38%	

Source: material gathered from an unpublished draft (private collection; unreferenced).

For the northern region, the average yield (kg/ha) of the stacked event RR2 was higher in 75% of the cases for both first and second crops of soybean. In this region, four records exceeded 10% yield compared to RR1 soybeans. Considering the experimental data of INASE that includes the northern region (**Table 1** and **Table 4**) for the estimation of field costs with partial budgeting, only in one of the eight analyzed harvests the average yield of the varieties with the RR2 event exceeded 10% compared to soybeans with the RR1 event. On this point, an interviewee mentioned: "The Intacta RR2 gene does not yield more, the variety does; there isn't a single variety with or without RR2 –they are different varieties–. When Intacta appeared, it came with a promise of higher yield, a promise that was necessary for you to buy the technology because the cost savings from fewer applications did not cover it" (2021 interview with a country manager from an agricultural company in Colonia and Paysandú; unreferenced).

On the other hand, the analysis of variance study conducted for INASE's experimental database in soybeans determined significant differences for the means of the genotypes with the transgenic event RR2 within each harvest, for the year but not for the genotype-year interaction (**Table 5**). This indicates that the genetic material of the RR2 events had a significant effect, and the annual effect was also significant, demonstrating changes over time. The lack of a significant genotype-year interaction suggests that the differences between genotypes remain consistent over time, confirming that the genotype is consistently superior.

Table 5. Analysis of variance of soybean yields with stacked event RR2 and event RR1

Number of obs. =	**1462**			**R-squared**	**= 0.5074**
Root MSE =	868.037			Adj R-sq	=0.5023
Source	Partial SS	df	MS	F	Prob>F
Model	1,12E+12	15	74812816	99.29	0.0000
variety	6009758.5	1	6009758.5	7.98	0.0048
year	8,60E+11	7	1,23E+11	163.05	0.0000
variety # year	7195244.1	7	1027892	1.36	0.2165
Residual	1,09E+12	1446	753489.05		
Total	2,21E+12	1461	1513851.8		

Source: material gathered from an unpublished draft (private collection; unreferenced).

For maize, there are very few observations (149), and no differences were found between varieties. Only time showed significant differences, indicating that the change is likely associated only with genetic progress over time, regardless of whether there are one or two stacked events.

3.1.4. Consumption of agrochemicals in soybean and corn crops in Uruguay

In Uruguay, in 2020, according to official data, 19,856 tons of herbicide, insecticide and fungicide formulations were imported. The herbicides accounted for 89% of the total imported agrochemicals, an increase of 10% compared to 2010 as the base year (**Table 6**). On the other hand, the share of all glyphosate salts in total herbicide imports reached 65%, when they represented 69% and 85%, in 2015 and 2010, respectively, of imported herbicides, indicating an increase in the use of other non-glyphosate herbicides.

Table 6. Imports and consumption of agrochemicals used in soybeans and corn

Year		**2010**			**2015**			**2020**	
Categories	Imports	Consumption S+M	% S+M	Imports	Consumption S+M	% S+M	Imports	Consumption S+M	% S+M
Herbicides	20.516	4121	20	18.368	5149	28	17.659	4241	24
Insecticides	3097	667	22	1100	222	20	763	158	22
Fungicides	2308	74	3	2190	114	5	1434	85	6
Soybean area (ha x 1000)		862			1250			908	
Corn area (ha x 1000)		81			83			143	

Note: Consumption S+M = consumption agrochemicals in soybean and corn; % S+M = share of the agrochemicals used in soybean and corn relative to total imports.

Source: material gathered from an unpublished draft (private collection; unreferenced).

Between 2010 and 2020, there was a decrease in imports of herbicides and insecticides of 14% and 75%, respectively, while, for the same period, the area of soybeans and corn grew by 11%. The highest agrochemical imports during this period were recorded in 2014, with 27,955 tons of herbicides and 3,841 tons of insecticides imported, which meant a growth of 36% in herbicides and 24% in insecticides compared to 2010. These higher volumes of imports coincide with a record soybean planting area in Uruguay of almost 1,500,000 hectares, as in 2013[(13)].

Regarding the consumption of agrochemicals in agricultural fields based on the budgeting of soybean and corn crops made for 2020 compared to 2010, a slight increase in the consumption of formulated herbicides and fungicides was observed, while the consumption of insecticides decreased by 76%, aligning with the 75% reduction in total insecticide imports at the national level during this period (Table 6).

3.1.5. Toxicity evolution of the most widely used plant protection products

3.1.5.1. Index according to acute mammalian toxicity

Based on the main herbicides and insecticides used according to representative management in soybean and corn fields between 2010 and 2020 by toxicological category, a decrease in category II (moderately hazardous; yellow band) was observed in absolute terms (Figure 1). This category includes four active ingredients, three insecticides of greater toxicity (cypermethrin, chlorpyrifos, lambdacyalothrin) and a herbicide (2,4 D-amine), with greater toxicity compared to category III of the blue band, where glyphosates are located.

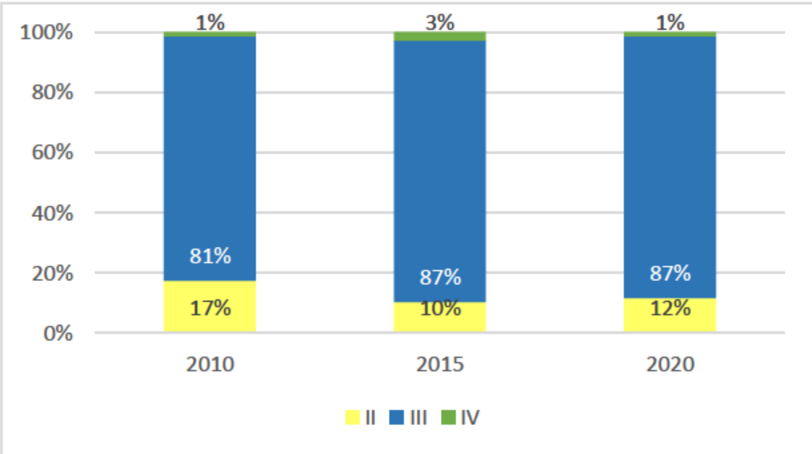

Figure 1. Evolution in percentage of the main herbicides and insecticides for use in soybeans and corn according to toxicological category for mammals - LD50 mg/kg (2010 – 2020)

The insecticide chlorpyrifos, used to control main pests in rainfed crops since 2015, was replaced by chlorantraniliprole (Figure 2), a category IV (green band) insecticide, and its use has been discouraged by the requirement to present a prescription(14). There was an increase in the green-band insecticides: triflumuron, which went on to represent 45% of the total insecticides applied to soybeans and corn. Combined with chlorantraniliprole, they accounted for 52% of application, as category IV.

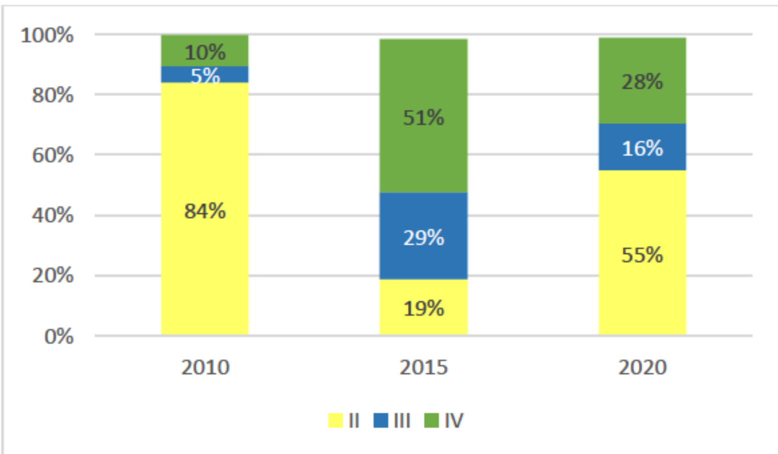

Figure 2. Evolution in percentage of the main insecticides for use in soybeans and corn according to toxicological category for mammals - LD50 mg/kg (2010 – 2020)

However, the use of category II insecticides grew again towards the end of the period due to the use of active ingredients such as abamectin and chlorpyrifos for the control of spider mites and thrips, influenced by annual pest pressures and the need to address pest species like stink bugs, which are not managed by the RR2 soybean trait.

One interviewee highlighted the toxicity reduction achieved by minimizing insecticide use in maize: "On a scale of 1 to 4, we evaluate it as a 4 because the impact of insecticides is significant. The spodoptera pest gets into the whorl of the corn, that's why they call it the whorlworm, and it only comes out to eat at night. So, either you apply at night or you apply two translaminar products that can pass through the leaf and kill the insect due to gases. They are strong products: if they are strong for the insect, they are strong for the environment, and all of us who are related to that application in some way. The truth is that with the Viptera 3 event (corn) we do not have these problems, so the impact is considerable" (2020 interview with an agronomic department manager from an agricultural cooperative in Dolores; unreferenced).

3.1.5.2. Toxicity index according to damage threshold for bees

When considering the ecotoxicological impact on bees, a consistent increase in the moderate toxicity threshold (M) was observed. Three herbicides are present at this threshold: diclosulam, sulfentrazone, and fomesafen. According to several of the actors interviewed, some of these herbicides have been increasingly used on agricultural fields due to the current complex problem of weeding, such as the control of *Amaranthus palmeri* (pigweed).

In the low-threshold group B (**Figure 3**) are the herbicides: glyphosates, 2,4 D amine, metribuzin, and bicyclopyrone. The first two are widely used in fallow, soybean and corn cultivation. The hormonal herbicide 2,4 D amine has seen increased usage as of the 2021/22 harvest due to the commercial introduction in the market of the event in soybeans with Enlist technology, owned by the multinational Corteva, which is tolerant to 2,4 D. Finally, at the most sensitive threshold (A), which poses the highest risk to bees, insecticides like chlorpyrifos, cypermethrin, lambda-cyhalothrin, bifenthrin, and thiamethoxam are included. These five insecticides with the greatest damage to bees decreased their imports between 2010 and 2020, with the exception of the active ingredients bifentrin and thiamethoxam, which are most commonly used in pest insects such as stink bugs.

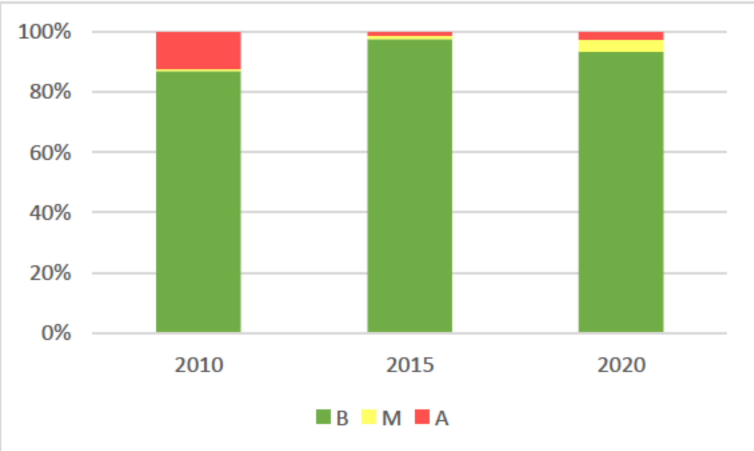

Figure 3. Evolution in percentage of the main herbicides and insecticides for use in soybeans and corn according to toxicological category for bees - LD50 ug-1 (2010 – 2020)

3.1.5.3. Chemical persistence index of agrochemicals in soil

From an environmental perspective, the greatest increase was for the "moderately persistent" threshold, in absolute values, where the herbicide S-metolachlor is located. This herbicide is selective for use in some agricultural crops, such as soybeans and corn. And, to a lesser extent, appears the use of the herbicide bicyclopyrone, which falls within the "persistent" threshold (**Figure 4**).

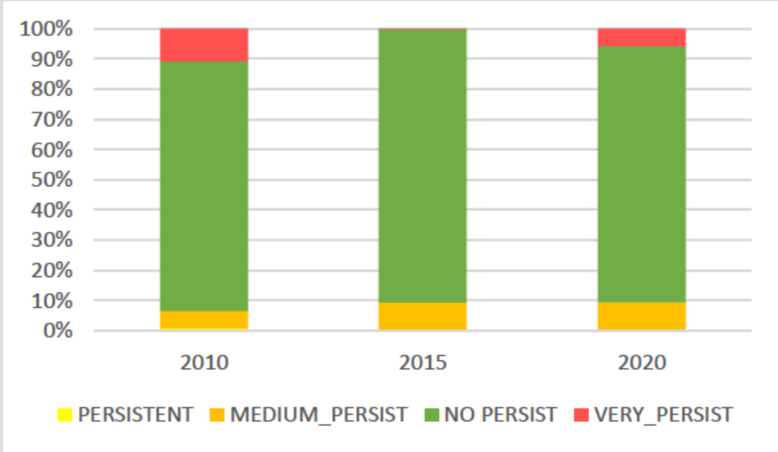

Figure 4. Evolution in percentage of the main herbicides and insecticides for use in soybean and corn according to persistence in soil – DT 50 (2010 – 2020)

On the other hand, the agrochemicals with the longest soil degradation times, categorized as "very persistent," include the herbicide sulfentrazone and the insecticides chlorpyrifos and chlorantraniliprole. The downward trend for this threshold was marked, as mentioned, by the decrease in imports of the insecticide chlorpyrifos. In its place, the active ingredient chlorantraniliprole emerged, which, although it exhibits low toxicity to mammals and bees, its chemical degradation rate in soils is among the highest (PPDB, 2021). The increase in the herbicide sulfentrazone is also observed at this threshold, which is used to control difficult weeds such as wild radish, pigweed and horseweed, and that, like chlorantraniliprole, has low toxicity to mammals and bees.

Another interviewee commented on perceptions regarding the toxicity of current insecticides: "The fact of suppressing pyrethroids and phosphorus organs has, in reality, had a noticeable impact. Honestly, I don't have the statistics, but we buy very little chlorpyrifos now, and we don't buy any first-generation pyrethroids, it has a positive assessment in the environment" (2021 interview with a country manager from an agricultural company in Río Negro and Durazno; unreferenced).

3.1.6. Application entries to fields

In four of the five analyzed harvests with data from fields belonging to FUCREA agricultural producers, one fewer insecticide application was observed for the soybean RR2 stack event compared to RR1 (Table 7). These results were validated with the Poisson technique and, in the case of RR2 soybean, three of the five analyzed harvests showed statistically significant differences in the number of entrances to field with a p-value below 8.2503e-05.

Table 7. Number of applications with insecticides in the fields according to soybean transgenic event

N.° events/Harvest year	RR1 15-16	RR2 15-16	RR1 16-17	RR2 16-17	RR1 17-18	RR2 17-18	RR1 18-19	RR2 18-19	RR1 19-20	RR2 19-20
Minimum	1	2	1	1	1	1	0	0	1	0
Media	4	2,5	2	3	3	2	3	2	3	2
Median (50%)	3,77	2,83	2,46	2,39	2,65	2,12	2,77	1,95	2,73	2
Maximum	6	4	5	5	7	4	6	4	5	5
Simple size (n)	287	6	13	33	386	200	619	197	806	398

Source: material gathered from an unpublished draft (private collection; unreferenced).

Regarding the number of applications in soybeans, an actor pointed out: "Insecticide applications have decreased, particularly with Intacta RR2 soybeans because Bt effectively controls pests. With RR2 soybeans, there's one fewer insecticide application. That is what you lower in costs, and the cost of an insecticide such as chlorantraniliprole, which works very well and has lowered the cost a lot. However, it does not justify the purchase of RR2 soybeans. Beyond the issue of GMOs, there are more and more resistant weeds, more mosquito infestation in the fields and even more tillage, as the only way to control weeds" (2021 interview with a head of technical department from an agricultural cooperative in Rio Negro; unreferenced).

Using the same database as for soybeans, the data for corn cultivation focused on cultivars with two and three stacked events (**Table 8**). Although not all the field records were present, a slight trend was observed, indicating fewer pesticide applications in fields planted with maize varieties featuring three events (e.g. Viptera 3).

Table 8. Number of applications with insecticides in fields according to 2 and 3 corn transgenic events

N° events/Harvest year	2_event_15-16	2_event_16-15	2_event_17-18	3_event_17-18	2_event_18-19	3_event_18-19	2_Event_19-20	3_Event_19-20
Minimum	1	1	0	0	0	0	0	0
Media	1,82	1	1,31	0,83	1,03	0,98	0,55	0,75
Median (50%)	1	1	1	0,5	1	0	0	1
Maximum	4	1	3	2	2	3	2	1
Simple size (n)	17	6	29	6	30	47	53	4

Source: material gathered from an unpublished draft (private collection; unreferenced).

When applying the Poisson technique, there were not statistically significant results for the three harvests for which the data on the number of entries to fields due to insecticide applications were available, between materials with three and two events, with a p-value above 0.42 due to the limited number of records from the spreadsheets obtained from the FUCREA producers.

One interviewee commented on the applications of insecticides: "In second-crop corn, having triple event Viptera 3 is an incredible tool. Two years ago, I planted corn with three stacked events in a rainy year and I had no insect problems" (2021 interview with a farmer in Flores; unreferenced).

In contrast, another interviewee commented: "There is a lot of difference with corn, the most modern stacks have to be taken with great care because they have already begun to create resistance. There would be a difference if we used maize with the first events. Maize with the Power Core event gets eaten up completely; Power Core does not work without insecticides" (2020 interview with a country manager from an agricultural company in Rocha; unreferenced).

3.2 Results obtained from the qualitative approach

This section presents the descriptive synthesis of the topics that emerge from the coded interviews.

3.2.1. Technological packages before and after 2010

According to the actors interviewed, a greater supply of these products has emerged in the Uruguayan market for herbicides and insecticides, regardless of the introduction of the latest transgenic events approved in 2011. In soybean cultivation, they highlighted the continuity in applications with the herbicide glyphosate as the only total weed control since the approval of the RR1 event in 1997. They also recognized that this has led to resistant weeds. As mentioned, a large percentage of fields have to rely on pre-emergent herbicides that had been abandoned since the introduction of the transgenic RR1 soybean. This situation has resulted in increased costs per hectare due to greater applications of other non-glyphosate herbicides, according to the opinion of the interviewees.

As for insecticides, there has been a substitution of organophosphate chemical groups (active ingredient-chlorpyrifos) and pyrethroid (e.g., cypermethrin) with new families of insecticides, such as growth regulators (IGRs) and anthranilic diamides of low toxicity.

Several interviewees highlighted that work is currently being done on the use of cover crops (planting winter greens or other crops after soybeans have been harvested), instead of applying herbicides to control weeds. This practice, associated with comprehensive weed control management, reduces the load of herbicides in the environment.

3.2.2. Productive impacts on yields per hectare

Most of the interviewees agreed that they obtained higher yields per hectare for maize crops with transgenic seed with three stacked events (Viptera 3) over those with one event (Bt 11 and MON 810) and two stacked events (VT3 PRO). This difference is mainly attributed to a genetic improvement of maize cultivars and not to the characteristics of stacked transgenic events *per se*. Additionally, they cited improved pest protection and weed control facilitated by stacked events as secondary factors contributing to yield increase.

For soybean crops with tolerance to glyphosate and resistance to lepidoptera (Bt) associated with the event RR2 INTACTA PRO, interviewees reported no yield increases compared to the first event with tolerance to glyphosate (RR1-without Bt), despite Monsanto's claims of a 10% yield increase per hectare. On the contrary, in some surveyed experiments the RR1 seed used as a refuge outperformed the RR2 variant. Although some mentioned achieving higher yields with the Intacta RR2 IPRO soybeans, they associated it with the variety rather than the transgenic event itself.

3.2.3. Toxicity of agrochemicals

As a synthesized result of this topic, it is noted that until 2015 glyphosate, despite its widespread use, allowed for a long period not to have to apply residual herbicides of greater toxicity, such as paraquat and atrazine. Regarding insecticides, as previously mentioned, growth regulators (IGRs) and anthranilic diamides of low toxicity and selectivity for non-target pests have emerged[(15)].

The actors provided a positive assessment when a decrease in toxicity levels was observed from the planting of maize with transgenic seed with three stacked events (Viptera 3), which does not require insecticide applications in most situations. The application of chlorpyrifos insecticide is avoided, for being the active ingredient that meets the three worst conditions evaluated in this study: toxicity in mammals, in bees and chemical persistence in soils. Similarly, maize with two stacked events, such as VT3 Pro, does not present resistance to all pests, so in high-pressure situations it still requires between one and two insecticide treatments.

The RR2 event of pest-resistant soybean was not given the same consideration, which stands out mainly in situations of high pest pressure. Otherwise, in a normal year, both soybean with glyphosate-tolerant RR1 event and RR2 soybean require control applications, particularly against stink bugs.

3.2.4. Entries to field for insecticide applications and costs per hectare

In the case of corn planted with the Viptera 3 event, interviewees commented that it is cheaper than older corn cultivars with the Bt 11 event. The Viptera 3 stacked event leads to at least two fewer insecticide applications compared to Bt11 seeds, and five fewer insecticide applications than corn without resistance to pests such as refuge material. This is verified with the partial budgeting methodology used in the quantitative approach, where four applications of insecticides were considered for corn with a stacked event as a representative management in Uruguay.

On the other hand, in most of the fields where soybean was planted with the RR2 event, the reduction in insecticide applications did not compensate for the cost of soybean seeds. "The cost reduction in insecticides is negligible," commented one of the interviewees. Although there were exceptions depending on environmental conditions and specific years, for example, in the northeast region and years with high pest pressure. These situations are common in northern Argentina, Paraguay and Brazil, where this technology provides significant benefits, according to other interviewees.

No conflicting opinions were collected for the four categories selected above, which respond to the objectives of the study. For this reason, it was not considered necessary to increase the number of interviewees. A saturation level was reached with half of the interviews conducted.

4. Discussion

It is abstracted from the information presented in tables 1 and 2 that the most important cost variation is the cost of soybean and corn seed according to transgenic event. These results are explained by the obligation to pay royalties when buying the seed for the first time and also when producers reserve their own seeds for the next sowing in the case of soybean. The Uruguayan producer pays US$ 450 + VAT per ton for a soybean seed royalty with the RR2 event that is equivalent to 9.20 ha planted with soybean seed of a variety that has the RR1 event at the 2020-2021 market price.

Regarding net profits per hectare from the use of transgenic seeds, a study conducted at an Embrapa station in Rio Grande do Sul for the 2014/15 and 2015/16 harvests found higher profits for the RR1 variety in Brazilian Reais per hectare ($R/ha), compared to RR2 materials, due to the low incidence of insects, in this case[16]. However, another study carried out in the southeastern region of the state of Mato Grosso for the 2013/14 harvest, which also estimated some economic indicators for both transgenic events, reported lower costs for RR2 soybean compared to RR1, but with favorable returns for both groups[5]. In northwestern Argentina, where they also compared the two soybean groups RR1 and RR2 in the 2013/14 harvest, advantages of US$ 55/ha were found in favor of the RR2 event due to lower insecticide application costs[17].

In the last five analyzed harvests of corn cultivation, the higher yields and protection offered by corn materials presenting three transgenic events to main pests are the main explanation for avoiding entering the fields to apply insecticides, and this dilutes the higher cost in this transgenic seed crop. Other studies consistent with this research obtained lower variable costs due to the greater resistance to pests offered by transgenic corn hybrids. One study found that Bt proteins expressed in materials with more than one transgenic event, among which Viptera 3 stands out, were effective for pest control without the need for insecticide applications[18]. This means more crop protection, less yield loss, and lower application costs. In the semi-arid region of La Pampa, similar results were obtained when evaluating five maize hybrids with different biotechnological events for controlling the pest *Agrotis robusta*[19]. Non-commercial maize hybrids with stacked transgenic events that express more than one protein for pest control have also been evaluated in Brazil, *pyramided proteins* which proved more effective in achieving greater pest protection compared to hybrids with only one or two Bt proteins[7].

Regarding soybean yields, the study conducted by Embrapa in Rio Grande do Sul found no significant differences in soybean yields between varieties with one (RR1) and two events (RR2 PRO) for the two harvests studied[16]. Similarly, another study by INTA Rafaela found no significant differences in yields for both technologies with RR1 and RR2 soybean for two analyzed harvests in 2013/14 and 2014/15[20]. However, the study carried out in Mato Grosso, which analyzed six producers, found differences in favor of the RR2 event with 4.52% higher than the average yields of RR1 soybeans[5]. Other authors, through the RECSO network for five harvests, also obtained a favorable trend in yields for soybean varieties with the RR2 PRO transgenic event, with a significant difference for 26% of the 167 trials conducted in some localities of Corrientes and Entre Ríos[21]. In light of these studies from Argentina and Brazil, the findings of this study and the interviewees, it appears that yield per hectare is more related to the genetic improvement of transgenic soybean varieties rather than to the difference in the number of transgenic events.

For the period under study, it was not possible to evaluate the evolution of agrochemical toxicity at field level due to the lack of records in the database obtained from CREA producers. However, through data on imports, use, and estimated toxicity levels of agrochemicals, a greater presence of herbicides for the control of weeds resistant to yellow-band glyphosate was observed. This was somewhat offset by increased use and imports of green-band insecticides with more selective control of non-target pests. Meanwhile, no absolute thresholds were reported of higher levels of toxicity for bees and chemical persistence in soils; instead, the observed thresholds were associated with the increased application of the same herbicides for the control of weeds that are difficult to control.

Regarding the frequency of field entries due to agrochemical applications, a study[8] highlighted that since the first commercial harvest of Intacta RR2 PRO soybean in 2012/13 containing the Cry1ac gene with resistance to major pests, the average number of insecticide applications decreased from 3.50 to 2.45 for both soybean groups between 2013 and 2019 across different states of Brazil. Finally, another study revealed an average of 3.75 insecticide applications for the control of stink bugs in the case of RR2 soybean and 6.5 applications for RR1 soybean for controlling caterpillars and bugs[5]. These studies align with this research, which observed a lower need for insecticides to control lepidoptera in RR2 soybean (Bt).

5. Conclusions

Cost savings were evidenced, which varied fundamentally for maize cultivars with stacked events. In contrast, for soybean cultivations with the Bt stacked event, the savings from reduced fumigation costs and applied insecticides did not compensate for the high cost of royalty payments, nor did this event protect against other insects of economic importance.

Regarding the net profits, there is a trend in favor of the non-Bt soybean event over Bt-protein varieties, due to higher seed costs including royalty payment for its technological value. Results were more evident for maize materials with stacked Bt protein events.

Considering the weighted average yields by field area, 25% of the records with Bt soybean seeds exceeded the yields of non-Bt seeds by 10%. Using the bootstrap resampling technique, significant differences in means and median yields were not verified in both transgenic groups. Meanwhile, yields in recent years have increased for maize cultivars with more than one event, mainly due to genetic improvement, as highlighted by the different actors interviewed.

The use and import of agrochemicals decreased in absolute terms, but their share for the non-glyphosate herbicides with high to moderate toxicity increased in soybean and corn crops; the insecticide category remained consistent in both crops throughout the analyzed period.

For agrochemical applications, in soybean crops with the Bt event, the Poisson technique confirmed a significant decrease in field entry due to unnecessary insecticide applications compared to the first soybean event that was not pest resistant. This benefit was most evident, as seen through the interviews, in regions such as Paraguay and Mato Grosso in Brazil, where pest pressure is greater.

Finally, in maize cultivation, the results of field entries due to insecticide applications were not statistically significant when applying the Poisson test. Likewise, all the interviewed actors highlighted the advantages of corn with three stacked events, which only required insecticide applications in exceptional cases compared to materials with one and two transgenic events with partial resistance to pests.

Transparency of data

The data set that supports the results of this study is available in the Master's Thesis in Agricultural Sciences, Social option, titled “Economic and environmental impacts of stacked transgenic events in soybean and corn from 2010 to 2020”.

Author contribution statement

Juan Lorente contributed to the project administration, conceptualization, data curation, methodology, formal analysis, writing – original draft, writing-review & editing.

Federico García: methodology, formal analysis, writing-review & editing.

Miguel Vassallo: writing-review & editing.

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