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BRIEF COMMUNICATION

Transgenic crops: trends and dynamics in the world and in Latin America

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Abstract Transgenic crops have been the recipient of strong support as well as vigorously opposed opinions since their appearance. In any case, their growth throughout the world has been remarkable, and the production and commercialization of transgenics in Latin America has been especially significant. The purpose of the present study was to analyze transgenic crop production trends around the world and the relationship between the area allocated to the cultivation of transgenic crops and the profits generated by this activity. Data concerning Latin American countries and their participation in transgenic crop production are addressed specifically. The present study used covariance analysis, Pearson's correlation coefficient, time series analysis, Dicker–Fuller test, Durbin–Watson statistic, standardization, and different measures of central tendency. Results for the period between 1996 and 2016 show that, despite the significant increase in the area planted with this type of crops, their production presented a deterministic growth behavior, which is explained using a non-stationary model. Current data are insufficient to establish a causal relationship between cultivated hectares and their derived profits. Finally, the present study showed that production increased considerably from 2004 to 2016 in the cases of Brazil, Argentina, Paraguay, and Uruguay, as well as a positive relationship between the global area planted with transgenics and the corresponding area in these selected countries.

Keywords Transgenic · Crops · Production · Commercialization · World · Latin America

Introduction

Genetic modification of plants to enhance their characteristics and bring increased added value to produce began early in the history of agriculture. Genetic engineering has significantly increased the possible changes and improvements to crops; nevertheless, since the introduction of genetically improved seeds, the discussion between communities in favor and against this technology has failed to move forward. Those whose opinion is favorable argue that increased production and reduced costs are ultimately beneficial to consumers. On the other hand, those who are against it are concerned about environmental and health risks (Barrows et al. 2014).

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The first account of the use of genetic engineering for commercial purposes in agriculture—an RNA-mediated gene suppression technique—dates from 1994, and it resulted in the creation of the Flavr Savr tomato. Although less money is invested on biotechnological horticultural crops than on agronomic crops, and the economic impact of the former is still lower, relevant applications are expected in the future, and they will have to face public opinion and meet regulatory and intellectual property requisites (Chi-Ham et al. 2010; Clark et al. 2004); thus, the advancement of transgenic crops depends on how well met are various demands to guarantee its biologically safe use and the preservation of local plant species, all of which are necessary to address the concerns expressed by society.

Concerning intellectual property protection, transgenic plant patenting schemes represent an option, but given their relevance, scientists all over the world must develop a global vision allowing for ad hoc technological management to address different related aspects, such as comprehensive protection and responsible transfer of such inventions, especially when the technology is transferred from developed to developing economies (Koo et al. 2004; Kowalski et al. 2002). In general, the protection of intellectual property over seeds has increased significantly. In addition, market leadership is limited to a very small group of agrochemical companies, which results in high prices and insufficient capabilities to conserve these seeds among farmers (Howard 2015).

The introduction of transgenic crops into the market is always mediated by regulatory criteria, market restrictions, and compliance-associated costs (Bradford et al. 2005a, b). The development of biotechnological intellectual property and its commercialization has clearly originated in developed economies, mainly the United States, although World Trade Organization (WTO) member countries have been strong supporters of the process (Wright and Pardey 2006). As a consequence of the increasing development and consumption of transgenic crops, the discussion on their benefits and risks has intensified, particularly regarding the risks derived from inadequate management of intellectual property rights (López 2004). Nevertheless, given the predominance of developed countries, the introduction of transgenics in developing countries must be conducted after thorough assessments orchestrated by government actors, stakeholders, and academic peers in recipient economies.

Herring (2008) points out that, although animosity is still active around the world (genetic engineering in agriculture has not been as welcome as in other areas, for instance in medical science), several agricultural issues have already been alleviated by genetic engineering. Although there are still critical pending challenges (drought-resistant crops, increased productivity and nutritional value, and attention to problems derived from climate change, among others), progress has been made in different countries despite controversy; among the most important factors blocking the introduction of transgenic crops into the market are commercial interests, problems associated with intellectual property, and especially political problems. Among the most critical problems identified as caused by transgenic crop development are undesired pollination between transgenic and conventional varieties and inadvertent planting of transgenic seeds in intensive crops, which entail unplanned costs for producers (Smyth et al. 2002).

Even though globally, and particularly in Europe, public opinion is reluctant to accept the production and commercialization of genetically modified crops, they have been associated with environmental and economic benefits. Most of the production is focused on a few crops with limited genetically modified characteristics, especially in countries such as the United States, Argentina, Canada, and Brazil, where private investments have been the vehicle for this technology to be introduced. It has also been argued that the use of noxious pesticides and herbicides has decreased significantly as a result of the increased resistance of transgenic crops. Another argument indicates that production has increased since the emergence of transgenics in number of cultivated hectares and number of countries where they are used, as well as the economic benefits derived from these activities. In addition, the new generation of transgenic crops is expected to incorporate technological upgrades and biosafety evaluation methods and to address health-related issues more extensively (increased nutritional value) (Chen and Lin 2013; Traxler 2006).

There is considerable discussion about genetic manipulation techniques and the development of transgenic crops in which biotechnology and its relationship with agriculture have been described as resulting from a neoliberal approach to food that imposes regulations and responds to the interests of large transnational companies; if so, governments of recipient countries have a central role in regulating biotechnology to create an adequate balance among actors. Among other issues, the discussion grapples with economic matters and legal and ethical considerations in which productivity becomes the central concern, and the value of transgenic crops is challenged based on their social, economic, and environmental effects (Azadi and Ho 2010; Otero 2012). For instance, it has been argued that the commercialization of transgenic crops has been hindered by the economic burden of regulatory requirements and the barriers imposed by the market itself. Nevertheless, the field of biotechnology has acquired experience in research and commercialization activities, and its body of knowledge has grown; these conditions could help the industry to meet its commercialization requirements while safekeeping consumer safety (Bradford et al. 2005a, b).

In this regard, in Latin America, biotechnology firms producing food and biofuels are facing important challenges and problems in terms of food and energy safety derived from the adopted investment strategies and the incentives provided by governments and markets, which define the dynamics of the industry and its impact on society, the economy, and the environment (Saravia-Matus et al. 2018). In Latin America, the landscape of human resources training, technological and scientific infrastructure, support programs, regulation, legislation, and in general, all activities associated with biotechnology (particularly agricultural biotechnology), is markedly heterogeneous, although the largest economies, such as Brazil, Argentina, Chile, Mexico, and Colombia, have achieved important progress (Trigo et al. 2000); therefore, mapping the configuration and evolution of the field is essential to make decisions in the sector, but especially concerning the production and commercialization of transgenic crops, which have a strong presence in the region. The following section demonstrates the presence of an increasing global trend, verified by its being a deterministic series and its having a sustained growth factor from 1996 to 2016. In addition, relevant data on the dynamics of transgenic crop production in certain Latin American countries are presented.

Methods

The total global area used for biotechnological transgenic crops increased from 1.7 million hectares in 1996 to 185.1 million hectares in 2016. This variation represents an average annual growth of 45.3 million hectares. In other words, the world has increased the territorial area allocated to transgenic produce every year between 1996 and 2016. The total worldwide variation over these 21 years was 10,788.2%. This growth has been sustained over the period and it presents a positive trend (see Fig. 1).

It is important to point out that the behavior of the total area cultivated with transgenic crops is clearly associated with time; when the covariance[1] between the two variables for the period from 1996 to 2016 was calculated, the statistic indicated a result of $\mathrm{Cov(X,Y)} = 356.7$, which suggests a positive association between the two variables. The intensity of the linear relationship was calculated for each pair of variables defined between the set of total numbers of hectares cultivated with transgenic produce (I_ω) and the set defined by the years (I_φ) using Pearson's linear correlation coefficient per the following formulation:

$$\rho_{\mathrm{I}_\omega \mathrm{I}_\varphi} = \frac{\sum \mathrm{I}_\omega \mathrm{I}_\varphi}{\sqrt{\sum \mathrm{I}_\omega^2}\sqrt{\sum \mathrm{I}_\varphi^2}}$$

where $I_\varphi = I_{\varphi i} - \bar{I}_\varphi$; $I_\omega = I_{\omega i} - \bar{I}_\omega$, with $\mathrm{i} = 1, 2, 3, \ldots\ldots, \mathrm{n} + 1$.

Thus, the result of the statistic was $\rho \mathrm{I}_\omega \mathrm{I}_\varphi = 0.9952$, which indicates a strong positive relationship of a linear nature between the global area used for planting transgenic produce and the year. Similarly, based on the calculation of $\rho \mathrm{I}_\omega \mathrm{I}_\varphi$, it can be argued that the global area allocated to transgenic produce increased 99.52% for each year considered in the present study. This deterministic growth (Chandler and Scott 2011) of the global area allocated to biotechnological transgenic crops was approached using time series analysis, which demonstrated that such growth was non-stationary from 1996 to 2016. In other words, the measures of central tendency (arithmetic mean and variance) associated with the annual records are not constant over time (Shumway and Stoffer 2006;

[1] This statistic was calculated as follows: $\mathrm{Cov(X,Y)} = \frac{\sum_{i=1}^{i=n}(X_i - \bar{X})(Y_i - \bar{Y})}{n}$.

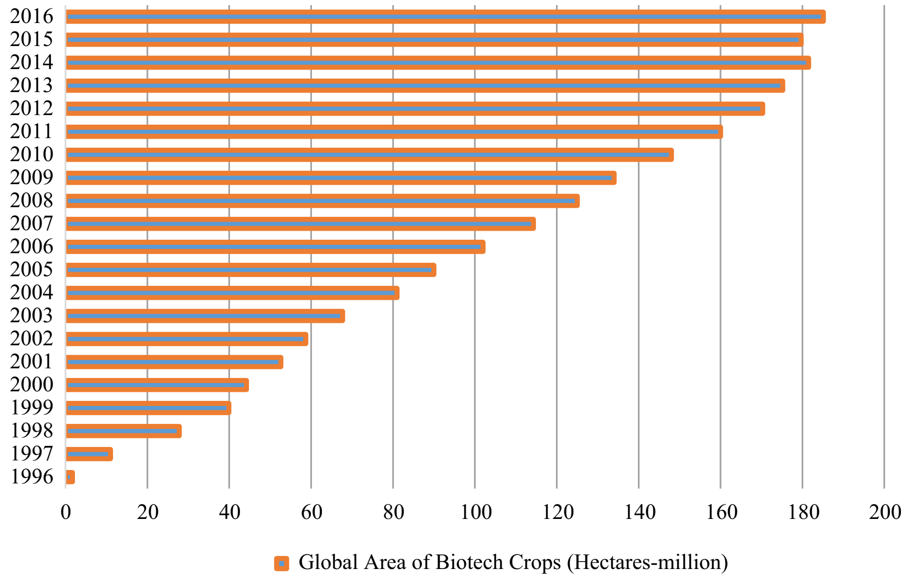

Fig. 1 Evolution of hectares planted with biotechnological transgenic crops, 1996–2016. *Source*: Created by the authors based on ISAAA (2016)

Leybourne et al. 2005; Fuller 1996). To verify that the series did not remain constant over time (weak stationarity)[2] (Steland 2007; Rodrigues and Rubia 2008; Mirakhor and Krichene 2014; Jannati et al. 2016), we carried out Dickey–Fuller test[3] for the first lag and the series tendency (Tanaka 2017; Lu et al. 2013; Guntukula 2018; Arltová and Fedorová 2016). The results of this test are presented in Table 1.

Results presented in Table 1 were also analyzed using Durbin–Watson statistic (D–W) = 1.978326; since the value is in the interval between $d_L = 1.85$ and $d_U = 2.15$, the lack of autocorrelation was validated (Greene 2003). Thus, the result of augmented Dickey–Fuller test was assumed as valid: the analyzed series contains a unit root, therefore, it is non-stationary. For its part, Table 2 presents results for the proposed linear regression model, and Fig. 2 shows both estimations based on the model and real values for the global area of transgenic produce from 1996 to 2016.

Table 1 Results of augmented Dickey–Fuller test. *Source*: Elaborated by the authors

Null hypothesis: D(Global_Area) has a unit root
Exogenous: constant, linear trend
Lag Length: 1 (Automatic—based on SIC, maxlag = 4)

		t-statistic	Prob.[a]
Augmented Dickey–Fuller test statistic		− 1.924884	0.6005
Test critical values:	1% level	− 4.571559	
	5% level	− 3.690814	
	10% level	− 3.286909	

[a]MacKinnon one-sided *p* values

Another relevant aspect to be analyzed is the cost–benefit relationship of transgenic crop production within the agricultural industry and the global value of biotechnology in the market from 1996 to 2016. Data in Fig. 3 show that each hectare used to grow transgenic crops produced an average profit of 0.07 million USD per year in the global market of crops developed using biotechnological developments during the study period. In other words, during the study period, an average of 14.86 ha produced one million USD per year on a global scale. It is also important to highlight that the behavior of these two variables was quite homogeneous throughout the period. The Pearson's coefficient (first order) for the correlation of the variables was calculated at 0.9904.

Although the two variables (growth in cultivated area and global value of crops) belong to different

[2] Weak stationarity is referred to mainly because the probabilistic distribution associated with the series analyzed in the present study is unknown, as well as any combination of observations and all of its moments, which are time-independent.

[3] Augmented Dickey-Fuller test validated the null hypothesis H_0 = The series contains a unit root (series is non-stationary) over the alternative hypothesis H_1 = The series does not contain a unit root (series is stationary).

Table 2 Results for the linear regression model without autocorrelation. *Source*: Elaborated by the authors

Augmented Dickey–Fuller test equation
Dependent variable: D(Global_Area,2)
Method: least squares
Sample (adjusted): 1999 2016
Included observations: 18 after adjustments

Variable	Coefficient	Std. error	t-statistic	Prob.
D(Global_Area(-1))	− 0.637530	0.331204	− 1.924884	0.0748
D(Global_Area(-1),2)	− 0.045256	0.304090	− 0.148825	0.8838
C	6.843785	4.505566	1.518962	0.1510
@Trend(“1996”)	− 0.133039	0.192413	− 0.691426	0.5006
R^2	0.368646	Mean dependent var		− 0.63333
Adjusted R^2	0.233356	S.D. dependent var		4.46028
S.E. of regression	3.905342	Akaike info criterion		5.7557
Sum squared resid	213.5238	Schwarz criterion		5.95356
Log likelihood	− 47.80128	Hannan-Quinn criter.		5.782980
F-statistic	2.724860	Durbin–Watson stat		1.97833
Prob(F-statistic)	0.083819			

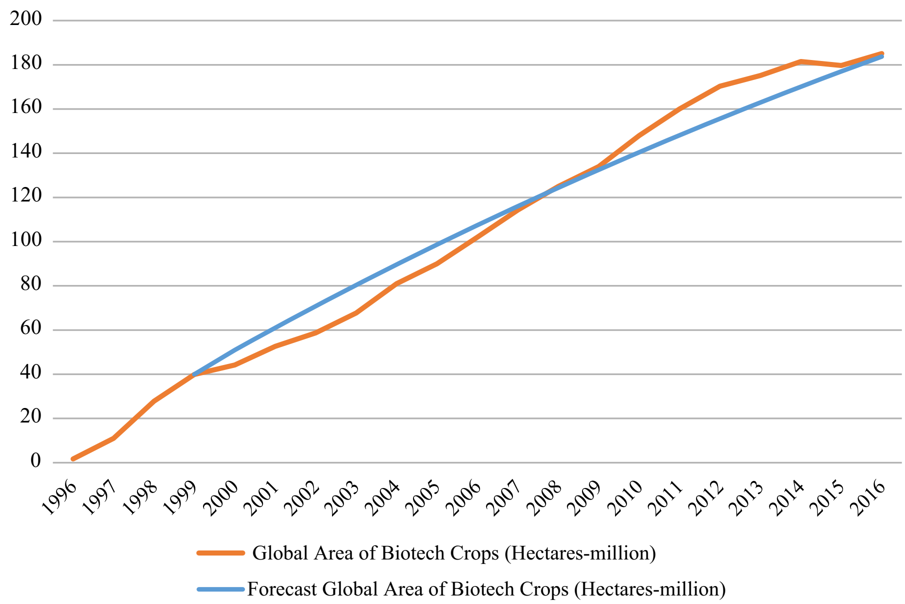

Fig. 2 Estimated and actual data describing the evolution of hectares planted with biotechnological transgenic crops, 1996–2016. *Source*: Created by the authors based on ISAAA (2016)

measurement scales, their trends can be used to reveal which variable increased the most during the study period. To this end, data were standardized[4] so that the averages of these two variables could be compared. The standardized average global area of transgenic crops was 0.863 (Z_1), and the standardized average of the global value of biotechnology (in millions of USD) in the agricultural market was 0.874 (Z_2). These values allow for two assertions: (1) The net increase in both variables was indeed homogeneous, and (2) growth in both variables was positive and sustained from 1996 to 2016. However, it should be mentioned that profits derived from developments in transgenic technology

[4] Standardization was carried out using the expression $Z_i = \frac{X_i - \bar{X}}{es(X_i)}$, a normal probability distribution function with a set mean of 0 and a variance of 1. This makes it possible to modify the variable $|Z_i|$, which in turn allows for variables of different measurement units to be compared.

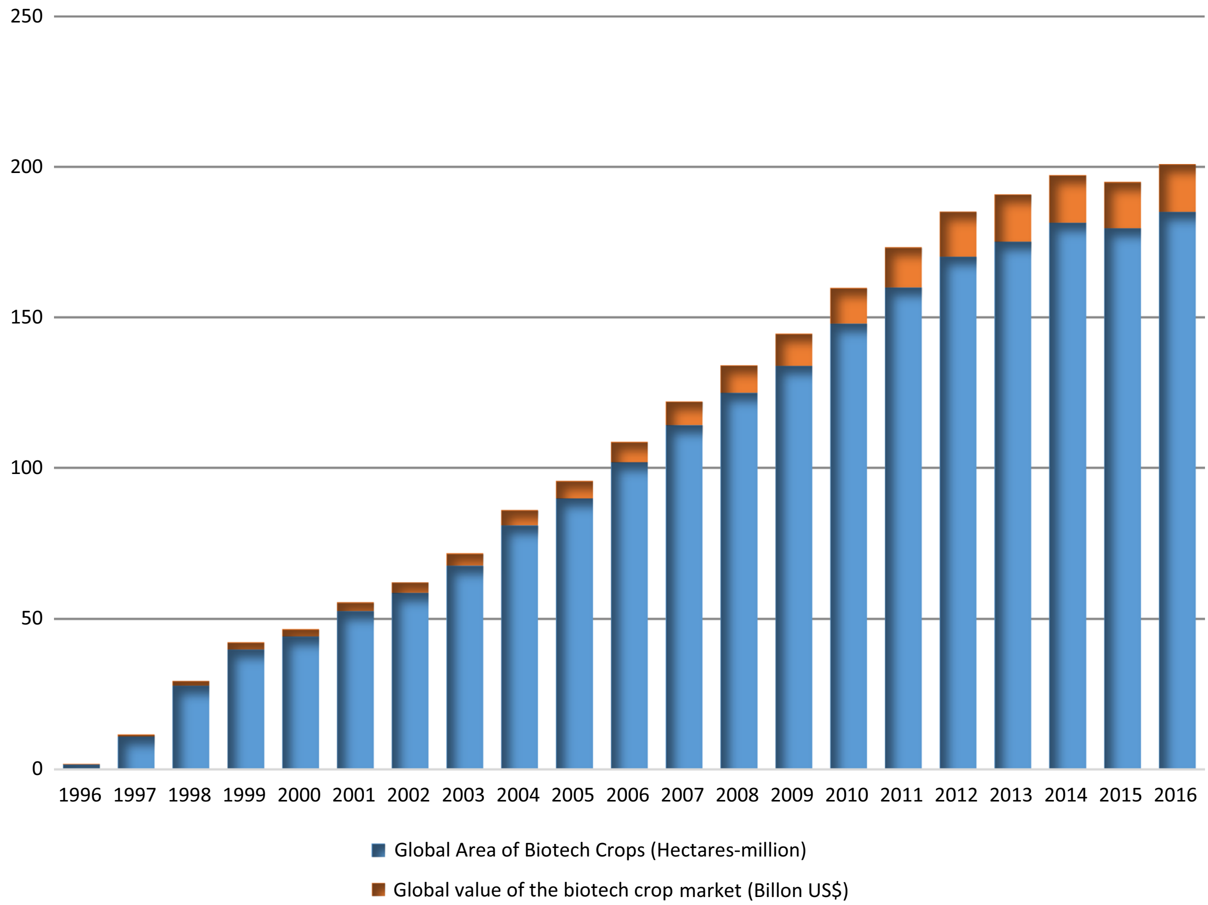

Fig. 3 Hectares (millions worldwide) allocated to transgenic crop cultivation and the global value of biotechnology in the produce market (millions of USD), 1996–2016. *Source*: Prepared by the authors based on ISAAA (2016)

failed to present multiple dividends as expected, at least during the study period.

Despite the simultaneous increase in the global value of biotechnology (millions of USD) in the produce market and area cultivated with transgenic crops at the global scale, as observed in Fig. 2, these variables were not correlated. In other words, a larger global surface planted with transgenic crops does not necessarily lead to higher profits derived from the global value of biotechnology in the produce market.

In Table 3, the participation of some Latin American countries in the production of transgenic crops is expressed as a percentage of global area of transgenic crops (millions of hectares) during the 1996–2016 period.

The participation of Latin American countries in transgenic cultivation, shown in Table 3, was modest during the 1996–2016 period. Brazil was the country with the highest number of hectares planted with transgenic crops (an average of 24.94 million hectares), while Argentina grew 16.28 million hectares,[5] Paraguay 2.77 million hectares, Uruguay 0.97 million hectares, and Mexico 0.12 million hectares. However, Argentina showed the greatest rate of growth in cultivated area allocated to transgenic crops; from 1996 to 2016, the area increased by 23,700.90%. Meanwhile, transgenic crop area increased by 1536.7% in Brazil during the 2003–2016 period, in Uruguay by 333.3% during the 2004–2016 period, and in Paraguay by 200% during the 2004–2016 period. No increase in transgenic crop area was observed for Mexico during the 2004–2016 period. These results suggest that the internal policies of some Latin American countries have been more favorable toward

[5] Average values.

Table 3 Global area of transgenic crops (millions of hectares) in selected countries of Latin America in comparison with worldwide area, 1996–2016. *Source*: Prepared by the authors based on James (2014) and ISAAA (2016)

Year	Worldwide total	Brazil	Argentina	Paraguay	Uruguay	Mexico
1996	1.7		0.1			
1997	11		1.4			
1998	27.8		4.3			
1999	39.9		6.7			
2000	44.2		10.0			
2001	52.6		11.8			
2002	58.7		13.5			
2003	67.7	3.0	13.9			
2004	81	5.0	16.2	1.2	0.3	0.1
2005	90	9.4	17.1	1.8	0.3	0.1
2006	102	11.5	18.0	2.0	0.4	0.1
2007	114.3	15.0	19.1	2.6	0.5	0.1
2008	125	15.8	21.0	2.7	0.7	0.1
2009	134	21.4	21.3	2.2	0.8	0.1
2010	148	25.4	22.9	2.6	1.1	0.1
2011	160	30.3	23.7	2.8	1.3	0.2
2012	170.3	36.6	23.9	3.4	1.4	0.2
2013	175.2	40.3	24.4	3.6	1.5	0.1
2014	181.5	42.2	24.3	3.9	1.6	0.2
2015	179.7	44.2	24.5	3.6	1.4	0.1
2016	185.1	49.1	23.8	3.6	1.3	0.1

Table 4 Statistics calculated for selected countries in Latin America, 2004–2016. *Source*: Prepared by the authors based on James (2014) and ISAAA (2016)

Statistic	Brazil	Argentina	Paraguay	Uruguay	Mexico
Pearson's correlation coefficient	0.9803	0.9805	0.9468	0.9764	0.4430
Covariance	493.02	100.28	26.47	16.10	0.66

the introduction of certain transgenic crops and, as a consequence, have led to an increase in the area allocated to transgenic crops. Several measures of central tendency were calculated to understand the relationship between the behavior of global transgenic crop area and transgenic crop area per country presented in Table 3 (see Table 4).[6]

The covariance statistic shown in Table 4 evinces a positive relationship between the global area cultivated with transgenic crops and the corresponding area of each selected country in Latin America. Additionally, these statistics show that the area planted with to transgenic crops in Brazil during the 2004–2016 period has the greatest positive linear relationship with the global area allocated to these crops. In other words, as the global area planted with transgenic crops increases, Brazil allocates a greater number of hectares for planting these crops in comparison with other countries in Latin America;

Argentina allocated the second highest number of hectares to transgenic crops, followed by Paraguay, Uruguay, and Mexico. The linear correlation between global area of transgenic crops and area allocated to transgenic crop production in Argentina, Brazil, Uruguay, and Paraguay was confirmed by Pearson correlation coefficients, which were near 1. Therefore,

[6] The selection of Latin American countries was based on the availability of data. Information is not available for all countries or records are only available for a distinct set of years.

an increase in the global area allocated to transgenic crops is confirmed, and the above mentioned Latin American countries will present a similar increasing trend in their number of hectares planted with transgenic crops.

Conclusions

At present, the advancement in production and commercialization of transgenic crops is still a controverted issue; therefore, awareness of its progress and dynamics throughout the world, and in specific regions such as Latin America, becomes a relevant endeavor to understand its evolution in the agricultural sector. Additionally, insights into the industry may support many actors in making decisions based on an adequate contextualization and identification of the problems and necessities characteristic of each specific region or country. These foundations lead directly to the discussion of issues associated with biosafety, conservation of local plant varieties, bioethics, promotion of endogenous capacities and technologies, legislation, and regulation, among other matters.

Time series analysis results helped to elucidate why the growth in the area of land allocated to transgenic crops around the world was deterministic and non-stationary from 1996 to 2016. On the other hand, the analysis carried out to find out the cost–benefit relationship between the global area of transgenic crops and the global value of biotechnology (in millions of USD) in the market during the same period revealed that an increase in the global area planted with transgenic crops does not necessarily correspond to increased profits derived from the global value of biotechnology in the agricultural market.

Finally, in the case of Latin America, results indicate that the internal policies of some countries have been more benevolent to the introduction of transgenic crops, which was directly reflected in the increased area used for planting transgenics in some of these countries. In other words, there is enough statistical evidence to assert that the global increase in the area allocated to transgenic crop cultivation is associated with an increase in such area in some Latin American countries.

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Compliance with ethical standards

Ethical approval This work fulfil with all requirements from Committee on Publication Ethics (COPE).

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