Revista Ibero-Americana de Ciências Ambientais
Ibero-American Journal of Environmental Sciences

Nov 2022 - v.13 - n.11

ISSN: **2179-6858**

This article is also available online at:
www.sustenere.co

The use of glyphosate and RR soybean productivity in Brazil from 2009 to 2018

There are indications that the volume of pesticides used is growing significantly worldwide, especially the herbicide glyphosate, after the introduction of genetically modified crops. In Brazil, the use of pesticides in crops has been the subject of constant reflection about their positive and negative impacts of this pesticide. This research sought evidence of the behavior of GM soy productivity related to glyphosate consumption in Brazilian States. A literature review on RR soy and publicly available government secondary data (namely IBAMA, and IBGE-SIDRA) allowed us to estimate the correlation between the commercialized amount of glyphosate and the productivity of the cultivated area of this crop, between 2009 to 2018. The results indicate that the quantity of glyphosate commercialization had an increase of 45% in this decade, approaching 1.5 billion tons, and corresponds to more than 50% of total agricultural pesticides sold in the country. However, no significant positive correlation was found between the productivity of RR soybean and the increase in glyphosate commercialization.

Keywords: Biotechnology; Transgenic seeds; Pesticides.

O uso do glifosato e produtividade da soja RR no Brasil de 2009 a 2018

Há indícios de que o volume usado de defensivos agrícolas está crescendo de forma significativa mundialmente, com destaque para o herbicida glifosato, após a introdução das culturas geneticamente modificadas. No Brasil a crescente utilização de defensivos agrícolas nas lavouras têm sido alvo de constantes reflexões sobre os impactos positivos e negativos deste defensivo agrícola. Esta pesquisa buscou evidências do comportamento da produtividade da soja transgênica relacionadas ao consumo de glifosato nos estados brasileiros. Uma revisão de literatura sobre a soja RR e dados secundários provenientes do IBAMA e do Instituto Brasileiro de Geografia e Estatística (IBGE-SIDRA), por Unidade da Federação, permitiram estimar a correlação entre a quantidade comercializada de glifosato em cultivos de soja RR e a produtividade da área cultivada dessa cultura, para o período de 2009 a 2018. Os resultados indicam que a quantidade da comercialização do glifosato teve um aumento de 45% nesta década, aproximando-se de 1,5 bilhões de toneladas, e corresponde a mais de 50% do total dos defensivos agrícolas comercializados no país. No entanto, não foi encontrada uma correlação positiva significativa entre a produtividade da área plantada de soja RR e o aumento da comercialização de glifosato.

Palavras-chave: Biotecnologia; Sementes transgênicas; Defensivos agrícolas.

Topic: **Biotecnologia**

Reviewed anonymously in the process of blind peer.

Received: **11/11/2022**
Approved: **23/11/2022**

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DOI: 10.6008/CBPC2179-6858.2022.011.0011

Referencing this:
MATIVI, C. S.; GIRARD, P.; PACHECO, L. P.; CABRAL, C. E. A.; RIGHI, R. S. M.. The use of glyphosate and RR soybean productivity in Brazil from 2009 to 2018. **Revista Ibero Americana de Ciências Ambientais**, v.13, n.11, p.129-138, 2022. DOI: http://doi.org/10.6008/CBPC2179-6858.2022.011.0011

INTRODUCTION

Soy is one of the most important agricultural commodities in the world. Brazil, since the 2019/20 harvest, has become the world's largest producer of soy, followed by the United States of America, Argentina and China. About 90% of soy cultivated today is the transgenic soybean [*Glycine max (L.) Merrill*], genetically modified, tolerant to the herbicide glyphosate (*Roundup Ready®* soybeans, GR or RR) (ISAAA, 2017; USDA, 2020; YANG et al., 2021).

The Brazilian climatic conditions, with high temperatures and a more humid environment, typical of the tropical climate, favor the development of weeds, especially during the off-season, when they further increase their potential for multiplication. Glyphosate used with RR soy has been used as the main technique for weed management, which has led to greater environmental risks (BENBROOK, 2016; GANDHI et al., 2021).

Although technologies similar to RR soy have contributed to produce more food, they can also cause imbalances in the ecosystem food chains, by reducing pest populations and decreasing soil biodiversity. This may lead to lower nitrogen fixation, which can cause significant declines in crop productivity and, consequently, can affect food security (ELVER et al., 2017).

In Brazil, increasing levels of glyphosate contamination can compromise mega biodiversity, which is relevant to the country's biotechnological potential (OECD, 2015; SOUZA et al., 2016; ABRANCHES, 2020), as well as human health (EPA, 2017).

It is thus important to ask whether the increase in glyphosate consumption can compromise soybean productivity. This paper seeks to understand whether the introduction of the RR soy has made a significant difference in the historical Brazilian soy production. It also proposes a way to use the available official secondary data in Brazil to assess the relation between glyphosate consumption and soy production in the main Brazilian soybean producing states.

MATERIALS AND METHODS

All data used in this study is secondary. Agricultural data, such as crop area, crop types by area, and crop productivity are from the IBGE-SIDRA platform (IBGE, 2019). Data regarding glyphosate consumption comes mostly from IBAMA, published between 2009 and 2018, which were collected on the platform in April 2020. To complement this analysis, glyphosate sales data in Brazil between 2000 and 2009 published by SINDAG (2020) were also used. See the Data Availability section for more details. Data files obtained from these sources are accessible in the supplementary information.

A simple time series analysis was performed to detect historical changes in soy productivity gains from 1974 to 2018, with a special focus on the introduction of RR soy in 2003. Linear regression of soy productivity over time were performed and the slope of the obtained regression equations were equated to growth trend in productivity. Comparison between growth trends were tested using ANCOVA ($p < 0.01$) (HAIR et al., 2009). Pearson’r and the probability (p) of the null hypothesis that r is equal to 0 was also calculated for each regression set.

Publicly available data was used to verify the relationship between the amount of glyphosate sold in Brazilian states producing mainly RR soy crops and the productivity of these crops between 2009 to 2018.

Firstly, Brazilian soybean producer states were defined as those states where the soy cultivated area remains on average at 100,000 ha or more between 2009 and 2018. When in a given year, the planted area was below this value, the average for the period was considered as the criterion.

Secondly, in the states considered as soybean producers (>100,000 ha), we sought to conserve only those states where there was a strong linear regression between the annual soy cultivated area and the annual purchase of glyphosate, in order to minimize other factors interfering in this relationship, in particular the fact that glyphosate is used in other crops. Only states in which the regression was significant ($p < 0.01$), and $R^2 \geq 0.70$ were retained. It was then assumed that, in the five retained states, the annually bought glyphosate was entirely used for soybans cultivation. For these states, Pearson'r and the probability (p) of the null hypothesis that r is equal to 0 was also calculated for each regression set.

Sets of empirical equations by state and by year were similarly calculated. These equations assume the following form:

$$G = gA + c \quad (1)$$

where:
G - is the glyphosate used in soybean crops;
g - is the rate of glyphosate used per hectare of soybean crop;
A - is area of soybean crop; and,
c - is a constant.

The slope of the trend line is obtained from the regression analysis between A and G. A high coefficient of determination ($R^2 \geq 0.70$) was chosen to minimize error associated with the determination of g. The value of g corresponds, in the study area and period, to a rate of glyphosate purchased per hectare of cultivated soybean, assimilated here to a rate of glyphosate use in soybean cultivation in kg of glyphosate per hectare of soybean (kg ha^{-1}).

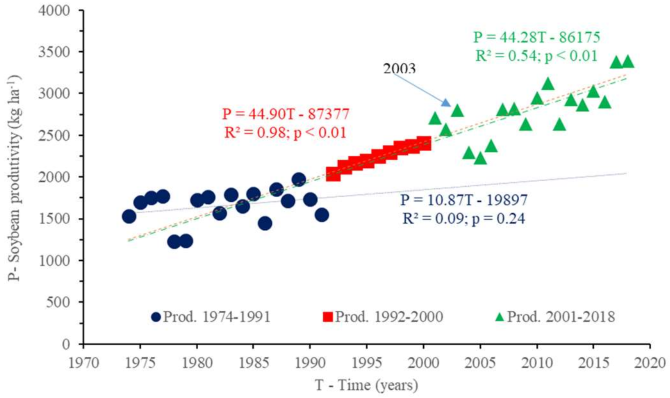
Across states a set of six g was obtained. One relates the bought glyphosate in the five states to the soy production between 2009 and 2018. The five others are state specific over the same period. Over time a set of 10 g, was obtained. One for each year of the study.

The empirical equation (Eq. 1) was used to calculate the amount of glyphosate (kg) used in soybean cultivation from the cultivated area in a given state and year. The rate of glyphosate used (g in kg ha^{-1}) in a state and year was then found by dividing this amount by the soybean crop area for the same state and year. A correlation analysis was then performed between the rate of glyphosate used in soybean cultivation and the soybean productivity (kg ha^{-1}) in the five retained soy producer states to verify any trend between rate of glyphosate used per hectare and soybean productivity.

Data was processed in MS Excel. The Online Web Statistical Calculators (astatsa.com) was used to calculate Pearson's r moment and the probability (p) of the null hypothesis that r is equal to 0.

RESULTS AND DISCUSSION

From the pattern of data dispersal (Figure 1) three phases in the Brazilian soybean productivity (P) can be perceived. In the first phase, from 1974 to 1991, the average productivity was 1655 kg ha^{-1} with a minimum of 1226 and a maximum of 1971 kg ha^{-1}. In this phase, productivity varies annually and no explicit growth trend is noticed.



Prod. - productivity. The regression lines and equations are also displayed
Figure 1: Evolution of soybean productivity in Brazil between 1974 and 2018.

The coefficient of determination ($R^2 = 0.09$) is small and the regression is not significant ($p = 0.24$). As well Pearson's r is small (0.26) and not significant ($p = 0.32$). In the second phase, from 1992 to 2000, the annual productivity growth trend obtained by the linear regression is significant ($p<0.01$) being 44.90 kg ha^{-1} per year. The coefficient of determination (R^2) of the linear adjustment relating the annual soybean productivity (P) with time (T) is 0.98, indicating that this explains 98% of the interannual variability of the soybean yield, that is, a consistent gain of productivity annually. The average annual productivity is 2243 kg ha^{-1} with a minimum of 2035 (in 1992) and a maximum of 2403 kg ha^{-1} (in 2000). Pearson's *r* is close to 1 (0.99) and significant ($p < 0.001$).

In the third phase, from 2001 to 2018, the annual productivity growth trend obtained by the linear regression is significant ($p < 0.01$), but it is not as consistent as in the period that preceded it ($R^2 = 0.54$). Pearson's r is large (0.77) and significant ($p < 0.001$). The average annual productivity is 2803 kg ha^{-1}, with a minimum of 2230 (in 2005) and a maximum of 3390 kg ha^{-1} (in 2018). The trend for productivity growth in this period is 44.28 kg ha^{-1} year and is not statistically different from the trend in the previous period (ANCOVA, $p = 0.77$). Note that it is not possible to graphically perceive a variation in soybean productivity from 2003 onward, the year in which the use of RR soybean was officially allowed. The productivity trend between 1992 and 2002 is 56.4 kg ha^{-1} year^{-1} while it is 54.73 kg ha^{-1} year^{-1} between 2003-2018 The difference between these two trends is not significantly different (ANCOVA, $p = 0.08$).

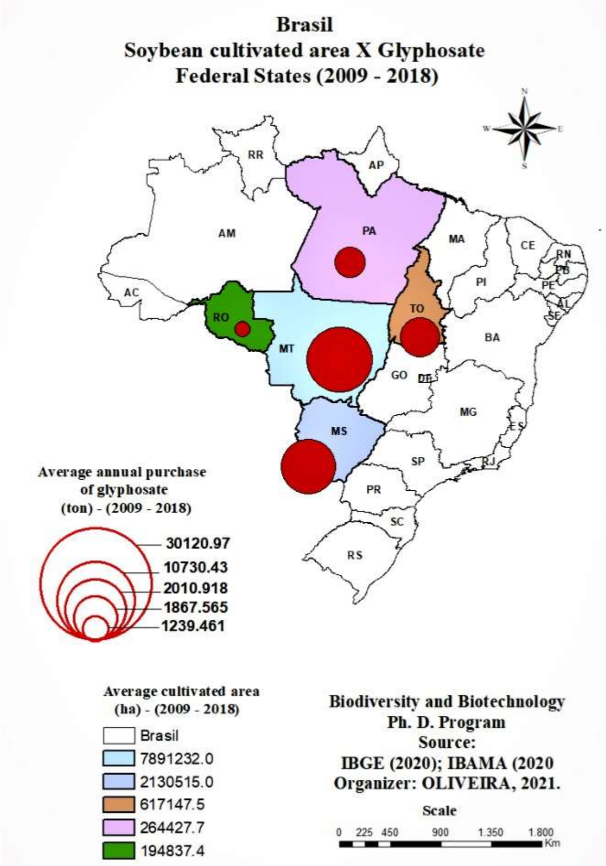
When analyzing in Figure 1 the historical evolution of soybean productivity in Brazil, it can be observed that the period 1992-2000 corresponds to a clear gain in productivity. It was in this period, in the late 1990s and early 2000, that the so-called “commodities boom” occurred, due to the intensification of trade relations between Brazil and China, the main consumer market for Brazilian soy. Growing Chinese demand has placed the country in the spotlight on the international scene, boosting the Brazilian trade balance surplus (HOOIJMAAIJERS, 2021).

In addition, in the 1990s, Brazil engaged in the improvement of soy crop management techniques.

Embrapa (Brazilian Agricultural Research Corporation) initiated a technology transfer and improvement program for soybean cultivars, in partnership with seed producers, which was responsible for greater professionalization of seed producers, through the systemic methodology used and its continuity for several seasons (DOMIT et al., 2007). This period (1992-2000) is a watershed moment in terms of annual soybean productivity in Brazil. Before 1992, from 1974-1991, there was an annual productivity gain, but it is not as evident as in 1992-2000. The linear correlation is not significant and weak. Even so, the equation obtained from the linear regression was calculated in order to compare the annual increase in productivity in this period, which is four times smaller than in 1992-2000.

After 2000, 2001-2018, the linear correlation is significant, but less than in the period 1992-2000 (Figure 1). The equation obtained from the linear regression shows an increase in annual production similar to 1992-2000. It is important to point out that the commercial introduction of RR soy took place in 2003 (legalization), but there are no consistent gains in production compared to the previous period.

The states retained for analysis were Rondônia - RO, Pará - PA, Tocantins - TO, Mato Grosso do Sul - MS and Mato Grosso - MT (Figure 2, Table 1). In these, the average annual soybean planted area ranged from ~195,000 ha (RO) to more than 7,800,000 ha (MT) between 2009 and 2018. In this same period, the average annual consumption of glyphosate per state ranged from ~1240 tons (RO) to more than 30,000 tons (MT).

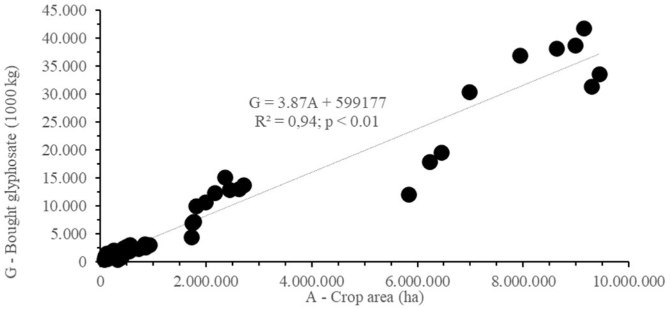

Brasil
Soybean cultivated area X Glyphosate
Federal States (2009 - 2018)

Biodiversity and Biotechnology
Ph. D. Program
Source:
IBGE (2020); IBAMA (2020
Organizer: OLIVEIRA, 2021.

MS stands for the state of Mato Grosso do Sul; MT for Mato Grosso; PA for Pará; RO for Rondônia; TO for Tocantins
Figure 2: Characteristics of soybean producers states in terms of average soy cultivated area and average purchase of glyphosate between 2009-2018.

Between 2009 and 2018, in the group of the five states included in this study (MS, MT, PA, RO and TO), the variation in the cultivated area (A) strongly correlates with the purchase of glyphosate (G) (Figure

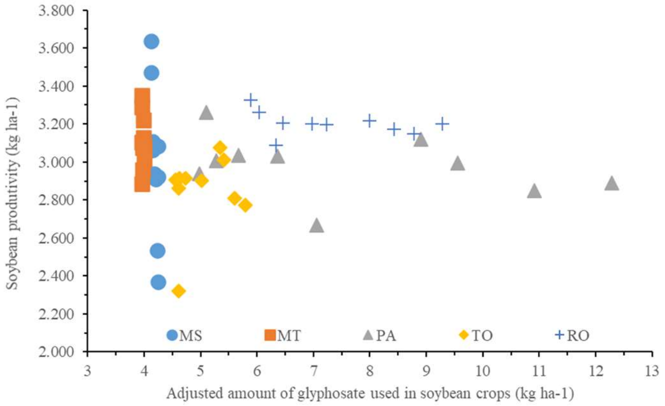
3). The linear regression between soybean cultivated area and glyphosate purchase is significant and the coefficient of determination approaches 1 ($R^2 = 0.94$). Pearson's r is close to 1 (0.97) and significant ($p < 0.001$).



The equation resulting from the linear regression between the purchase of glyphosate (G) and the area cultivated in soybean (A). The regression lines and equations are also displayed
Figure 3: Relation between soybean cultivated area and glyphosate purchase.

For the group of the retained five soybean producers states, the value of g (rate of glyphosate use in soybean cultivation) is 3.87 kg ha^{-1}. It ranges from 3.39 kg ha^{-1} in TO to 6.21 kg ha^{-1} in PA. The ANCOVA test verified that across states these rates are not statistically different ($p = 0.94$). Over the study period, between 2009 and 2018, there was a statistically significant variation in the rate of glyphosate use ($p < 0.01$) between 2.13 and 4.70 kg ha^{-1}.

The relation between the rate of glyphosate used in soybean crops (kg ha^{-1}) and soybean productivity (kg ha^{-1}) is displayed in Figure 4.



MS stands for the state of Mato Grosso do Sul; MT for Mato Grosso; PA for Pará; RO for Rondônia; TO for Tocantins
Figure 4: Soybean productivity - glyphosate use relationship.

Considering the dispersion of points in Figure 4, the glyphosate use rate for the states of MT and MS remains around 4 kg ha^{-1}, while soybean productivities from MT vary between 2,900 and 3,350 kg ha^{-1} and from 2,350 to 3,650 kg ha^{-1} in MS. For the state of TO, the rate of glyphosate use ranged from ~4.5 and ~6 kg ha^{-1}, for productivities ranging from around 2,300 to 3,100 kg ha^{-1}. PA and RO show greater variation in glyphosate use rates, which can reach almost 13 kg ha^{-1} with crop productivities ranging from around 2,700 to 3,300 kg ha^{-1}.

The results of the correlation between the adjusted amount of glyphosate used in the soybean crop and the soybean yield are demonstrated by Pearson's Coefficient (r) (Table 1) were calculated for the group of five states is not significant, except in the case of MS. However, in this case a negative relation is found indicating a decrease in productivity with increasing amount of glyphosate.

Research work carried out by Andrade et al. (2020) shows that the application of glyphosate in plants that contain the herbicide tolerance gene can alter the physiological processes of the plant, compromising the functioning of important metabolic pathways, reducing the synthesis of secondary metabolites leading to a reduction in the accumulation of biomass, affecting the growth and the development of the plant, which can lead to a decrease in crop grain yield.

Table 1: Pearson's coefficient (r) of the correlation between the adjusted amount of glyphosate used in soybean crops and soybean productivity.

States	Pearson's r	p
Group of 5 states	-0.02	0.91
MS	-0.74	0.02
MT	-0.14	0.72
PA	-0.29	0.45
TO	0.37	0.33
RO	-0.42	0.26

The probability of the null hypothesis that r is equal to 0 is also given.

When comparing the results presented in this study with those found in the literature, it is possible to identify that the area used for the production of RR soy is predominant among the main crops that use glyphosate, having been gradually increased over the years.

The introduction of GM crops simplified weed control and enabled the growth of conservation practices, such as no-tillage, no-tillage with straw and stubble EMBRAPA (2019). However, dependence on the exclusive use of glyphosate has resulted in changes in weed species and herbicide tolerant weed populations (Westwood et al., 2018), leading the producer to increase the number of applications and the amount of glyphosate in the crop (DUKE, 2015; BENBROOK, 2016; BONNY, 2016).

The analysis of the results obtained in Figure 1 does not reveal any gains in soy productivity on a Brazilian scale from 2003, the year of the introduction of RR soy, since productivities before and after these dates are practically the same.

In this aspect of the relationship between RR soy and glyphosate, Brookes et al. (2018) showed that the introduction of this technology resulted in a decrease in the sales and application of glyphosate, which can be considered an economic and environmental gain. However, the study by Belz et al. (2022), highlights that over-application of herbicides causes the hormesis effect and makes weeds more resistant.

These results reinforce the low correlation between glyphosate consumption and soybean productivity, also verified in the study by Almeida et al. (2017). In this, the authors related the use of herbicide per area (kg ha^{-1}) and soybean production per kg of herbicide used. Initially, herbicide per area decreased by 9%, while soybean production per kg of herbicide increased by 18%. However, from 2003, after the introduction of RR soy, herbicide use per area increased by 64% while soybean productivity per kg of herbicide consumed dropped by 43%.

Given the evidence, the authors concluded that the introduction of RR soy led to a reduction in productivity. In this sense, the studies by Duke (2015), Benbrook (2016) and Bonny (2016) also consider that the introduction of GM crops led to an increase in the use of pesticides, maximizing the negative impacts arising from the more intense use of these substances.

A similar result was verified in a previous study by Carneiro (2015), since, while sales of pesticides grew 288% (US$) and 162% (tons), in the period between 2000 and 2012, soy production had grown 100%, corn 120%, sugarcane 121% and cotton 147% (in tons).

Another study, by Almeida et al. (2017), found that for this same period, the cumulative growth of the total use of pesticides in Brazil increased 3.2 percentage points (pp) and 1.78 pp in the use of pesticides per area, while overall agricultural productivity was lower, getting only 1 pp. In the case of soy, the authors recorded an increase in the use of pesticides of 13 pp per cultivated area and the smallest gain in productivity, in the order of 1 pp, showing a contradiction in the prediction that the introduction of transgenic soy would minimize the use of pesticides.

It is verified, therefore, in the researched literature that soy has shown an increase in the use of glyphosate and a lower productivity gain, corroborating the results of this study. One of the arguments described by Almeida et al. (2017), for this situation, is that the genetic modification was not intended to increase productivity or seek an edaphoclimatic adaptation of the crop, but, exclusively, to make the cultivars tolerant to herbicides.

The research by Belz et al. (2022) demonstrates that the changes observed in herbicide use patterns such as the increase in the use of glyphosate (kg ha^{-1}) are related to the adoption of RR soy, and the mechanism of the increasing evolution of weed resistance to glyphosate is still little understood.

Although the use of glyphosate does not seem to influence the productivity of Brazilian soybeans, it is clear that there have been gains in productivity in the soybean crop over the years and it is important to know the causes of this increase in productivity.

In general, productivity gains in RR soy are related to several other factors such as the cultivars used in the crop and the edaphoclimatic conditions of the environment (LI et al., 2014). Although the genotype is decisive in the phenotypic characteristics, there is the possibility of improving the productivity and quality of soybean varieties, through selection of favorable environmental conditions or soil improvement.

Technologies such as no-till systems using crop diversification and production of organic residues on the soil locally modify environmental conditions and are important tools to help herbicides in the integrated management of weeds in grain production systems (SÃO MIGUEL et al., 2018). By maintaining soil cover, the producer contributes to favoring environmental conditions that increase crop productivity, which usually occurs with soy (GIMENEZ et al., 2021).

There are technologies available to Brazilian farmers, with the potential to maintain high productivity by reducing the use of agricultural inputs. Among these, we can mention the intercropping, the integration of livestock farming and mixed farming systems, the agroforestry (ANDRADE et al., 2017). These technologies contribute to nitrogen fixation in the soil, increase microbial biomass (DAS et al., 2018), reduce the use of herbicides and fungicides (ANDERT et al., 2016), optimize pest control management, minimize the use of water and reduces soil erosion, surpassing the productivity of monoculture crops (GUAY et al., 2018; CUNHA et al., 2020).

CONCLUSIONS

It was not possible to associate the increased use of glyphosate by the RR soybean crop with productivity gains of this crop during the study period. It can be inferred that the observed productivity gains seem to be more related to the transfer of technology to soybean cultivars, such as those obtained in the period 1992 to 2000 related to the program developed by EMBRAPA, since there are studies showing that the productivity of the crop is closely related to the correct handling of the herbicide and the yield of the cultivar used.

The researched literature showed that there is an increase in weed resistance despite the increased use of glyphosate, whose consumption increases faster than the planted area, while environmental damage is mounting.

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