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Full Length Article

Herbicides in Pre-Harvest Desiccation of X-Tend Soybean

João Victor de Oliveira Moura[1], Elias da Silva Medeiros[1], Paulo Vinicius da Silva[1], Bruna Ferrari Schedenffeldt[2*], Patricia Andrea Monquero[2], Guilherme Pereira da Silva[1], Munir Mauad[1], Rafael Pessoa Pereira Nascimento Borges[1], Nayane França[1], Pedro Antônio Vougodo Salmazo[1], Mateus Sales Monteiro[1] and Thatiana Elisa Masetto[1]
[1]*Federal University of Grande Dourados, Dourados, Mato Grosso do Sul, Brazil*
[2]*Federal University of São Carlos, Araras, São Paulo, Brazil*
[*]For correspondence: bfschedenffeldt@gmail.com
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Abstract

Desiccation prior to soybean harvest is vital for controlling invasive plants and standardizing the area before harvesting. The objective of this study was to evaluate the efficacy of different desiccant herbicide treatments in the pre-harvest desiccation of X-Tend soybeans. For this purpose, a field experiment was conducted using a randomized complete block design with blocks containing 17 treatments each. The herbicides tested were glufosinate, saflufenacil, flumioxazin, carfentrazone, diquat, tiafenacil, and combinations such as diquat + flumioxazin, diquat + amicarbazone, diquat + carfentrazone, diquat + glufosinate, diquat + tiefenacil, diquat + saflufenacil, glufosinate + saflufenacil, glufosinate + flumioxazin, glufosinate + carfentrazone, and glufosinate + tiafenacil, along with a control treatment that did not involve herbicide application. Visual assessments of phytotoxicity, defoliation, and plant desiccation were conducted through photographs of the plots at 3, 5, 7 and 10 days after application (DAA), accompanied by measurements of grain moisture content. However, there were variations in phytotoxicity and defoliation between treatments. In terms of the desiccant effect, diquat showed a rapid response in phytotoxicity to weeds and defoliation in soybean, while glufosinate ammonium had a slower action. Notably, thiafenacil exhibited a rapid phytotoxic action. In addition, the combination of saflufenacil with glufosinate ammonium resulted in faster desiccation than when applied separately. In conclusion, the use of the herbicide diquat in desiccation provided higher productivity compared to the control without herbicide application. These results highlight the importance of the appropriate choice of herbicides in desiccation to improve soybean yield.

Keywords: *Glycine max;* Desiccant; Anticipation; Alternatives; Maturation

Introduction

Soybean (*Glycine max* (L.) Merril) is a crucial leguminous crop in the global agricultural economy (Voora *et al.* 2020). Advances in genetic engineering, such as the development of herbicide-tolerant varieties like Intacta 2 Xtend soybeans, have significantly transformed agricultural practices (Medina 2021). These cultivars are tolerant to both glyphosate and dicamba, the latter due to the dicamba monooxygenase gene from *Pseudomonas maltophilia*, enabling innovative weed management strategies near sowing times without damaging the crop. This flexibility is pivotal as it allows farmers to manage planting and desiccation schedules more efficiently, which is essential for maximizing yield and optimizing harvest times (Nandula 2019).

Thus, it presents itself as an innovative alternative to pre-sowing desiccation of soybeans, as it allows the positioning of dicamba close to its sowing and/or in appliqué and planting (sowing immediately after application), without phytotoxic effects. to this crop, providing greater temporal flexibility and plant back evolution, without the need to wait 60 days between the application of dicamba and soybean sowing (Oliveira and Ferreira 2020).

In view of the use of Intacta 2 X-tend soybean, questions about the effectiveness of pre-harvest desiccation become relevant, especially considering possible influence of the tolerance of the herbicides contained in this technological system (Wechsler *et al.* 2019). A clarification of these doubts is crucial because desiccation is a strategic practice for maximizing productivity, inducing dehydration of the grains, leaf drop and drying of the stems of the plants, promoting the uniformity of the planted area and allowing the grains to reach the ideal humidity, between 13 and 15%. This practice makes it possible to anticipate the harvesting process (Kamphorst and Paulus 2019), in addition to anticipating the sowing of the next crop (de Quadros *et al.* 2023).

Currently, for pre-harvest soybean desiccation, there are several herbicide options available. Among them,

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diquat, an inhibitor of photosystem I, and glufosinate ammonium, which acts by inhibiting the enzyme glutamine synthetase (GS) in the nitrogen assimilation route, stand out as viable choices (references). In addition, lesser used herbicides, such as flumioxazin, carfentrazone and saflufenacil, which are protoporphyrinogen oxidase inhibitors (PROTOX), are also options for producers (Carmo *et al.* 2023). A recent addition is tiefenacil, which also inhibits PROTOX (Park *et al.* 2018). However, it is important to note that the effectiveness of these products can vary considerably according to environmental conditions.

This information is significant because in recent years, there has been considerable environmental variability regarding rainfall and light intensity during the soybean harvesting period, impacting the positioning and agronomic performance of desiccants. An example of this was observed in Dourados, Mato Grosso do Sul, in 2023, where low light in the plantations delayed the closing of the crop cycle, delaying an average of 7 to 10 days (Famasul 2023). This situation was accompanied by intense rainfall, recurring between January and February, totaling 580.2 mm of rainfall in this period (EBDPA 2023). This resulted in the delay of the harvest, where on February 24, 2023; the harvest should have been 47.1% but reached only 25% of the area. This combination of excessive rainfall and high temperatures in the final stage of the crop (R8) directly affected the quality of the grains, contributing to the formation of damaged and germinated grains (Famasul 2023).

In this context, the association of contact and systemic herbicides in the pre-harvest desiccation of soybean may provide better performance, in addition to logistical and economic gains. These gains are obtained because the combination of products can result in improvement of the individual performance of the herbicides and may even allow the reduction of doses due to the synergistic effect, such as the combinations of glufosinate ammonium with PROTOX inhibiting herbicides (Takano *et al.* 2020; Silva *et al.* 2023).

Given these advancements, it becomes increasingly important to stay updated with the evolving practices in the field. Therefore, in view of the ongoing changes in the herbicide application scenario for pre-harvest desiccation of soybeans, driven by increasingly frequent and recurrent environmental variables in crops, this study aims to evaluate the efficacy of different desiccant herbicide treatments in the pre-harvest desiccation of X-Tend soybeans.

Materials and Methods

Location of the experiment

The field experiment was installed and conducted at the Experimental Farm of Agricultural Sciences (FAECA) of the Federal University of Grande Dourados, located in the municipality of Dourados, Mato Grosso do Sul, at an altitude of 411 m, at the following geographical coordinates: 21°57'south latitude and 46°51' west longitude. The Köppen climate classification is characterized by Cwa (humid mesothermic climate, hot summers and dry winters) with an average annual temperature of 22.7°C (Fietz *et al.* 2020). The experiment was installed in December 2022 and followed up until the end of February 2023. The evaluations of the experiment were performed between February 18 and March 1, 2023.

Installation and conduct of the experiment

The experimental units consisted of 3 × 5 m plots, totaling 15 m², with 6 soybean rows in each experimental unit. Soil samples were taken from the experimental area before the beginning of the experiment. The soil of the experimental area was classified as Dystroferric Red Oxisol (Santos *et al.* 2018), as shown in Table 1.

The experimental design was randomized blocks, with four replicates, with 16 herbicide treatments, in addition to the control without herbicide application, totaling 17 treatments. The active ingredients and their respective doses are described in Table 2.

The soil was then prepared for direct sowing, based on pre-sowing desiccation and sowing itself, under the straw remaining from the previous maize crop. The cultivar selected was M 6410 IPRO (Soja Intacta 2 Xtend), which received seed treatment with fungicide and insecticide, pyraclostrobin (5 g ai ha^{-1}) + thiophanate methyl (45 g ai ha^{-1}) + fipronil (50 g ai ha^{-1}), for 100 kg of soybean seeds before sowing.

Sowing was performed using a mechanical seeder consisting of twenty-six rows distributed at a spacing of 0.45 m. The distribution of 12 seeds per linear m resulted in a final population of approximately 266 thousand plants per hectare. The fertilization at sowing was based on 300 kg ha^{-1} of formulated fertilizer 0-20-20, according to soil analysis.

In the management of the experimental area, the crop was monitored and underwent regular maintenance with fungicides and insecticides. Initially, fipronil (240 g a.i. ha^{-1}) was applied against *Diabrotica speciosa*. Subsequently, the fungicides Orkestra (fluxapyroxad 58.45 g a.i. ha^{-1}, pyraclostrobin 116.55 g a.i. ha^{-1}) and Bold (acetamiprid 37.5 g a.i. ha^{-1}, fenpropathrin 56.25 g a.i. ha^{-1}) were used, followed by the fungicide Viovan (picoxystrobin 60 g a.i. ha^{-1}, prothioconazole 70 g a.i. ha^{-1}). The fourth application included the insecticide Talisman (bifenthrin 30 g a.i. ha^{-1}, carbosulfan 90 g a.i. ha^{-1}). The maintenance cycle concluded with another application of Orkestra.

During the experiment, daily rainfall checks were performed in the execution area. For this, the database of the agrometeorological station of Embrapa, interconnected to the climate guide, based at the Experimental Farm of Agricultural Sciences of the university, was used. The data collected were related to the temperature, rainfall and treatment evaluation period (Fig. 1), and visual captures of the plot representative of the treatments (Fig. 2).

The soybean plants, when reaching the R7.3 stage

Table 1: Chemical analysis of the soil at the experiment site at 0–20 cm depth

pH	*OM (g dm^{-3})	P (mg dm^{-3})	K (mg dm^{-3})	Ca	Mg	Al	H + Al	SB	V (%)	CEC
				(cmolc dm^{-3})						
4.7	6.7	28.3	18.0	3.6	1.5	0.2	6.5	5.2	44.5	11.7

*OM: organic matter; SB: sum-of-bases; V: basic saturation; CEC: cation exchange capacity. Source: Laboratory of Soil Fertility and Plant Mineral Nutrition, FCA

Table 2: Description of the isolated or associated treatments and their respective doses used for desiccation in the soybean pre-harvest

Treatments	Products	Dose (g a.i. ha^{-1})
T1	Glufosinate + Flumioxazin	300 + 20
T2	Flumioxazin	50
T3	Diquat + Carfentrazone	300 + 20
T4	Diquat	400
T5	Glufosinate + Saflufenacil	300 + 35
T6	Glufosinate	400
T7	Diquat + flumioxazin	400 + 50
T8	Diquat + saflufenacil	300 + 35
T9	Glufosinate + carfentrazone	300 + 20
T10	Witness	---------
T11	Saflufenacil	70
T12	Diquat + thiafenacyl	300 + 50,85
T13	Carfentrazone	20
T14	Thiafenacyl	67,8
T15	Diquat + amicarbazone	400 + 100
T16	Glufosinate + thiafenacyl	300 + 50,85
T17	Diquat + glufosinate	300 + 300

a. I: Active ingredient. *Treatments containing herbicides received the addition of 5% oil (Joint)

(76% of the leaves and pods yellowing, 98% of the grains already detached from the pods and grain moisture between 50 and 54%), received different herbicide treatments aimed at desiccation. In total, 16 treatments were used, in addition to a control without application (Table 2). A CO_2 pressurized sprayer equipped with a six-point boom, model TTI 110.02, spaced 0.50 m, maintained at 0.50 m from the height of the plants, with a spray volume of 150 L ha^{-1} and working pressure of 2 kgf.cm^{-2}. Treatments were applied on February 28, 2023, when the plants were at the R7.2 stage. During the applications, the environment presented 42% humidity, a temperature of 30.7°C and a wind speed of 4.32 km h^{-1}.

Evaluations experimental

Evaluation of desiccation and defoliation: To evaluate the effect of desiccation on soybean, the methodology proposed by the Brazilian Society of Science of Weeds (SBCPD) was followed, and phytotoxicity analyses were conducted on days 3, 5, 7 and 10 after application (DAA). This method establishes a relationship between the percentage of visual damage and the manifestation of phytotoxicity symptoms, where 0% represents the absence of damage, up to 80–100%, indicating plant mortality (SBCPD 1995).

In the same period, defoliation evaluations were performed using visual observations. For this purpose, the diagrammatic scale proposed by Hirano *et al.* (2010) was adapted to measure the effectiveness of herbicides in plant defoliation.

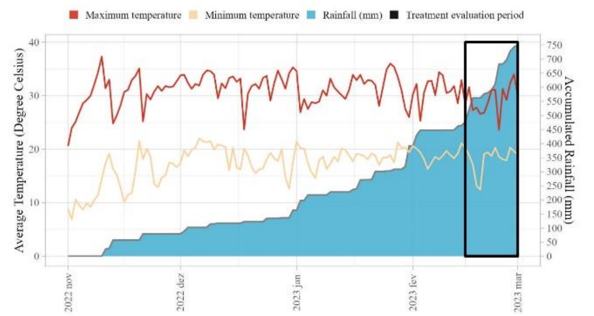

Fig. 1: Climogram of daily maximum and minimum temperatures and accumulated rainfall in the study region during the experimental period from 11/15/2022 to 03/01/2023. Dourados-MS, UFGD, 2022-2023. The bold rectangle indicates the period of application (18/02/2023) and evaluation of the treatments (21 to 28 February 2023)

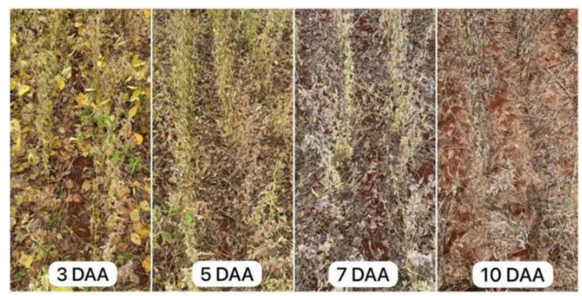

Fig. 2: Visual captures of the plots representative of the treatments with 3, 5, 7 and 10 DAA (days after application). The treatment containing isolated diquat was used as an example in the images. Source: Personal archive (2023)

To determine the desiccated area, photos of representative plants were captured in all plots at 3, 5, 7 and 10 days after application (DAA), according to the methodology proposed by Silva *et al.* (2023) and were subsequently analyzed using the image processing and analysis software ImageJ, which is in the public domain (National Institute of Mental Health USA 2012). To minimize possible influences of the edges of the plots, the images were adjusted. The program selects a spectrum range of params such as color, matrix, saturation and luminosity as a function of differentiating the pixels corresponding to the green parts of the plant from those that present aspects of desiccated tissue. The percentage of desiccated area is obtained through the relationship between the total number of image pixels and those with active photosynthetic activity. Fig. 3 represents an example of images that were captured and later processed by ImageJ to evaluate desiccation over time.

Determination of the water content – through a greenhouse at 105 ± 3°C

The method proposed by Brasil (1992) was used, which is the

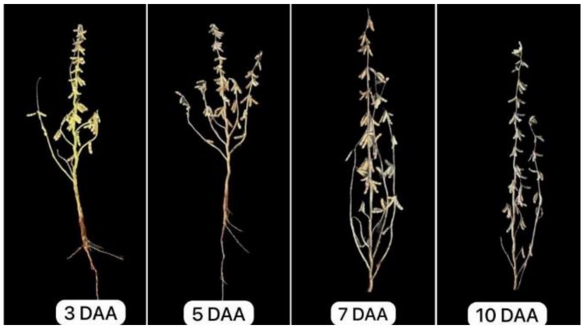

Fig. 3: Visual captures of the plots that were subsequently used in the ImageJ software, in a way that was representative of the treatments at 3, 5, 7 and 10 DAA. The treatment containing isolated diquat was used as an example in the images. Source: Personal archive (2023)

standard method for determining the moisture content of soybeans, known as the greenhouse method. The determinations were performed with whole soybeans in an oven at 10.5°C, allowing for a variation of 3°C. Three metal crucibles with lids were placed per treatment and kept for 24 h. After this period, the crucibles were removed from the oven and transferred to a desiccator for one hour. After removing the metal capsules with the lids from the desiccator, with the aid of an analytical balance, the weight of the containers with their lids was measured. The percentage of moisture was determined by the ratio between the weight of the fresh sample and the weight at the end of the drying process.

Productivity

After the end of the evaluation periods, the experimental units were harvested individually and manually by removing the three central lines of each plot, thus avoiding the occurrence of errors in the estimation of productivity per plot. Soon after, the plants were subjected to a stationary threshing machine with a rotary threshing system, allowing the extraction of the grains for later weighing on a scale with accuracy to three decimal places. The data were transformed into kg ha^{-1}.

Analysis statistics

For the statistical analysis of the variables defoliation, phytotoxicity and percentage of desiccation by image analysis, generalized additive location, scale and shape models (GAMLSS) with the family Beta Inflated of 1 were used, the mean and for the variance. The effects of treatment, period and interaction were evaluated using the F-statistic test. The comparison between treatment levels was performed using the marginal means estimated with adjustment using Tukey's test. For the analysis of moisture and yield, linear models with a normal distribution were used. The remaining variables were subjected to analysis of variance using the F test ($P \leq 0.05$), and the means were compared using Tukey's test at 5% probability ($P \leq 0.05$).

For deviance analysis, the Generalized Additive Models for Location, Scale and Shape (GAMLSS) were used, with a Beta distribution for the variables ImageJ and Water Content and an inflated Beta of 1's for Defoliation and Phyto. The logit link function has been used to model the location param related to the mean. In the location param, the factors Block, Treatment, DAA and the interaction, Treatment versus DAA, were considered fixed effects, and the plot, formed by the combination of blocks with Treatment, was inserted as a random effect.

The Shapiro–Wilk test was used to verify the adequacy of the normal distribution to the model residuals. The F test of the deviance analysis was used to verify the significance of the factors inserted as a fixed effect. Tukey's test was applied to compare the treatment levels. The logistic model was used to adjust the response variables as a function of the DAA. In all tests, a 5% significance level was adopted.

All statistical analyses were performed in R software (R Core Team 2022) with support from the gamlss (Rigby and Stasinopoulos 2005), emmeans (Lenth 2023) and ggplot2 (Wickham 2016) libraries.

Results

Deviance analysis (Table 3) identified a significant difference in all variables (ImageJ, water content, phytotoxicity and defoliation) with respect to days after application (DAA), showing that there was an evolution of desiccation over the days. Furthermore, all the adjustment residuals of the aforementioned variables are normally distributed, as can be observed by the Shapiro–Wilk test ($P > 0.05$) and are suitable for GAMLSS regression. Through the coefficient of variation (CV), it was also determined that the analyses had low variability. The interaction between treatments and days after application had a significant effect on the evaluation of phytotoxicity and defoliation, but for the water content of the grains and the percentage of desiccated area, as evaluated by ImageJ software, there was no significant interaction.

There was no significant difference between treatments for phytotoxicity, only in relation to desiccation action over time; thus, Fig. 4 presents the results of regression adjustment of the variable ImageJ through the mean of the treatments evaluated at 3, 5, 7 and 10 DAA. Through this evaluation method, it was observed that there

Table 3: Results of the fit of the GAMLSS models to the variables related to percentage

Variable	F test			SH	CV
	Treatment (T)	DAA (D)	T versus D		
ImageJ	1.73	545.82**	0.76	0.81	12.57%
Water Content	0.92	683.08**	0.88	0.06	18.59%
Phyto	0.78	252.68**	2.31**	0.70	2.34%
Defoliation	6.38**	365.06**	3.98**	0.07	3.63%

** Significant at 5% by the F test of the deviance analysis; SH, *P* value of the Shapiro–Wilk normality test; CV (%), coefficient of variation

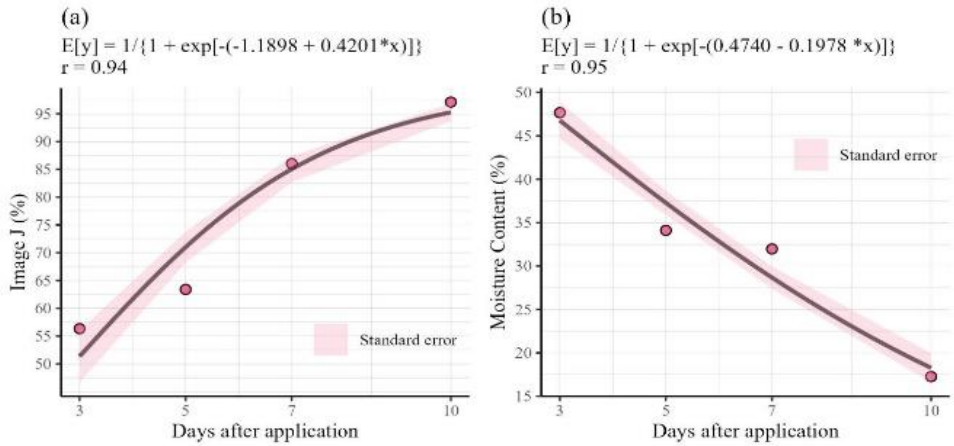

Fig. 4: Results of the regression fit of the variables ImageJ (**a**) and water content (**b**) in relation to DAA

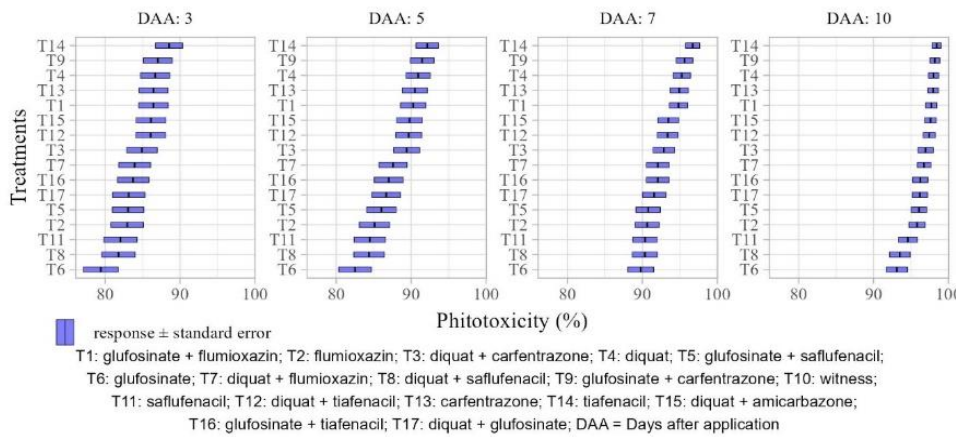

Fig. 5: Caterpillar plot when the phytotoxicity was evaluated for each treatment at each DAA level evaluated

was an increasing trend in the percentage of desiccation over time regardless of the treatment with the presence of herbicides; that is, the desiccation evaluated by ImageJ was homogeneous for all treatments. At 3 DAA, the mean values of the treatments showed values close to 55% desiccated area, followed by approximately 65% at 5 DAA, values above 85% at 7 DAA, and finally, at 10 DAA, they reached values close to 100%.

Similar to the percentage of desiccation (Image J), the water content also showed no significant interaction between treatments, differing only between days after application. Fig. 5 shows the results of the regression fit of the variable water content through the mean of the treatments, evaluated at 3, 5, 7 and 10 days after application. In general, for all treatments, there was a decrease in the percentage of moisture over time and therefore a decreasing curve, which indicates the loss of water in the grain. At 3 DAA, values close to 50% were observed, at 5 DAA and 7 DAA approximately 35%, and at 10 DAA, there was a significant decrease to about 15%.

The observations of phytotoxicity and percentage of defoliation caused by the herbicides showed a significant effect for the interaction of the factors treatment and evaluation period, according to the result of the F test of the *deviance* analysis (Table 3). Thus, the results of the treatments were broken down according to the evaluation periods and, for each treatment, their behavior over time. It is possible to observe that at 3 DAA (Fig. 5), there was no significant difference between the herbicides for the percentage of phytotoxicity, and all treatments presented results of approximately 80% or above on the first evaluation date. At 5 DAA, it was observed that the thiafenacil treatment, which presented phytotoxicity between 90–95%, differed significantly from the glufosinate ammonium treatment, with a value lower than 85%. The other treatments did not differ in this period.

The same behavior was observed at 7 and 10 DAA, with the thiafenacil and glufosinate ammonium treatments statistically differing from each other. In these last two evaluation periods, thiafenacil caused phytotoxicity of approximately 100%, differing from the treatment with glufosinate ammonium, which obtained percentages close to

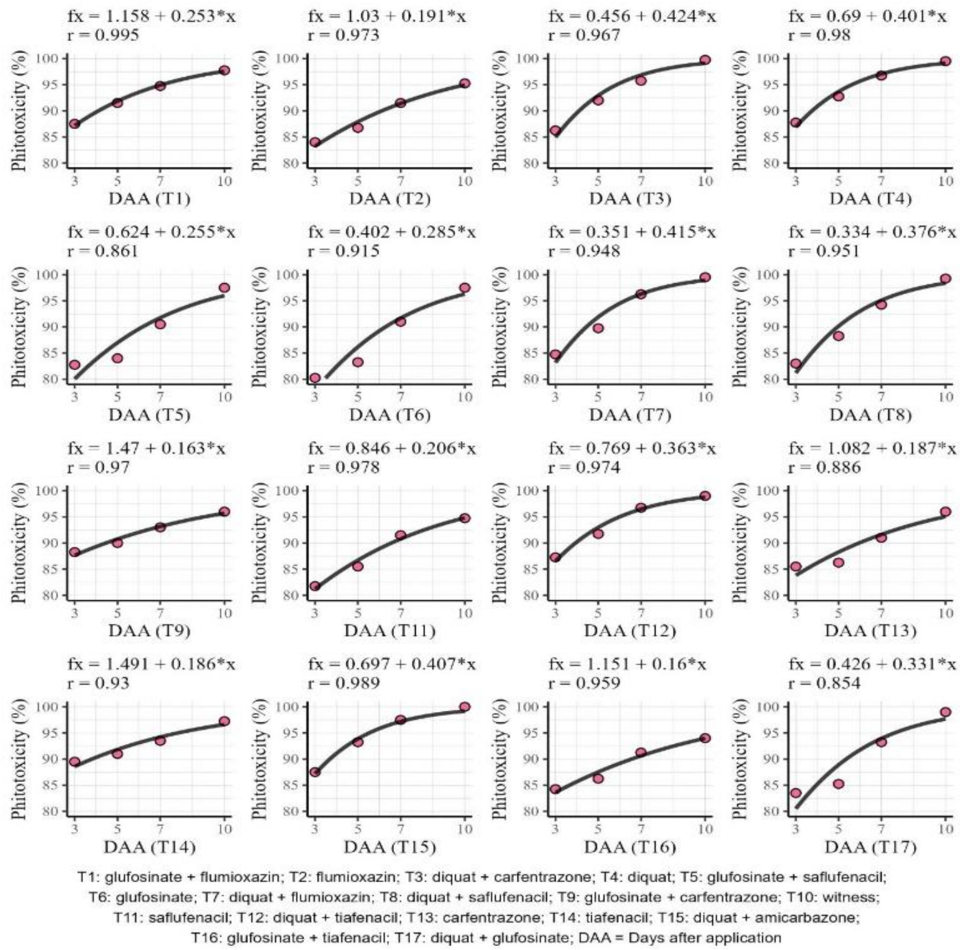

Fig. 6: GAMLSS regression with 1's inflated beta distribution for phytotoxicity (%) of each treatment in relation to DAA. The red points are the mean values, and the smoothed lines (black color) represent the fit of the logistic model, 1/[1+exp(-fx)]

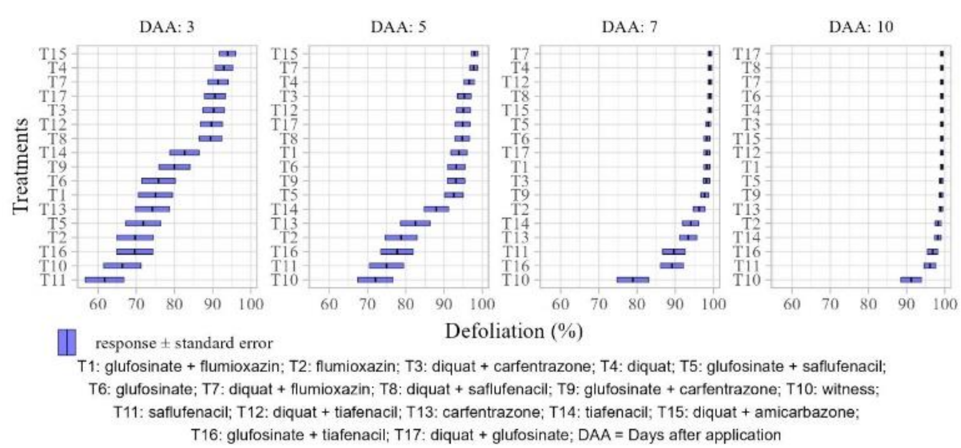

Fig. 7: Caterpillar plot of the percentage of defoliation for each treatment at each AAD level assessed

95%. Again, both treatments did not differ from the others in the aforementioned periods.

Figs. 6 and 7 show the results of the regression fit for phytotoxicity percentage as a function of the evaluation periods for each treatment and indicates that all treatments showed increasing evolution. Some treatments had a slower evolution to reach phytotoxicity until the tenth day, starting with lower values close to 80%, such as the treatments glufosinate + saflufenacil, glufosinate, diquat + flumioxazin, diquat + saflufenacil and diquat + glufosinate. Nevertheless, the herbicides cited established values close to 100% phytotoxicity at 10 DAA (Fig. 6).

The treatments that had a slower evolution of phytotoxicity until the tenth day, starting in the first evaluations with values close to 90% phytotoxicity and at 10 days after application reaching close to 100%, were glufosinate + flumioxazin, diquat, glufosinate + carfentrazone, diquat + thiafenacil, thiafenacil and diquat + amicarbazone, indicating high efficiency in a shorter time after application (Fig. 6).

The visual analysis of the percentage of defoliation, depicted in the breakdown of the effect of the treatments, revealed that at 3 DAA, the plots with the diquat + amicarbazone treatment reached approximately 95% defoliation, showing a significant difference compared to the other treatments, that obtained values equal to or lower than 75% defoliation.

At 5, 7 and 10 DAA, different treatments presented varying levels of defoliation. Some treatments, such as diquat, diquat + flumioxazin, and diquat + amicarbazone, showed significant differences compared to the control at 5 DAA. In contrast, flumioxazin, saflufenacil, carfentrazone and glufosinate with thiafenacil showed no significant differences compared to the control, maintaining results below 85%. In addition, Fig. 8 shows the results of the regression fit for the percentage of defoliation in relation to the time postapplication for each treatment. All treatments caused a progressive increase in defoliation, but in the treatments that combined glufosinate + saflufenacil, saflufenacil and carfentrazone, the evolution was slower in the first days, reaching levels close to 100% defoliation at 10 DAA.

The treatments that presented the fastest evolution to reach defoliation until the tenth day were the treatments with the herbicide diquat alone or in combination with the herbicides flumioxazin or amicarbazone. Despite a lower slope in the curve, *i.e*., lower defoliation evolution over time, they indicated greater efficiency for this variable, with 95% in the first evaluation (3 DAA), reaching close to 100% only at 5 DAA.

For the analysis of the weight of one thousand grains (PMMG), there was no significant difference, with very similar values. Regarding the yield analysis (Fig. 9), diquat reached values close to 3,900 kg.ha^{-1}, significantly differing from the glufosinate + flumioxazin, glufosinate + saflufenacil and control treatments, with yields close to 3,000 kg.ha^{-1}. These treatments did not differ statistically from the others evaluated for this variable.

Discussion

The average defoliation at 5 DAA, as we saw earlier, was lower than expected, and this result is remarkable considering that the expectation when placing desiccant herbicides in soybean areas is to make harvest possible from the third day onward (Silva *et al.* 2023). Thus, it was expected that some herbicide treatments would have higher value. These results are justified by the climatic conditions observed after the application of desiccants, with a rainfall of 152 mm and average temperature close to 25°C (Fig. 1).

This behavior was also observed in agricultural crops because in the state of Mato Grosso do Sul, in February, the high rainfall affected the harvesting operations, resulting in a risk of loss in grain quality because in this period, more than 50% of the crops were maturing and only 24% had been harvested. In addition to these aspects, high humidity favored soybean rust foci in grain filling crops in addition to attacks by caterpillars and bed bugs (Conab 2023).

Thus, the reduction in efficacy, especially under rainy conditions, is due to the deceleration in plant metabolism, which results in lower herbicide action (Tenório *et al.* 2023). In addition, low temperatures can affect the natural senescence of C3 plants. Albrecht *et al.* (2023) state that higher temperatures increase enzymatic activity and plant metabolism, but at higher temperatures, soybean tends to reduce net photosynthesis, influencing transpiration flow and the production of hormones that decrease the preservation of green areas, favoring senescence. Thus, the delay in desiccation of soybean plants can be attributed to a combination of factors. The isolated or combined application of herbicides has the potential to cause significant impacts on defoliation rates, as well as on visual evaluations of the percentage of desiccation, within a period of up to ten days after applications. Throughout the analyses, the variation in the effects of these products on the defoliation processes and on the phytotoxic effects becomes evident.

Thiafenacil exhibited a remarkable phytotoxic action over time, surpassing saflufenacil, another PROTOX inhibitor. This herbicide is a highlight, being a recent addition to the Brazilian market (Agrofit 2023), and has fundamental characteristics for the practice of pre-harvest soybean desiccation. Studies such as the one by Yoon *et al.* (2019) showed that thiafenacil binds to the enzyme protoporphyrinogen oxidase more efficiently than saflufenacil, thus ensuring improved efficacy. On the other hand, the combination of saflufenacil with glufosinate ammonium provided better results in plant defoliation compared to the use of the product alone (Silva *et al.* 2023), which was observed during the defoliation evaluations in this study.

A more progressive effect of the herbicide glufosinate ammonium was observed in the phytotoxicity evaluations, reaching 90% phytotoxicity at 7 DAA. However, in the application of this herbicide, a rapid action is expected due to the accumulation of ammonia in the tissues, causing the destruction of chloroplasts, limiting photosynthesis and resulting in cell death (Ribeiro *et al.* 2023). This allows for ideal harvesting conditions starting at 5 DAA (Silva *et al.* 2023). Thus, the photodependence of glufosinate-ammonium, which leads to the development of symptoms only in the presence of light (Takano *et al.* 2020), is a factor

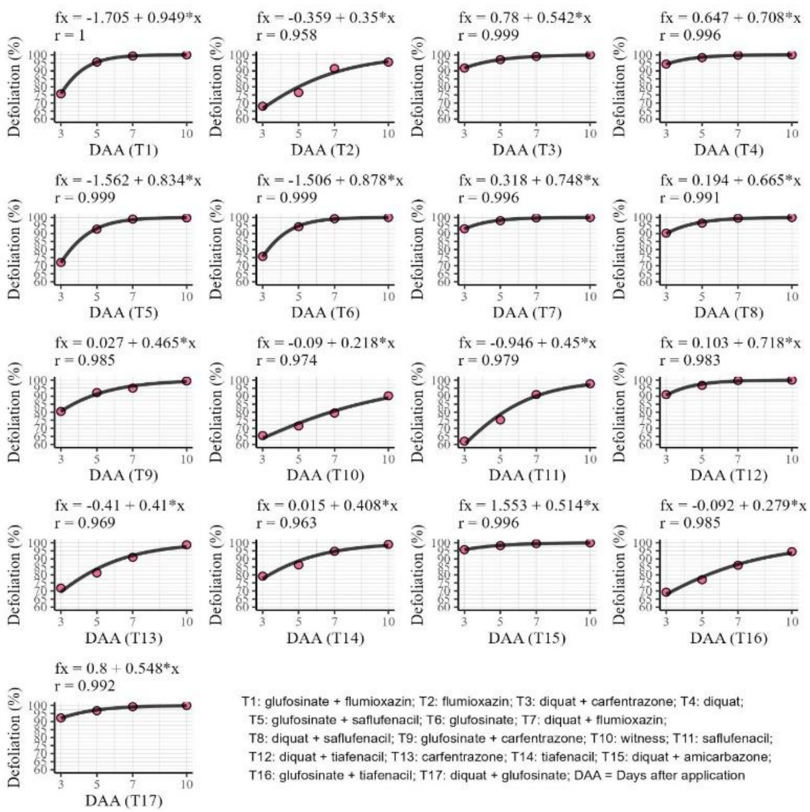

Fig. 8: GAMLSS regression with 1's inflated Beta distribution for Defoliation (%) in relation to DAA. The red points are the mean values, and the smoothed lines (black color) represent the fit of the logistic model, 1/[1+exp(-fx)]

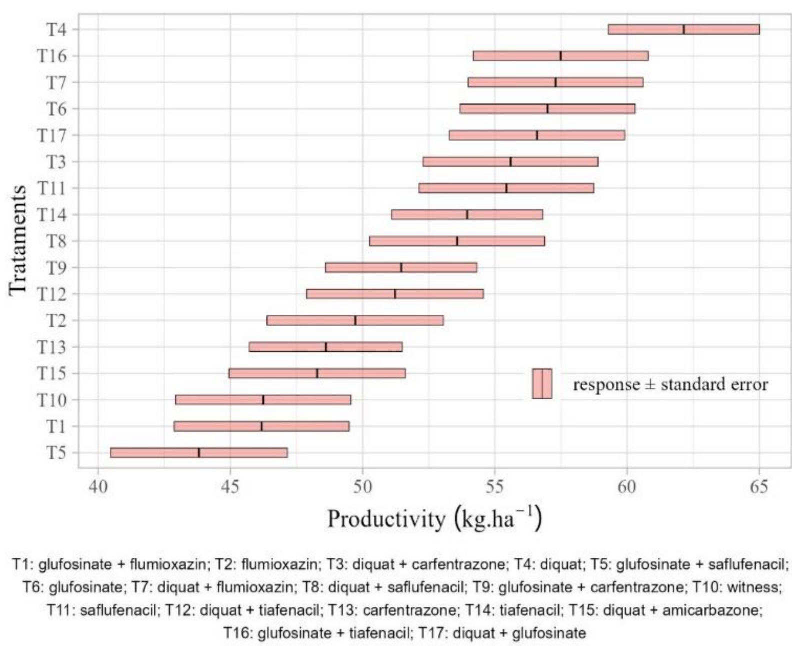

Fig. 9: Caterpillar plot of estimated yield (kg.ha^{-1}) for each treatment at the end of the evaluation cycle (10 DAA)

that reinforces the influence of climatic conditions, indicated in Fig. 1, on the efficacy of the herbicide. In addition, the effect of glufosinate ammonium is more rapidly expressed when combined with PROTOX inhibitors, suggesting a possible reduction in light dependence for the activation of this herbicide (Takano *et al.* 2020).

Although high rainfall (Fig. 1) significantly influenced the effectiveness of many herbicides, diquat maintained its efficiency. This behavior can be explained by the intrinsic characteristics of the herbicide, which is an inhibitor of photosystem I (PSI), which acts directly on photosynthesis, deflecting electrons that would be used to obtain chemical energy (reference). This product has high water solubility, rapid adsorption by soil colloids and efficient absorption by leaves due to its rapid passage through the cuticle. These properties, combined with its fast action in the presence of light, its non-selectivity and its effective translocation relative to the target (Parreira *et al.* 2023), demonstrate the consistent efficiency of diquat even in adverse weather conditions. In addition, the synergistic effect of diquat when associated with flumioxazin can be observed, since greater defoliation and phytotoxicity occurred, especially when compared to the application of flumioxazin alone.

In addition, at the time of application, there was a low light intensity, which may favor the action of this herbicide if followed by high light intensity. This occurs because the translocation of diquat is inhibited by the rapid action and intense induction of cell death in the presence of light, restricting the effect of the herbicide (Tahmasebi *et al.* 2018). The application of PSI-inhibiting herbicides at low light intensity may result in greater efficacy, possibly by reducing the accumulation of reactive oxygen species (ROS) and cell death, which allows greater translocation of herbicides (Montgomery *et al.* 2017). Thus, the delay in light reception by plants may improve herbicide distribution and increase the intensity of oxidative stress as soon as the plants come into contact with light (Pitelli *et al.* 2011).

Another point to highlight is that desiccation with the herbicide diquat resulted in significantly higher productivity compared to the control. The swift efficacy of this herbicide leads to reduced energy expenditure by the grains, often exacerbated by the prolongation of the vegetative period due to excessive rainfall, a phenomenon that may be intensified by climate changes. Such conditions can negatively impact productivity, as observed by Pinheiro (2019). In evaluations of pre-harvest soybean desiccation, Chrusciak and Lazaretti (2022) also identified superior productivity in soybeans treated with diquat compared to the untreated control.

Finally, the results obtained reveal significant aspects regarding the efficacy of the herbicides investigated in soybean desiccation. Although no notable differences were observed between herbicides used alone or in combination, the data corroborate previous research, reinforcing the consistency in effects on the percentage of desiccated area, grain moisture content and thousand-grain weight (Silva *et al.* 2023). Despite similarities in the evaluations performed, this study provides valuable information to the existing literature on pre-harvest soybean desiccation, contributing new analyses and approaches.

These climatic challenges underscore the importance of incorporating environmental considerations in the development and application of agricultural technologies, aiming for resilience in production processes. In this way, the study not only reaffirms previous findings but also proposes new strategies for adjusting agricultural management to climatic realities, ensuring more effective and sustainable interventions.

Conclusion

Based on the study conditions, the evaluated herbicides demonstrated effectiveness in pre-harvest desiccation of dicamba-tolerant X-Tend soybean. Diquat stood out for its rapid phytotoxicity and defoliation, while ammonium glufosinate showed a more gradual response due to climatic conditions. The combination of tiafenacil and saflufenacil with ammonium glufosinate also showed promising results. Additionally, desiccation with diquat resulted in higher productivity compared to the control without application. These findings contribute significantly to improving pre-harvest desiccation practices for X-Tend soybean, aiming to optimize agricultural production efficiency and outcomes.

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Author Contributions

JVOM, GPS, RPPNB, PAVS, NF and MSM worked on performing the experiments and collecting data; PVS, ESM, BFS, PAM, MM and TEM worked on performing the data analysis, implementation of the computational models, preparing the first version of the manuscript, conducting a literature review, making corrections to the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest in this manuscript.

Data Availability

The data that support the findings of this study are available from the corresponding author, Paulo Vinicius da Silva, upon reasonable request.

Ethics Approval

Not applicable

References

Agrofit (2023). *Phytosanitary pesticide systems*. Available at: https://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons. (Accessed: 08 March 2023)

Albrecht LP, AJP Albrecht, AS Yokoyama, AFM Silva, AA Bottcher, MGD Carvalho, FM Battiston (2023). Formulations of glufosinate in pre-harvest soybean desiccation. *Nativa* 11:96–100

Brasil NC (1992). *Regras para análise de sementes*, p: 365. *Ministério da Agricultura e da Reforma Agrária*. Brasília DF: SNDA/ DNPV/CLAV

Carmo GLD, FR Cabral Filho, CLLD Andrade, MB Teixeira, DKM Alves (2023). Use of ammonium glufosinate and diquat in soybean field desiccation. *Braz J Sci* 2:54–63

Chrusciak BM, NS Lazaretti (2022). Effect of different desiccants on soybean yield characteristics. *In: Cultivating Knowledge Magazine*, pp:23–30. University of Arizona Press, Chicago, Illinois, USA

Conab (2023). *Monitoring of the Brazilian crop: grains. Sixth survey 2022/23 Crop*. Available at: https://www.conab.gov.br/info-agro/safras/graos. (Accessed: 20 March 2023)

Core Team R (2022). *A: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria

de Quadros AS, L Bandeir, N Kasper, PLDCA Alves, L de Conti, PRF Giancotti (2020). Herbicide combinations in soybean presowing desiccation. *Braz J Herb* 19:1–9

EBDPA (2023). *Empresa Brasileira de Pesquisa Agropecuária*. Universidade Federal da Grande Dourados Estação Meteorológica da Embrapa na UFGD. Dourados, Mato Grosso do Sul, Brazil

FAMASUL – Federação da agricultura e pecuária Mato Grosso do Sul. Notícias – Grãos (2023). Disponível em: https://portal.sistemafamasul.com.br/noticias/cadeia/gr%C3%A3os . (Acessed on: September 30, 2023)

Fietz CR, E Comunello, RA Garcia, DL Flumignam, G Ceccon (2020). Demanda hídrica e coeficientes de cultivo de milho safrinha consorciado com braquiária. *Agrometeoros* 2020:325–330

Hirano M, Hikishima, AJ Silva, SA Xavier, C Giovannetti (2010). Validação de escala diagramática para estimativa de desfolha provocada pela ferrugem asiática em soja. *Summa Phytopathol* 36:248–250

Kamphorst A, C Paulus (2019). Herbicidas para dessecação pré-colheita em soja como alternativa em substituição ao Paraquat. *Rev Cultiv Saber* 2019:54–62

Lenth R (2023). Emmeans: Estimated Marginal Means, aka Least-Squares Means. *R Package Version* 1.8.4-1. Available at: https://CRAN.R-project.org/package=emmeans

Medina GDS (2021). Economia do agronegócio no Brasil: participação brasileira na cadeia produtiva da soja entre 2015 e 2020. *Nov Cader NAEA* 24:231–254

Mendonça Bezera, M, ESD Medeiros, T Carvalho Dambrós, M Mauad, PA Monquero, FA Nunes, BF Schedenffeldt (2022). Pre-harvest desiccation strategies of soybean culture: a scenario without paraquat. *J Environ Sci Health B* 57:710–719

Montgomery GB, JA Treadway, JL Reeves, LE Steckel (2017). Effect of time of day of application of 2, 4-D, dicamba, glufosinate, paraquat, and saflufenacil on horseweed (*Conyza canadensis*) control. *Weed Technol* 31:550–556

Nandula VK (2019). Herbicide resistance traits in maize and soybean: current status and future outlook. *Plants* 8:337

Oliveira AP, De, BS Ferreira (2020). Biotecnologia aliada da agricultura e na produtividade da soja. *Rev Cient Eletr Ciênc Aplic Fait* 2:1–13

Park J, YO Ahn, JW Nam, MK Hong, N Song, T Kim, GH Yu, SK Sung (2018). Biochemical and physiological mode of action of tiafenacil, a new protoporphyrinogen IX oxidase-inhibiting herbicide. *Pest Biochem Physiol* 152:38–44

Parreira ML, FR Côrrea, NFD Silva, WSDS Cavalcante, DF Ribeiro, E Rodrigues (2023). Herbicides with potential for desiccation of soybean presowing area. *Braz J Sci* 2:46–59

Pinheiro DT (2019). Pre-harvest moisture deterioration of soybean seeds: physical, physiological and biochemical changes. *Sci Agric* 78:e20200166

Pitelli RA, AT Bisigatto, I Kawaguchi, RLCM Pitelli (2011). Doses e horário de aplicação do diquat no controle de Eichhornia crassipes. *Plant Danin* 29:269–277

Ribeiro DF, FR Corrêa, NF Silva, WSS Cavalcante, E Rodrigues (2023). Alternativas de herbicidas para dessecação de áreas em pousio. *Braz J Sci* 2:71–85

Rigby RA, DM Stasinopoulos (2005). Generalized additive models for location, scale and shape (with discussion). *Appl Stat* 54:507–554

Santos HG, PKT Jacomine, LHC Anjos, VA Oliveira, JF Lumbreras, MR Coelho, JA Almeida, JC Araujo Filho, JB Oliveira, TJ Cunha Sistema (2018). *Brasileiro de Classificação de Solos*, 5th edn, p:187. Embrapa, Brasília

SBCPD – Brazilian Society of Weed Science (1995). *Procedures for Installation, Evaluation and Analysis of Herbicide Experiments*, p:42. Londrina, Brazil

Silva GFD, L Chamma, BCO Luperini, PPN Chaves, JC Calonego, J Nakagawa, EAAD Silva (2023). Physiological quality of soybean seeds as a function of soil management systems and pre-harvest desiccation. *Agronomy* 13:847

Tahmasebi BK, RADL Cruz, E Alcántara, J Torra, JA Domínguez-Valenzuela, HE Cruz-Hipólito, AM Rojano-Delgado, RD Prado (2018). Multiple resistance evolution in bipyridylium-resistant *Epilobium ciliatum* after recurrent selection. *Front Plant Sci* 9:695

Takano HK, R Beffa, C Preston, P Westra, FE Dayan. (2020). Physiological factors affecting uptake and translocation of glufosinate. *J Agric Food Chem* 68:3026–3032

Tenório Filho LCJ, LEL Bulhões, LAR de Lima, AB da Silva Júnior, JLXL Cunha, RC de Souza (2023). Efficiency of glyphosate in association with protox-inhibiting herbicides in the control of *Paspalum maritimum* Trind. *Rev Científica FAEMA* 14:295-306

Voora V, C Larrea, S Bermudez (2020). *Global Market Report: Soybeans*. The International Institute for Sustainable Development, Winnipeg, Canada

Wechsler SJ, D Smith, J McFadden, L Dodson, S Williamson (2019). *The use of genetically engineered dicamba-tolerant soybean seeds has increased rapidly, benefiting adopters but damaging crops in some fields*. The Economics of Food, Farming, Natural Resources, and Rural America. Amber Waves, Farm, Market & Café, New York, USA

Wickham H (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York, USA

Yoon J, Y Han, YO Ahn, MK Hong, SK Sung (2019). Characterization of HemY-type protoporphyrinogen IX oxidase genes from cyanobacteria and their functioning in transgenic *Arabidopsis*. *Plant Mol Biol* 101:561–574