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Selectivity and efficacy of PROTOX inhibitors in cassava varieties cultivated in clayey and sandy soils

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ABSTRACT. The selectivity and efficacy of protoporphyrinogen oxidase (PROTOX) inhibitor herbicides in cassava varieties depend on product formulation, dosage, and soil texture. The aim of this study was to assess the selectivity and efficacy of flumioxazin and sulfentrazone in the cassava variety 'IPR B36' and the clone 'VN 117'. Two experiments were carried out: one in a clayey soil and one in a sandy soil. Both experiments were laid in a split-plot randomized block design with three replicates. The two cassava varieties were used as main plots, with subplots consisting in 10 treatments including, flumioxazin at 50, 75, 100, and 125 g ha^{-1}; sulfentrazone at 250, 500, 750, and 1000 g ha^{-1}; one weed-free control, and one unweeded control. Flumioxazin (⩾75 g ha^{-1}) and sulfentrazone (⩾250 g ha^{-1}) achieved mean weed control rates > 70 and 90% in both types of soil for up to 90 days after application. Flumioxazin exhibited fewer residual effects on the cassava varieties than sulfentrazone, particularly in clayey soil. Flumioxazin was selective to the different cassava varieties planted in both soil types, whereas sulfentrazone was more selective in clayey soil. PROTOX inhibitors were effective in controlling weed growth in cassava plots, and there were no varietal differences in herbicide selectivity; however, the use of sulfentrazone should be restricted to maximum spray rates of 250 g ha^{-1} in sandy soils.

Keywords: *Manihot esculenta*; weed control; soil texture; flumioxazin; sulfentrazone.

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Introduction

Cassava (*Manihot esculenta* Crantz) originated in the Amazon region and is currently one of the main food staples consumed in Africa, Asia, the Americas, and Oceania. Cassava can be cultivated in almost all regions of Brazil, and the production system practiced in the southern region is highly technified and predominantly intended for the starch industry. In 2019, the total area under cassava cultivation in Brazil was approximately 1.3 million hectares, producing 19.1 million tons of cassava roots, with an average yield of 14.8 t ha^{-1} (IBGE, 2021).

Cultivation across large areas exposes cassava crops to the negative effects caused by interference from weeds, whereby, routine control measures are essential to ensure optimal productivity levels and high economic returns. The total period of time that cassava plants must remain free from weed competition is 100 days after planting (DAP); otherwise, root-yield losses can be as high as 100% (Johanns & Contiero, 2006; Biffe et al., 2010). This is due to the slow growth of cassava plants in the first two weeks after planting. Additionally, cassava plants differentiate between the fibrous and tuber roots and begin accumulating photoassimilate produced in the aerial part of the plant as starch in the root system in the period comprised between 60 and 100 DAP (Souza et al., 2017); over the duration of this physiological stage, the cassava plant it is highly sensitive to weed competition for sunlight, water, and nutrients.

In intensive cassava farming systems, chemical weed control has been widely used because of its high selectivity and control efficiency, in addition to its low cost, compared to that of manual or mechanized weeding (Alabi, Ayeni, Agboola, & Majek, 2004; Silva et al., 2012). Particularly, herbicides that inhibit the protoporphyrinogen oxidase (PROTOX) enzyme, such as flumioxazin and sulfentrazone, have shown high effectiveness in controlling broadleaf weeds, grass weeds, and Cyperaceous weeds growing in cassava fields (Scariot, Costa, Bosquese, Andrade, & Sontag, 2013).

Soil physicochemical characteristics (pH, clay, cation exchange capacity [CEC], and organic matter) have a significant influence on the absorption of flumioxazin and sulfentrazone by plants because of the adsorption process of colloidal particles, which reduces the concentration of active ingredients dissolved in the soil solution (Grey et al., 2000; Ferrell, Witt, & Vencill, 2003; Jaremtchuk et al., 2009; Wehtje, Gilliam, & Marble, 2012), and microbial degradation, which diminishes the residual effects of herbicides (Ferrell & Vencill, 2003).

These issues highlight the need for recommended formulations and specific dosages of herbicides for distinct soil types to ensure effective weed control and crop selectivity.

According to Kerr, Stahlman, and Dille (2004), sunflower plants are more tolerant to sulfentrazone when applied in clayey soils than in sandy soils. Similar results have been reported by Costa, Ferreira, Ramella, Moratelli, and Dourado (2015) for cassava crops; however, there is little information regarding the selectivity and efficacy of flumioxazin for cassava cultivated in soils with different textures, or the varietal tolerance to PROTOX inhibitors. Further, the selectivity of PROTOX inhibitors for cassava cultivars and their effectiveness for controlling weeds presumably depend on herbicide formulation, dosage, and the physicochemical characteristics of the cultivated soil. Therefore, the aim of this study was to assess the selectivity and effectiveness of flumioxazin and sulfentrazone in the cassava cultivar 'IPR B36' and the clone 'VN 117' grown in clayey and sandy soils.

Material and methods

Two experiments were conducted simultaneously under field conditions in 2018/2019. One experiment was conducted in the western region of Paraná State, Brazil (24°30'33.02" S, 54°18'34.02" W) in a clayey soil (eutrophic Red Latosol). The other experiment was conducted in the northwestern region of Paraná State, Brazil (23°47'28" S, 53°15'09" W) in a sandy soil (typical dystrophic Red Latosol).

A split-plot randomized block design with three replicates was used for each experiment. In each case, the main plot consisted of two cassava varieties ('IPR B36' and 'VN 117'), while each subplot consisted of 10 treatments, namely, flumioxazin applied at 50, 75, 100, and 125 g ha^{-1}; sulfentrazone applied at 250, 500, 750, and 1000 g ha^{-1}; and two controls, with and without manual weeding, with no herbicide application in either case. Each subplot consisted of four rows, 5 m in length and spaced 0.90 m apart (total area: 18 m^2). Weed control in the control treatment was achieved by manual weeding.

A two-line planter (model BAZUCA, Planti Center) was used to plant the cassava cuttings (12 cm long) in the 0.90 × 0.70 m subplot rows, where cuttings were laid 10 cm below the soil surface. A conventional soil management system was used, with plowing in one pass followed by harrowing in two passes, approximately 30 days before planting.

The experiment conducted in the western region of Paraná State was established in August, 2018, in a clayey soil with the following textural characteristics: 37.7% clay, 55.0% silt, and 7.2% sand, and the following chemical characteristics: pH ($CaCl_2$) = 5.56; H+Al = 2.90 cmol$_c$ dm^{-3}; Al^{3+} = 0.0 cmol$_c$ dm^{-3}; Ca^{2+} = 5.54 cmol$_c$ dm^{-3}; Mg^{2+} = 1.69 cmol$_c$ dm^{-3}; P = 23.47 mg dm^{-3}; K = 1.30 cmol$_c$ dm^{-3}; organic matter = 24.61 g dm^{-3}; CEC = 11.43 cmol$_c$ dm^{-3}, and V% = 74.63.

The experiment conducted in the northwestern region of Paraná State was established in September, 2018, in a sandy soil with the following textural characteristics: 12.8% clay, 7.4% silt, and 79.8% sand, and the following chemical characteristics: pH ($CaCl_2$) = 4.64; H+Al = 3.29 cmol$_c$ dm^{-3}; Al^{3+} = 0.1 cmol$_c$ dm^{-3}; Ca^{2+} = 1.12 cmol$_c$ dm^{-3}; Mg^{2+} = 1.56 cmol$_c$ dm^{-3}; P = 38.79 mg dm^{-3}; K = 0.08 cmol$_c$ dm^{-3}; organic matter = 8.20 g dm^{-3}; CEC = 6.06 cmol$_c$ dm^{-3}, and V% = 45.71. Fertilizers were not applied at planting in either experiment.

A backpack sprayer pressurized with CO_2 at 3.6 kg cm^{-2} and equipped with a four-nozzle boom (model 11002 AD-MagnoJet) was used for herbicide application. The nozzles were spaced 0.5 m apart and the spray flow rate was 200 L ha^{-1}.

In the clayey soil, herbicides were applied 23 days after planting (DAP) the cassava varieties. The weather conditions at the time of application were 27.7°C air temperature, 61.0% RH, and wind speed ranging from 1.4 to 2.1 m s^{-1}. The soil was moist and the stem cuttings of the length of the buds of 'IPR B36' and 'VN117' were 1.0 - 3.0 cm and 0.2 - 0.8 cm, respectively.

In sandy soil, herbicides were applied five DAP. The weather conditions at the time of application were 30.0°C air temperature, 58.0% RH, and wind speed ranging from 0.7 to 1.2 m s^{-1}. The soil was moist and the cuttings did not exhibit any buds.

The percentage of injuries in the cassava plants and evaluation of weed control were carried out at 20, 30, 40, 50, 60, 70, 80, and 90 days after herbicide application (DAA). The scores of injuries in the cassava plants and weed control were based on a percentage scale, where 0 (zero) corresponded to no visible injury in the cassava or weed plants, and 100 (hundred) corresponded to cassava plant death and full weed control. The observed characteristics of cassava plant injuries and controlled weeds that informed the percentage scores were as follows: germination/growth inhibition, quantity and uniformity of injuries, plant regrowth ability, and number of dead plants.

In both experiments, the biomass of the weed community (t ha^{-1}) was determined at 90 DAA by collecting all plants found within a metal quadrat (50 × 50 cm), which was thrown twice to the center of each plot. The harvested species were dried in a forced-air circulation oven at 60°C for 72h and then weighed on a precision scale (0.001 g). The floristic composition of the species was determined in each experimental area, and the similarity between the communities was compared based on the similarity index (SI) of Sørensen (1948).

The cassava plants grown in the western region were harvested on July 1, 2019 (11 months after planting), and those cultivated in the northwestern region were harvested on June 14, 2019 (nine months after planting). In both harvests, the plants grown in the two central lines of the plots were assessed, disregarding one plant from each end of the lines. The roots were weighed using a digital scale (dynamometer type), and the yield was determined (t ha^{-1}). For starch content, a 5 kg sample of cassava roots was collected from each plot using the hydrostatic scale method (Grossman & Freitas, 1950).

The percent values of cassava plant injuries and weed control are shown graphically based on herbicide spray rates and the dates of assessment in each experiment; the data were adjusted to surface regression models. Data relating to weed dry weight and cassava root and starch yields were analyzed by conjoint analysis of variance ($F \leqslant 0.05$). Means were adjusted to linear and nonlinear regression models according to herbicide application rate. The models were chosen after considering the logics of the biological phenomenon, normality, significance of regressions ($F \leqslant 0.05$), and high coefficient of determination (R^2).

Results

Application of flumioxazin in sandy soil (Figure 1) and of sulfentrazone in clayey soil (Figure 2) did not cause any injuries to either plant material tested. Conversely, at 30 DAA, sulfentrazone was harmful to cassava plants growing in sandy soil, causing moderate injuries (20% - 40%) at doses of up to 500 g ha^{-1} (Figure 2C and D). Furthermore, at 40 DAA, higher doses (>500 g ha^{-1}) caused extremely severe injuries to the cassava plants (>60%), and plant growth in both varieties was reduced by up to 35% (data not shown).

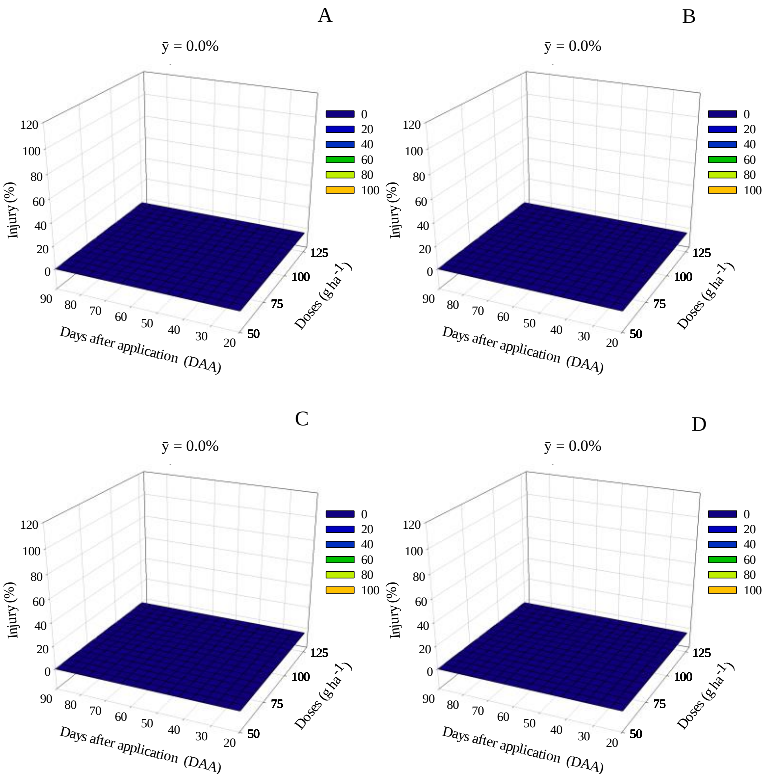

Figure 1. Percentage of injury in cassava plants after application of flumioxazin in a clayey (A and B) and in a sandy soil (C and D). A and C, variety 'IPR B36'; B and D, clone 'VN 117'.

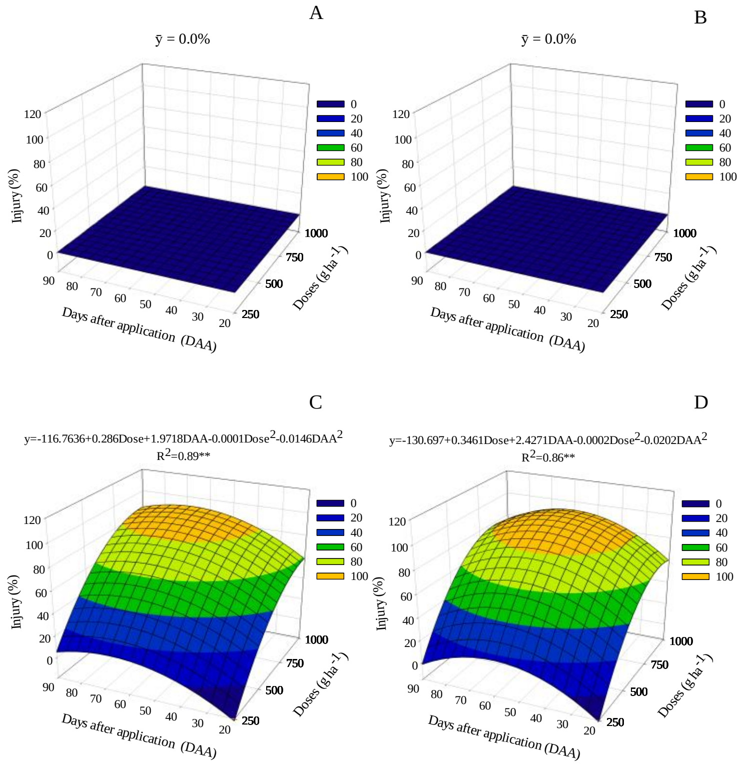

Figure 2. Percentage of injury in cassava plants after sulfentrazone application in a clayey (A and B) and in a sandy soil (C and D). A and C, variety 'IPR B36'; B and D, clone 'VN 117'. **Significant at 1% (F < 0.01) as per the F-test.

In both cassava varieties, application of ⩽ 100 g ha^{-1} flumioxazin to clayey soil provided over 80% effective weed control at approximately 70 DAA. Higher rates of application were necessary to achieve residual effects (>80%) up to 90 DAA (Figure 3). In sandy soil, the residual effect (>80%) of flumioxazin remained for a longer period, especially for the cassava variety 'IPR B36' (Figure 3C and D). In contrast, sulfentrazone (>250 g ha^{-1}) provided over 90% weed control at 90 DAA, both in clayey and sandy soils (Figure 4).

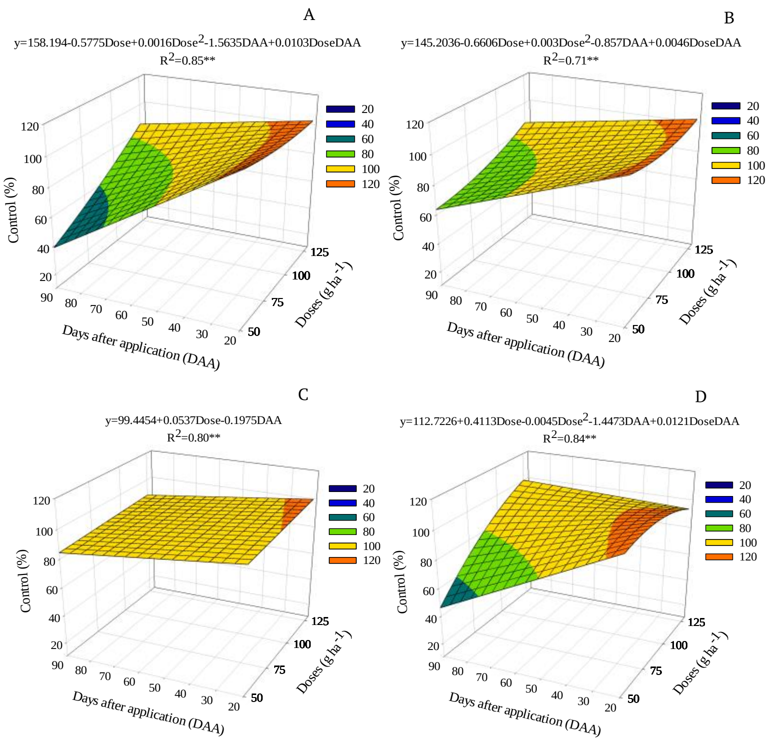

Figure 3. Percentage of weed control after flumioxazin application in a clayey (A and B) and in a sandy soil (C and D). A and C, variety 'IPR B36'; B and D, clone 'VN 117'. **Significant at 1% (F < 0.01) as per the F-test.

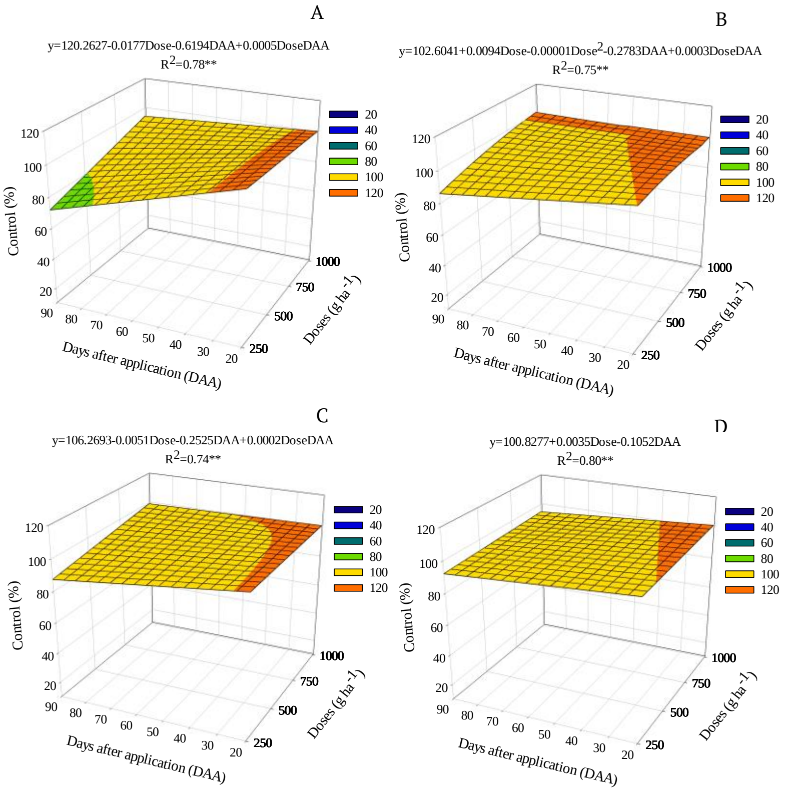

Figure 4. Percentage of weed control after sulfentrazone application in a clayey (A and B) and in a sandy soil (C and D). A and C, variety 'IPR B36'; B and D, clone 'VN 117'. **Significant at 1% (F < 0.01) as per the F-test.

Species diversity in the area of sandy soil was greater than that recorded for the area of clayey soil, with a low level of similarity (38.5%) between the weed communities of the experimental areas (Table 1). The most common species recorded in the experimental areas were the monocot species *Avena sativa*, *Commelina benghalensis,* and *Digitaria horizontalis*, and the broadleaf weed species *Bidens pilosa* and *Phyllanthus niruri*. *C. benghalensis* and *D. horizontalis* showed the highest densities in clayey and sandy soils, respectively. These data indicate that applications of sulfentrazone and flumioxazin resulted in an excellent control of the weed species grown in clayey and sandy soils.

Table 1. Floristic composition and similarity of weed communities found in the experimental areas 90 days after herbicide application.

Species*	Clayey soil	Sandy soil
	Density (plant m^{-2})	
Aeschynomene sp.	---	4.0
Amaranthus hybridus	---	14.0
Avena sativa	0.7	1.5
Bidens Pilosa	4.7	0.5
Brachiaria plantaginea	---	0.5
Commelina benghalensis	22.7	3.5
Cyperus spp.	---	7.5
Digitaria horizontalis	13.3	26.0
Digitaria insularis	---	2.5
Eleusine indica	---	9.5
Ipomoea grandifolia	---	0.5
Leonurus sibiricus	4.0	---
Phyllanthus niruri	16.0	0.5
Portulaca oleracea	---	0.5
Raphanus sativus	1.3	---
Richardia brasiliensis	---	12.0
Senna obtusifolia	---	1.0
Sida rhombifolia	---	6.5
Sonchus oleraceus	0.7	---
Similarity Index (%)	38.5	

*species found in the non-weeded (i.e., the weedy) control subplots of the experimental areas.

A summary of the ANOVA conjoint analysis for the dry weight of weeds, root yields, and starch content between experiments is shown in Table 2. Weed dry weight data at 90 DAA (Figure 5) are consistent with the data on weed control (%), thus confirming that both herbicides were effective in controlling weed growth.

Table 2. Summary of ANOVA conjoint analysis for the dry weight of weeds (DWW), root yields, and starch content after PROTOX-inhibiting herbicides were applied on cassava varieties cultivated in a clayey and in a sandy soil.

	DWW (t ha^{-1})[1]		Roots (t ha^{-1})		Starch (%)		
Site	IPR B36	VN 117	IPR B36	VN 117	IPR B36	VN 117	Avg
Clayey	2.45aA	1.25bA	22.79aB	31.65aA	26.80	26.63	26.72a
Sandy	2.35aA	3.32aA	22.72aA	17.91bA	25.80	25.32	25.56b
Variation sources	Mean Square						
Block (Location)	4.60ns		51.17ns		5.6ns		
Location (L)	28.98*		1429.59**		40.18*		
Varieties (V)	0.40ns		122.94ns		3.18ns		
L x V	35.30*		1400.51**		0.76ns		
Error 1	2.98		69.76		3.02		
Treatment (T)	27.13**		271.84**		1.29ns		
L x T	6.00ns		157.54**		1.70ns		
V x T	7.50ns		47.40ns		0.52ns		
L x V x T	2.46ns		20.88ns		1.00ns		
Error 2	4.64		25.21		1.37		
CV1 (%)	73.57		35.13		6.65		
CV2 (%)	91.91		21.12		4.48		

Means followed by the same lowercase letter within columns, and uppercase letters within rows, do not significantly differ from each other as per Tukey's test, at the 5% probability level. ns, not significant; ** and *, significant at 1% and 5% as per the F-test, respectively. [1]Weed dry weight was determined at 90 DAA.

The variety 'IPR B36' registered an average root yield of 22.7 t ha^{-1} in both soils, which is higher than the Brazilian average of 14.8 t ha^{-1} and similar to the Paraná State average of 23.1 t ha^{-1} (IBGE, 2021). In turn, the clone 'VN 117' was more productive when cultivated in clayey soil (31.7 t ha^{-1}). The cassava crop has the potential to produce root yields from 36.3 to 50.0 t ha^{-1} after 10 and 18 months of cultivation, respectively (Devide et al., 2009; Otsubo, Mercante, Silva, & Borges, 2013; Streck et al., 2014).

The average root-starch content did not differ between herbicide treatments and was slightly higher in the cassava plants cultivated in clayey soil (26.8%) than in sandy soil (25.6%) (Table 2).

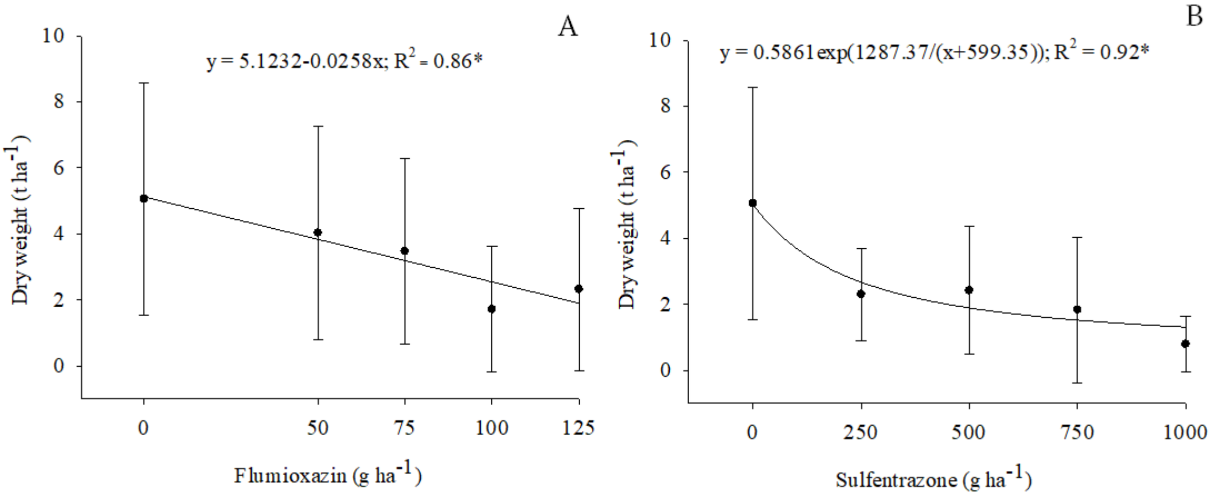

Figure 5. Average weed dry weight at 90 DAA of flumioxazin (A) and sulfentrazone (B) on cassava varieties cultivated in soils with different textures. * Significant at 5% as per the F-test. Bars indicate standard deviations of the means.

When no weed control was applied (unweeded control), there was a reduction in cassava root yield of approximately 37.5% and 74.7% in clayey and sandy soils, respectively, relative to the weeded control (Figure 6).

The application of flumioxazin did not cause a reduction in cassava root yield, and was selective for variety 'IPR B36' and clone 'VN 117', regardless of soil texture (Figure 6A). In contrast, sulfentrazone did not cause a decrease in root yield only when applied to clayey soil (Figure 6B). In sandy soil, sulfentrazone applied at a rate of 250 g ha^{-1} may be considered selective, as it caused few injuries to the cassava plants and had no significant impact on root yields.

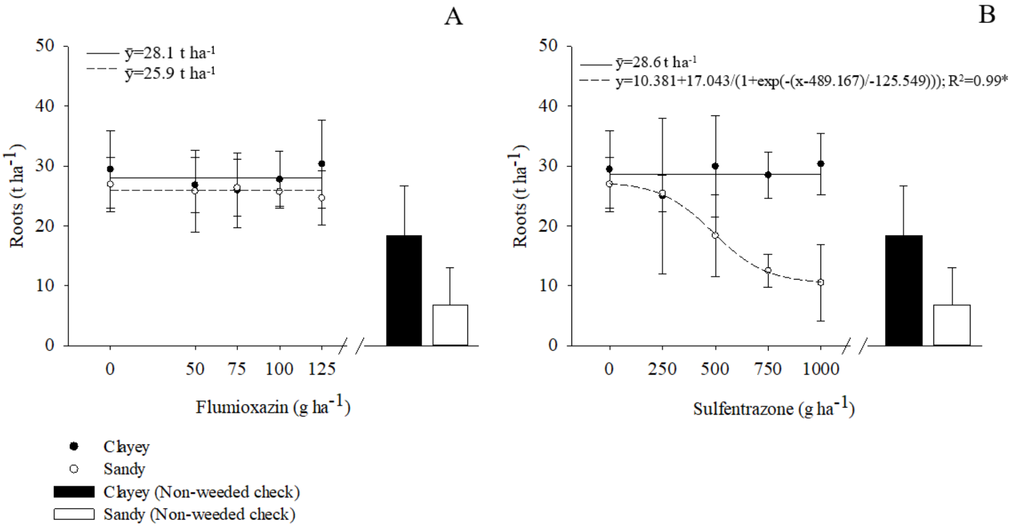

Figure 6. Cassava root yields after flumioxazin (A) and sulfentrazone (B) applications in a clayey and in a sandy soil. *significant at 5% as per the F-test. Bars indicate standard deviations of the means.

Discussion

Sulfentrazone was more harmful to both cassava varieties than flumioxazin, especially in sandy soil, where injuries were detected already in the initial phase of plant growth. Conversely, no visible symptoms of injury were identified in cassava plants of the variety 'Cascuda' when flumioxazin or sulfentrazone are applied at 60 and 600 g ha^{-1}, respectively (Scariot et al., 2013).

Cassava cutting bud-emergence after planting is relatively slow, occurring within 15 days, and largely depends on weather conditions (El-Sharkawy, 2004). During this period, the plants use energy stored in the cuttings to produce a large number of fibrous roots and leaves. When these structures are formed, the plants absorb the active ingredients of the herbicides that are dissolved in the soil solution. In this study, injury symptoms were clearly visible in the foliar tissues at 20 DAA (Figure 2C and D). Thus, sulfentrazone caused leaf chlorosis in some areas, followed by necrosis in older leaves and stunting of new leaf growth at the plant apex, while higher doses (>750 g ha^{-1}) induced full stunting of plant growth with the occurrence of abnormal leaves, but did not cause plant death. In some of our field assessments after a rain event, we observed accumulation of soil particles on the leaves of the lower third of the plant, which showed stronger chlorosis symptoms, especially plants growing in sandy soil. It is likely that the soil particles were contaminated with the herbicide molecules, whereby absorption by the leaf was subsequently favored.

The residual effect of preemergence herbicides must persist until the end of the critical period for weed control (CPWC) (Knezevic, Evans, Blankenship, Van Acker, & Lindquist, 2002). For cassava crops, the CPWC ranges from 75 to 100 DAP, depending on the cultivation system, soil and weather conditions, variety, and composition and density of the weed community (Alabi, Ayeni, Agboola, & Majek, 2001; Aihi, Juraimi, Hamdani, Halim, & Hakim, 2017; Albuquerque et al., 2012). In the present study, both flumioxazin and sulfentrazone exhibited excellent weed control in cassava cultivated regardless of soil texture; however, optimal weed control conditions were found in clayey soil treated with sulfentrazone, where weed control was higher than 80% and the residual effect lasted to up 90 DAA (close to the final CPWC of the crop).

Application of flumioxazin (60 g ha^{-1}) and sulfentrazone (600 g ha^{-1}) in cassava cultivar 'Cascuda' grown in a clayey soil provided 79.7% and 90.3% weed control, respectively, at 105 DAA. Further, when these herbicides are tank-mixed with clomazone (900 g ha^{-1}), the control spectrum is broadened (Scariot et al., 2013).

The broad weed control-spectrum provided by flumioxazin and sulfentrazone has been identified in other studies, demonstrating the potential for isolated applications of herbicides to control weed communities of a mixed composition including broad-leaved and grassy species. The application of sulfentrazone (600 g ha^{-1}) is sufficient in controlling broadleaf weed growth to obtain 90% soybean production in soils of different textures (Walsh, Soltani, Hooker, Nurse, & Sikkema, 2015). In potato crops, sulfentrazone (140–420 g ha^{-1}) and flumioxazin (35–53 g ha^{-1}) are reportedly selective and effective in controlling various weed species in the western United States (Wilson, Nissen, & Thompson, 2002). Further, *B. plantaginea*, *D. horizontalis*, and

D. insularis grasses and the broadleaf weed *R. brasiliensis* are sensitive to flumioxazin application (25 and 40 g ha^{-1}) in both clayey and sandy soils (Jaremtchuk et al., 2009).

Weed control efficacy and selectivity in cassava crops can be explained by the differential absorption and translocation of the herbicide and the ability of the plant to metabolize PROTOX inhibitors. Notably, the physiological basis of herbicide-tolerant cassava varieties has not been reported; however, the available studies can aid in understanding the mechanisms underlying plant tolerance or susceptibility to PROTOX inhibitors.

The weed plant species *Chenopodium album* and *Datura stramonium*, and potato plants (*Solanum tuberosum*) have been shown to accumulate 52.2, 56.8, and 78.3% [^{14}C] sulfentrazone into their roots after 48h of exposure, respectively. Further; translocation of sulfentrazone to the aboveground parts of potato plants (21.7%) was approximately two times lower than that in *C. album* (47.8%) and *D. stramonium* (43.2%) (Bailey, Hatzios, Bradley, & Wilson, 2003). Similarly, seedlings of the tolerant cultivar ‘Stonewall ’absorbed 37% less herbicide than the sensitive cultivar ‘Asgrow 6785’, after 24h of soybean seed exposure to [^{14}C] sulfentrazone (Li, Wehtje, & Walker, 2000). Consistently, although *Ipomoea hederacea* (a weed species) and peanut (*Arachis hypogaea*) plants exhibited similar rates of ^{14}C-flumioxazin translocation to the aboveground parts of the plants (16% after 72h after application [HAA]), the weed species contained 41% of non-metabolized herbicide at 72 HAA, whereas peanut plants contained only 11%, indicating that *I. hederacea* metabolizes the herbicidal active ingredient more slowly than peanut (Price, Wilcut, & Cranmer, 2004). Furthermore, in PROTOX inhibitor-resistant biotypes of the grass weed *Poa annua*, lipid peroxidation, as measured by malondialdehyde levels, was, on average, 25% lower than that of the susceptible biotype at 72 HAA of flumioxazin application at 280 and 560 g ha^{-1} (Yu, McCullough, & Czarnota, 2018).

Flumioxazin belongs to the cyclohexene-dicarboximide chemical group, while sulfentrazone belongs to the triazolone chemical group. Further, the physicochemical characteristics of flumioxazin (pKa = non-ionizable, solubility in water = 1.8 mg L^{-1}, Koc = 889, and Kow = 2.55) differ from those of sulfentrazone (pKa = 6.56, solubility in water = 490 mg L^{-1}, Koc = 43, and Kow = 1.48) (Grey et al., 2000; Kerr et al., 2004; Shaner, 2012; Mueller, Boswell, Mueller, & Steckel, 2014). Considering the physicochemical characteristics of the soil in the Paraná State, Brazil (37.7% clay, organic matter = 24.61 g dm^{-3}, pH = 5.56, and CEC = 11.43 cmol$_c$ dm^{-3} in the western region; and 12.8% clay, organic matter = 8.20 g dm^{-3}, pH = 4.64, and CEC = 6.06 cmol$_c$ dm^{-3} in the northwestern region), we observed that sulfentrazone provided a higher concentration of dissolved molecules (high pKa and solubility) and lower adsorption of clay colloids and organic matter (low Koc and Kow) in sandy soil than in clayey soil, compared with that of flumioxazin (Ferrell & Vencill, 2003; Szmigielski et al., 2009). Therefore, soils with low levels of clay and organic matter favored sulfentrazone absorption by cassava plant roots by cutting the buds at the early stages of development, thus, reducing selectivity, while the residual effect on the soil seed-bank increased. The low solubility and high Koc and Kow coefficients may explain the high selectivity of flumioxazin for cassava plants, regardless of soil texture.

No significant differences were found between cassava varieties in tolerance to the assessed PROTOX inhibitors. Generally, flumioxazin was more selective than sulfentrazone in sandy soil; however, in clayey soil, both formulations were selective.

Sulfentrazone (250–1000 g ha^{-1}) was not selective for cassava cultivar ‘Olho Junto’ when cultivated in either sandy (21.2% of clay) or clayey (54.5% of clay) soils (Costa et al., 2015), suggesting the occurrence of varietal tolerance to PROTOX inhibitors, even in clayey soil. Further studies are necessary to determine which cassava varieties are more or less tolerant to PROTOX inhibitors in soils with different textures, as well as the most selective dosages.

The average root-starch content in the cassava varieties assessed in this study tended to be higher in clayey soil crops than in sandy soil crops (Table 2). However, the use of herbicides and the presence of weed competition did not have an effect on root starch content, and the observed reduced starch yields were likely related to the reduced number of roots produced. These results are consistent with those obtained by Franciscon et al. (2016).

Effective chemical management of weed communities must be based on bioecological and agronomic criteria to avoid future complications, considering that the use of high doses of herbicides can enhance the selection pressure for biotypes resistant to PROTOX inhibitors in cassava cropping areas (Beckie, 2006). In contrast, single application of low doses of herbicide may not provide sufficient residual effect to correspond to the CPWC of the crop (Costa, Salvalaggio, Ferreira, Barbosa, & Gibbert, 2020). Further, except for that of sulfentrazone in the sandy soil treatment, it was not possible to adjust the root yield data of the other treatments to any regression model that would allow the estimation of the optimal dose of each herbicide for each variety and soil texture. Therefore, considering the tolerance of variety 'IPR B36' and clone 'VN 117' to PROTOX inhibitors, we recommend that herbicide application rates should range between 50 and 100 g ha^{-1} for flumioxazin applications in sandy and clayey soils, and between 500 and 750 g ha^{-1} for sulfentrazone applications in clayey soils, while, in sandy soils, the use of sulfentrazone must be restricted to doses below 250 g ha^{-1}.

Conclusion

PROTOX inhibitor herbicides were effective in managing weed communities in cassava crops; however, herbicide formulation and soil type should be considered in crop management design in order to achieve higher residual effects and crop selectivity. There was no significant difference between the selectivity of flumioxazin and that of sulfentrazone; however, sulfentrazone was less selective in cassava cultivated in sandy soil.

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