Research Article

Oxyfluorfen bioavailability in Brazilian Savanna soils[1]

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ABSTRACT

Oxyfluorfen is a pre-emergent herbicide applied via soil; however, the soil attributes have not been considered to predict the herbicide doses. This study aimed to evaluate the bioavailability of the oxyfluorfen herbicide in Brazilian Savanna soils with contrasting attributes. The experiment was carried out in a 6 x 8 factorial scheme, with 6 replications. The evaluated factors were soil types [Gleissolo Melânico distrófico - GMd (Typic Humaquept); Latossolo Vermelho ácrico - LVw (Rhodic Acrustox); Latossolo Vermelho distrófico - LVd (Rhodic Haplustox); Neossolo Quartzarênico órtico - RQo (Typic Quartzpsamment); Neossolo Flúvico Tb distrófico - RYbd (Fluventic Dystrustept); and washed sand] and oxyfluorfen doses (0; 360; 480; 720; 1,440; 2,880; 4,320; and 5,760 g a.i. ha^{-1}). The herbicide bioavailability was determined according to the bioassay methodology. The dose that provided 80 % of *Cucumis sativum* control (C80%) ranged from 9.9 (LVw) to 1,884.4 g a.i. ha^{-1} (GMd), what can be attributed to the high sorption of the herbicide in the GMd, as observed by the adsorptive rate. The soil texture did not show correlation with the oxyfluorfen bioavailability. In the LVd, which is from the same order and with texture similar to that of the LVw, the C80% was 76 times higher (754.28 g a.i. ha^{-1}). Furthermore, for the RYbd, which is a sandy soil, the C80% was even high (1,256.9 g a.i. ha^{-1}). The cation exchange capacity (CEC) (-0.83**) was the only soil attribute able to predict the herbicide bioavailability. The oxyfluorfen bioavailability is highly dependent on the soil attributes, and, in Brazilian Savanna soils, it can be predicted using the CEC.

KEYWORDS: Pre-emergent herbicide, weed control, oxisoils.

RESUMO

Biodisponibilidade de oxyfluorfen em solos de Cerrado

O oxyfluorfen é um herbicida pré-emergente aplicado via solo; porém, os atributos do solo não vêm sendo considerados na determinação das doses do produto. Objetivou-se avaliar a biodisponibilidade do herbicida oxyfluorfen em solos do Cerrado com atributos contrastantes. O experimento foi desenvolvido em esquema fatorial 6 x 8, com 6 repetições. Os fatores avaliados foram tipos de solo [Gleissolo Melânico distrófico (GMd), Latossolo Vermelho ácrico (LVw), Latossolo Vermelho distrófico (LVd), Neossolo Quartzarênico órtico (RQo), Neossolo Flúvico Tb distrófico (RYbd) e areia lavada] e doses de oxyfluorfen (0; 360; 480; 720; 1.440; 2.880; 4.320; e 5.760 g i.a. ha^{-1}). A biodisponibilidade do herbicida foi determinada pela metodologia do bioensaio. A dose que garantiu 80 % de controle de *Cucumis sativum* (C80%) variou de 9,9 (LVw) a 1.884,4 g i.a. ha^{-1} (GMd), o que pode ser atribuído à elevada capacidade de retenção do herbicida no GMd, conforme verificado pela relação adsortiva. A textura do solo não apresentou correlação com a biodisponibilidade de oxyfluorfen. No LVd, solo da mesma classe e com textura semelhante (argilosa) à do LVw, a CR80% foi 76 vezes maior (754,28 g i.a. ha^{-1}). Além disso, no RYbd, que apresenta textura arenosa, a C80% foi ainda maior (1.256,9 g i.a. ha^{-1}). A capacidade de troca catiônica (CTC) (-0,83**) foi o único atributo do solo capaz de predizer a biodisponibilidade do herbicida. A biodisponibilidade do oxyfluorfen é altamente dependente dos atributos do solo e, em solos do Cerrado, pode ser predita pela CTC.

PALAVRAS-CHAVE: Herbicidas pré-emergentes, controle de plantas daninhas, latossolos.

INTRODUCTION

Nowadays, Brazil is one of the biggest pesticides consumers worldwide, with herbicides responding for more than 50 % of the selling products (Bombardi 2017). Despite this fact, the national average rate of pesticides application per hectare is not high, except for some regions with large-scale agriculture, as the Midwest region (Bombardi 2017), which accounts for 46 and 32 %, respectively for grain and sugarcane production (Conab 2020), for crops usually cultivated with a high input of herbicides (Bombardi 2017).

[1] Received: June 13, 2022. Accepted: Nov. 09, 2022. Published: Dec. 14, 2022. DOI: 10.1590/1983-40632022v5273107.
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Herbicides can be applied on plant leaves or directly to the soil prior to weed and/or crop germination, respectively being called post-emergent and pre-emergent herbicides. Since pre-emergent herbicides are applied directly to the soil, its availability, efficacy on weed control, residual effect and toxicity to non-target organisms may be affected by soil attributes (Rodrigues & Almeida 2011). Indeed, some researches demonstrated that there is a great variation in residual effect and phytotoxic potential for some pre-emergent herbicides like sulfentrazone in Brazilian Savanna soils (Arruda 2020, Damin et al. 2021). Furthermore, these authors did not find a correlation among these measurements and soil texture.

Brazilian Savanna is the main biome in the Midwest region, and it is considered one of the 34 hotspots of biodiversity in the world (Myers et al. 2000). The edaphoclimatic conditions in this biome are very distinct from the other Brazilian biomes: soils with low organic matter content and high amounts of oxides, where positive charges generated by protonation are common (Santos et al. 2018). These soil attributes may change the herbicide bioavailability and, therefore, its efficacy, residual effect and impact on non-target organisms.

Herbicides recommendation guides usually consider the weed type and crop selectivity to stablish the herbicide rate; however, soil attributes are rarely considered (Andrade et al. 2010). Attributes such as cation exchange capacity, soil texture, pH, organic matter content, water content and microbial communities may affect the herbicide bioavailability (Christoffoleti et al. 2008). Among the soil attributes, texture has been the only one used to predict the herbicide dosage (Manzano 2013), and only for some herbicides.

Oxyfluorfen (2-chloro-a,a,a-trifluoro-p-tolyl 3-ethoxy-4-nitro-phenyl ether) is a widely used herbicide recommended to control dicots and grasses in pre or post-emergence in many crops, such as cotton, rice, sugarcane, citrus, pinus and eucalyptus (Thakare et al. 2002, Sondhia & Dixit 2007, Rodrigues & Almeida 2011). It is a nonionic molecule, with low solubility (0.116 mg L^{-1}) and high molecular weight (University of Hertfordshire & Footprint 2020), which inhibits the protoporphyrinogen oxidase enzyme (Park et al. 2018). Oxyfluorfen is not easily degraded by soil microorganisms, showing a dissipation half-life of 72-150 days (Hall et al. 2015, Delgado-Moreno et al. 2017, EFSA et al. 2020).

When applied to the soil, it is highly adsorbed by soil colloids, mainly in soils with high clay and organic matter content (Mantzos et al. 2014, Beltrão & Pereira 2000). However, even adsorbed, the herbicide can be transported to water bodies by surface runoff, showing a deleterious effect on fish and other living organisms (Yen et al. 2003, Nilsen et al. 2014, Yang et al. 2014, Xia et al. 2016, Powe et al. 2018, El-Rahman et al. 2019, Li et al. 2022). Furthermore, the US Environmental Protection Agency considers this herbicide to have carcinogenic potential for humans (Carmichael et al. 2016).

In soils with low adsorptive capacity and low organic matter (OM) content, such as some highly weathered tropical soils from the Brazilian Savanna biome (with an acric character), some herbicides may have a high bioavailability and, consequently, high phytotoxic potential for crops and biota in general, even in soils with clayey texture.

Using plant species as bioindicators is a low-cost technique to assess the herbicide bioavailability, being more accessible than analytical techniques involving the use of radioisotopes and high-performance liquid chromatography (Silva et al. 2007). The bioindicator quantifies only the biologically active fraction of the herbicide (the one with the highest potential to cause damage to non-target organisms), being related to the product effectiveness (Silva et al. 2007). Bioindicators can be used to build dose-response curves, which describe the biological response of a weed or bioindicator to increasing herbicide doses, providing an objective interpretation of the results and adequate treatments comparison (Kruse et al. 2006).

Despite the widespread use of oxyfluorfen in Brazilian Savanna agroecosystems and its potential effects on non-target organisms, there are no studies evaluating the herbicide bioavailability in soils from this biome. This information is important to develop weed management strategies that guarantee high yields associated to a low environmental impact. In this way, this study aimed to evaluate the oxyfluorfen bioavailability in soils from the Brazilian Savanna biome, identifying soil attributes that can be useful to predict the herbicide dose for each soil type.

MATERIAL AND METHODS

A pot experiment was carried out under greenhouse conditions at the Universidade Federal de Goiás, in Goiânia, Brazil (17º29'S, 48º12'W and 76 m of altitude), from February to April 2016. The regional climate is Tropical Savanna (Aw), with dry winter and rainy summer, according to the Köppen classification.

A completely randomized design was used, with a 6 x 8 factorial scheme, and six replications. The factors included six soil types [Gleissolo Melânico distrófico - GMd (Typic Humaquept); Latossolo Vermelho ácrico - LVw (Rhodic Acrustox); Latossolo Vermelho distrófico - LVd (Rhodic Haplustox); Neossolo Quartzarênico órtico - RQo (Typic Quartzpsamment); Neossolo Flúvico Tb distrófico - RYbd (Fluventic Dystrustept), according to Santos et al. (2018) and USDA (2014), respectively; and washed sandy] and increasing herbicide doses (0; 360; 480; 720; 1,440; 2,880; 4,320 and 5,760 g a.i. ha^{-1}).

Plastic pots were filled with 0.84 dm^3 of soil, from the 0.00-0.20 m depth. The chemical characterization and texture of each soil type were assessed according to Embrapa (2011) and are described in Tables 1 and 2, respectively. The mineralogical characterization was determined by X-ray diffraction (Moore & Reynolds 1989) (Figure 1).

A bioassay approach (Vivian et al. 2007) was used to determine the dose-response curve and the herbicide persistence indirectly in the environment, using *Cucumis sativum* as bioindicator. Prior to the herbicide application, the soil moisture was raised to 60 % of its maximum water retention capacity and maintained during all the experimental period by daily weighing. Then, ten seeds were sown at 24 hours before the herbicide application.

The oxyfluorfen herbicide was applied using increasing doses of the commercial formulation Goal®, with 240 g L^{-1} of the active ingredient. The herbicide application was performed using a back-pack sprayer pressurized with CO_2, equipped with a 2-m-wide boom and four flat-fan nozzles (XR 110.02). The meteorological parameters were 50 % of the relative humidity, air temperature of 20.5 ºC and wind speed of 3.96 km h^{-1}.

The herbicide phytotoxicity to *C. sativum* was quantified using a diagrammatic scale ranging from 0 to 100, with zero corresponding to absence of symptoms and 100 to the death of all plants in each plot. At 28 days after the herbicide application (DAA), the aboveground part and roots were cut and air-forced dried at 65 ºC, for 72 h, to dry mass

Table 1. Soil chemical attributes.

Soils	pH	OM	P	S	K	Ca	Mg	Al	H + Al	CEC	V	m
	$CaCl_2$	mg dm³				cmol$_c$ dm³					%	
WS	5.9	4.0	6.7	7.1	0.05	0.5	0.3	0.0	0.8	1.7	53.7	0.0
GMd	4.4	32.0	34.4	34.4	0.15	2.2	1.4	0.5	5.5	9.3	41.2	11.8
LVw	5.6	23.0	1.2	2.8	0.05	0.3	0.2	0.0	2.0	2.6	22.1	0.0
LVd	4.6	25.0	0.8	3.4	0.06	0.3	0.2	0.4	5.8	6.4	9.2	41.7
RQo	4.3	9.0	3.4	5.0	0.06	0.4	0.2	0.3	2.3	3.0	22.9	31.2
RYbd	4.3	29.0	2.4	7.1	0.04	0.3	0.2	0.5	4.2	4.8	12.1	48.1

OM: organic matter; P: phosphorus; S: sulfur; CEC: cation exchange capacity at pH 7.0; V: base saturation; m: aluminum saturation; WS: washed sand; GMd: Gleissolo Melânico distrófico (Typic Humaquept); LVw: Latossolo Vermelho ácrico (Rhodic Acrustox); LVd: Latossolo Vermelho distrófico (Rhodic Haplustox); RQo: Neossolo Quartzarênico órtico (Typic Quartzpsamment); RYbd: Neossolo Flúvico Tb distrófico (Fluventic Dystrustept).

Table 2. Soil texture (g kg^{-1}) and clay mineralogy.

Soils	Clay	Silt	Sand	Clay mineralogy
WS	70	30	900	Caulinite, VHI, gibsite, talc and clorite
RQo	90	40	870	Caulinite, gibsite and VHI
RYbd	110	50	840	Caulinite, VHI and gibsite
GMd	320	90	590	Caulinite, VHI and gibsite
LVw	440	110	450	Gibsite, caulinite and VHI
LVd	500	110	390	Caulinite, gibsite and VHI

VHI: vermiculite with hydroxy interlayer; WS: washed sand; GMd: Gleissolo Melânico distrófico (Typic Humaquept); LVw: Latossolo Vermelho ácrico (Rhodic Acrustox); LVd: Latossolo Vermelho distrófico (Rhodic Haplustox); RQo: Neossolo Quartzarênico órtico (Typic Quartzpsamment); RYbd: Neossolo Flúvico Tb distrófico (Fluventic Dystrustept).

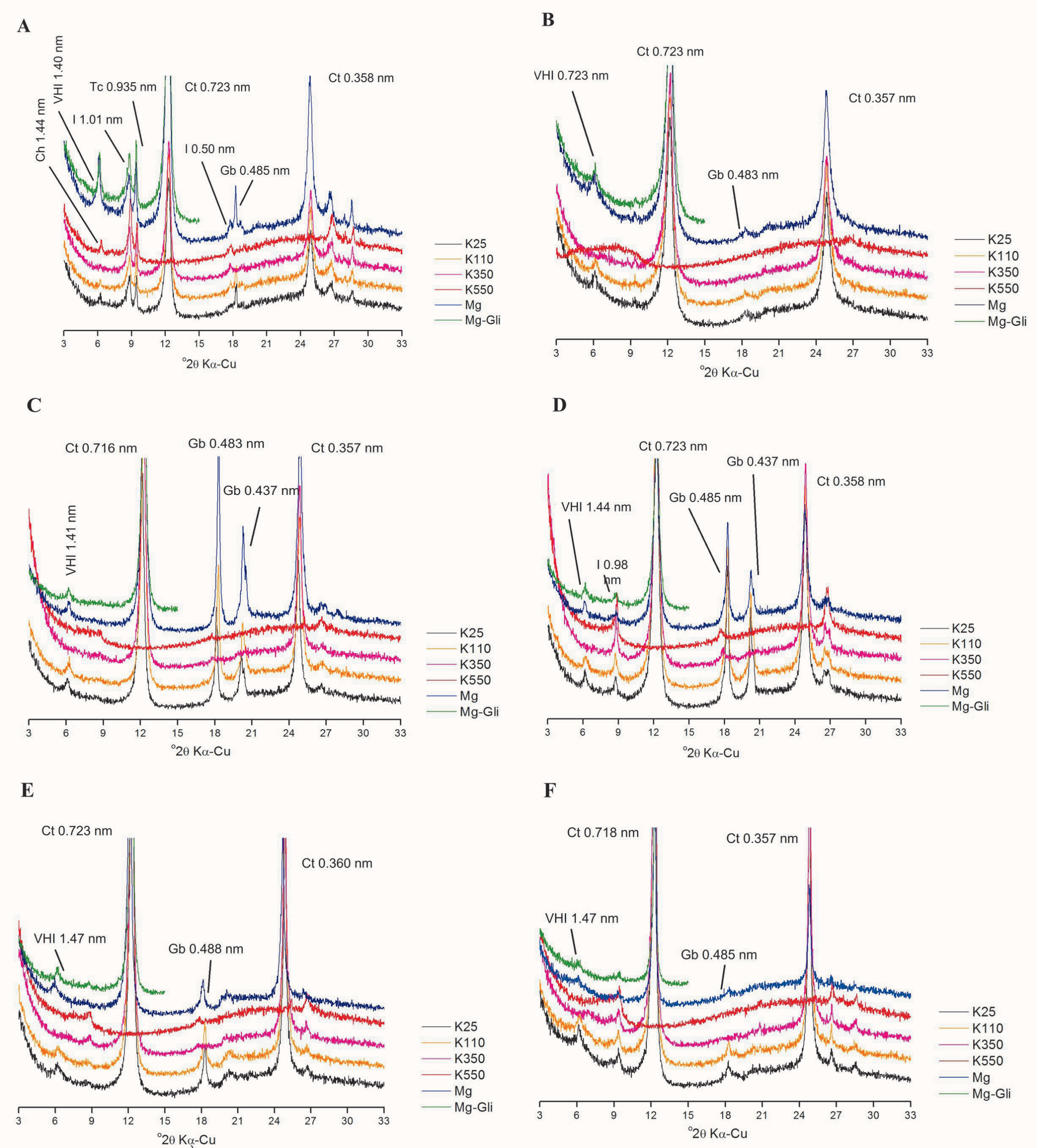

Figure 1. X-ray diffractograms from clay fraction of Brazilian Savanna soils. A) washed sand; B) Gleissolo Melânico distrófico (Typic Humaquept); C) Latossolo Vermelho ácrico (Rhodic Acrustox); D) Latossolo Vermelho distrófico (Rhodic Haplustox); E) Neossolo Quartzarênico órtico (Typic Quartzpsamment); F) Neossolo Flúvico Tb distrófico (Fluventic Dystrustept). Ct: caulinite; Gi: gibbsite; VHI: vermiculite hydroxy interlayer; I: ilite; Tc: talc. K25: sample saturation with KCl at 25 ºC; K110: sample saturation with KCl at 110 ºC; K350: sample saturation with KCl at 350 ºC; K550: sample saturation with KCl at 550 ºC; Mg: sample saturation with $MgCl_2$ at room temperature; Mg-Gli: sample saturation with $MgCl_2$ and solvation with glycerol at room temperature.

quantification. The dry mass data were transformed to percentage of *C. sativum* related to the control, without herbicide application.

Statistical analyses were performed and, when the F test was significant ($p = 0.05$), the soil types were compared by the Tukey test ($p = 0.05$) and the herbicide dose behavior described by regression analysis. The F test significance ($p < 0.05$), predicted and adjusted R^2 (higher than 0.8), and the residual plots independence (including the Durbin-Watson test to verify the correlation between adjacent residuals) were used to choose the model with the best fit. If more than one model matched these criteria, the model with the lowest number of parameters was chosen. Following these criteria, the data for control percentage (C%) and phytotoxicity (FT%) were adjusted to the Streibig (1988) model: $y = a + \{b/[1 + (x/C50)^c]\}$, where: y is the percentage of *C. sativum* dry mass reduction related to the control, without herbicide application; x the herbicide dose (g a.i. ha^{-1}); a the amplitude existing between the maximum and minimum point of the variable; b the slope of the curve near to b; C50 the dose-response referring to the control of 50 % of the bioindicator dry mass. This model was used to calculate the herbicide dose able to guarantee 50, 80 and 95 % of *C. sativum* control in each soil type. The values obtained for C50 in soils and washed sand were used to calculate the adsorption ratio (AR) of the herbicide in the soil, expressed by the formula: AR = (C50soil - C50 sand)/C50 sand.

Finally, Pearson's correlations were used to identify possible relationships between herbicide efficacy and soil texture and chemical attributes of Brazilian Savanna soils.

RESULTS AND DISCUSSION

The phytotoxicity (PT%) and the percentage of *C. sativum* control (C%) were affected by herbicide doses, soil type and the interaction between them (Table 3). In lower doses (¼, ⅓ and ½ of the recommended dose of 1,440 g a.i. ha^{-1}), there was a higher PT% and C% in the Rhodic Acrustox (Latossolo Vermelho ácrico - LVw) and washed sand, in relation to the others (Table 3); while the Typic Humaquept (Gleissolo Melânico distrófico - GMd) and Fluventic Dystrustept (Neossolo Flúvico Tb distrófico - RYbd) showed the lowest PT% and C% values up to the dose of 1,440 g a.i. ha^{-1}. When doses higher than that were applied, no differences were observed among the soil types; however, a lower FT% was observed for GMd, when compared to the others (Table 3).

The log logistic model (Streibig 1988) showed an adequate adjustment to PT% (Figure 2) and C% (Figure 3) data. The adjusted equations for each soil type were used to calculate the herbicide dose that guaranteed 50, 80 and 95 % of *C. sativum* control (C50%, C80% and C95%) (Table 4). These doses were greatly affected by the soil type; while, in LVw and Typic Quartzpsamment (Neossolo Quartzarênico órtico - RQo), the herbicide dose controlling at least 80 % was much lower than the recommended one, and, in GMd, the dose of 1,440 g a.i. ha^{-1} was not

Table 3. Phytotoxicity (PT%) and percentage of *C. sativum* control (C%) following oxyfluorfen application to Brazilian Savanna soils.

Soil type	Fraction of the recommended oxyfluorfen dose (1,440 g a.i. ha^{-1} = X)							
	0X	¼X	⅓X	½X	1X	2X	3X	4X
	Phytotoxicity percentage (FT%)							
WS	0.0	90.0 a	100.0 a	100.0 a	98.3 a	100.0 a	100.0 a	100.0 a
GMd	0.0	5.0 c	11.7 c	18.3 c	41.7 b	73.3 b	76.7 b	85.0 b
LVw	0.0	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a
LVd	0.0	25.0 c	21.7 c	65.0 b	98.3 a	96.7 a	91.7 a	95.0 a
RQo	0.0	58.3 b	66.7 b	66.7 b	96.7 a	100.0 a	98.3 a	100.0 a
RYbd	0.0	25.0 c	13.3 c	26.7 c	61.7 b	68.3 b	86.7 ab	88.3 ab
F value	F_{soil} = 84.3**	F_{dose} = 157.3**	$F_{interaction}$ = 7.9**					
	Control percentage (C%)							
WS	0.0	95.7 a	100.0 a	100.0 a	99.3 a	100.0 a	100.0 a	100.0 a
GMd	0.0	24.7 c	41.2 c	51.8 c	68.5 b	92.7 a	93.5 a	94.9 a
LVw	0.0	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a
LVd	0.0	0.0 d	8.5 d	74.6 b	95.0 a	94.0 a	90.2 a	89.5 a
RQo	0.0	58.5 b	70.9 b	81.4 b	98.2 a	100.0 a	98.9 a	100.0 a
RYbd	0.0	75.1 b	37.2 c	62.7 bc	78.9 b	83.4 a	94.1 a	94.3 a
F value	F_{soil} = 63.5**	F_{dose} = 271.1**	$F_{interaction}$ = 12.6**					

WS: washed sand; GMd: Gleissolo Melânico distrófico (Typic Humaquept); LVw: Latossolo Vermelho ácrico (Rhodic Acrustox); LVd: Latossolo Vermelho distrófico (Rhodic Haplustox); RQo: Neossolo Quartzarênico órtico (Typic Quartzpsamment); RYbd: Neossolo Flúvico Tb distrófico (Fluventic Dystrustept). Means with the same letter in the column do not differ among them by the Tukey test (p = 0.01). ** Significant at 1 % by the Tukey test.

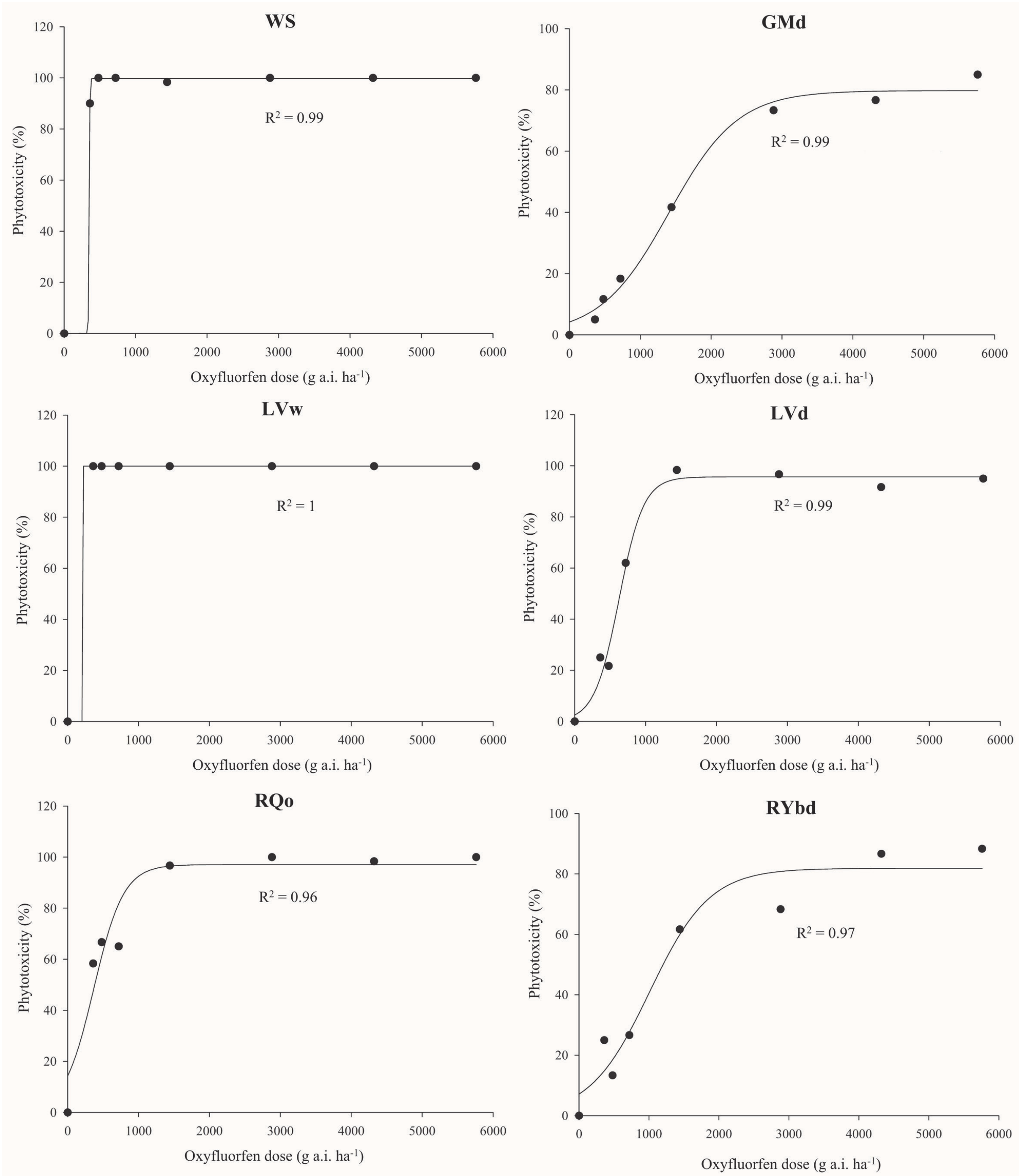

Figure 2. Phytotoxicity (%) of oxyfluorfen to *Cucumis sativum* following increasing herbicide doses application to Brazilian Savanna soils. WS: washed sand; GMd: Gleissolo Melânico distrófico (Typic Humaquept); LVw: Latossolo Vermelho ácrico (Rhodic Acrustox); LVd: Latossolo Vermelho distrófico (Rhodic Haplustox); RQo: Neossolo Quartzarênico órtico (Typic Quartzpsamment); RYbd: Neossolo Flúvico Tb distrófico (Fluventic Dystrustept).

enough to guarantee C80% (Figure 4; Table 4). In LVw, C95% was achieved using less than ¼ of the recommended rate.

The low FT% and C% values obtained for GMd and RYbd demonstrated that there is a lower herbicide availability in these soils. The herbicide effectiveness in the soil can be related to processes like sorption, degradation and leaching. Among them, sorption is a key process, since it will determine the number of herbicide molecules available in the solution, which

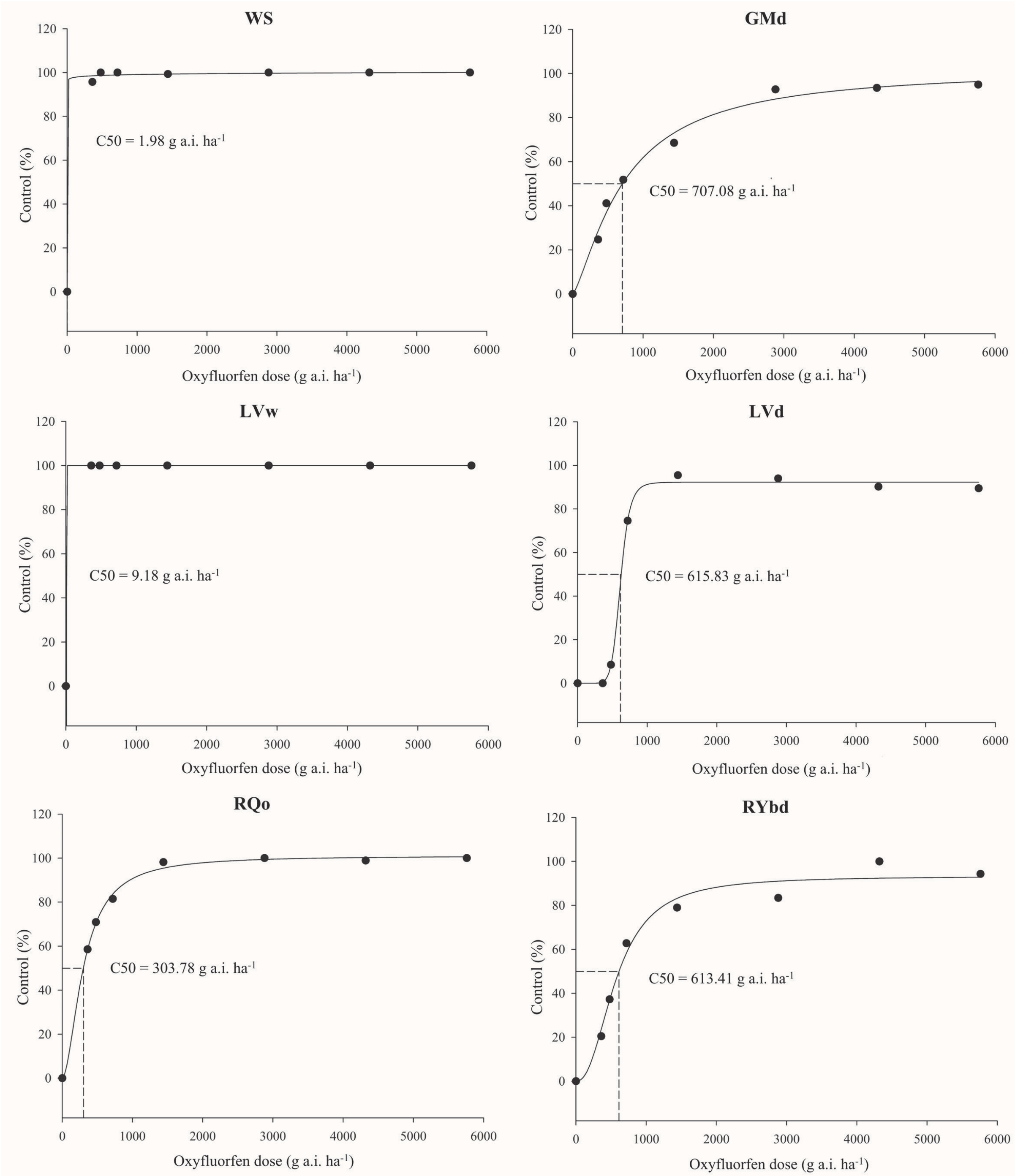

Figure 3. Control (C%) of *Cucumis sativum* following increasing herbicide doses application to Brazilian Savanna soils. WS: washed sand; GMd: Gleissolo Melânico distrófico (Typic Humaquept); LVw: Latossolo Vermelho ácrico (Rhodic Acrustox); LVd: Latossolo Vermelho distrófico (Rhodic Haplustox); RQo: Neossolo Quartzarênico órtico (Typic Quartzpsamment); RYbd: Neossolo Flúvico Tb distrófico (Fluventic Dystrustept).

may affect the other processes (Christofoletti et al. 2008). The oxyfluorfen adsorptive rate in each soil, related to washed sand, was higher in the GMd, with value of 356.11 (Table 4), while the LVw showed the lowest rate, favoring a higher herbicide bioavailability and, as a result, a higher bioindicator control in lower doses (Table 3; Figure 3). With the increase of the herbicide bioavailability in the soil, an increase in the herbicide effectiveness to control weeds is expected; however, an increase in

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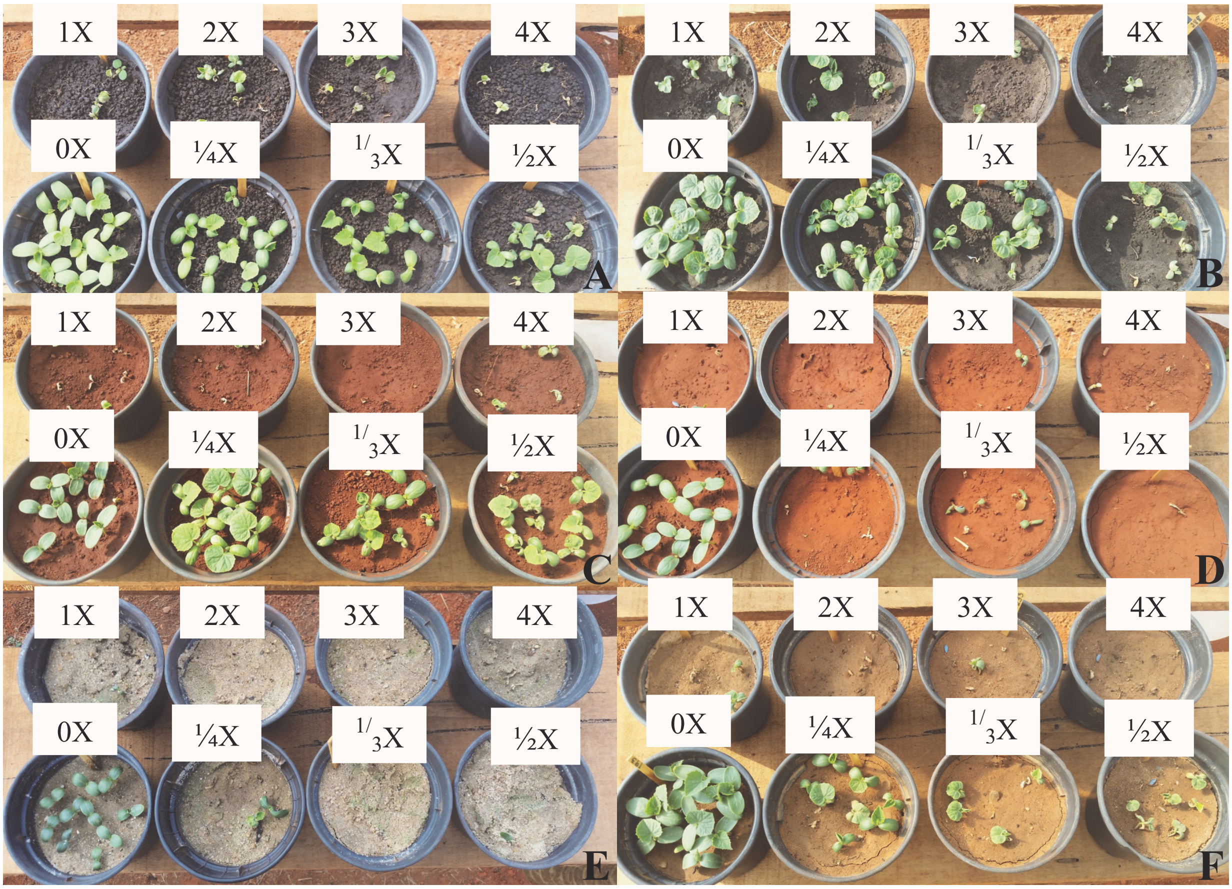

Figure 4. Phytotoxicity of oxyfluorfen to *Cucumis sativum* at 21 days after the herbicide application (0X = 0 g a.i. ha^{-1}; ¼X = 360 g a.i. ha^{-1}; ⅓X = 480 g a.i. ha^{-1}; ½X = 720 g a.i. ha^{-1}; 1X = 1,440 g a.i. ha^{-1}; 2X = 2,880 g a.i. ha^{-1}; 3X = 4,320 g a.i. ha^{-1}; 4X = 5,760 g a.i. ha^{-1}). A) Gleissolo Melânico distrófico (Typic Humaquept); B) Neossolo Flúvico Tb distrófico (Fluventic Dystrustept); C) Latossolo Vermelho distrófico (Rhodic Haplustox); D) Latossolo Vermelho ácrico (Rhodic Acrustox); E) Washed sand; F) Neossolo Quartzarênico órtico (Typic Quartzpsamment).

Table 4. Oxyfluorfen doses estimated by the log-logistic model (Streibig 1988), which provided *Cucumis sativum* control of 50 (C50), 80 (C80) and 95 % (C95), and adsorptive rate (AR).

Soils	C50	C80	C95	AR
		g a.i. ha^{-1}		
WS	1.98	-	-	-
GMd	707.08	1,885.41	4,903.97	356.11
LVw	9.18	9.88	10.30	3.64
LVd	615.83	754.28	> 5,760.00	310.03
RQo	303.78	632.68	1,380.05	152.42
RYbd	613.41	1,256.94	> 5,760.00	308.80

WS: washed sand; GMd: Gleissolo Melânico distrófico (Typic Humaquept); LVw: Latossolo Vermelho ácrico (Rhodic Acrustox); LVd: Latossolo Vermelho distrófico (Rhodic Haplustox); RQo: Neossolo Quartzarênico órtico (Typic Quartzpsamment); RYbd: Neossolo Flúvico Tb distrófico (Fluventic Dystrustept).

its phytotoxic effect on the crop of interest and other non-target organisms is also expected.

Oxyfluorfen is a nonionic herbicide; then, it has no charge in the soil. Its sorption coefficient standardized to organic carbon (Koc) and distribution coefficient octanol-water (Kow) are 6.831 and 4.73, respectively, indicating a low mobility of its molecules in the soil by leaching (Melo et al. 2010). Its colloid retention has been associated with high soil organic matter (OM) and clay content (Wauchope et al. 1992, WSSA 1994, Rodrigues & Almeida 2011). In fact, Devi et al. (2015) verified a lower leaching of oxyfluorfen in clayey soils with high OM (more than 2 %), when compared to sandy soils with low OM. The authors attributed these results to the high OM, particularly in the topsoil.

The higher OM capacity to bind pesticides, if compared to soil minerals, is related to its high superficial area and presence of many functional groups, such as carboxyls, hydroxyls and amine groups, and aliphatic and aromatic structures (Stearman et al. 1989, Kuckuk et al. 1997). In the present study, GMd and RYbd showed the highest OM content (Table 1) and the lowest oxyfluorfen efficacy to the bioindicator control (Table 3).

There was no correlation between C% and clay or OM content; however, a high negative correlation was observed between C% and CEC (Table 5), indicating some C% reduction with the increase of CEC. The soil retention of nonionic herbicides and apolar as oxyfluorfen is commonly associated with the OM content, and soils with a high OM showed a lower herbicide bioavailability. Generally, Brazilian Savanna soils do not have a high OM content and, then, the CEC may be the main soil attribute affecting the herbicide retention.

Ionizable herbicides usually are retained to the soil colloids with the opposite charge of the herbicide molecules. In this way, acid herbicides (herbicide molecules with negative or no charge) usually are retained by positive charges of the soil colloids (such as those charges found in oxides); while basic herbicides (herbicide molecules with positive or no charge) are retained by negative charges from the colloids (Christofoletti et al. 2008). Indeed, nonionic herbicides can also be retained by colloid charges by dipole-dipole interaction, if molecules are polar, or by induced dipole, if the herbicide molecules are apolar, being the herbicide retention increased in molecules with high molecular weight (Oepen et al. 1991), as oxyfluorfen. That can explain the strong correlation between %C and soil CEC.

By interpreting the obtained results, it is possible to verify the importance of considering the soil attributes to establish oxyfluorfen doses in each soil. Although soil attributes like organic matter and clay content have been used to predict some herbicide doses (Gundy & Dille 2022), they have no correlation with the bioavailability of some pre-emergent herbicides like sulfentrazone, ioxaflutole and diclosulan (Pacheco 2017, Arruda 2020), as

Table 5. Pearson's correlation between the *Cucumis sativum* percentage control (C%) and some soil attributes.

Parameter	CEC	OM	V	Clay content	pH
	$cmol_c\ dm^{-3}$	$g\ dm^{-3}$	%		$CaCl_2$
C%	- 0.82*	-0.73^{ns}	-0.06^{ns}	-0.03^{ns}	0.58^{ns}

CEC: cation exchange capacity at pH 7.0; OM: organic matter; V: base saturation. * Significant correlation ($p < 0.05$); ns non-significant.

demonstrated in the present study. The herbicide application according to edaphoclimatic conditions can increase the herbicide efficacy, providing benefits such as financial savings and lower potential of environmental impacts. However, the identification of soil attributes that have correlation with herbicide efficacy in different edaphoclimatic conditions is necessary, and, for oxyfluorfen, the soil CEC is the soil attribute showing the strongest correlation with herbicide efficacy.

CONCLUSIONS

1. The oxyfluorfen bioavailability and efficacy are affected by soil attributes;
2. In highly weathered Brazilian Savanna soils, the oxyfluorfen bioavailability is high, indicating that lower doses of oxyfluorfen can be applied;
3. In Brazilian Savanna soils, the clay content has no correlation with the oxyfluorfen efficacy; then, this parameter should not be used to predict herbicide doses;
4. The cation exchange capacity has a high correlation with oxyfluorfen efficacy in Brazilian Savanna soils, being the best soil attribute to predict herbicide doses for each soil.

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