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Scientific Article

SELECTIVITY OF HERBICIDES FOR SEEDLINGS OF TREE SPECIES

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ABSTRACT

The scarce knowledge about the behavior of seedlings of native forest species relative to sensitivity to herbicides associated with the current strategies for restoring degraded natural ecosystems justifies the execution of studies to assist in this management. This study aimed to evaluate the initial selectivity of two herbicides at three different doses for 80 species that occur in seasonal semideciduous forests and are widely used in restoration projects. Two experiments were conducted to evaluate the herbicides oxyfluorfen (Experiment I) and sulfentrazone (Experiment II) at commercial dose, half the dose, and double the dose, as well as control without herbicide application. The experimental design of each experiment was completely randomized, with four replications. The percentage of phytotoxicity following a specific scale in the weed science field was evaluated at 7, 14, 21, 28, and 35 days after treatment application (DAT), while the shoot dry mass was evaluated at 35 DAT. Most native species were classified in the range of 0–10% phytotoxicity for both herbicides. Considering phytotoxicity, the herbicide oxyfluorfen negatively affected the species *Inga uruguensis*, *Erythroxylum argentinum*, *Pterogyne nitens*, *Miconia rigidiuscula*, and *Simira sampaioana*. Sulfentrazone showed harmful effects on the species *Myrciaria vexator*, *Piptadenia gonoacantha*, *Lonchocarpus campestris*, *Erythroxylum argentinum*, *Cariniana legalis*, *Randia armata*, *Inga vera*, *Solanum granulosoleprosum*, *Cupania vernalis*, *Seguieria langsdorffii*, *S. sampaioana*, *Maytenus gonoclada*, and *Handroanthus ochraceus*. Only the species *R. armata*, *Croton floribundus*, and *I. uruguensis* showed a reduction in dry biomass relative to the control. Therefore, the herbicides oxyfluorfen and sulfentrazone can be recommended for weed management for most of the species studied in this study, except those listed above.

Keywords: Sulfentrazone; Oxyfluorfen; Phytotoxicity; Forest management; Reforestation

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SELETIVIDADE DE HERBICIDAS PARA MUDAS DE ESPÉCIES ARBÓREAS

RESUMO – Diante das estratégias para restauração de ecossistemas naturais degradados e considerando o conhecimento escasso sobre o comportamento de mudas de espécies florestais nativas em relação à sensibilidade a herbicidas, tornam-se necessários estudos que auxiliem neste manejo. O objetivo deste trabalho foi avaliar a seletividade inicial de dois herbicidas em três doses distintas para 80 espécies que ocorrem em florestas estacionais semideciduais, as quais são amplamente utilizadas em projetos de restauração. Foram realizados dois experimentos, sendo avaliados herbicidas oxyfluorfen (experimento I) e sulfentrazone (experimento II) nas doses comercial, metade e dobro da dose, além de testemunha sem aplicação de herbicidas. O delineamento experimental, para cada experimento, foi inteiramente casualizado, com quatro repetições. A porcentagem de fitotoxicidade seguindo escala específica da área da ciência das plantas daninhas foi avaliada aos 7, 14, 21, 28 e 35 dias após a aplicação dos tratamentos (DAT) e a massa da matéria seca da parte aérea aos 35 DAT. De acordo com os resultados, a maioria das espécies nativas avaliadas foi classificada na faixa de 0 – 10% de fitotoxicidade para ambos os herbicidas. Considerando a fitotoxicidade, o herbicida oxyfluorfen afetou negativamente as espécies *Inga uruguensis*, *Erythroxylum argentinum*, *Pterogyne nitens*, *Miconia rigidiuscula* e *Simira sampaioana*. O sulfentrazone interferiu de forma prejudicial as espécies *Myrciaria vexator*, *Piptadenia gonocantha*, *Lonchocarpus campestres*, *Erythroxylum argentinum*, *Cariniana legalis*, *Randia armata*, *Inga vera*, *Solanum granulosoleprosum*, *Cupania vernalis*, *Seguieria langsdorffii*, *S. sampaioana*, *Maytenus gonoclada* e *Handroanthus ochraceus*. Considerando a redução de biomassa seca, somente as espécies *R. armata*, *Croton floribundus* e *I. uruguensis* apresentaram redução de biomassa seca em relação a testemunha. Portanto, conclui-se que os herbicidas oxyfluorfen e sulfentrazone podem ser recomendados para o manejo de plantas daninhas para a maioria das espécies estudadas nesse trabalho, exceto as listadas acima.

Palavras-Chave: Sulfentrazone; Oxyfluorfen; Fitotoxicidade; Manejo florestal; Reflorestamento.

1. INTRODUCTION

The conservation and recovery of degraded areas over the years has been an important demand worldwide. The recovery of these areas contributes to the conservation of biodiversity, the promotion of sustainability, the maintenance of air, soil, and water quality, and the mitigation of climate change (Simões et al., 2022).

Therefore, mechanisms that accelerate the recovery process of degraded areas are necessary (Oliveira et al., 2019). There are different methods applied to the recovery of these areas, among which the following stand out: natural regeneration, high-density planting, use of legumes, mixed planting, direct sowing, and seedling planting. Seedling planting has been the most used currently, being indicated mainly for areas where the native vegetation is partially or totally degraded and the surrounding vegetation is very compromised or non-existent, that is, areas where natural regeneration and nucleation, which provide results closer to the original ecosystem, are unfeasible (Rodrigues et al., 2020).

The difficulty in managing weeds in all these techniques has been considered one of the main obstacles to the success of vegetation recovery projects in degraded areas (Marchi et al., 2018). In this sense, one of the factors that reduces plant growth is the interference of weeds. In addition to reducing seedling growth, several weed species can cause ecological imbalance by colonizing remaining areas of native vegetation and hindering natural regeneration (Brancalion et al., 2009; Hooper et al., 2005), which causes environmental degradation and threatens biodiversity conservation (Nepstad et al., 1990; D'Antonio & Meyerson, 2002). Thus, these plants interfere with the integrity of the ecosystem and the survival of native species (Ogden and Rejmánek, 2005; Regan et al., 2006).

Actions to control weed species, such as mechanical, cultural, and chemical control (Machado et al., 2012), although desirable, must be cautious, considering that they can benefit some species and harm others (Duncan and Chapman, 2003; Simmons et al., 2007) and damage non-target organisms (Howe et al., 2004; Cauble and Wagner, 2005). Therefore, the control of weed species can be complicated and must be performed with discretion as it causes changes in the abiotic and biotic parameters that interact with the germination, growth, and survival of native plants (Zimmerman et al., 2000; Campanello et al., 2007).

Chemical control is considered an efficient alternative, as certain herbicides can control multiple weed species, offering both speed and cost-effectiveness. Herbicides with known selective action for some crops have been empirically used aiming to improve weed control methods in forest reforestation (Doust et al., 2006). Importantly, studies about the damage resulting from the application of these herbicides are still scarce for native species.

The use of herbicides has gradually increased in environmental restoration areas, with glyphosate being the most used despite its lack of selectivity. Alternative herbicides that eventually present different selectivity over native species are necessary and, therefore, should be the target of studies (Ngoze et al., 2008; Dawson et al., 2009).

Herbicides with different mechanisms of action and the definition of adequate doses must be evaluated in native species to improve the management of restoration areas. This type of assessment is still limited due to the high richness of species that occur in seasonal semideciduous forests, associated with the variation in the chemical properties of herbicides.

In this context, this study aimed to evaluate the phytotoxicity caused by the herbicides oxyfluorfen and sulfentrazone applied at different doses on the initial development of 80 tree species used in restoration projects.

2. MATERIAL AND METHODS

The research was carried out in a greenhouse at the Agricultural Sciences Center (CCA) of the Federal University of São Carlos (UFSCar), campus of Araras-SP, Brazil. Two experiments were conducted. Experiment I aimed to evaluate the effect of the herbicide oxyfluorfen and Experiment II the herbicide sulfentrazone, both in a completely randomized experimental design, with four replications. The experimental units consisted of a pot with a seedling of each tree species. The mean height of the species at the time of herbicide application ranged from 30 to 70 cm, depending on the species.

Table 1 shows the seedlings of the studied tree species. The species were grown in pots with a volumetric capacity of 5 L filled with a commercial substrate (biostabilized Pinus bark) and kept in a greenhouse with automated irrigation. The seedlings were acquired from the company BioFlora, with the participation of the Company Granus, responsible for

Table 1. Native species used in the experiment, with their respective scientific and common names.

Tabela 1. Espécies nativas utilizadas no experimento, com seus respectivos nomes científicos e nomes comuns

No.	Common name	Scientific name	Family
1	Flor de sino	*Abutilon rufinerve* A. St.-Hil.	Malvaceae
2	Fruta de sabia	*Acnistus arborescens* (L.) Schltdl.	Solanaceae
3	Chau chau	*Allophylus edulis* (A.St.-Hil. et al.) Hieron. ex Niederl.	Sapindaceae
4	Guaritá	*Astronium graveolens* Jacq.	Anacardiaceae
5	Farinha-seca	*Balfourodendron riedelianum* (Engl.) Engl.	Rutaceae
6	Pata-de-vaca	*Bauhinia variegeta* L.	Fabaceae
7	Murici	*Byrsonima laxiflora* Griseb.	Malpighiaceae
8	Canjarana	*Cabralea canjerana* (Vell.) Mart.	Meliaceae

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No.	Common name	Scientific name	Family
9	Guanxuma	*Callianthe rufinerva* A.St.-Hil.	Malvaceae
10	Jequitibá-branco	*Cariniana estrellensis* (Raddi) Kuntze	Lecythidaceae
11	Jequitibá-rosa	*Cariniana legalis* (Mart.) Kuntze	Lecythidaceae
12	Laranjinha	*Casearie gossypiospermo* Briq.	Salicaceae
13	Cedro-rosa	*Cedrela fissilis* Vell.	Meliaceae
14	Paineira-rosa	*Ceiba speciosa* (A.St.-Hil.) Ravenna	Malvaceae
15	Sobrasil	*Colubrina glandulosa* Perk.	Rhamnaceae
16	Babosa-branca	*Cordia superba* Cham.	Boraginaceae
17	Louro-pardo	*Cordia trichotoma* (Vell.) Arráb. ex Steud.	Boraginaceae
18	Capixingui	*Croton floribundus* Spreng.	Euphorbiaceae
19	Sangra-d´água	*Croton urucurana* Baill.	Euphorbiaceae
20	Camboatá	*Cupania vernalis* Cambess.	Sapindaceae
21	Canafístula	*Dalbergia brasiliensis* Vogel	Fabaceae
22	Guarantá	*Esenbeckia leiocarpa* Engl.	Rutaceae
23	Cocão	*Erythroxylum argentinum* O.E.Schulz	Erythroxylaceae
24	Grumixama	*Eugenia brasiliensis* Lam.	Myrtaceae
25	Uvaia	*Eugenia piryformis* Cambess.	Myrtaceae
26	Pitanga	*Eugenia uniflora* L.	Myrtaceae
27	Gameleira	*Ficus obtusifolia* Kunth	Moraceae
28	Pau dálho	*Gallesia integrifolia* (Spreng.) Harms	Phytolaccaceae
29	Maria mole	*Guapira opposita* (Vell.) Reitz	Nyctaginaceae
30	Marinheiro	*Guarea guidonia* (L.) Sleumer	Meliaceae
31	Canjambo	*Guarea Kunthiana* (A.) Juss	Meliaceae
32	Mutambo	*Guazuma ulmifolia* Lam.	Malvaceae
33	Ipê-amarelo-cascudo	*Handroanthus chrysotrichus* (Mart. ex DC.) Mattos	Bignoniaceae
34	Ipê-amarelo	*Handroanthus ochraceus* (Cham.) Mattos	Bignoniaceae
35	Algodoeiro	*Heliocarpus popayanensis* Kunth	Malvaceae
36	Ingá-de-metro	*Inga sessilis* (Vell.) Mart.	Fabaceae
37	Ingá-mirim	*Inga laurina* (Sw.) Willd.	Fabaceae
38	Ingá do rio	*Inga uruguensis* Hook. & Arn.	Fabaceae
39	Ingá-do-brejo	*Inga vera* subsp. *affinis* (DC.) T.D.Penn.	Fabaceae
40	Dedaleiro	*Lafoensia pacari* A. St.-Hil.	Lythraceae
41	Embira-de-sapo	*Lonchocarpus campestris* Mart. ex Benth.	Fabaceae
42	Açoita-cavalo	*Luehea divaricata* Mart. & Zucc.	Malvaceae
43	Sabugueiro	*Maytenus gonoclada* Mart.	Celastraceae
44	Pixirica	*Miconia chamissois* Naudin	Melastomataceae
45	Quaresmeira	*Miconia pussilliflora* (DC.) Naudin	Melastomataceae
46	Cabreúva	*Miconia rigidiuscula* (DC.) Naudin	Melastomataceae

Cont...

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No.	Common name	Scientific name	Family
47	Erva de sto antonio	*Mollinedia uleana* Perkins	Monimiaceae
48	Embira de sapo	*Muellera campestris* (Mart. ex Benth.)	Fabaceae
49	Aroeira-preta	*Myracrodruon urundeuva* Allemão	Anacardiaceae
50	Goiaba-brava	*Myrcia ilheosensis* Kiaersk.	Myrtaceae
51	Jaboticaba azul	*Myrciaria vexator* McVaugh	Myrtaceae
52	Brauna	*Myrocarpus frondosus* Allemão	Fabaceae
53	Capororoca-vermelha	*Myrsine coriacea* (Sw.) R.Br.	Primulaceae
54	Canela	*Ocotea puberula* (Rich.) Nees	Lauraceae
55	Abacateiro do mato	*Ocotea silvestres* Vattimo-Gil	Lauraceae
56	Guarucaia	*Parapiptadenia rigida* (Benth.) Brenan	Fabaceae
57	Abacateiro do mato	*Persea willdenovii* Kosterm.	Lauraceae
58	Pau-jacaré	*Piptadenia gonoacantha* (Mart.) J.F. Macbr.	Fabaceae
59	Baga de macaco	*Posoqueria acutifolia* Mart.	Rubiacea
60	Pessegueiro bravo	*Prunus myrtifolia* (L.) Urb.	Rosaceae
61	Araçá-amarelo	*Psidium cattleianum* Sabine	Myrtaceae
62	Amendoim-bravo	*Pterogyne nitens* Tul.	Fabaceae
63	Limão bravo	*Randia armata* (Sw.) DC.	Rubiaceae
64	Aroeira-pimenteira	*Schinus terebinthifolius* Raddi	Anacardiaceae
65	Laranjeira brava	*Seguieria langsdorfii* Moqui	Phytolaccaceae
66	Fedegoso	*Senna silvestres* (Vell.) H.S.Irwin & Barneby	Fabaceae
67	Pau-cigarra	*Senna multijuga* (Rich.) H. S.Irwin & Barneby	Fabaceae
68	Arariba	*Simira sampaioana* (Standl.)	Rubiaceae
69	Joá	*Solanum granulosoleprosum* Dunal	Solanaceae
70	Esporão de galo	*Strychnos brasiliensis* (Spreng.) Mart.,	Loganiaceae
71	Ipê-branco-do-brejo	*Tabebuia insignis* (Miq.) Sandwith	Bignoniaceae
72	Ipê-branco	*Tabebuia roseoalba* (Ridl.) Sandwith	Bignoniaceae
73	Fruto de sabia	*Tachigali denudata* (Vogel) Oliveira-Filho	Fabaceae
74	Amarelinho	*Terminalia brasiliensis* (Cambess.) Eichl.	Combretaceae
75	Canemaçu	*Tetrorchidium rubrivenium* Poepp. & Endl.	Euphorbiaceae
76	Araça	*Psidium cattleyanum* Sabine	Myrtaceae
77	Acacia amarela	*Peltophorum dubium* (Spreng.) Taub.	Fabaceae
78	Aroeira branca	*Lithraea molleoide* (Vell.) Engl.	Anacardiaceae
79	Lapacho	*Poecilanthe parviflora* Benth.	Fabaceae
80	Arco de peneira	*Trichillia pallens* C.DC.	Meliaceae

Source: The authors.
Fonte: Autores.

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ecological restoration activities.

Oxyfluorfen doses of 420, 840 (commercial dose), and 1680 g ai ha^{-1} were applied in Experiment I, and sulfentrazone doses of 500, 1,000, and 2,000 g ai ha^{-1} were applied in Experiment 2, in addition to the controls without herbicide in both experiments. The doses were defined according to the technical recommendations for each herbicide, using half the commercial dose, the commercial dose, and double the commercial dose to determine the sensitivity of the species to herbicides. The herbicides were applied with a CO_2^-pressurized knapsack sprayer at a constant pressure of 245.16 kPa using an application boom equipped with fan spray tips 110.03. The spray solution volume was 200 L ha^{-1}. The relative humidity during application was 79.8% and the ambient temperature was 26.3 °C. The herbicide application was performed outside the greenhouse, and the plants were placed back in the greenhouse 24 hours after application, with the substrate maintained at adequate moisture through irrigation. Herbicide phytotoxicity was evaluated at 7, 14, 21, 28, and 35 days after treatment application (DAT), using a percentage scale of phytotoxicity scores, where zero corresponds to no injury and 100% to plant death, according to Table 2.

Table 2. Scale of phytotoxicity scores caused by herbicides on plants

Tabela 2. Escala de Fitotoxicidade provocada por herbicidas em plantas

Percentage of phytotoxicity (%)	Symptom description
0–10	Absence of symptoms (score 0) or symptoms that are not very evident
11–20	Chlorosis with mild deformities and slight reduction in growth
21–40	Intense chlorosis with necrosis, but it is recoverable. Reduction in plant growth/size
41–60	Intense chlorosis with necrosis, more pronounced deformations. Reduction in plant growth/size
61–80	Intense necrosis and marked deformations. Doubtful recovery. Stand reduction
81–100	Intense necrosis and marked deformations. Stand reduction. Score 100 for plant death

Source: ALAM (1974).
Fonte: ALAM (1974).

After the evaluation carried out at 35 DAT, the entire shoot of the tree species was cut close to the ground and the dry biomass was determined after drying in a forced-air circulation oven at a constant temperature (70 °C) for 72 hours.

The data were subjected to analysis of variance (ANOVA) and, when significant, the qualitative measures were compared using the Tukey test at a 5% probability, and regression equations were adjusted for the 35 DAT assessments for the quantitative measures.

3. RESULTS

3.1 Oxyfluorfen

The results of phytotoxicity at 35 DAT caused by the herbicide oxyfluorfen on tree species were classified according to the number of species in different phytotoxicity ranges and the plants that received herbicides were compared with the respective controls (absence of herbicide use) (Figure 1).

The herbicide oxyfluorfen caused phytointoxication in some species, with no

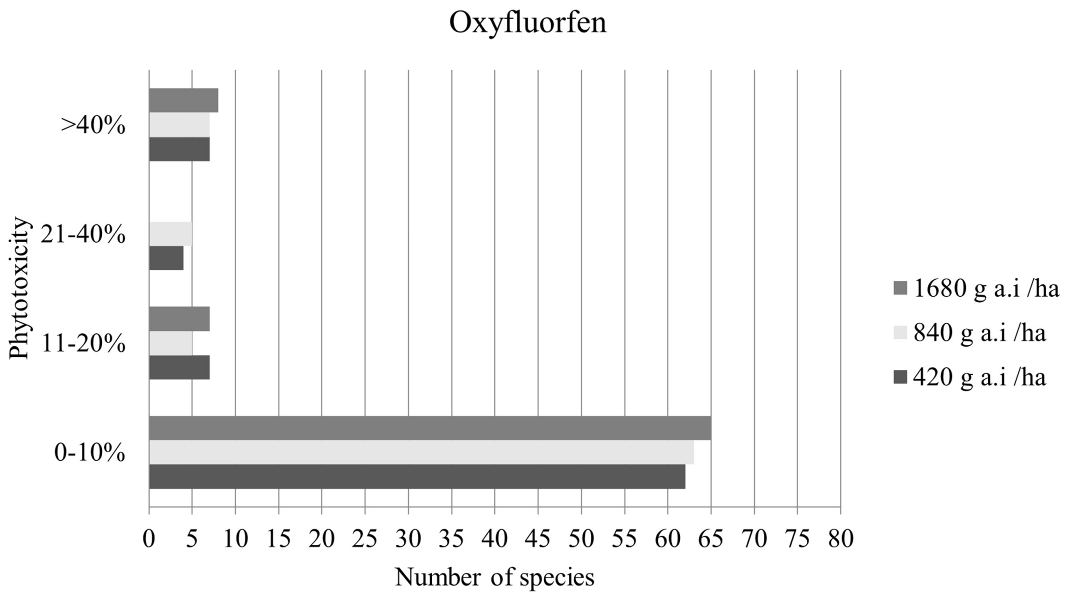

Figure 1. Phytotoxicity ranges of the herbicide oxyfluorfen in different tree species

Figura 1. Intervalos de fitotoxicidade do herbicida oxyfluorfen em diferentes especies de árvores.

significant interaction between doses and evaluation times (data not shown). Sixty-two species showed 0–10% phytotoxicity at the dose of 420 g ai ha^{-1} according to the scale presented previously, and 29 species among them had zero phytotoxicity: *Poecilanthe parviflora*, *Ficus obtusifolia*, *Myrocarpus frondosus*, *Tabebuia roseoalba*, *Myracrodruon urundeuva*, *Handroanthus chrysotrichus*, *Croton urucurana*, *Cedrela fissilis*, *Parapiptadenia rigida*, *Mollinedia uleana*, *Eugenia pyriformis*, *Bauhinia variegata*, *Heliocarpus popayanensis*, *Eugenia brasiliensis*, *Cabralea canjerana*, *Cordia superba*, *Cordia trichotoma*, *Ocotea silvestris*, *Prunus myrtifolia*, *Terminalia brasiliensis*, *Myrciaria vexator*, *Piptadenia gonoacantha*, *Randia armata*, *H. ochraceus*, *Myrcia ilheosensis*, *Guarea guidonia*, *Seguieria langsdorffii*, *Cariniana legalis*, and *M. gonoclada*.

Sixty-three species presented phytointoxication in the range of 0−10% when using the recommended dose (840 g ai ha^{-1}), that is, an absence of phytointoxication or low-intensity and little evident symptoms. Importantly, the species *P. parviflora*, *F. obtusifolia*, *M. frondosus*, *T. roseoalba*, *M. urundeuva*, *H. chrysotrichus*, *C. urucurana*, *C. fissilis*, *P. rigida*, *M. uleana*, *E. pyriformis*, *B. variegata*, *H. popayanensis*, *E. brasiliensis*, *C. canjerana*, *C. superba*, *C. trichotoma*, *O. silvestris*, *P. myrtifolia*, *T. brasiliensis*, *M. vexator*, *P. gonoacantha*, *R. armata*, *H. ochraceus*, M. ilheosensis, *G. guidonia*, *S. langsdorffii*, *C. legalis*, *M. gonoclada*, *Tetrorchidium rubrivenium*, *Inga sessilis*, *Senna multijuga*, and *Schinus terebinthifolius* presented no phytotoxicity. The species that showed 40% phytotoxicity at 35 DAT for this dose were the same as those mentioned at half the commercial dose but with no significant differences between treatments and evaluation times.

Doubling the dose (1680 g ai ha^{-1}) resulted in phytotoxicity between 11 and 20% for the species *Peltophorum dubium*, *Psidium cattleyanum*, *C. estrellensis*, *Astronium graveolens*, *Casearie gossypiosperma*, *Guapira opposita*, and *Lafoensia pacari*. The species *Colubrina glandulosa*, *Guazuma ulmifolia*, *I. vera*, *Cupania vernalis*, *Esenbeckia leiocarpa*, *Persea willdenovii*, and *Solanum granulosoleprosum* presented a 45% phytointoxication. The remaining species showed 0–10% phytotoxicity in all assessments. The species *C. glandulosa*, *G. ulmifolia*, *I. vera*, *P. willdenovii*, *S. granulosoleprosum*, *C. vernalis*, and *E. leiocarpa* presented a phytointoxication of approximately 40% at 35 DAT, regardless of the dose.

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A significant interaction was observed between doses and evaluation times for the species *Inga uruguensis*, *Erythroxylum argentinum*, *Pterogyne nitens*, *Miconia rigidiuscula*, and *Simira sampaioana*.

I. ucra was sensitive to the herbicide oxyfluorfen, with phytotoxicity evolving throughout the evaluations. The application of half the recommended dose resulted in phytotoxicity of 35% at 35 DAT (Figure 2A), with leaf fall observed. The recommended dose caused 52% of phytotoxicity, while twice the dose caused 62% phytotoxicity, compromising seedling establishment. *E. argentinum* showed an increase in phytotoxicity with increasing dose, with a value of 5.8% at 35 DAT at the commercial dose. However, phytotoxicity reached around 34% at the end of this same period when it was subjected to double the dose. Phytotoxicity was reduced throughout the evaluations, with the highest values observed at 14 DAT (Figure 2B).

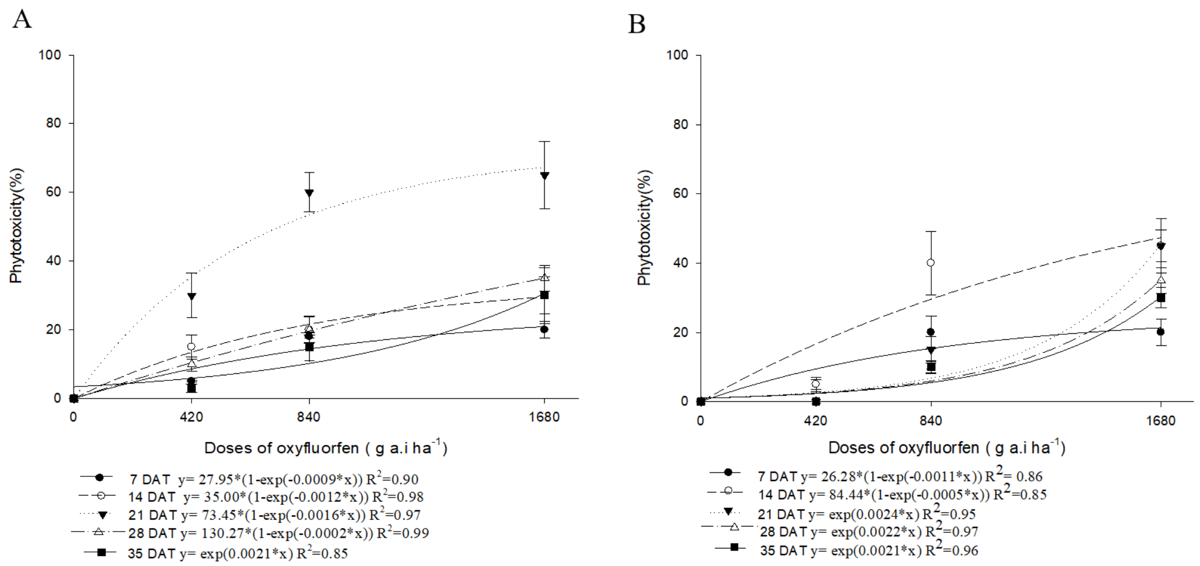

Figure 2. Phytotoxicity of the herbicide oxyfluorfen at different doses on the species *I. uruguensis* (A) and *E. argentinum* (B), evaluated at 7, 14, 21, 28, and 35 DAT

Figura 2. Fitotoxicidade do herbicida oxyfluorfen em diferentes doses sobre as especies *I. uruguensis* (A) e *E. argentinum* (B), avaliadas aos 7, 14, 21, 28 e 35 DAT

P. nitens showed higher phytointoxication relative to the doses used in the evaluation conducted at 21 DAT, showing subsequent recovery at 35 DAT, with less than 40% phytointoxication at the commercial dose (Figure 3A).

Unlike previous species, *M. rigidiuscula* showed an increase in phytotoxicity over time. The commercial dose caused 71.3% phytotoxicity in the final evaluation (35 DAT), with necrotic and twisted leaves, while phytotoxicity reached 76.2% at double the dose (Figure 3B).

S. sampaioana showed similar behavior to *M. rigidiuscula*, with phytotoxicity above 71.7% from the recommended dose at 35 DAT, with an evolution of symptoms throughout the evaluations and with an increase at the herbicide dose, culminating in 79.1% with double the dose at 35 DAT (Figure 3C).

3.2 Sulfentrazone

Figure 4 shows data on the percentage of phytotoxicity of the herbicide sulfentrazone in native tree species, which were classified into the classes 0–10%, 11–20%, 21–40%, and >40% at 35 DAT. Table 2 shows the description of symptoms for each of these ranges.

Sixty-one species showed phytotoxicity

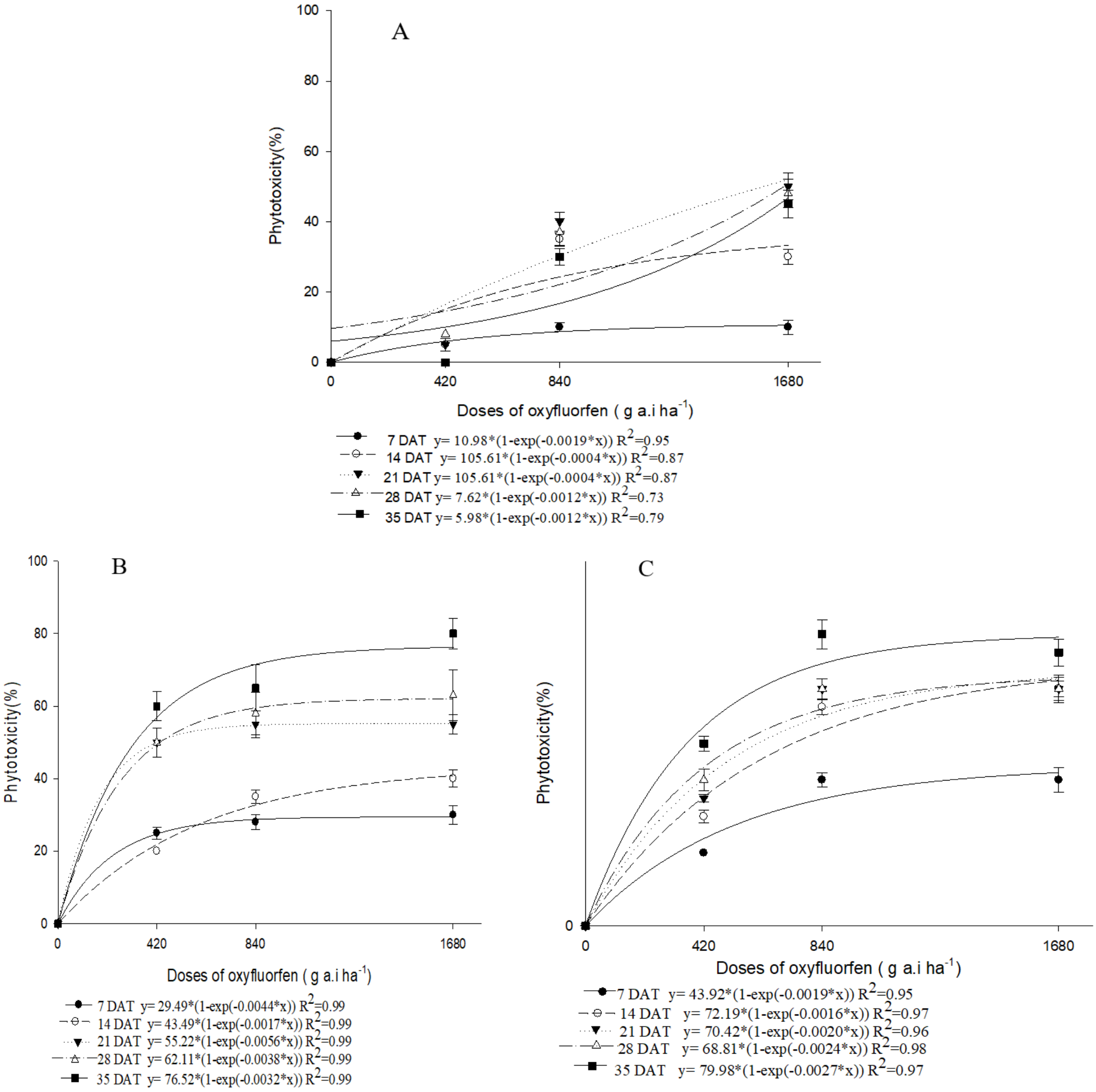

Figure 3. Phytotoxicity of the herbicide oxyfluorfen at different doses on the species *P. nitens* (A), *M. rigidiuscula* (B), and *S. sampaioana* (C), evaluated at 7, 14, 21, 28, and 35 DAT

Figura 3. Fitotoxicidade do herbicida oxyfluorfen em diferentes doses sobre as especies *P. nitens* (A), *M. rigidiuscula* (B) e *S. sampaiona* (C), avaliadas aos 7, 14, 21, 28 e 35 DAT

in the range of 0–10% when considering the application of half the dose of the herbicide sulfentrazone (500 g ai ha^{-1}), that is, no symptoms or very mild symptoms. In this sense, the following species showed no phytotoxicity (score 0): *Lithraea molleoide*s, *P. cattleyanum*, *P. parviflora*, *M. frondosus*, *M. rigidiuscula*, *M. urundeuva*, *Byrsonima laxiflora*, *A. graveolens*, *Balfourodendron riedelianum*, *C. urucurana*, *T. rubrivenium*, *M. uleana*, *E. pyriformis*, *B. variegata*, *M. gonoclada*, *C. canjerana*, *C. superba*, *C. trichotoma*, *O. silvestris*, *P. myrtifolia*, *I. sessilis*, *S. multijuga*, *M. rigidiuscula*, *C. estrellensis*, *E. leiocarpa*, *P. nitens*, and *Abutilon rufinerve*.

No phytotoxicity was observed in the evaluations conducted in 45 and 46 species relative to the recommended dose and twice the dose, respectively (Figure 4). Only 11 species were included in the phytotoxicity range >40%, which means severe symptoms with chlorosis and necrosis of the shoot: *C. glandulosa*, *L. pacari*, *G. ulmifolia*, *I. vera*, *P. willdenovii*, *S. granulosoleprosum*, *C. vernalis*, *G. guidonia*, *S. langsdorffii*, *P. gonoacantha*,

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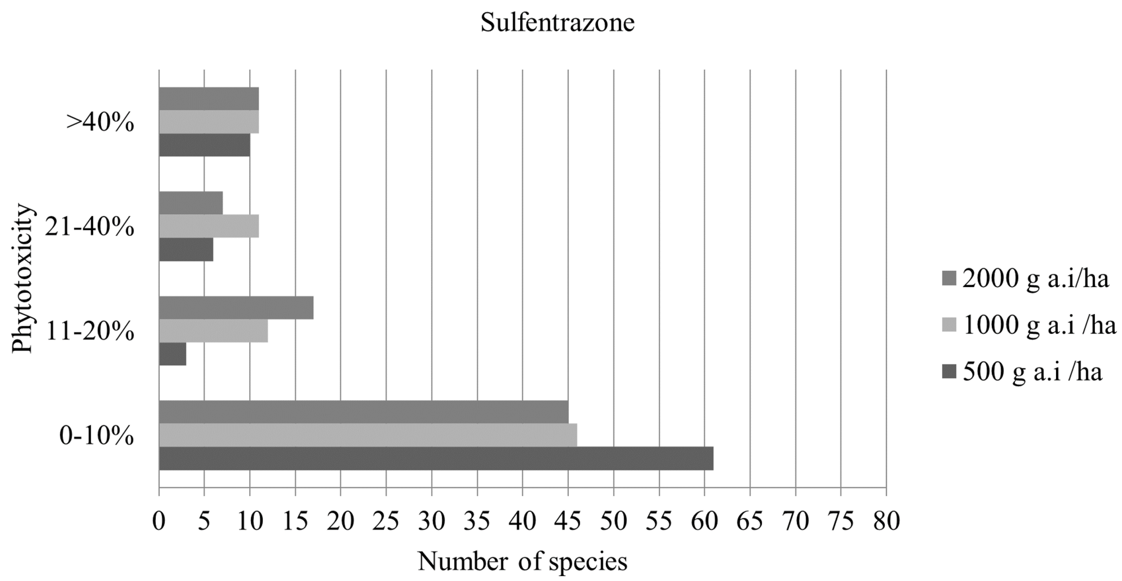

Figure 4. Ranges of phytotoxicity caused by sulfentrazone in tree species

Figura 4. Intervalos de fitotoxicidade do herbicida sulfentrazone em diferentes especies de árvores

and *Lonchocarpus campestris*.

Statistical differences relative to doses and evaluation times were detected in a few species, with a significant interaction between doses and evaluation times being verified for *M. vexator*, *L. campestris*, *E. argentinum*, *C. legalis*, *R. armata*, *I. vera*, *S. granulosoleprosum*, *C. vernalis*, *S. langsdorffii*, *M. gonoclada*, *P. gonoacantha*, and *H. ochraceus* (Figures 5 to 9).

The phytotoxicity of sulfentrazone to *M. vexator* was proportional to the increase in dose and evaluation times. The commercial dose caused 51.2% phytotoxicity and twice the dose 75.2% phytotoxicity at 35 DAT, with necrosis and deformation of leaves (Figure 5A).

P. gonoacantha was sensitive to sulfentrazone. Initially (7 DAT), phytotoxicity varied from 25.4 to 47.4% at the lowest and highest doses, respectively. Furthermore, symptoms progressed until 28 DAT, with a slight recovery at 35 DAT. However, phytotoxicity was 46.7% at the commercial dose, which could make the use of this herbicide unviable in areas with this species. The phytotoxicity caused by the herbicide reached 78.0% with twice the dose (Figure 5B).

Sulfentrazone caused significant phytotoxicity in the species *L. campestris*. There was an increase in phytotoxicity in the species throughout the evaluations. Plant phytotoxicity at 35 DAT was 74.4% at the commercial dose and 85.5% at double this dose. Symptoms included generalized chlorosis and necrotic leaves (Figure 5C). Therefore, the results show that the herbicide behaved non-selectively to the species and is not recommended.

The species *E. argentinum* showed an increase in phytotoxicity from 21 DAT. Therefore, the evolution was slower. However, phytotoxicity ranged from 44.5 to 72.9% in the final evaluation (35 DAT) at the lowest and highest doses, respectively, with chlorosis observed in the plants and some necrotic leaves (Figure 5D).

C. legalis showed sensitivity to an increase in the dose of the herbicide sulfentrazone throughout the evaluations. The phytotoxicity caused by the herbicide at 35 DAT ranged from 40.4 to 78.2% at the lowest and highest doses, respectively. Phytotoxicity at the commercial dose was 61.4%, which does not represent lethal phytotoxicity (Figure 6A). Similarly, the commercial dose resulted in a 59.4% phytotoxicity for *R. armata*, reaching 83.5% with twice the commercial dose (Figure 6B).

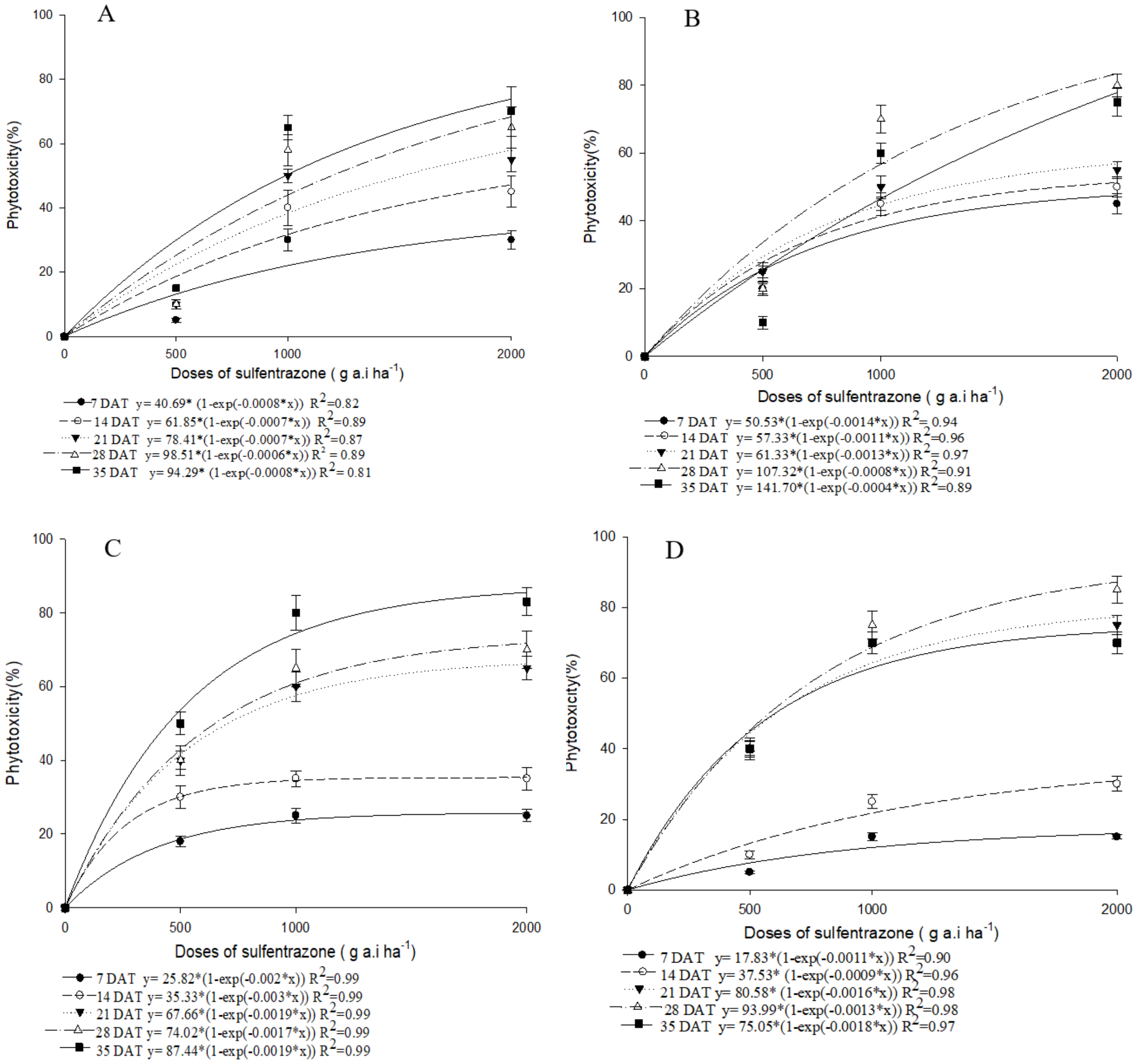

Figure 5. Phytotoxicity of the herbicide sulfentrazone at different doses on the species *M. vexator* (A), *P. gonoacantha* (B), *L. campestris* (C), and *E. argentinum* (D), evaluated at 7, 14, 21, 28, and 35 DAT

Figura 5. Fitotoxicidade do herbicida sulfentrazone em diferentes doses sobre as especies *M. vexator* (A), *P. gonoacantha* (B), *L. campestris* (C) e *E. argentinum* (D), avaliadas aos 7, 14, 21, 28 e 35 DAT

M. gonoclada showed higher sensitivity to sulfentrazone as the dose increased and throughout the evaluations. However, little difference in phytotoxicity was observed between the recommended dose (57.4%) and double the dose (66.0%) in the final assessment (35 DAT) (Figure 7A). The herbicide sulfentrazone caused significant phytotoxicity (80%) in the species *H. ochraceus* at 35 DAT when twice the recommended dose was applied, showing necrotic leaves. On the contrary, phytotoxicity was 52.50% at the recommended dose (1000 g ai ha^{-1}), showing leaf chlorosis (Figure 7B). A high evolution in phytotoxicity was observed from 28 DAT.

I. vera (Figure 7C) showed little difference in response between doses, with phytotoxicity varying from 64.8% (500 g ai ha^{-1}) to 67.6% (2000 g ai ha^{-1}). The phytotoxicity between doses was also low for *S. granulosoleprosum* (Figure 7D), being practically equal between the commercial dose and double the dose,

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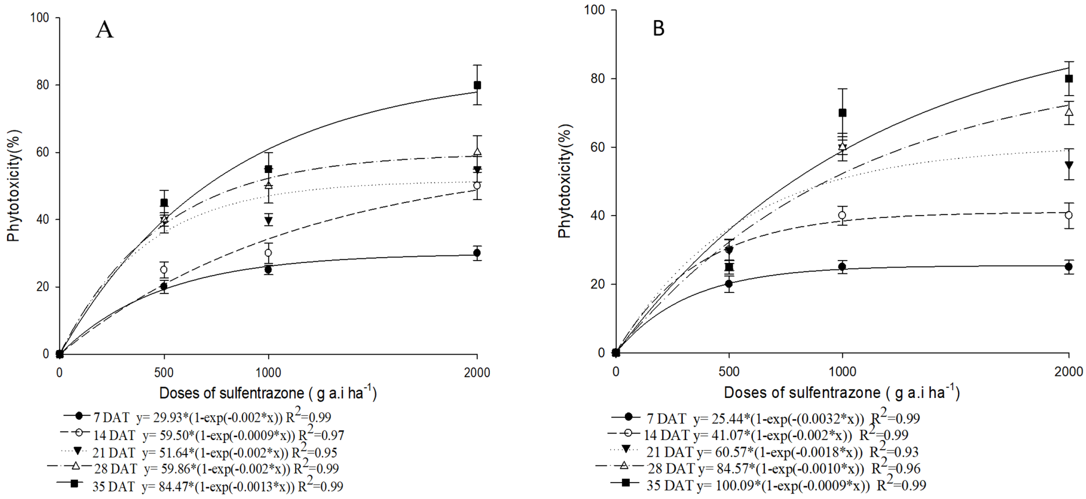

Figure 6. Phytotoxicity of the herbicide sulfentrazone at different doses on the species *C. legalis* (A) and *R. armata* (B), evaluated at 7, 14, 21, 28, and 35 DAT

Figura 6. Fitotoxicidade do herbicida sulfentrazone em diferentes doses sobre as especies *C. legalis* (A) e *R. armata* (B), avaliadas aos 7, 14, 21, 28 e 35 DAT

reaching approximately 76.0%. Phytotoxicity for both species increased throughout the evaluations.

Sulfentrazone also caused phytotoxicity above the tolerable level for the species *C. vernalis* and *S. langsdorffii*, with values of 72.5% and 86.16%, respectively, when using the recommended dose at 35 DAT, with practically no difference with double the dose. The species *S. sampaioana* showed an evolution of phytotoxicity throughout the evaluations and at all doses, with the recommended dose causing an 80% phytotoxicity at 35 DAT, which makes the use of this product unfeasible in the area with this forest species.

3.3 Dry biomass

The shoot dry biomass of the species treated with the herbicides sulfentrazone and oxyfluorfen showed statistical differences between treatments only for the species *I. ucra*, *R. armata*, and *C. floribundus*. The reduction in dry biomass was significant when compared to the treatment without herbicide application, with a higher difference between the commercial dose and double the dose for *C. floribundus*.

4. DISCUSSION

Selective herbicides are not common in environmental restoration areas due to the lack of technical information on the selectivity of molecules on the species. Therefore, studies involving these products are important to expand the possibilities of managing weeds in this system without causing damage to seedlings of tree species.

The degradation of oxyfluorfen in the environment is essentially through photolysis and, therefore, its residual period and, therefore, its effect, can be prolonged in humid areas with shading conditions (Freitas et al., 2007 ; Rodrigues and Almeida, 2018). Cassamassimo (2005) evaluated the dissipation of oxyfluorfen in soils with forestry activities, shaded and in full sun, and found slower herbicide dissipation in shaded areas. Seedling permanence in the greenhouse may have been a favorable factor for the herbicide action. However, many species visually recovered from phytointoxication, as the herbicide has a contact action, and new leaves emitted after application were not affected and had a normal appearance. Alves et al. (2000) emphasized that the phytotoxic effects observed for this herbicide are restricted to places of contact between the product and the plant, with no

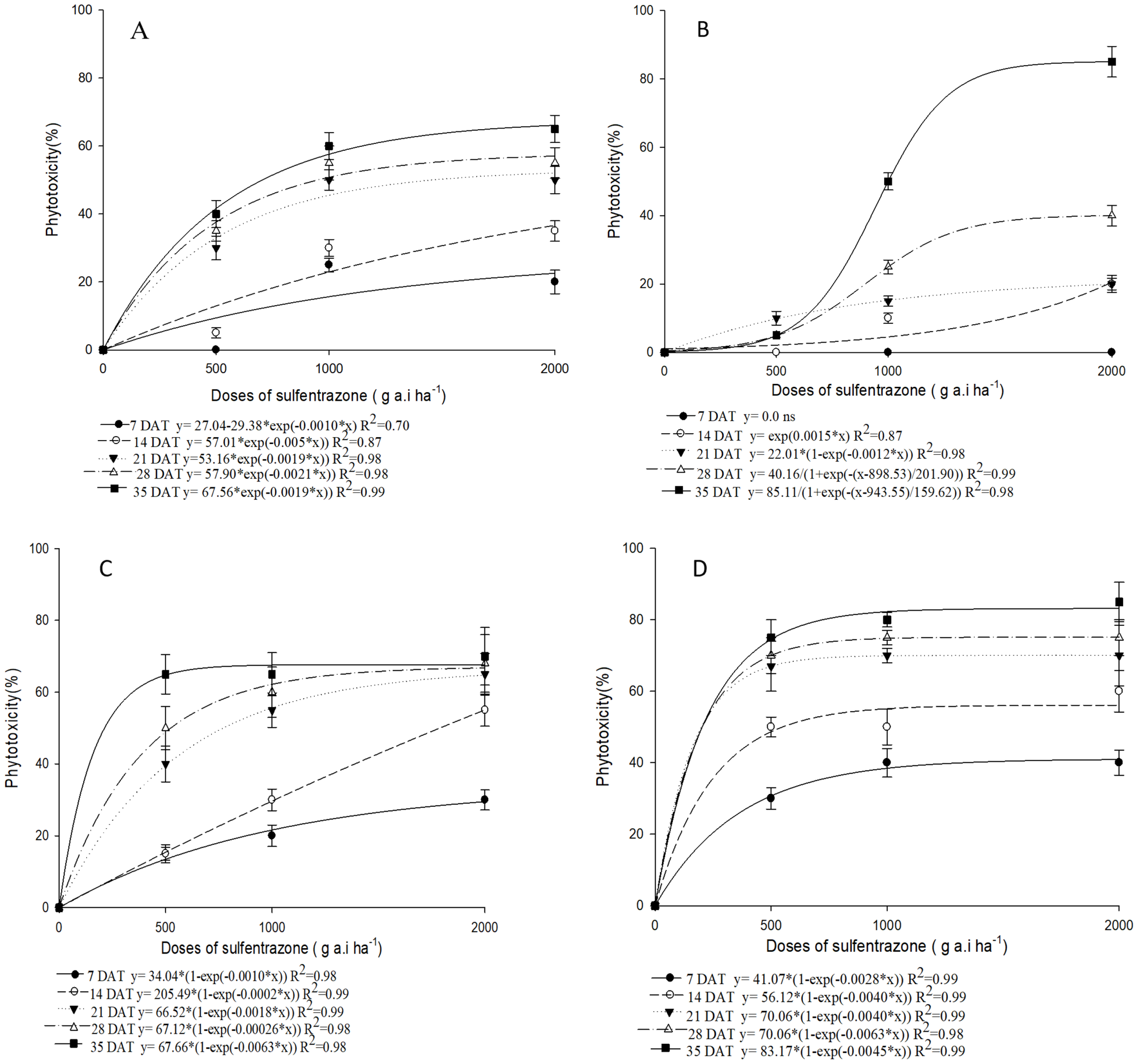

Figure 7. Phytotoxicity of the herbicide sulfentrazone at different doses on the species *M. gonoclada* (A), *H. ochraceus* (B), *I. vera* (C), and *S. granulosoleprosum* (D), evaluated at 7, 14, 21, 28, and 35 DAT

Figura 7. Fitotoxicidade do herbicida sulfentrazone em diferentes doses sobre as especies *M. gonoclada* (A), *H. ochaceus* (B), *I. vera* (C) e *S. granulosolesprosum* (D), avaliadas aos 7, 14, 21, 28 e 35 DAT

evolution of the effects with its development, which was also observed in this experiment.

Importantly, the mechanism of action of this herbicide is the protoporphyrinogen oxidase (PROTOX) inhibition, a key enzyme in chlorophyll production. Oxyfluorfen adheres strongly to colloidal particles (clay and organic matter) when it reaches the soil, forming a chemical barrier in the first centimeters of the surface, which acts on weed species that emerge. This herbicide is registered in Brazil for forest species such as pine and eucalyptus. Oxyfluorfen is very poorly soluble in water (<0.1 ppm) and, therefore, difficult to wash or leach into the soil, consisting of a significant advantage in tropical regions, where high precipitations are usual (Rodrigues and Almeida, 2018).

In the present study, oxyfluorfen caused marked phytotoxicity in some forest species, progressing to leaf chlorosis and necrosis. Its translocation occurs with little movement

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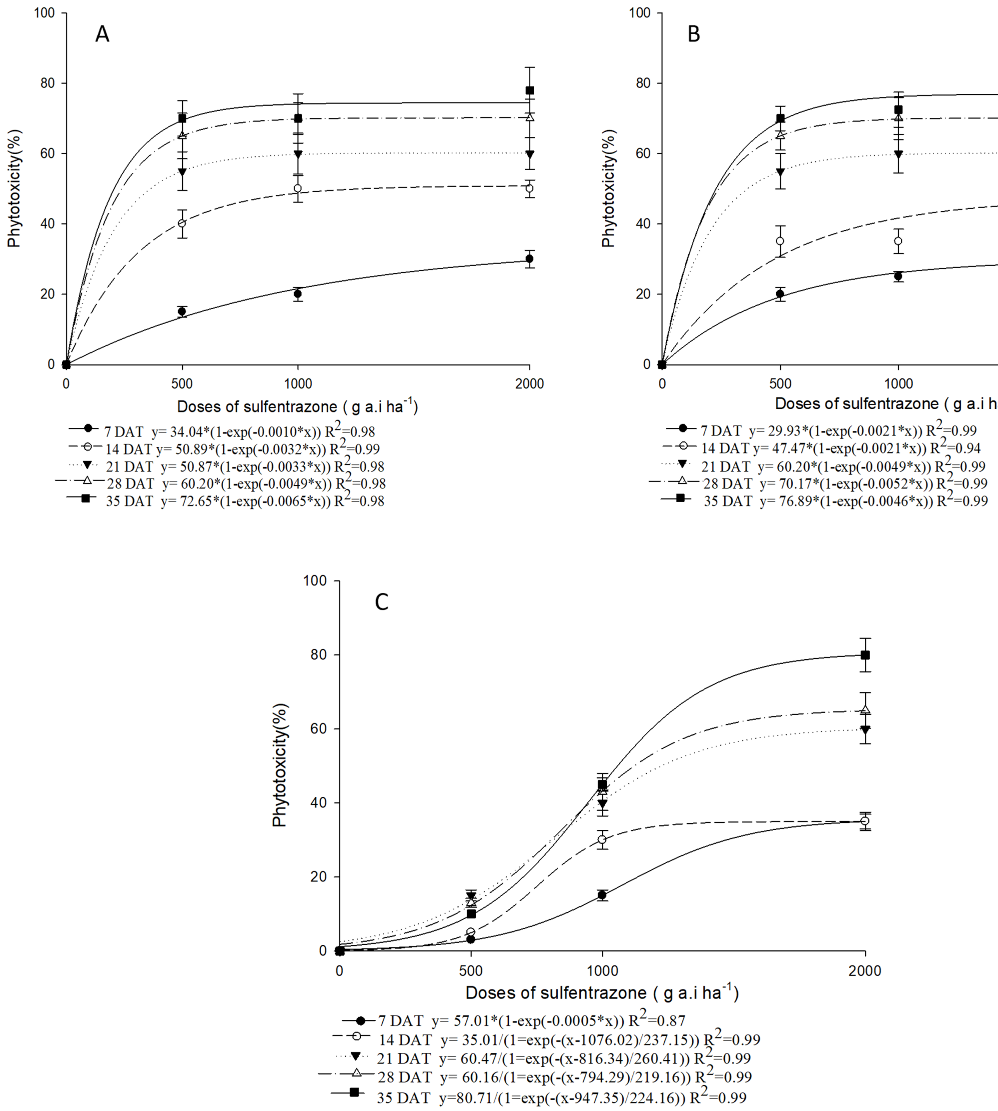

Figure 8. Phytotoxicity of the herbicide sulfentrazone at different doses on the species *C. vernalis*, *S. langsdorffii*, and *S. sampaioana*, evaluated at 7, 14, 21, 28, and 35 DAT

Figura 8. Fitotoxicidade do herbicida sulfentrazone em diferentes doses sobre as especies *C. vernalis* (A), *S. langsdorffii* (B) e *S. sampaiona* (C), avaliadas aos 7, 14, 21, 28 e 35 DAT

through the phloem because leaf desiccation occurs quickly. Thus, the observed symptoms were leaf browning followed by necrosis. On the other hand, the ability to resprout is an intrinsic characteristic of trees in general, and, therefore, seedlings of some species were, apparently, able to recover and emit new leaves.

Araujo Neto et al. (2021) observed the toxicity of doses of the herbicide oxyfluorfen applied in pre-emergence via irrigation water in the implementation of a eucalyptus plantation, clone VCC865 (a hybrid of *Eucalyptus urophylla* x *Eucalyptus grandis*). The authors concluded that oxyfluorfen in irrigation water was selective to the crop at the evaluated doses regardless of the irrigation water volume, promoting an efficient pre-emergence control of weeds at the highest doses (1080 and 1440 g ai ha^{-1}) and an increase in the initial eucalyptus growth, mainly the number of leaves, leaf area, and shoot dry mass accumulation.

Duarte et al. (2006) found that the herbicides haloxyfop-methyl (120, 240, and 480 g ha^{-1}), sulfentrazone (300, 600, and 1200 g ha^{-1}), and oxyfluorfen (720, 1440, and 2880

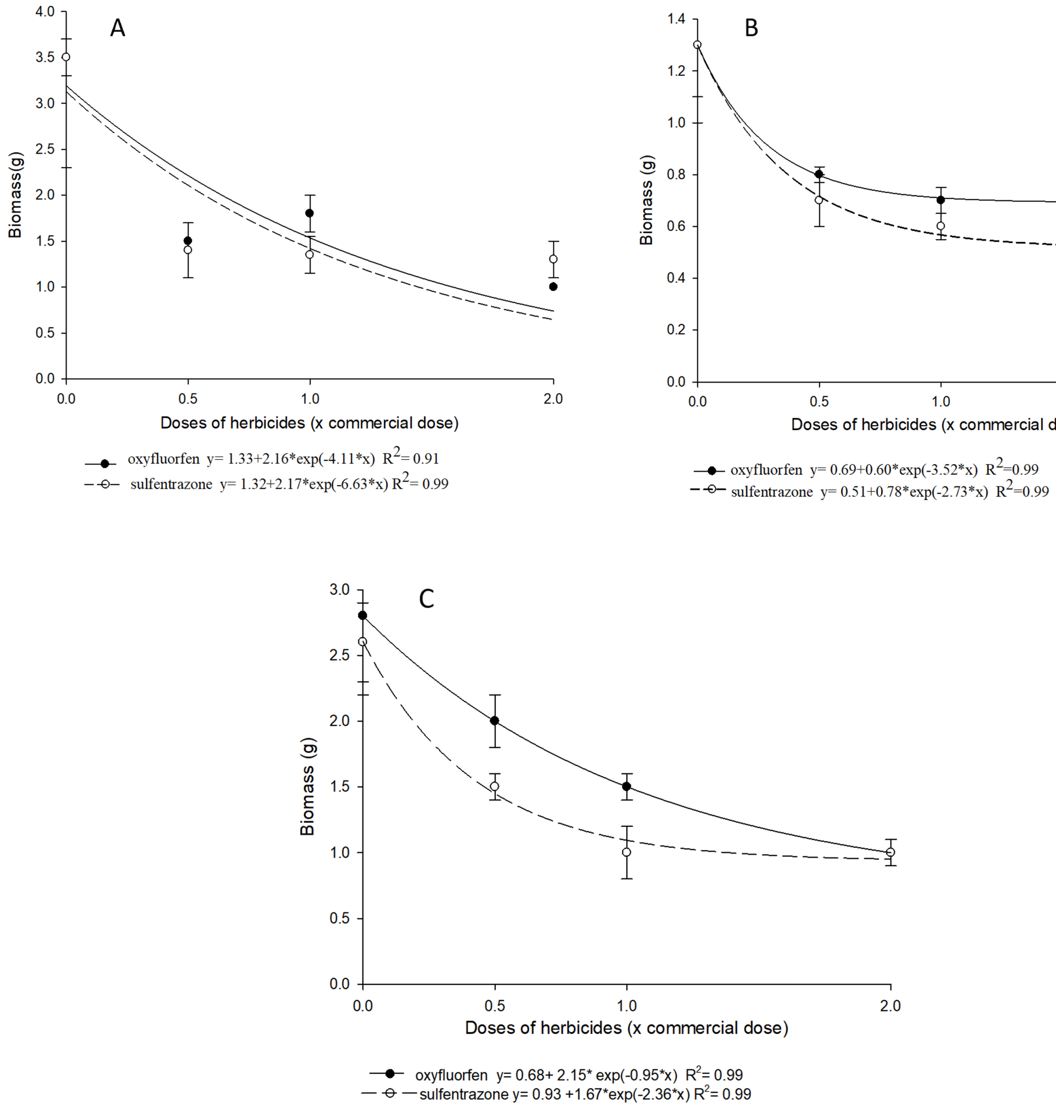

Figure 9. Shoot dry biomass of *I. ucra* (A), *R. armata* (B), and *C. floribundus* (C) treated with the herbicides oxyfluorfen and sulfentrazone at different doses

Figura 9. Biomassa seca da parte aérea de *I. ucra* (A), *R. armata* (B), and *C. floribundus* (C) tratadas com os herbicidas oxyfluorfen e sulfentrazone em diferentes doses

g ha^{-1}) did not interfere with development of *M. urundeuva* seedlings. Moreover, some species were not affected by the herbicides and had normal development.

Thomas et al. (2005) found that the selectivity of the herbicide sulfentrazone involves several isolated or combined mechanisms such as absorption, translocation, and differential metabolism between different species. Shaner (2014) observed that although leaves can absorb the herbicide sulfentrazone, its symplastic translocation through the phloem is low due to the rapid leaf desiccation.

Sulfentrazone is relatively persistent in the soil, with a mean half-life of 150 days, varying from 121 to 302 days depending on climate and soil conditions. In many cases, the high residual of sulfentrazone can become a restricting factor for the planting of some sensitive species (Gehrke et al., 2020). The physicochemical characteristics of sulfentrazone (high solubility (S = 780 ppm) and low organic carbon partition coefficient (Koc = 43 mL g^{-1}) indicate a high leaching potential of its molecule. However, this behavior is rarely observed, except in situations with sandy soils, under conditions

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of increased rainfall events (Melo et al., 2010). It is classified as very dangerous to the environment (class II) due to its mobility and high persistence.

The results show that the herbicide sulfentrazone had similar behavior to oxyfluorfen, not being selective for some species. Thus, both herbicides can be used to manage weeds in species in which phytotoxicity was not high (below 30%) and species that showed total tolerance. Importantly, field tests are necessary to evaluate the behavior of these species, considering that field and greenhouse conditions are different.

5. CONCLUSION

The species that showed a negative significant difference regarding the phytotoxicity of the herbicide oxyfluorfen relative to the control were *I. uruguensis*, *E. argentinum*, *P. nitens*, *M. rigidiuscula*, and *S. sampaioana*.

The species that showed a negative significant difference regarding the phytotoxicity of the herbicide sulfentrazone relative to the control were *M. vexator*, *P. gonoacantha*, *L. campestris*, *E. argentinum*, *C. legalis*, *R. armata*, *I. vera*, *S. granulosoleprosum*, *C. vernalis*, *S. langsdorffii*, *S. sampaioana*, *M. gonoclada*, and *H. ochraceus*.

Only the species *R. armata*, *C. floribundus*, and *I. uruguensis* presented a reduction in shoot biomass relative to the control.

The herbicides oxyfluorfen and sulfentrazone can be recommended for weed management in most of the species studied in this research, except for those mentioned above.

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AUTHOR CONTRIBUTIONS

Camila Tonelotti Simões supported data analysis and the acquisition of experimental results. Altemar de Rezende designed the research project. Patricia Andrea Monquero drafted and discussed the statistical, experimental, and estimated data. Andreia Cristina Silva Hirata contributed to writing the paper and supported data analysis.

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