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Use of a wiper applicator for the control of the invasive species *Eragrostis plana* with glyphosate salts

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Abstract: Background: *Eragrostis plana* is an invasive plant in native grassland areas associated with degradation of the Pampa biome. Selective control of *E. plana* is difficult due to its similarity to other grassland species. There is a lack of information about *E. plana* control using selective herbicide application equipment.

Objective: The present study aimed to evaluate the efficacy of a pressurize rope wick applicator for controlling the invasive plant *E. plana* as function of different salts of glyphosate, application volumes, and year seasons.

Methods: The studies were carried out under field conditions and repeated. The first study evaluated glyphosate salts of isopropylamine, dimethylamine, monoammonium, diammonium, and potassium at doses of 720 and 1440 g ha^{-1} and clethodim at 60 and 120 g ha^{-1}. The second study assessed application volumes of 8, 24, 40, and 56 L ha^{-1} using isopropylamine and potassium salts of glyphosate.

Results: Glyphosate applied in summer was more effective at controlling *E. plana*, with less regrowth than glyphosate application in winter. The glyphosate diammonium was more effective at controlling *E. plana* than isopropylamine, dimethylamine, monoammonium, or potassium salt formulations at 1440 g ha^{-1}. Application volume of glyphosate between 8 and 40 L ha^{-1} provided similar control of *E. plana* and pasture selectivity.

Conclusions: Glyphosate applied with a rope wick selective applicator was effective in controlling *E. plana* clumps and was selective to grassland. The control efficacy varied as a function of glyphosate salts and year season, but not due to application volume of 8 and 40 L ha^{-1}.

Keywords: Campo Limpo®; grassland; invasive plants; Pampa Biome; South African lovegrass

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1. Introduction

South African lovegrass (*Eragrostis plana* Nees) is one of the main invasive species in the native grasslands of southern Brazil. It was accidentally introduced to the state of Rio Grande do Sul in the early 1950s (Medeiros et al., 2014). Propagules of the species were imported as contaminants in seeds of weeping lovegrass (*Eragrostis curvula* Schrad) and Rhodes grass (*Chloris gayana* Kunth), both of which were brought over from South Africa as new pasture species (Medeiros, Focht, 2007). Due to the species' tolerance to trampling, frost, and drought, seeds of *E. plana* began to be propagated and sold under the name *E. plana-2* (Medeiros, Focht, 2007). However, within a few years of adopting the plant as a forage grass, it was noted that the species had low nutritional quality and palatability and quickly wore down animals' teeth (Reis, Coelho, 2000), resulting in decreased livestock production.

Invasiveness of *E. plana* has become a geographically widespread problem in South America (Ferreira, Filippi, 2010). The species has spread rapidly throughout Rio Grande do Sul and is currently present in other Brazilian states and other Mercosur countries, such as Argentina and Uruguay (Barbosa et al., 2013). *E. plana* is one of the main culprits of the ecological devastation of the Pampa biome, causing unprecedented disturbances to the area's natural grasslands, exacerbating their ongoing replacement with agricultural and silvicultural monocrops. This degradation is associated with broadcast herbicide application over the original vegetation with the aim of controlling *E. plana* and introducing forage species (Ferri et al., 2001), as well as the improper management of natural grasslands and indiscriminate use of burning. *E. plana* and the native grasses of the Pampa biome are highly genetically similar (Medeiros et al., 2007), limiting the range of herbicides that can be used in broadcast applications to control *E. plana* while preserving other species of forage grasses.

The control of *E. plana* is challenging after it becomes established in natural grasslands (Goulart et al., 2009). Various practices for managing *E. plana* have been studied since the late 1970s (Medeiros, Focht, 2007) when this grass stopped being promoted as forage and emerged as a harmful invasive species. Winter and summer annual crops (Guterres, 1993) and integrated control methods combining conventional crops with herbicide use (Reis, Coelho, 2000) have been attempted, along with techniques such as mowing, intense grazing, and chemical control with broadcast spray of herbicides, all with little success (Goulart et al., 2009). In addition to these approaches, attempts to use herbicide safeners that could control *E. plana* without affecting the natural grassland could only be verified in greenhouse conditions. In the field, no additional herbicide selectivity against *E. plana* has been observed (Goulart et al., 2012).

Limited large-scale cultural and physical approaches and continued increase in the problems caused by *E. plana* have led to a search for viable and cost-effective options to control the invasive species. This was the rationale behind the development of Campo Limpo® by Embrapa Pecuária Sul, a selective herbicide applicator that aims to control invasive plants without damaging forage species caused by conventional spraying (Perez, 2018). The equipment allows application using ropes dipped in herbicide solutions, with selectivity accomplished due to the difference in height between the forage plants consumed by cattle and the undesirable species, which grow to a greater height. Herbicide application with wiper applicators was introduced in the US beginning in 1978 and has been acknowledged for its simplicity, low operating cost, and efficient use of the herbicide (Prudente, Matuo, 1985). However, little information is available on the use of wiper applicators in general (Harrington, Ghanizadeh, 2017), and no specific information is available on the optimal dose and application volume to control *E. plana*. Furthermore, it should be noted that glyphosate salt formulations applied using the wiper applicator may affect the product's effectiveness in controlling this grass.

Glyphosate is one of the few products registered for use in pasture areas (Ministério da Agricultura, 2022) and is the only product recommended for application with the Campo Limpo® selective applicator. Glyphosate is a systemic, post-emergent, and non-selective herbicide that effectively controls a wide spectrum of harmful annual and perennial plants in a wide range of agricultural and non-agricultural settings. Various formulations of glyphosate have been created and are widely available for use. In Brazil, these include glyphosate products formulated with isopropylamine, dimethylamine, monoammonium, diammonium, and potassium salts (Ministério da Agricultura, 2022). The specific glyphosate salt formulation may affect its translocation and speed of action (Molin, Hirase, 2005) and its ability to control certain plant species (Jakelaits et al., 2001; Molin, Hirase, 2004; Li et al., 2005). The hypothesis of this study is that the interaction between glyphosate salt formulations and the application volume affects the control efficacy of *E. plana* using a pressurized rope wick applicator in native grasslands. The present study aimed to evaluate the efficacy of a pressurize rope wick applicator for controlling the invasive plant *E. plana* as a function of different salts of glyphosate, application volumes, and year seasons.

2. Material and Methods

2.1 Study area and application of treatments

The experiments were conducted at the Agronomy Experimental Station of the Federal University of Rio Grande do Sul (UFRGS) in Eldorado do Sul, Rio Grande do Sul (RS), Brazil. The geographical coordinates of the area are 30°5'57.79" S and 51°40'38.42" W. The study area, measuring approximately 3 ha, was established in a natural grassland with clumps of *E. plana* measuring 25-40 cm in diameter that covered, on average, 60% of the soil surface. The study area had a slope of approximately 6% perpendicular to the application of treatments (Figure 1 A). Each plot was 10 x 4.5 m with 5 m alley between plots to allow tractor maneuvering during application of treatments. The area was grazed by cattle approximately 15 days before the treatments. Treatments were applied using the Campo Limpo® rope wick applicator (Figure 1 B). The applicator dispersed the herbicide using a series of ropes, saturated with herbicide that is pumped from the equipment tank. The applicator was mounted at a height, which allows the herbicide-saturated ropes to come into contact with the tall, ungrazed plants, ensuring minimal contact with the plants located closer to the soil. After applying each treatment, the equipment and the filters were washed using a high-pressure washer and liquid soap. Freshwater was pumped through the system for 5 minutes to eliminate residues of the previous treatment. The tractor and applicator were driven at a velocity of 3.67 km h^{-1}.

2.2 Evaluation of the effect of salts of glyphosate

In the first experiment, the treatments were applied on January 18, 2017, between 9:00 a.m. and 9:30 p.m., with temperatures between 26 and 32°C and relative humidity (RH) between 52 and 73%. The clumps of *E. plana* were at the beginning of the panicle exertion, with an average of 92% of leaves photosynthetically active. The experiment was repeated on September 4, 2017, when the treatments were applied between 9:00 a.m. and 6:30 p.m., with temperatures between 26 and 32 °C and RH between 67 and 70%. At this time, the clumps had an average of 45% photosynthetically active leaves, which is characteristic of the renewal of vegetative growth following dormancy during the winter period.

The experiments were conducted in a random block design with four replicates in a two-factor scheme with an additional treatment, in which the first factor consisted of five glyphosate salts and the herbicide clethodim (Table 1). The second factor comprised the herbicides doses that were 720 and 1440 g ha^{-1} of acid equivalent for glyphosate salt formulations and 60 and 120 g ha^{-1} for clethodim, which represents the half-recommended and the full recommended dose, respectively, in addition to a nontreated check, for a total of 13 treatments. The application volume was 24 L ha^{-1}, which was calibrated before each treatment application. Doses of the herbicides and application volume were selected based on the recommendation of the equipment manufacturer.

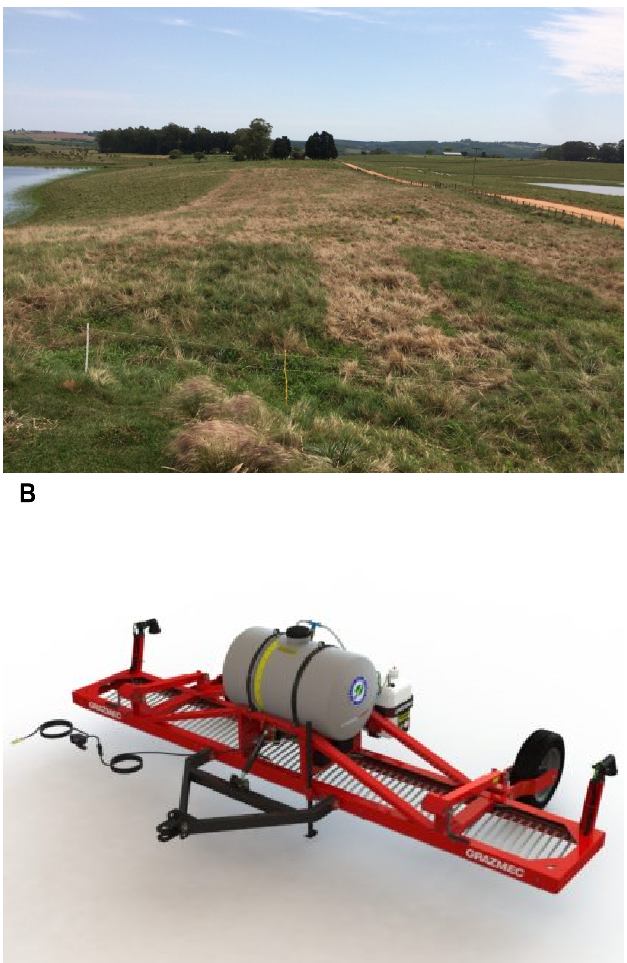

Figure 1 - The study area (A) and the Campo Limpo® rope wick applicator (B)

2.3 Effect of application volume

The experiment was carried out in a random block design with four replicates and a two-factor scheme with additional treatment. The first factor consisted of the isopropylamine and potassium salts of glyphosate, and the second factor was the application volume of 8, 24, 50, and 56 L ha^{-1} based on the recommended application volume of the equipment manufacturer (24 L ha^{-1}), in addition to a nontreated check, for a total of nine treatments. Isopropylamine salt of glyphosate was chosen because it is most commonly used and has the largest diversity of commercial brands available, while potassium salt was used because it has a greater translocation potential (Satchivi et al., 2000). The lowest dose was chosen to detect potential differences among treatments. The experiment was initiated on January 18, 2017. Different application volumes were obtained by regulating the pumping pressure of the Campo Limpo® applicator. The experiment was repeated on September 4, 2017. The environmental conditions at the time treatments were applied and the developmental stage of *E. plana* plants were similar to those described in glyphosate salt experiment.

2.4 Plant evaluations and data analysis

E. plana control was evaluated at 7, 56, and 150 days after application (DAA) using a visual scale of 0% to 100%, with 0% indicating an absence of symptoms and 100% indicating plant death (Frans et al., 1986). Aboveground biomass of *E. plana* and pasture grasses was estimated by sampling a 0.25 m^2 area of each plot at 35 and 90 DAA. At 270 DAA, all plots were mowed to evaluate the regrowth of *E. plana* clumps. Plant control and biomass were evaluated again in a sampling area of 0.5 m^2 at 90 days after mowing or 360 DAA. Biomass samples were dried in a forced-air circulation oven at 60 °C and weighed. Pasture productivity was calculated in g per 0.5 m^2 and extrapolated to kg ha^{-1}. The dry mass of *E. plana* clumps was used to calculate the percentage reduction in *E. plana* clump mass relative to the nontreated check.

Table 1 - Active ingredient, commercial product, and acid equivalent concentration of each herbicide utilized in the experiments

Active ingredient	Commercial product	Acid equivalent concentration (g L^{-1}, kg^{-1})
Glyphosate isopropylamine	Gli-Up 480 SL	360
Glyphosate dimethylamine	Glizmax Prime	480
Glyphosate monoammonium	Roundup WG	720
Glyphosate diammonium	Roundup Original DI	370
Glyphosate potassium	Roundup Transorb R	480
Clethodim	Select OnePack	120

Normality of the residuals was analyzed using the Shapiro-Wilk test, and homogeneity of variance was examined using the Bartlett test ($p \leq 0.05$). When residuals were not normally distributed, the data were transformed using a Box-Cox transformation using the *Forecast* package in R (Hyndman, Khandakar, 2008). Subsequently, the hypotheses were tested using the F-test ($p<0.05$). The Scott-Knott test was used as a complementary analysis to compare the means ($p<0.05$). The two repetitions in each study were compared considering the seasons as the main plot in a split-plot scheme. When the season effect was significant, the data was analyzed and presented separately for each season. Statistical analyses were conducted using Winstat (Machado, Conceição, 2005), SigmaPlot 14.0, and the *ExpDes* package in R (Ferreira et al., 2018).

3. Results and Discussion

3.1 Effect of glyphosate salt formulations

There were significant differences between the repetitions of the experiments ($p<0.05$), so the data were analyzed separately. In both experiments, interaction between glyphosate salts and doses was significant ($p<0.05$). Control levels in the first experiment in the summer (Figures 2 A, C, E, and G), were significantly higher than control levels in the winter (Figures 2 B, D, F, and H), except with respect to the evaluations at 90 days after mowing, or 360 DAA ($p<0.05$) (Figures 2 G and H). The efficacy of glyphosate is affected by environmental conditions to a greater degree than it is by adjuvants or water quality (Devkota, Johnson, 2016; Le, Morell, 2021) and is particularly sensitive to changes in air temperature and light intensity (Masiunas, Weller, 1988). These conditions, along with the lower amount of living biomass at the time of application, explain the lower control levels obtained in winter than in summer.

Significant differences ($p<0.05$) in the control of *E. plana* were observed between the formulations and doses evaluated. Overall, no significant differences were observed between formulations at the lower glyphosate dose (720 g ha^{-1}) during any evaluation. At the higher dose (1440 g ha^{-1}), the diammonium salt of glyphosate controlled *E. plana* clumps better than all other treatments during the summer evaluations. The only exception was at 7 DAA (Figure 2 A) when the dimethylamine salt of glyphosate was equivalent to that of diammonium. At 1440 g ha^{-1}, the monoammonium salt of glyphosate exhibited lower control than all other glyphosate salts during the summer, though it was not significantly different from isopropylamine at some evaluation times. At the lower dose, the potassium salt of glyphosate was at least 10% superior to the other treatments, mainly in the winter experiment (Figures 2 B, D, F, and H), while the diammonium salt excelled over other formulations at the higher dose during the summer (Figures 2 A, C, E, and G) and winter experiments (Figures 2 B, D, F, and H). At 90 days after mowing (360 DAA), the observed control was lower than the previous evaluations. However, the differences between treatments remained, with the potassium salt of glyphosate being most effective at the lower dose, while the diammonium salt had the best control at the higher dose in the summer (Figure 2 G) and winter (Figure 2 H) experiments.

Weak acid herbicides such as glyphosate are modified to improve the stability of the commercial formulation, which leads to gains in the product's efficiency at controlling weeds (Travlos et al., 2017). Glyphosate salts are formed by replacing their carboxylic acid hydrogen with a complementary ion. In Brazil, glyphosate is marketed as isopropylamine, dimethylamine, monoammonium, diammonium, and potassium formulations, though products containing isopropylamine salt are the most common (AGROFIT, 2022). Some researchers found no significant differences in weed control between different salts of glyphosate (Richardson et al., 2003; Li et al., 2005; Barroso et al., 2014), while others observed such differences (Molin, Hirase, 2004; Oliveira et al., 2015; Travlos et al., 2017). In general, the largest differences between glyphosate salt formulations are associated with rainfastness following application, incompatibility in tank mixtures, and, especially, speed of action (Barroso et al., 2014; Merotto Jr. et al., 2015; Jakelaitis et al., 2001). In the present study, evaluations were made up to 360 DAA (Figure 2), making it possible to determine the long-term effect on *E. plana*, which is important in controlling perennial species. Isopropylamine, diammonium, potassium, and monoammonium formulations salts of glyphosate were assessed for their ability to control *E. plana* in a previous trial using broadcast spraying application (Bastiani et al., 2021). The authors indicated that potassium and isopropylamine salts had the highest and lowest action speeds, respectively. Variations insusceptibility to glyphosate among weed species are also caused by reduced herbicide translocation and absorption. The diammonium salt of glyphosate was translocated into the roots of *Abutilon theophrasti* Medik., *Amaranthus rudis* L., and *Ipomoea lacunosa* L. at a rate 27% higher than the diammonium salt formulation measured at 74 h after application at 750 g ha^{-1} (Li et al., 2005). However, initial differences in the absorption and translocation in different species have not been observed to affect the ultimate efficacy of the formulations. The higher translocation of the diammonium salt of glyphosate may help explain the higher efficacy of the formulation compared to the other salts in the present study (Figure 2).

Doses of 720 and 1,440 g ha^{-1} had variable effects, with the lower dose only showing reduced efficacy in 13 of the 48 evaluations across all salt formulations (Figure 2). The salts evaluated could have had their greatest effect at the lower dose of glyphosate, and this could have occurred due to a saturation effect at the higher dose since the maximum level of control would already be reached. However, the opposite occurred: the greatest differences between

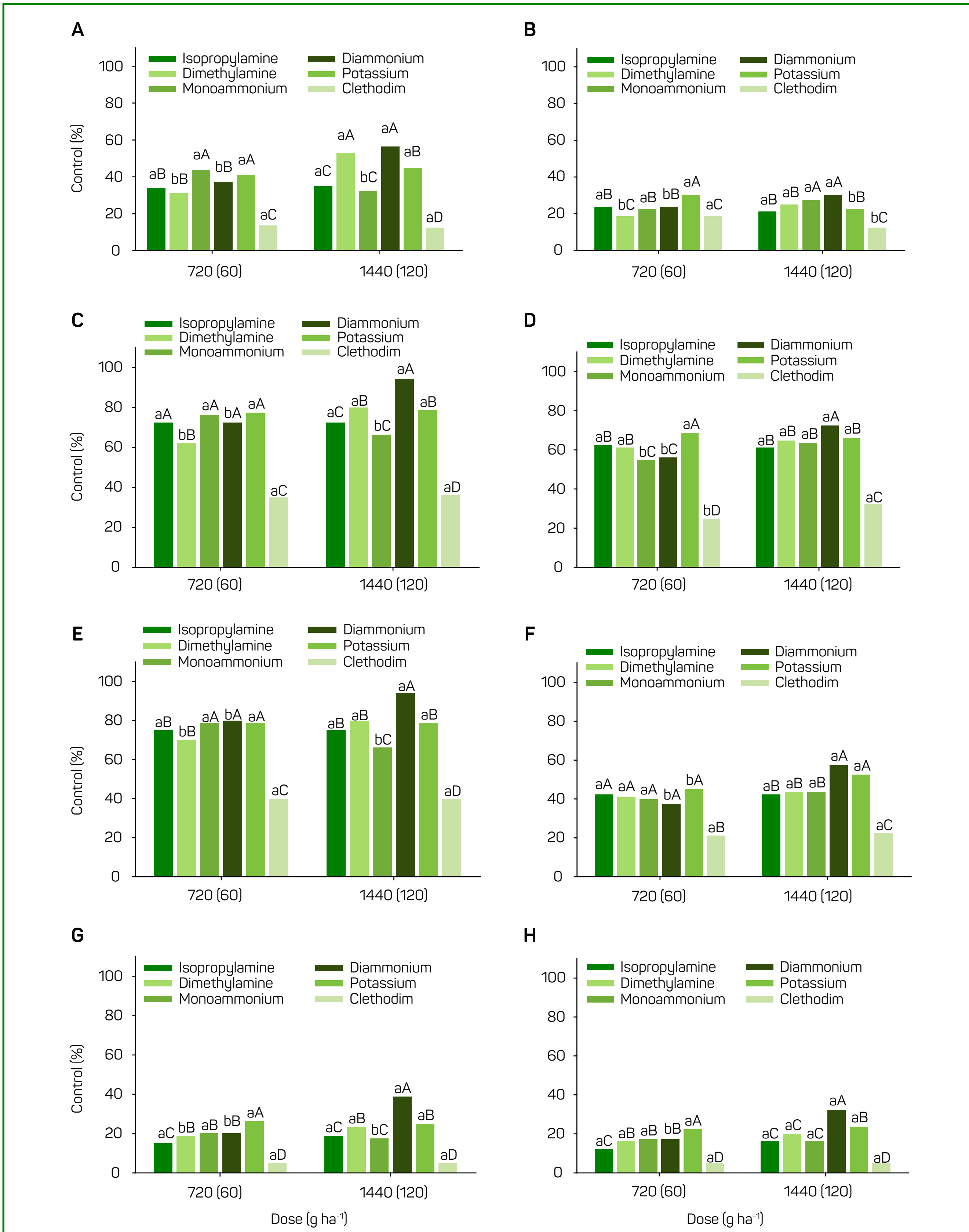

Figure 2 - *Eragrostis plana* control (%) at 7 (A and B), 56 (C and D), 150 (E and F) days after application (DAA) and 90 days after mowing (360 DAA) (G and H) of five glyphosate salts and clethodim at two doses applied with a rope wick applicator in the summer (A, C, E, and G) or winter (B, D, F, and H). Bars with similar lowercases and uppercases indicate similar effects of doses and herbicide salts, respectively (Scott-Knott, $p<0.05$)

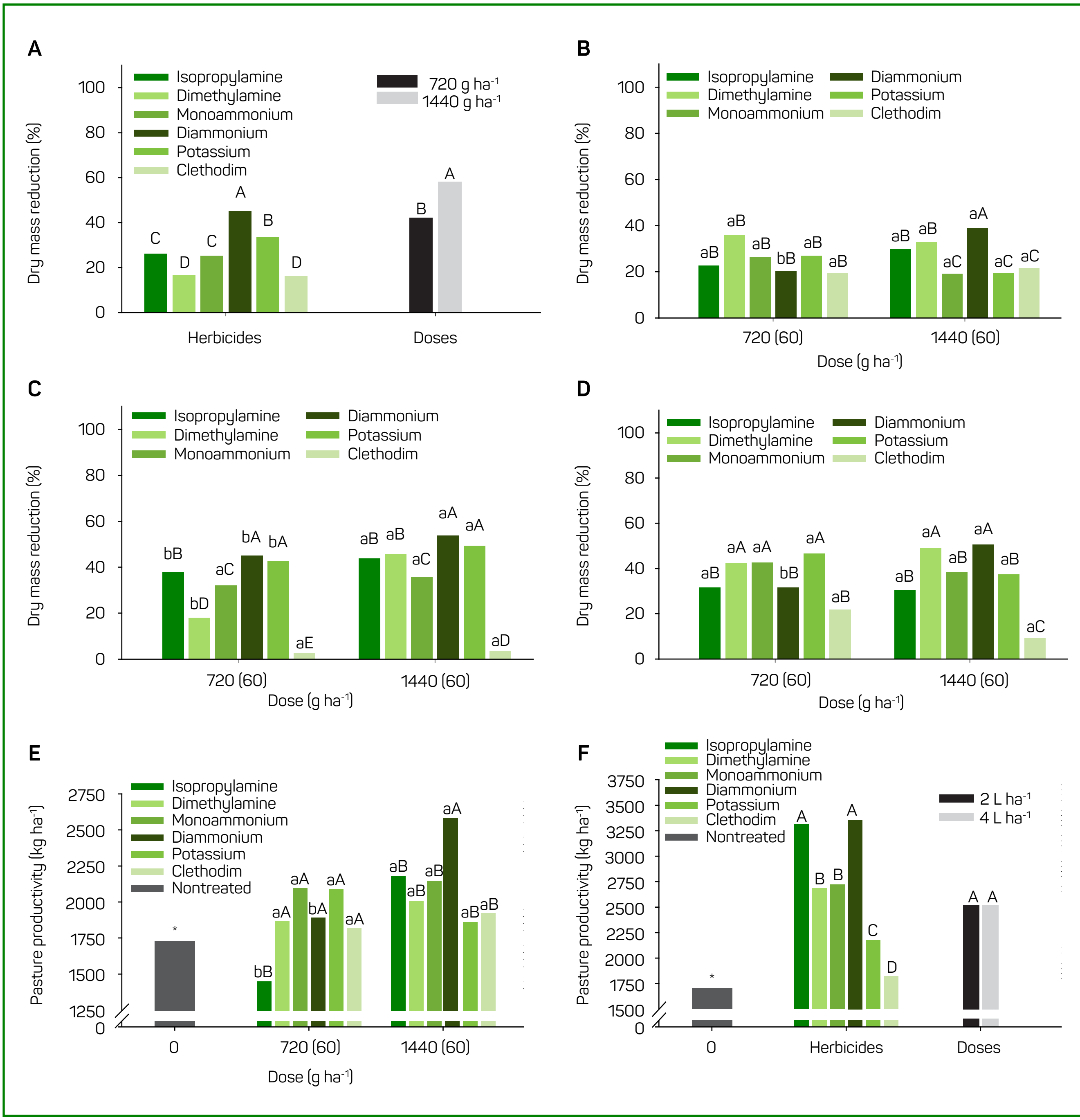

Figure 3 - Aboveground dry mass reduction of *Eragrostis plana* at 35 DAA (A and B) and 90 days after mowing (360 DAA) (C and D), and pasture productivity (E and F) at 35 DAA treated with five glyphosate salts and clethodim at two doses applied with a rope wick applicator in the summer (A, C, and E) or winter (B, D, and F). Bars with similar lowercases and uppercases indicate similar effects of doses and herbicide salts, respectively (Scott-Knott, $p<0.05$)

glyphosate salts occurred at the higher dose, indicating that the optimum dose was not reached. The current reference doses and application volumes for glyphosate and other herbicides have been established for spraying applications. Rope wick applicators, meanwhile, deposit the herbicide solution using a different system, leading to differences in optimum doses between application systems. In an experiment involving glyphosate sprayed at 540 g ha^{-1}, control levels of 33% were attained for isopropylamine, 35% for diammonium, 55% for potassium, and 57% for monoammonium salt in plants at the full tillering stage (Bastiani et al., 2021), similar application timing to the present study.

In all evaluations, clethodim controlled *E. plana* clumps to a lesser degree than any glyphosate treatment (Figures 2 A to H). Control levels were between 20 and 35%

in the evaluations up to 150 DAA (Figures 2 A to F) and approximately 5% in the inspection 90 days after mowing (360 DAA) (Figures 2 G and H). Furthermore, no differences were observed between the two doses, indicating that the low control level of clethodim may not be related to the dose, but is rather due to the low efficacy of the herbicide against *E. plana* in this mode of application. The purpose of using clethodim in the experiments was to evaluate an alternative to glyphosate for controlling *E. plana*. Glyphosate is one of the few herbicides that has been registered for weed control in pastures and is the only one recommended for use with the Campo Limpo® selective applicator. Clethodim is recommended for use against sourgrass (*Digitaria insularis* L.), which is somewhat similar to *E. plana* due to large clumps and life cycle. However, the regular control of *D. insularis* is performed during the early developmental stages (Leal et al., 2021), while control of perennial *D. insularis* is obtained with multiple clethodim applications or shortly after mowing, as the plants are resprouting.

Reduction intensity in the dry mass of *E. plana* clumps varied significantly between herbicides, except during the evaluation carried out at 35 DAA in the summer application (Figure 3 A). In that evaluation, the greatest reduction in dry mass of *E. plana* clumps was observed with the diammonium salt of glyphosate, with the 1,440 g ha^{-1} dose showing higher control than the 720 g ha^{-1} dose (Figure 3 A). Reductions of 45-55% in the dry mass of the *E. plana* clumps were observed at 90 days after mowing (360 DAA; Figure 3 C) in treatments with diammonium and potassium salts of glyphosate at both doses. These control levels were higher than any other treatment tested during the summer experiment. In the winter experiment, only clethodim treatments exhibited consistently lower control than any other treatment (Figures 3 B and D). The benefits in terms of *E. plana* control and the lower dry mass of clumps are related to lower interference with the pasture, the consequences of which will be discussed alongside the results from the application volume study.

3.2 Effect of application volumes

The season effect and the interaction between the herbicides and application volumes were significant ($p<0.05$), therefore the data were analyzed separately. In the summer experiment, treatments with isopropylamine salt formulation had higher control levels with an application volume of 56 L ha^{-1}, while control levels with potassium salt formulations were similar across all application volumes (Figures 4 A, C, E, and G). In general, no differences between the salts and application volumes were observed in the winter experiment. Control levels were 30% at 7 DAA, 60% at 56 DAA, 40% at 150 DAA, and 20% at 360 DAA, or 90 days after mowing (Figures 4 B, D, F, and H). Overall, potassium salt was more effective than isopropylamine salt at 56 and 150 DAA and at volumes of 8 and 24 L ha^{-1}.

In general, no significant and consistent differences were observed between application volumes at any of the periods evaluated (Figure 4). The current recommendation for application volume to control *E. plana* with the Campo Limpo® selective applicator is 24 L ha^{-1}. The present results show that the volume could feasibly be reduced from 24 to 8 L ha^{-1}. Besides not reducing the control of *E. plana* clumps, such low application volume can improve operational efficiency since less water is needed to treat a given area. Study conducted with conventional spraying in different weed species showed that the decrease in the application volume from 150 to 90 or 50 L ha^{-1} caused no significant difference in the coverage of weeds applied with ammonium salt glyphosate, indicating that reducing the application volume is technically viable for this herbicide use (Campos et al., 2020).

Herbicide delivered using the selective applicator Campo Limpo® method involves contacting the ropes that have been soaked with the herbicide solution with the plants. This is entirely different from conventional spraying, which delivers the herbicide applied into droplets. The Campo Limpo® application system eliminates herbicide drift, which makes using 8 L ha^{-1} possible, as observed in the present study. The conventional spray application uses volumes of 80-200 L ha^{-1}. Given these factors, the differences in the control of *E. plana* between the salts and application volumes tested may be due to differences in evaporation loss of the herbicide solution or mainly due to variations in the absorption and translocation of the intercepted product. Variations in evaporation were assessed in a study of glyphosate salts isopropylamine, monoammonium, and potassium on the foliar surface of *Bidens pilosa* L. and *Cenchrus echinatus* L (Oliveira et al., 2015). The authors indicated that the potassium salt formulation had the longest evaporation time, while the isopropylamine salt evaporated more quickly in both species. Hence, the contact area and the amount of herbicide deposited are smaller for applications using Campo Limpo® than for spraying, as indicated in Oliveira et al. (2015). Differences in the length of time the herbicide remains on the foliar surface are expected to be accentuated by the conditions during application, which may explain the differences observed in the present study (Figure 4). The efficacy of a herbicide is related to the amounts that are intercepted, absorbed, translocated, metabolized, and finally reach and remain at the site of action. These processes are extremely dynamic and may be compensated over time. This provides a general explanation for the small differences across glyphosate salts and application volumes observed in the present study (Figures 2 and 4).

The dry mass of *E. plana* clumps did not differ significantly across treatments at 35 DAA in the summer and winter experiments (Figures 5 A and B) or at 90 days after mowing (360 DAA) in the winter experiment (Figure 5 D). Changing the application volume did not change

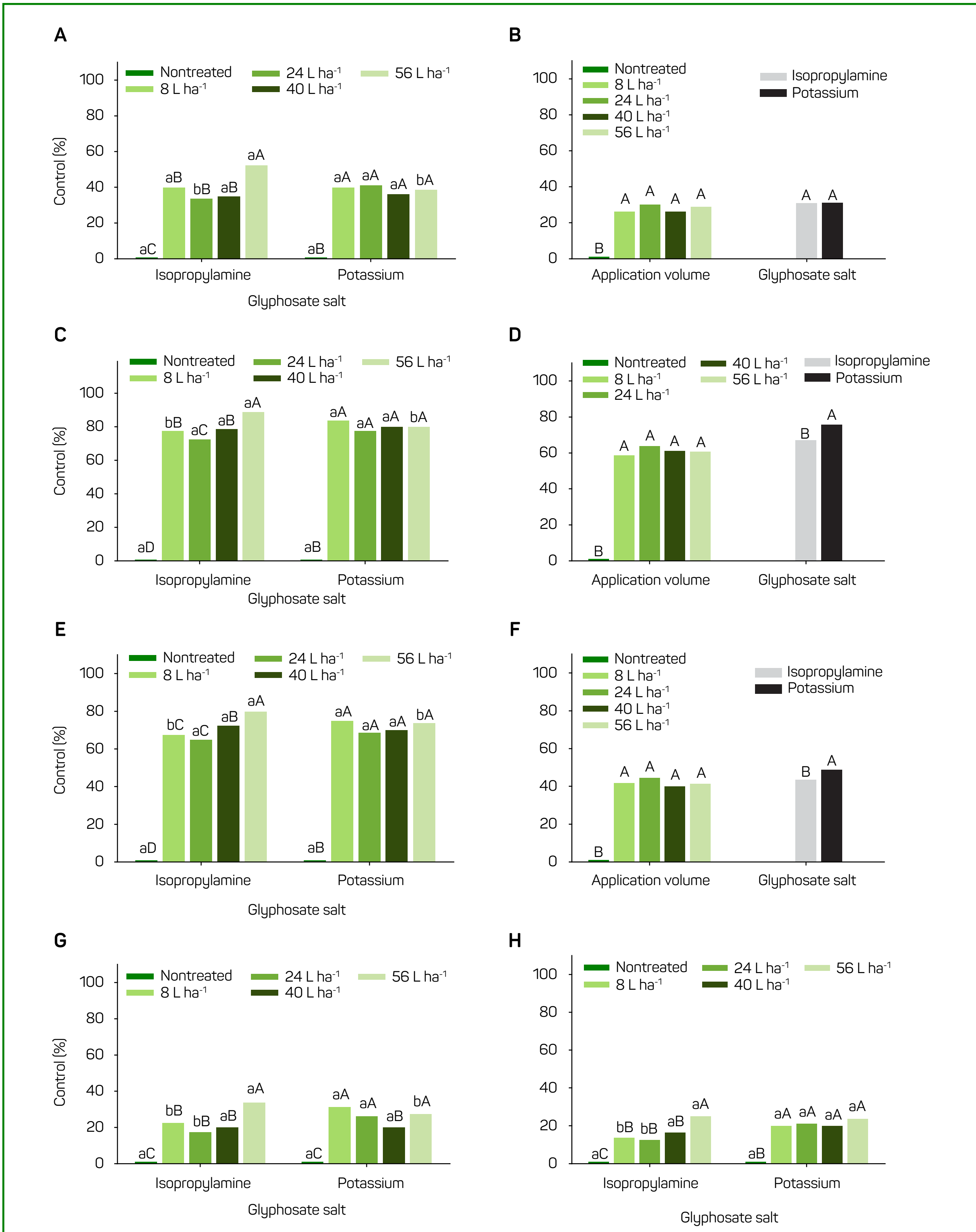

Figure 4 - *Eragrostis plana* control (%) at 7 (A and B), 56 (C and D), 150 (E and F) days after application (DAA) and 90 days after mowing (360 DAA) (G and H) of two glyphosate salts and four volumes of application applied with a rope wick applicator in the summer (A, C, E, and G) or winter (B, D, F, and H). Bars with similar lowercases and uppercases indicate similar effects of glyphosate salts and volumes of application, respectively (Scott-Knott, $p<0.05$)

the effect of glyphosate salt formulations on dry shoot biomass of *E. plana* (Figures 5 A, B, and D). The major difference associated with reducing the application volume was the higher efficacy of isopropylamine salt relative to potassium salt at 90 days after mowing (360 DAA) at the application volume of 8 L ha^{-1} (Figure 5 C). There was a 30% reduction in the dry mass of *E. plana* at 35 DAA evaluation for the summer and winter experiments, while the reduction at 90 days after mowing was 50% in summer and 40% in winter (Figures 5 A, B, C, and D). The reduction in biomass of *E. plana* clumps is related to the growth and productivity of pastures.

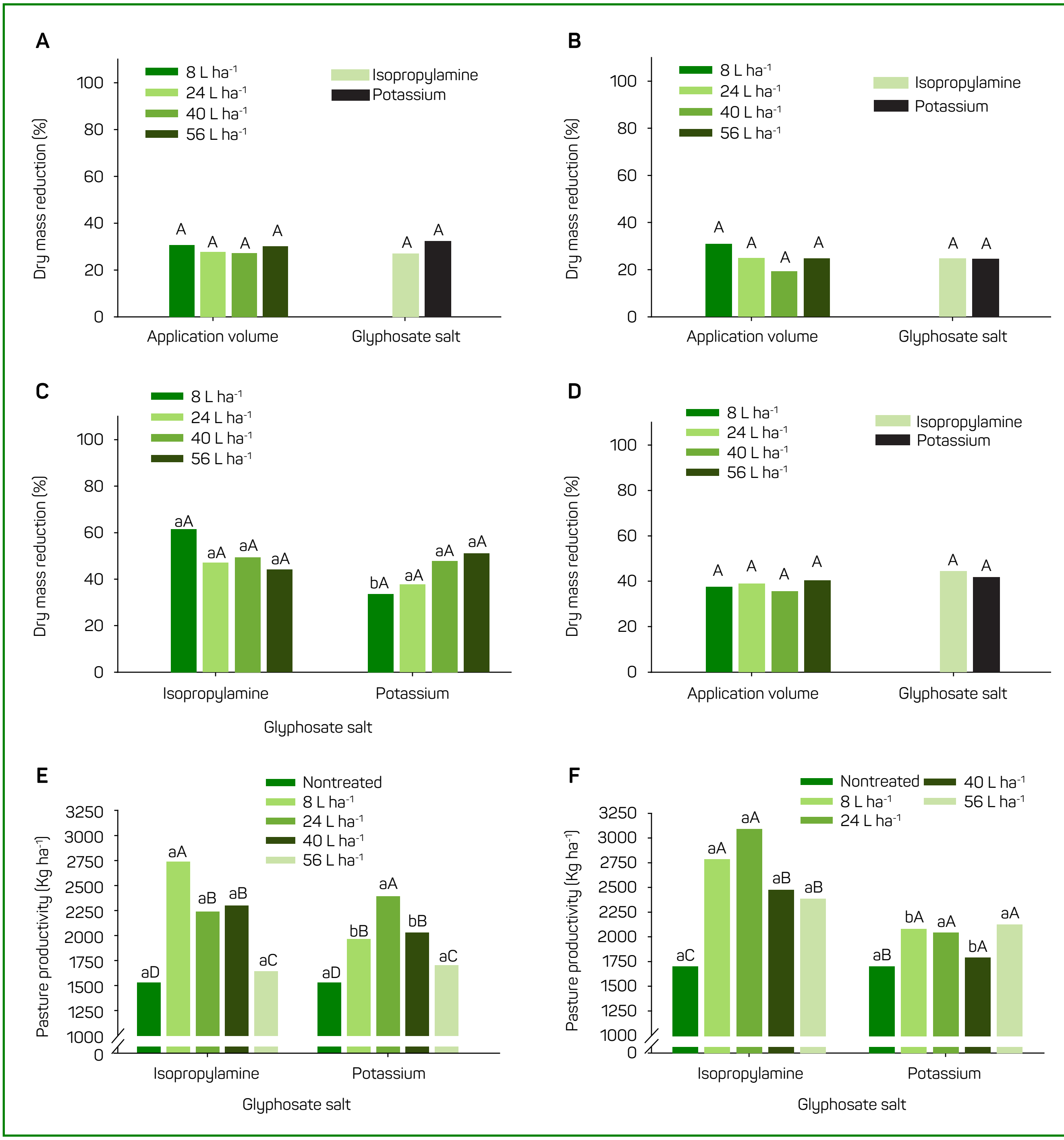

Figure 5 - Aboveground dry mass reduction of *Eragrostis plana* at 35 DAA (A and B) and 90 days after mowing (360 DAA) (C and D), and pasture productivity (E and F) at 35 DAA treated with two glyphosate salts and four volumes of application applied with a rope wick applicator in the summer (A, C, E, and G) or winter (B, D, F, and H). Bars with similar lowercases and uppercases indicate similar effects of glyphosate salts and volumes of application, respectively (Scott-Knott, $p<0.05$)

3.3 Productivity of pasture and benefits of *E. plana* control with localized application equipment

The interaction effect of glyphosate salt formulations and doses on *E. plana* control was significant in the summer, but not in the winter. Productivity of the pasture in the summer was higher in all treated plots than the nontreated check, except for the lower dose of isopropylamine salt (Figure 3 E). The diammonium salt of glyphosate at the higher dose was significantly more productive than other treatments, with a growth of 800 kg ha^{-1} higher than the check. In the winter experiment, there was no significant interaction between the herbicides and doses used (Figure 3 F). The treatments that resulted in the greatest pasture productivity gains were those that received isopropylamine and diammonium salts. No differences in pasture productivity were observed between the two doses averaged over formulations.

In the application volume study, the interaction between the glyphosate salts and volumes were significant in both seasons. Pasture productivity with application volumes of 40 and 56 L ha^{-1} with the isopropylamine salt of glyphosate was lower than the productivity when volumes of 8 and 24 L ha^{-1} were used in the summer (Figure 5 E) and winter experiments (Figure 5 F). For the potassium salt, only the dose of 56 L ha^{-1} was inferior than the other treatments in the summer experiment. Application volumes of 8 and 24 L ha^{-1} produced 500 kg ha^{-1} more dry matter in comparison with 40 and 56 L ha^{-1} application volumes, and 1,000 kg ha^{-1} more than the nontreated check. The same effect was not observed for treatments with the potassium salt of glyphosate.

Treatment evaluation at 90 days after mowing (360 DAA) showed a high rate of *E. plana* resprouting in the winter and summer experiments (Figures 2 E, 3 E, 4 B, and 5 B). This indicates that the clumps were partially controlled initially, then began to regrow in the next growing season. *E. plana* is a difficult species to control, mainly in a selective approach in natural pastures. Thus, the control methods and equipment should not be evaluated with the same control parameters used for weeds in crop production systems where herbicides are sprayed in weeds at the early developmental stages. The results obtained indicate a 60–80% control level, even at 150 DAA. Even after mowing to simulate the effect of grazing, the control was still 30-40% at 360 DAA.

Pasture productivity was higher in the treatments that receive herbicide (Figures 3 D and F and 5 D and F) ensuring the efficiency of the Campo Limpo® selective herbicide delivery method. Pasture productivity is directly related to reduced growth of *E. plana*, as discussed earlier. The effective and early interruption of the development of *E. plana* clumps treated with glyphosate, mainly with diammonium salt formulation, allowed the pasture to emerge and resume its growth. The only reservation with respect to the equipment's selectivity was with the application volume of 56 L ha^{-1}. At the time of treatment evaluations, we also observed dead native forage species around the clumps of *E. plana,* where the treatment was applied using a higher application volume. This could explain the reduced pasture productivity at high application volumes. Therefore, the Campo Limpo® applicator may have the undesirable effect of causing damage to the pasture grasses at application volumes of 56 L ha^{-1}.

Selective control is one of the greatest advantages of the Campo Limpo® applicator. The herbicide delivery method promoted control of *E. plana* clumps without the necessity to be applied by spraying all plants in the pasture, which results in biodiversity losses. This means that grasslands in the Pampa biome, which have long been affected by *E. plana* (Medeiros et al., 2007, Guido et al., 2019), may be recovered without eliminating all species present, which would happen as a result of broadcast spraying. Furthermore, the control of *E. plana* allows for rapid recovery of pastures, which can be seen in the pasture productivity evaluations as early as 90 DAA (Figures 3 E and F, 5 D and F). Since the selective control was based on height differences, directed management of *E. plana* may be applicable to controlling other weeds with a height differential over pasture species, such as *Eryngium* spp., *Baccharis trimera*, *B. coridifolia*, and *Eupatorium buniifolium*, which are also considered important pasture weeds. This form of direct herbicide application, without the need for spraying, also makes the application safer since it reduces drift and unwanted inhalation by the operator (Harrington, Ghanizadeh, 2017).

The efficiency of *E. plana* control using Campo Limpo® equipment may be increased by repeating the application of glyphosate and, principally, by improving pasture management concerning fertilization, animal grazing pressure, and changes in the species composition to include better adapted and more competitive species, among other practices. Although successive applications may favor evolution of herbicide resistance, the adoption of integrated weed management and utilization of other herbicides with different site of action reduces the possibility of resistance evolution (Evans et al., 2016). Despite its demonstrable efficiency at controlling *E. plana* clumps, the use of exclusively chemical control, whether via conventional application or using the Campo Limpo® applicator, is unlikely to totally control or eradicate the species from natural pastures. Adopting other interference methods related to animal and pasture management is vital to reduce the presence of *E. plana* in pastures and its resulting damage.

4. Conclusions

The present findings indicate the efficiency of Campo Limpo® equipment at controlling *E. plana* and provide a greater understanding of the proper specifications with respect to the main application variables. In addition to the higher control levels observed for treatments using a diammonium salt of glyphosate formulation, it is also important to note that glyphosate formulated with isopropylamine salt, which may be the most common formulation on the market, showed lower efficiency than the other salts in most analyses, indicating that it may not be the best alternative for this application method. Another important result is the observation of the best time of year to ensure the effective control of the invasive species. Winter applications, which occur while the plant is dormant or growing less rapidly, are less effective and therefore not justified due to their inability to kill all the tillers in a clump, resulting in high regrowth rates compared with the summer application. The lack of differentiation between the application volumes of 8 and 50 L ha^{-1} indicates that it might be possible to change the volume used in a given application to suit the specific needs without compromising the overall efficiency of the operation.

Author's contributions

All authors read and agreed to the published version of the manuscript. AMJ, MG, and NBP: conceptualization of the manuscript and development of the methodology. MG, GMT, IM, PSA, and LC: data collection and curation. MG, LC, and GMT: data analysis. AMJ, MG, GMT, and FPL: data interpretation. AMJ, NBP, and FPL: funding acquisition and resources. AMJ, NBP, and FPL: project administration. AMJ: supervision. MG and AMJ: writing the original draft of the manuscript. AMJ, MG, and GMT: writing, review, and editing.

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