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Weed control in natural grasslands: A case study using a perennial native forb from the South American *Campos*

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Abstract Management of native weeds in natural grasslands is a challenging task. Often, recommendations are based on short-term studies of the response of weed cover and density to different control methods. However, perennial species well adapted to disturbances typically recover from commonly used control techniques. In this long-term study, we focused on a rosette native to the South American *Campos*: *Eryngium horridum* Malme (Apiaceae). This plant is strongly avoided by cattle due to its spiny leaves and tends to form dense patches, reducing the available grazing area. We aimed at understanding how key demographic processes, such as size-related plant survival and seedling establishment, are affected by different control treatments. For this, *E. horridum* cover, density and size structure were assessed over three years in response to mechanical, chemical and integrated (mechanical + chemical) control methods. In a field experiment, we used a weighted rim and a wiper applicator with 2,4-D + picloram for the mechanical and chemical control, respectively. Cover was reduced by control treatments ('control phase'), but this was not sustained in the long term ('recovery phase'). Regardless of the method used, control success was closely related to effects on population size structure. Mortality was high and rapid in large rosettes, which effectively led to a rapid and widespread cover reduction in all control treatments. However, only herbicide reduced rosette density delaying the recovery phase. Seedling density was low during the experimental period and scarcely affected by treatments. We conclude that cover reduction depends on removing all large rosettes, but recovery is related both to the size of the remaining pool of small rosettes and to the ability of buried rhizomes to resprout. Finally, we highlight the importance of finding a balance between productive goals and biodiversity conservation. In that context, integrated control successfully reduced cover, delayed recovery and minimised the amount of herbicide used. Abstract in Spanish is available with online material.

Key words: demography, *Río de la Plata* grasslands, undesirable species, Uruguay.

INTRODUCTION

The *Río de la Plata* grasslands region extends over 750 000 km^2 in South America, and it has two subregions: *Campos*, located mainly in Uruguay and southern Brazil, and *Pampas* located in eastern Argentina (Soriano 1992). This region harbours large areas of native grasslands used for extensive meat and wool production (Pallarés *et al*. 2005; Baeza & Paruelo 2020). Weedy native plants reported for *Campos* include forbs, shrubs and tussock grasses (Crancio *et al*. 2007), most of which are perennial and tolerate fire, grazing (Fidelis *et al*. 2008, 2010), drought and frost. Since these plants are scarcely consumed by cattle (Da Trindade *et al*. 2017; Azambuja 2019), they act as a vertical and horizontal barrier that limits forage access. Consequently, short-term intake rate and bite mass decrease, and grazing time increases as compensation (Da Trindade *et al.* 2012, 2015). Besides, weedy native plants make animal husbandry difficult, especially vigilance tasks during calving or myiasis detection.

Rangeland weeds have several impacts on livestock systems, and problematic species include native and exotic plants which are generally controlled by chemical, mechanical and cultural techniques (DiTomaso 2000; Brown & Bestelmeyer 2012). Nevertheless, a combination of methods is often needed to achieve successful results in the long term (DiTomaso *et al.* 2010). To plan the best sequence of management techniques, it is important to identify critical stages or processes that disproportionally influence population growth (Ghersa *et al*. 2000; Magda *et al*. 2004). Size, despite being an important life-history characteristic (Kirkpatrick 1984), has been poorly used in rangeland weed control studies. To explore this, we used one of the most problematic plants, the perennial forb *Eryngium horridum* Malme (Apiaceae), as focus species.

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Eryngium horridum is a perennial rosette that has numerous spiny linear leaves up to 65 cm long and 2 cm wide, and the inflorescence axis can reach 2 m or more (Burkart & Bacigalupo 2005). It has a thick rhizome with great resprouting capacity, and each plant can produce up to 150 000 viable seeds (Elizalde *et al.* 2005). Mowing or dragging a heavy object (e.g. trunk) is useful to achieve some cover reduction (Carámbula *et al.* 1995). But responses of rosette density are less clear: it can decrease, increase or remain unchanged, depending on timing and frequency of treatment. For instance, Carámbula *et al.* (1995) reported that after two consecutive years of mowing in spring, rosette density increased up to 40% and cover only reduced by 10%. In a much severe treatment, Lallana *et al.* (2006) did not find an effect on rosette density one year after passing an offset disc harrow. Autumn control reduces cover and minimises the density increase (Carámbula *et al.* 1995), whereas auxinic herbicides (2.4-D + picloram) used alone or after mowing tend to be effective in reducing both rosette cover and density (Lallana *et al.* 2005; Lallana 2007). In all cases, recovery of *E. horridum* has been observed (Lallana *et al.* 2005). Ríos (2007) mentions that 30 days after herbicide application, rosettes seem to be dead, but 30 days afterwards, resprout begins. We deem necessary to complement the pure agronomical approach of many of these studies and include ecological management principles.

Here, we assess the success of mechanical, chemical and integrated (mechanical + chemical) control methods in reducing *E. horridum* canopy cover. The dynamics of both initial reduction and post-control recovery were related to changes in rosette population size and structure against the baseline provided by the species natural dynamic in an untreated treatment. Our aim is to gain understanding of the short- and long-term effects of control methods on *E. horridum* population to support management decisions at the farm level.

METHODS

Study site

The experiment was located in a natural grassland paddock at the Palo a Pique Experimental Unit of the National Institute of Agricultural Research (INIA), located in Treinta y Tres, Uruguay (33°24′S; 54°50′W, 50 m a.s.l.). According to the Köppen–Geiger classification, the climate in Uruguay is subtropical humid (Cfa). The monthly mean temperature ranges from 22.8°C in January to 10.8°C in July. Mean annual precipitation is 1310 mm, on average evenly distributed through the year, with high interannual variability. During the experimental period, soil water content, estimated through a theoretical water balance, was high in cool months and low in summer (Fig. 1).

The topography of the study site is softly hilly, and the soil is an Abruptic Argiaquoll (Durán *et al.* 2006). Vegetation has two strata: the upper one covers 30 % and most frequent species are *E. horridum* and *Baccharis trimera* (Less.) DC, and the lower stratum covers around 65 % and is dominated by perennial grasses with C4 metabolism. The stand corresponds to the *E. horridum–Juncus capillaceus* community described in Lezama *et al.* (2019).

Experimental design

A three-year field experiment (from December 2013 to January 2017) was established in a randomised complete block design with three replicates; experimental unit dimension was 30 × 40 m. We evaluated three *E. horridum* control methods: chemical control (CC), mechanical control (MC) and integrated control (IC). Also, untreated plots (U) were included. Controls were applied three times**:** late spring 2013 and fall and late spring 2014 (12/27/2013; 4/28/2014; and 12/26/2014, respectively). The experimental area was continuously grazed.

A weighted rim passed two times across the experimental unit was used for MC. This tool comprises two cart rims joined together in the upper part by a train rail. It weighs 322 kg and has an operating width of 3.45 m. This kind of tool is usually craft made by farmers to cut and remove some rhizomes. For CC, we used 2.4-D + picloram (240 + 64 g L^{-1}) with a nonionic surfactant. The application was done with a wiper applicator, and the solution was composed of 1/3 of herbicide and 2/3 of water. The doses of herbicide for the first, second and third applications were 19, 7 and 3 L ha^{-1}, respectively. For IC, we used the sequence of MC in late spring 2013, CC in fall 2014 and MC in late spring 2014. Herbicide dose was 7 L ha^{-1}.

Data collection

Eryngium horridum was characterised by its canopy cover, rosette density, seedling density and rosette diameter. We used rosette diameter to describe size structure through the cumulative rosette diameter and the cumulative abundance profiles.

Daubenmire (1959, p. 50) defined canopy cover as ‘an approximation of the area over which a plant exerts its influence upon other components of the ecosystem. It is not intended to estimate shading of the ground’. Although it is generally used in forest studies, it also has been used in grasslands (Wilson 2011). This method was used to emulate farmers’ perception; they do not only see the problem as the presence of *E. horridum* but the ‘waste’ of area and forage that its patches create. For that purpose, in three fixed transects, each of 20 m long, we quantified the length of *E. horridum* patches, including the rosettes and other plants between them. The beginning and end of each patch were defined by leaf line interception. The sum of all patches was expressed as a percentage of total transect

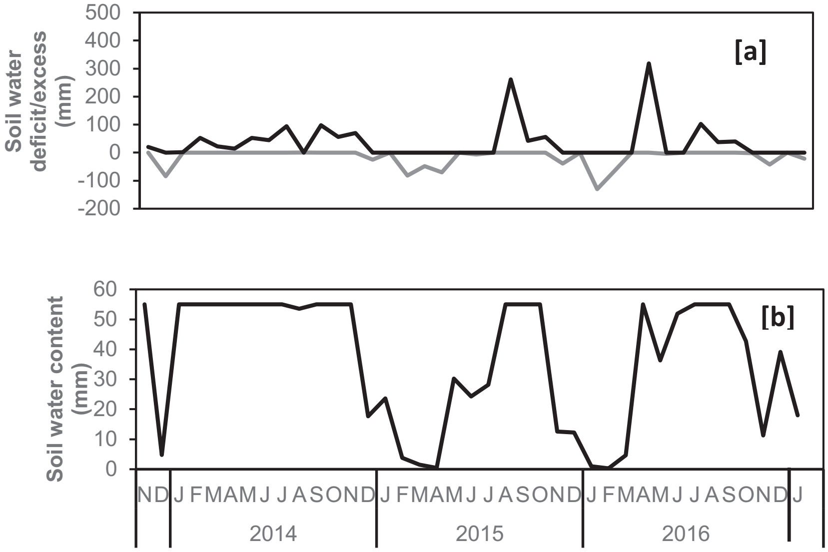

Fig. 1. Monthly soil water deficit (grey) and excess (black) (mm) (a), and soil water content (mm) (b) at the experimental site. Data were obtained from a theoretical water balance.

length. Rosette density (rosettes m^{-2}) and seedling density (seedlings m^{-2}) were counted in six fixed quadrants of 1 m^2. While we counted, we also measured the length of the longest green leaf of each rosette, and the double of this value was used as rosette diameter. Details of measurement procedures and dates are provided in Fig. 2 and Table 1, respectively.

Diameter values were used to calculate cumulative rosette diameter and cumulative abundance profiles, as shown in Eqns (1) and (2), respectively.

$$\text{Cumulative rosette diameter}\,(\text{cm m}^{-2}) = \left(\sum_{i=0}^{27} f_i \cdot \left(\frac{m_i + m_{i-1}}{2}\right)\right)/6 \qquad (1)$$

where i is diameter class of rosettes, from $i = 0$ to $i = 27$ (0 and 130 cm, respectively) being the class length of 5 cm; f_i is the absolute number of rosettes in class i; and m_i is diameter (cm) of class i (0,5,10,…, 130).

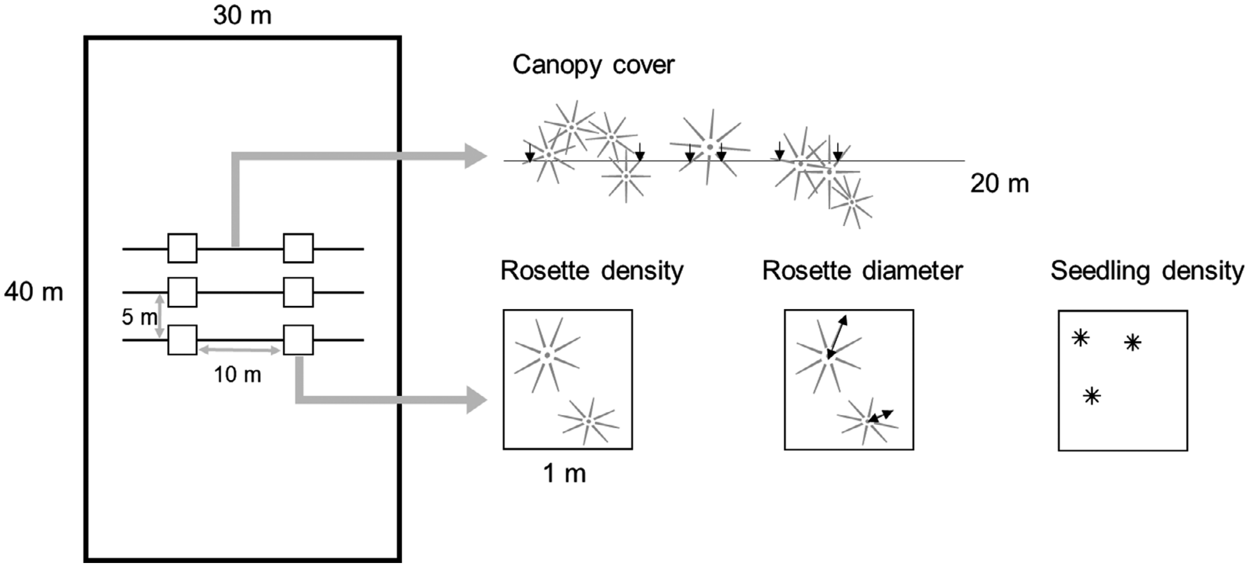

Fig. 2. Schematic representation of transect and quadrant location in plots (left) and of data collection (right). Arrows in canopy cover represent the beginning and end of each patch determined by leaf line interception. Rosette diameter was estimated as twice the length of the longest green leaf. Drawings do no respect scale.

Table 1. Data collection dates of canopy cover, rosette and seedling density, and rosette diameter

	Canopy cover	Rosette density and diameter	Seedling density
Dec. 13	x	x	
First control			
Feb. 14	x		
Apr. 14	x	x	x
Second control			
May 14	x		
Jul. 14		x	x
Aug. 14	x		
Oct. 14	x	x	x
Dec. 14	x		
Third control			
Jan. 15		x	x
Apr. 15	x	x	x
Feb. 16	x	x	x
May 16	x		
Nov. 16	x		
Jan. 17		x	x

Control treatments were applied in December 2013, April 2014 and December 2014.

$$\text{Cumulative abundance profile}\,(t) = \sum\nolimits_{u=1}^{12} x(u) \qquad (2)$$

where $x(u)$ is the recorded abundance of *E. horridum* in size class u.

We ordered rosette diameter values in twelve discrete classes t ($t = 1, \ldots, 12$) from 10 to 120 cm, and seedlings were excluded.

Cumulative abundance profiles were defined by De Cáceres *et al.* (2013, p. 1168) ‘as a function that takes a value of size as input and returns the cumulative abundance of organisms whose size is equal to or larger than the input value’. If the population is sampled into s-ordered classes of sizes, from small to large, and the abundance of individuals within each size class t ($t = 1, \ldots, s$) is recorded, cumulative abundance profile is represented as a vector of s values and the value for a given class t is the sum of abundances in all classes $u \geq t$. An example of the calculation of the cumulative abundance profile is presented in Appendix S1.

Cumulative rosette diameter and cumulative abundance profile provide complementary information to characterise the aggregated structure of *E. horridum*. Several small rosettes are located beneath medium and large rosettes, frequently with their leaves poorly expanded. So, the sum of all rosette diameter per surface gives a notion on the potential rosette expression, and the relative importance of each rosette size is well represented by the abundance profile.

Data analysis

Treatment effect in canopy cover and rosette and seedling density was compared using repeated-measures ANOVA. We adjusted different models for each variable and selected the ones with a lower Akaike information criterion. Canopy cover was described using a linear model and rosette density with a generalised linear model, using Poisson distribution. Factors considered as fixed on both models were as follows: treatment, month, treatment × month and block. Quadrant was also included for the rosette density model. Nagelkerke pseudo-*R*-squared was used to indicate the power of explanation of the model. Generalised linear models explored to describe seedling density did not converge, so we used generalised additive models. The best model considered the factors treatment, month and treatment × month and as random factors block and quadrant. Treatment means were compared using least squared means with Tukey’s test ($\alpha = 0.05$). Shapiro–Wilk test was used to test the homogeneity distribution of residuals in canopy cover. To discard initial differences, we analysed separately canopy cover and rosette density data from December 2013.

Simple linear regression models were fitted between canopy cover and rosette density and between canopy cover and mean cumulative rosette diameter. Cumulative abundance profile’s comparisons were done by generating a dissimilarity matrix of coefficient percentage difference (alias Bray–Curtis). Afterwards, the treatment effect was compared through a permutational multivariate analysis of variance (Anderson 2001), as in Fritschie and Olden (2016).

Software

Analyses were carried out with R software version 3.6.1 (R Core Team 2019), using the following packages: lme4 package (Bates *et al.* 2015), nmle (Pinheiro *et al.* 2017), car (Fox & Weisberg 2019), multcomp (Hothorn *et al.* 2008), lsmeans (Lenth 2016), rcompanion (Mangiafico 2019), mgcv (Wood *et al.* 2016), stats (R Core Team 2019), vegan (Oksanen *et al.* 2019) and vegclust (De Cáceres *et al.* 2010).

RESULTS

At the begging of the experimental period, plots had on average 36% of *E. horridum* canopy cover and 7 rosettes m^{-2} with diameter from 10 to 100 cm, evenly distributed. No significant differences among plots assigned to treatments were detected before control application (December 2013, Fig. 3a,b and Fig. 5). Control of *E. horridum* affected its canopy cover, rosette and seedling density, and

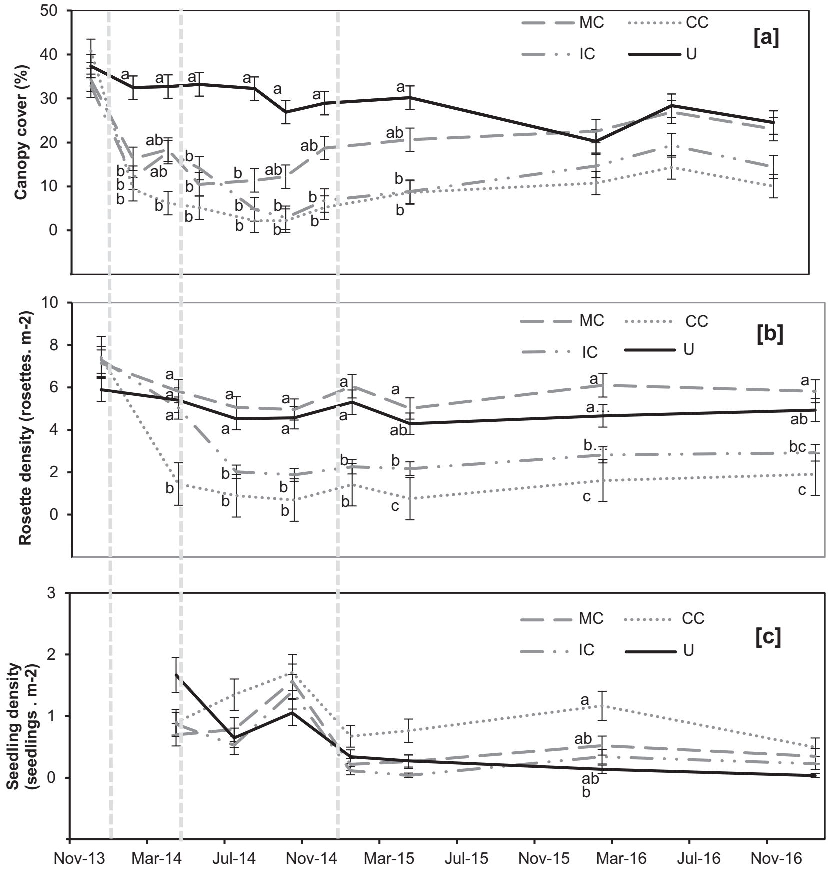

Fig. 3. Canopy cover, rosette and seedling density of *Eryngium horridum* in response to control treatment: mechanical (MC), chemical (CC), integrated control (IC) and untreated (U). Points represent adjusted means and bars standard errors. Means followed by the same letter on the same date do not differ (Tukey's test, $P > 0.05$). Dates with no letters indicate that no differences among treatments were found. Vertical dashed lines across panels indicate control application (December 2013, April 2014, and December 2014).

treatment × time interaction was found (Fig. 3, Table 2). Size structure was also affected by treatments (Fig. 5).

From February 2014 to November 2016, canopy cover averaged 30% in U and was rather stable, and minimal and maximal values were 20% and 33% (Table 3, Fig. 3a). The minimum was registered in February 2016, after a period of low water content in soil (Fig. 1). After the first control application (December 2013), CC also behaved rather stable; the average, minimal and maximal values, in parenthesis, were 7% (2–14%). Meanwhile, IC and MC presented more variation, the average, minimal and maximal values, in parenthesis, were in IC 12% (3–19%) and on MC 18% (10–27%).

Comparison between treatments showed significant differences in canopy cover among control versus untreated from February 2014 until April 2015. After first control, in December 2013, canopy cover was rapidly reduced by all control treatments to a similar extent. So, by February 2014 control treatments had on average 13% with no differences among them (Fig. 3a). Rapidly, treatments that received weighted rim (MC and IC) increased canopy cover, and by April 2014, they were not different from U. After second control, in April 2014, until August 2014, control treatments had lower canopy cover than U, and again, no difference was detected between them. From October 2014 onwards, MC augmented its canopy cover, with no differences with U during the rest of the period, a fact that was not reversed by third control in December 2014. Meanwhile, IC and CC had lower canopy cover than U until April 2015. From February 2016 until the end of the experimental period, no differences between treatments were found. At the last observation, 3 years after first control, canopy cover was 24%, 23%, 14% and 10% on U, MC, IC and CC, respectively (Fig. 3a).

Rosette density of *E. horridum* was invariable in U, averaging 5 rosettes m^{-2} during the three years of experimental (Fig. 3b, Table 3). The application of the weighted rim did not reduce rosette density, neither in the short term nor in the long term. Even after three applications, MC did not differ from U.

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Table 2. ANOVA results for canopy cover, rosette density and seedling density

	d.f.	Chi-sq	Pr(>Chi)
Canopy cover			
Treatment	3	375.358	<2.2e-16
Month	9	50.672	8.051e-08
Block	2	47.417	5.053e-11
TreatxMonth	27	68.076	2.101e-05
Pseudo r^2 (Nagelkerke) 0.875			

	d.f.	Deviance	Resid. d.f.	Residual dev.	Pr(>Chi)
Rosette density					
Null			503	1408.27	
Treatment	3	388.01	500	1020.26	<2.2e-16
Month	6	44.78	494	975.48	5.174e-08
Block	2	47.75	492	927.73	4.284e-11
Quad	66	603.82	426	323.91	<2.2e-16
TreatxMonth	18	47.42	408	276.49	0.0001837
Pseudo r^2 (Nagelkerke) 0.897					

	d.f.	Chi-sq	Pr(>Chi)	
Seedling density				
Parametric terms				
Treatment	3	4.816	0.18579	
Month	6	22.372	0.00104	
TreatxMonth	18	54.985	1.29e-05	
	edf	**Ref. d.f.**	**Chi-sq**	***P*-value**
Approximate significance of smooth terms				
s(Block)	5.694e-04	2e00	0.0	0.932
s(Quad)	5.269e+01	6.8e+01	418.3	<2e-16
R-sq.(adj) = 0.581 deviance explained = 58%				

On the other side, one herbicide application was enough to attain a great reduction on rosette density, particularly on IC averaged 2.3 rosettes m^{-2} from April 2014 onwards (Fig. 3b). Moreover, CC did not have an extra reduction after the second nor the third herbicide application (Table 3), with an average of 1.2 rosettes m^{-2} during the experimental period. Seedling density was very low during the whole

Table 3. Results of mean comparison over time for mechanical, chemical and integrated control plus an untreated treatment (MC, IC, CC and U, respectively) for canopy cover, rosette density and seedling density

	Feb. 14	Apr. 14	May 14	Jul. 14	Aug. 14	Oct. 14	Dec. 14	Jan. 15	Apr. 15	Feb. 16	May 16	Nov. 16	Jan. 17
Canopy cover													
U	a	a	a		a	a	a		a	a	a	a	
MC	ab	ab	b		b	ab	ab		ab	ab	a	ab	
IC	ab	ab	ab		ab	b	ab		ab	ab	a	ab	
CC	a	a	a		a	a	a		a	a	a	a	
Rosette density													
U		a		a		a		a	a	a			a
MC		a		a		a		a	a	a			a
IC		a		b		b		b	b	ab			ab
CC		ab		ab		b		ab	b	ab			a
Seedling density													
U		a		abc		ab		bc	bc	b			bc
MC		ab		ab		a		b	b	ab			b
IC		ab		ab		a		b	ab	b			b
CC		a		a		a		a	a	a			a

The same letters within a row imply that means were not different according to Tukey's test ($P > 0.05$).

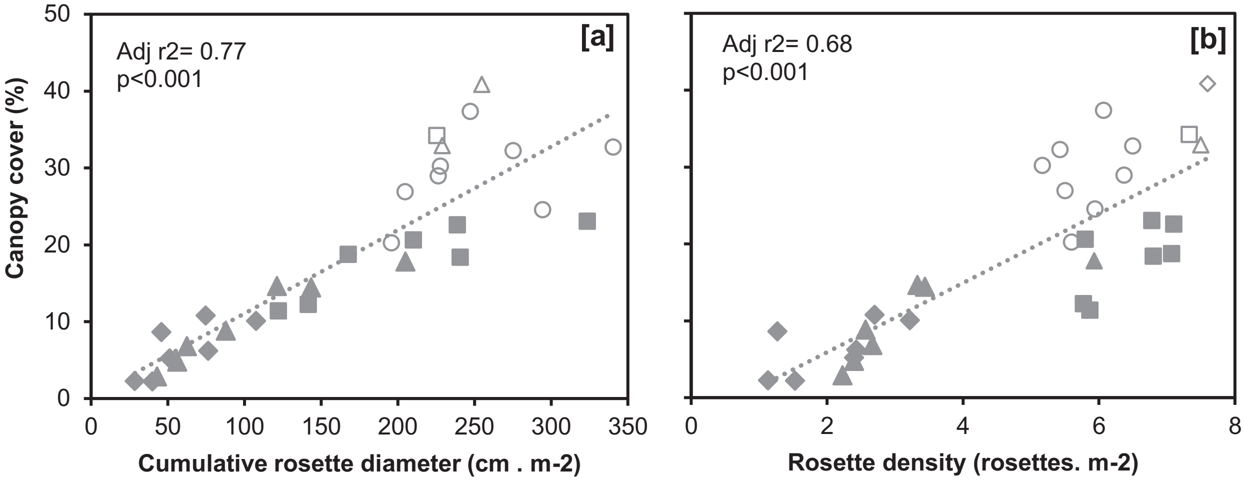

Fig. 4. Relationship between canopy cover and cumulative rosette diameter (a) and rosette density of *Eryngium horridum* (b). Control treatments are represented as closed symbols: mechanical (squares), chemical (rhombi) and integrated (triangles). Open symbols represent untreated plots (circles) and data of December 2013 (before control application) from plots that were assigned to control treatments. Lines show simple linear regression (n = 32, adjusted R^2, and P values are shown).

experimental period and scarcely affected by treatments (Table 2, Fig. 3c). Average cumulative rosette diameter (cm m^{-2}) from April 2014 to January 2017 was 252, 206, 103 and 61 for U, MC, CC and IC, respectively.

Canopy cover correlated well with cumulative rosette diameter (r^2 = 0.77), but dispersion increased with greater values. In fact, a breakpoint is clear after 20% of canopy cover and 200 cm m^{-2} of cumulative rosette diameter; most of those values were from U an MC (Fig. 4a). The correlation between rosette density and cumulative rosette diameter was weaker (r^2 = 0.68; Fig. 4b).

The population size structure was affected by control treatments. After the first control date, larger rosettes were eliminated (>60 cm diameter; April 2014, Fig. 5). The second control date exacerbated this phenomenon: by July 2014, *E. horridum* populations in control treatments were dominated by small rosettes (<30 cm diameter). This occurred in all control treatments, independently of the effect on rosette density. Therefore, in MC the loss of large individuals would have been compensated by the appearance of smaller ones. After October 2014, a gradual recovery of medium- and large-sized rosettes began in all control treatments, and a tendency of convergence in structure is shown until the last date. This was more rapid in MC: by April 2015 onwards, it had a very similar abundance profile than U (Fig. 5).

DISCUSSION

Eryngium horridum density, both of adult rosettes and seedlings, rosette size structure and canopy cover, were all rather stable throughout the three years of experimental period in the untreated plots (Table 3). In contrast, in all treated plots two distinct phases of canopy cover were identified: control and recovery (Fig. 3a). Control strategies behaved rather similar in the extent of the initial decline in canopy cover and differed on how rapidly they recovered; mechanical control was the least effective and chemical the most effective one (Fig. 3a,b). *Eryngium horridum* population dynamic was driven by mature individuals and their resprouting. Seedling density was low in all treatments throughout the experimental period (Fig. 3c). Our results are in accordance with a previous study by Fidelis *et al.* (2008) that indicates that seedling density is generally low and that disturbance (grazing and fire, control in our case) is not a prerequisite for seedling establishment.

The control phase lasted for approximately one year (December 2013–October 2014) and was characterised by a rapid and important reduction in the number of large rosettes (>60 cm). In fact, after the second control date, *E. horridum* plots were mostly formed by small rosettes (<30 cm). Control treatments (MC, CC and IC) behaved similarly at reducing canopy cover because they were equally effective at removing large rosettes. Large rosettes disproportionately increase canopy cover because, as they grow in patches, the inter-rosette area increases. The recovery phase was characterised by a steady increase in canopy cover and the number of medium (40–60 cm) and large rosettes (>60 cm). Recovery started earlier and went faster in MC so that by April 2015, its canopy cover and size structure were indistinguishable from U. This phase also occurred in IC and CC, but herbicide delayed this phase, and

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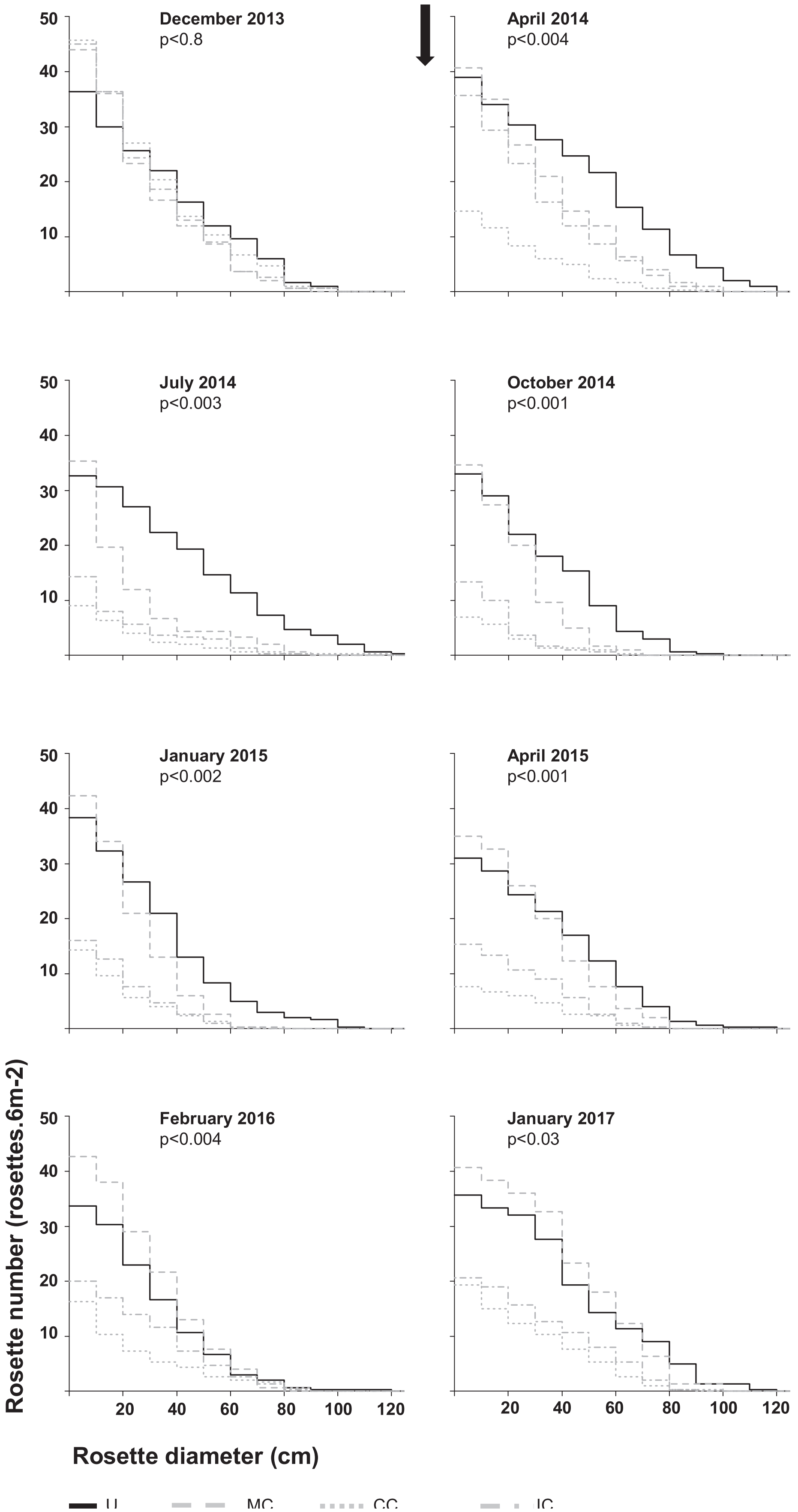
December 2013
p<0.8
April 2014
p<0.004
July 2014
p<0.003
October 2014
p<0.001
January 2015
p<0.002
April 2015
p<0.001
February 2016
p<0.004
January 2017
p<0.03
50
40
30
20
10
20
40
60
80
100
120
Rosette number (rosettes.6m-2)
Rosette diameter (cm)
U
MC
CC
IC

Fig. 5. Rosette diameter structure of *Eryngium horridum* in response to control treatment: mechanical (MC), chemical (CC), integrated (IC) and untreated (U). Arrows indicate control dates (December 2013, April 2014 and December 2014). Lines represent block average cumulative abundance profiles. The treatment effect was tested with permutational multivariate ANOVA. We used a distance matrix obtained from cumulative abundance profiles and percentage difference (alias Bray–Curtis) as a dissimilarity coefficient.

canopy cover recovered by February 2016. However, rosette density and size structure were still different from U at the end of the experimental period. By that time, CC and IC had few rosettes larger than 60 cm.

Plant size and canopy cover proved to be adequate to describe the abundance of native weeds from the farmer`s perspective. Besides, both variables are easy and simple to measure. Although a reduction in mean rosette diameter in response to control was previously reported by Lallana *et al.* (2005, 2006), size structure seems a more robust approach to analyse how control methods induced population changes. Our results lend support to the idea that short-term control success is achieved when few large rosettes are eliminated and that long-term control success depends on reducing the number of total rosettes. Nevertheless, for the design of long-term management plans a deeper understanding of the structure and dynamics of *E. horridum* patches is still necessary. Smaller patches seem to be mainly composed of small- and medium-sized rosettes, and the proportion of rejected forage between rosettes is generally low. Instead, larger patches could be formed by many medium and large rosettes or by few medium and large rosettes and plenty of rejected forage between them. This would explain the dispersion on values of accumulated rosette diameter when canopy cover exceeded 20% (Fig. 4). On the other hand, when forage is scarce (e.g. during a drought or overgrazing), the consumption of forage previously rejected could increase, and even rosettes may be browsed (Azambuja 2019). So, patch size and available forage are important sources of variation in the proportion of rosette/rejected forage within patches, which on turn could affect canopy cover. High levels of canopy cover could be reduced directly by reducing *E. horridum* population (browsing) or indirectly by patch fragmentation (consumption of rejected forage).

Chemical or mechanical control of *Eryngium horridum*?

Mechanical and chemical control methods have shown the opposite effects on plant performance. On the one hand, above-ground biomass removal or rhizome cutting promotes resprouting, especially in spring (Carámbula *et al.* 1995; Lallana *et al.* 2006; Fidelis *et al.* 2008). Fidelis *et al.* (2008) counted 80% of rosettes with at least one resprout two weeks after all above-ground biomass was cut, and reproductive individuals had between 2 and 6 new rosettes per plant. Carámbula *et al.* (1995) reported a 40% increase in population size after two years of mowing in spring. On the other hand, herbicides – such as 2.4-D + picloram – are known to reduce rhizome survival, and consequently resprouting capacity decreases (Lallana *et al.* 2003, 2005). But when wiper applicators are used, some rhizomes survive, and within few months, resprout begins (Ríos 2007).

Wiper applicators are widely used to control weeds in grasslands. The benefits assigned to this technology are the low doses of herbicide used, virtually no drift and reduced damage to nontarget species. But, in practice, variable results have been observed, and knowledge about the concentration needed to kill weeds and the amount of herbicide deposited by each device needs to be improved (Moyo 2008; Harrington & Ghanizadeh 2017). Poor control may be due to plant escape, failures in herbicide deposition (Harrington & Ghanizadeh 2017) or absorption (Billard *et al.* 2005) and lower doses than lethal or plant detoxification (e.g. by root exudation of herbicide, Hickman *et al.* 1990). In our experiment, on the first application date in CC grasses were flowering profusely, and as a consequence, the dose was extremely large (19 L ha^{-1}) compared to label recommendations (5 L ha^{-1}). Beyond that, the wiper application produced the most effective and longer-lasting control of *E. horridum* (Figs. 3a,b).

We conclude that both chemical and mechanical controls are effective to rapidly reduce cover. Mechanical control would have to have been repeated annually to attain the same cover. Our experiment also evidences that the presence of large rosettes is a prerequisite to reduce canopy cover to a great extent. Indeed, if control is repeated too frequently when rosettes are still small, changes in cover would be negligible (e.g. third control date in this study). Therefore, to establish reintervention moments at the farm level it would be important to measure the number of large rosettes. An approximate threshold that could be drawn from the present study is 2 or more rosettes larger than 60 cm per square meter.

The drastic reduction of rosette density observed in response to herbicide application, and the poor establishment of seedlings suggests that repeated chemical treatments could effectively eliminate *E. horridum*. Potentially, this would affect community structure by two processes that need to be further assessed. Plant survival and reproductive output of numerous herb and forb species could be directly affected by auxinic herbicides. Also, palatable grasses may be reduced, since the positive role that *E. horridum* rosettes have as a grazing refuge would be removed (Fidelis *et al.* 2009; Noëll Estapé *et al.* 2013).

Our underlying conception is that weedy natives must not be eradicated from *Campos* and a balance between ecosystems services provision and productive goals must be found. The path to this goal seems to be integrated control: the sequence of mechanical followed by chemical control. This is the most cost-effective and sustainable approach, as it combined the rapid and cheap reduction of cover, provided by mechanical treatments, and the delayed post-control recovery of the chemical treatment, mediated by a reduction of rosette density but with considerably less use of herbicide (7 *vs.* 30 L ha^{-1}).

Native weeds control: past, present and future

Campos grasslands have long been underestimated as a productive resource. The poor performance of livestock systems was often adjudicated to low biomass production of native grasslands. In fact, during the 19th century, *Campos* were somehow related to national economy delay (Astori 1979). To overcome this, technologies including seeding of exotic legumes with phosphorus addition were promoted. In that context, where the desired pastoral environment was homogenous, weedy natives were perceived as part of the problem. So, for decades investigation efforts focused on finding the most effective control method (Spangenberg 1930; Cerri *et al.*1991).

From the 2000s onwards, native grasslands have been positively perceived. Now, there are several techniques available that increase livestock productivity, with low external input. Besides, key ecosystem services provided by *Campos* have been highlighted (Modernel *et al.* 2016). Nowadays, it is widely accepted that vertical and structural heterogeneity is part of grasslands (Fuhlendorf *et al.* 2017) and that fact must be accepted, treasured and promoted by farmers. Moreover, the negative influence of weedy natives on the grazing process is being addressed more accurately. For instance, Da Trindade *et al.* (2012, 2015) have postulated that forage consumption on *Campos* is influenced by inter-tussock biomass and height, and when both are at optimal levels, the cover of weedy natives can reach until 30%. Currently, studies are relativising the actual damage of weedy natives and control studies have captured less attention.

We deem necessary that future studies on weedy natives consider the balance between positive (Fidelis *et al.* 2009; Noëll Estapé *et al.* 2013) and negative effects on plant community (Pellegrini *et al.* 2007), animal performance (Pizzio *et al.* 2013) and the environmental impact of control methods (Rodríguez *et al.* 2018). Demographic studies could help in the design of a long-term control scheme in diverse types of weeds and grasslands. The use of size classes seems to be an excellent way to quantify control success, particularly in perennial species, in which impact is related to their height or biomass. It is a simple, cheap and rapid indicator to measure, and in the case of *Río de la Plata* grasslands, it could be used in several native forb species such as *Baccharis sp.* and *Acanthostyles buniifolius*.

SPECIES NOMENCLATURE

Sensu Zuloaga *et al.* (2008).

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AUTHOR CONTRIBUTIONS

Amparo Quiñones: Conceptualization (equal); investigation (lead); methodology (equal); writing-original draft (lead); writing-review & editing (lead). Fernando Lattanzi: Conceptualization (equal); formal analysis (supporting); writing-original draft (supporting); writing-review & editing (supporting). Néstor Saldain: Conceptualization (equal); formal analysis (supporting); methodology (equal); supervision (supporting); writing-original draft (supporting); writing-review & editing (supporting). Felipe Miguel Lezama: Conceptualization (equal); methodology (equal); supervision (lead); writing-original draft (supporting); writing-review & editing (supporting).

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REFERENCES

Anderson M. J. (2001) A new method for non-parametric multivariate analysis of variance. *Austral Ecol.* **26,** 32–46.

Astori D. (1979) *La evolución tecnológica de la ganadería uruguaya (1930–1977)*. Banda Oriental, Montevideo (in Spanish).

Azambuja J. C. R. (2019) Estratégias de forrageamento de bovinos em campo nativo: identificando categorias funcionais de bocados e suas relações com atributos de ingestão de nutrientes [phD thesis]. Universidade Federal do Rio Grande Do Sul, Porto Alegre (in Portuguese).

Baeza S. & Paruelo J. M. (2020) Land use/land cover change (2000–2014) in the Rio de la Plata grasslands: an analysis based on MODIS NDVI time series. *Remote Sens.* **12,** 381.

Bates D., Maechler M., Bolker B. & Walker S. (2015) Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **67,** 1–48.

Billard C., Lallana M. C., Elizalde J. H. I., Foti N. & Lallana V. H. (2005) Efecto de un herbicida hormonal en aplicaciones en el haz y el envés de hojas de *Eryngium horridum* Malme. *Rev. Cient. Agrop.* **9,** 13–7 (in Spanish).

Brown J. R. & Bestelmeyer B. T. (2012) Managing invasive species in heterogeneous ecosystems. In: *Invasive Plant Ecology and Management: Linking Processes to Practice* (eds T. A. Monaco & R. L. Sheley) pp. 3–18. CABI, Wallingford.

Burkart A. & Bacigalupo N. M. (2005) *Flora Ilustrada de Entre Ríos (Argentina), Parte IV Dicotiledóneas Arquiclamídeas, B: Geraniales a Umbelliflorales*. INTA, Buenos Aires (in Spanish).

Carámbula M., Ayala W., Bermúdez R. & Carriquiry E. (1995) *Control de cardilla*. INIA, Montevideo (in Spanish).

Cerri F., Díaz A. & Giménez A. (1991) *Malezas: bibliografía nacional: período 1980–1990*. INIA, Montevideo (in Spanish).

Crancio L. A., Carvalho P., Nabinger C. & Boldrini I. I. (2007) Controle de plantas nativas indesejáveis dos campos naturais do Rio Grande do Sul. *Pesqui. Agropecu. Gaúcha* **13,** 115–24 (in Portuguese).

Da Trindade J., Pinto C., Neves F. *et al.* (2012) Forage allowance as a target of grazing management: implications on grazing time and forage searching. *Rangeland Ecol. Manag.* **65,** 382–93.

Da Trindade J., Neves F., Pinto C. *et al.* (2015) Daily forage intake by cattle on natural grassland: response to forage allowance and sward structure. *Rangeland Ecol. Manag.* **69,** 59–67.

Da Trindade J. K., Bonnet O., de David D. B. *et al.* (2017) Comportamento ingestivo y seleção de dietas. In: *Nativão; 30 anhos de pesquisa em campo nativo* (eds P. C. F. Carvalho, M. Wallau & C. Bremm) pp. 42–6. UFRGS, Porto Alegre (in Portuguese).

Daubenmire R. (1959) A canopy-coverage method of vegetational analysis. *Northwest Sci.* **33,** 43–64.

De Cáceres M., Font X. & Oliva F. (2010) The management of vegetation classifications with fuzzy clustering. *J. Veg. Sci.* **21,** 1138–51.

De Cáceres M., Legendre P. & He F. (2013) Dissimilarity measurements and the size structure of ecological communities. *Methods Ecol. Evol.* **4,** 1167–77.

DiTomaso J. M. (2000) Invasive weeds in rangelands: species, impacts, and management. *Weed Sci.* **48,** 255–65.

DiTomaso J. M., Masters R. A. & Peterson V. F. (2010) Rangeland invasive plant management. *Rangelands* **32,** 43–7.

Durán A., Califra A., Molfino J. H. & Lynn W. (2006) *Keys to Soil Taxonomy for Uruguay*. USDA, Washington.

Elizalde J. H., Salinas A. R. & Lallana V. H. (2005) Lluvia de semillas de una población de *Eryngium horridum* Malme en un campo de Oro Verde, Entre Ríos, Argentina. *Rev. Cient. Agropecu.* **9,** 39–45 (in Spanish).

Fidelis A., Overbeck G. E., Pillar V. D. & Pfadenhauer J. (2008) Effects of disturbance on population biology of the rosette species *Eryngium horridum* Malme in grasslands in the southern Brazil. *Plant Ecol.* **195,** 55–67.

Fidelis A., Overbeck G. E., Pillar V. D. & Pfadenhauer J. (2009) The ecological value of *Eryngium horridum* in maintaining biodiversity in subtropical grasslands. *Austral Ecol.* **34,** 558–66.

Fidelis A., Müller S. C., Pillar V. D. & Pfadenhauer J. (2010) Population biology and regeneration of forbs and shrubs after fire in Brazilian *Campos* grasslands. *Plant Ecol.* **211,** 107–17.

Fox J. & Weisberg S. (2019) *An R Companion to Applied Regression*. Sage, Thousand Oaks.

Fritschie K. J. & Olden J. D. (2016) Disentangling the influences of mean body size and size structure on ecosystem functioning: an example of nutrient recycling by a non-native crayfish. *Ecol. Evol.* **6,** 159–69.

Fuhlendorf S. D., Fynn R. W. S., McGranahan D. A. & Twidwell D. (2017) Heterogeneity as the basis for rangeland management. In: *Rangeland Systems* (ed D. Briske) pp. 169–96. Springer, Cham.

Ghersa C. M., Benech-Arnold R. L., Satorre E. H. & Martínez-Ghersa M. A. (2000) Advances in weed management strategies. *Field Crop. Res.* **67,** 95–104.

Harrington K. C. & Ghanizadeh H. (2017) Herbicide application using wiper applicators – a review. *Crop Prot.* **102,** 56–62.

Hickman M. V., Messersmith C. G. & Lym R. G. (1990) Picloram release from leafy spurge roots. *J. Range Manage.* **43,** 442–5.

Hothorn T., Brezt F. & Westfall P. (2008) Simultaneous inference in general parametric models. *Biometrical J.* **50,** 346–63.

Kirkpatrick M. (1984) Demographic models based on size, not age, for organisms with indeterminate growth. *Ecology* **65,** 1874–84.

Lallana V. H. (2007) Ecofisiología de la cardilla (*Eryngium horridum* Malme). In: *Seminario de actualización técnica en manejo de malezas* (eds W. Ayala & H. Saravia) pp. 79–106. Montevideo, INIA (in Spanish).

Lallana M. C., Billard C., Elizalde J. H. I. & Lallana V. H. (2003) Control químico de *Eryngium horridum* Malme "caraguatá". *Rev. Cient. Agropecu.* **7,** 29–33 (in Spanish).

Lallana V. H., Lallana M. C., Elizalde J. H. *et al.* (2005) Control mecánico y químico de *Eryngium horridum* Malme en un pastizal bajo pastoreo. *Rev. Argent. Prod. Anim.* **25,** 123–5 (in Spanish).

Lallana V. H., Elizalde J. H., Billard C. & Lallana M. C. (2006) Control mecánico de *Eryngium horridum* ("Caraguatá") en un pastizal naturalizado de Entre Ríos. *Argentina. Agrocienc. Urug.* **10,** 47–57 (in Spanish).

Lenth R. V. (2016) Least-squares means: the R Package lsmeans. *J. Stat. Softw.* **69,** 1–33.

Lezama F., Pereira M., Altesor A. & Paruelo J. M. (2019) Grasslands of Uruguay: classification based on vegetation plots. *Phytocoenologia* **49,** 211–29.

Magda D., Duru M. & Theau J. P. (2004) Defining management rules for grasslands using weed demographic characteristics. *Weed Sci.* **52,** 339–45.

doi:10.1111/aec.12904

Mangiafico S. (2019) rcompanion: functions to support extension education program evaluation. R package version 2.3.7.

Modernel P., Rossing W. A. H., Corbeels M., Dogliotti S., Picasso V. & Tittonell P. (2016) Land use change and ecosystem service provision in Pampas and Campos grasslands of southern South America. *Environ. Res. Lett.* **11,** 113002.

Moyo C. (2008) Improving the efficiency of herbicide application to pasture weeds by weed-wiping and spot-spraying [PhD thesis]. Massey University, Palmerston North.

Noëll Estapé S. E., Semmartin M. & Paruelo J. M. (2013) Refuge effect of an unpalatable forb on community structure and grass morphology in a temperate grassland. *Plant Ecol.* **214,** 363–72.

Oksanen J., Blanchet F. G. & Friendly M. *et al.* (2019) vegan: community ecology package. R package version 2.5-4.

Pallarés O. R., Berretta E. J. & Maraschin G. E. (2005) The South American Campos ecosystem. In: *Grasslands of the world* (eds J. M. Suttie, S. G. Reynolds & C. Batello) pp. 171–219. FAO, Rome.

Pellegrini L., Nabinger C., Carvalho P. C. F. & Neumann M. (2007) Diferentes métodos de controle de plantas indesejáveis em pastagem nativa. *Rev. Bras. Zootecn.* **36,** 1247–54 (in Portuguese).

Pinheiro J., Bates D., DebRoy S., Sarkar D. & R Core Team (2017) nlme: linear and nonlinear mixed effects models. R package version 3.1-131.

Pizzio R., Bendersky D. & Barbera P. (2013) *Malezas arbustivas en los pastizales naturales de Corrientes*. INTA, Mercedes (in Spanish).

R Core Team (2019) *R: A Language and Environment for Statistical Computing [Computer Program]*. R Foundation for Statistical Computing, Vienna.

Ríos A. (2007) Control posicional de cardilla (*Eryngium horridum*) en campo sucio. In: *Seminario de actualización técnica en manejo y control de malezas de campo sucio* (eds W. Ayala & H. Saravia) pp. 35–47. INTA, Mercedes (in Spanish).

Rodríguez A. M., Jacobo E. J. & Golluscio R. A. (2018) Glyphosate alters aboveground net primary production, soil organic carbon, and nutrients in Pampean grasslands (Argentina). *Rangeland Ecol. Manag.* **71,** 119–25.

Soriano A. (1992) Río de la Plata grasslands. In: *Natural Grasslands: Introduction and Western Hemisphere, 8A* (ed R. T. Coupland) pp. 367–407. Elsevier, Amsterdam.

Spangenberg G. E. (1930) Normas a observar en el mejoramiento de nuestras praderas naturales. *Rev. Fac. Agron. Urug.* **3,** 311–402 (in Spanish).

Wilson J. B. (2011) Cover plus: ways of measuring plant canopies and the terms used for them. *J. Veg. Sci.* **22,** 197–206.

Wood S. N., Pya N. & Saefken B. (2016) Smoothing parameter and model selection for general smooth models. *J. Am. Stat. Assoc.* **111,** 1548–75.

Zuloaga F. O., Morrone O. & Belgrano M. J. (eds.) (2008) *Catálogo de las plantas vasculares del Cono Sur (Argentina, sur de Brasil, Chile, Paraguay y Uruguay)*. Monographs in Systematic Botany from the Missouri Botanical Garden 107 (1–3). MBG Press, St. Louis (in Spanish).

SUPPORTING INFORMATION

Additional supporting information may/can be found online in the supporting information tab for this article.

Appendix S1. Example of cumulative abundance profile calculation.