Rangeland Ecology & Management 71 (2018) 58–66

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: http://www.elsevier.com/locate/rama

Original Research

Defoliation Intensity and Simulated Grazing Strategy Effects on Three C4 Rangeland Bunchgrasses☆

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ARTICLE INFO

Article history:
Received 24 May 2016
Received in revised form 18 January 2017
Accepted 8 September 2017

Key Words:
defoliation
Digitaria californica
forage
grazing
Pappophorum vaginatum
Trichloris crinita

ABSTRACT

Defoliation intensity and timing are two important factors determining plants response to grazing. These factors can be managed by adjusting stocking rate and applying a grazing strategy. In a 6-yr clipping experiment conducted in northwestern Argentina, we assessed the effect of different defoliation intensities (~30%, ~50%, and ~70% removal of the annually produced aboveground biomass) and simulated grazing strategies (continuous grazing, two-paddock rest-rotation, three-paddock rest-rotation, dormant season grazing) on plots of three C4 native bunchgrasses (*Pappophorum vaginatum, Trichloris crinita,* and *Digitaria californica*). Response variables were mean and trend of clipped-off biomass during the 6 yr of treatments, number of inflorescences, and aboveground biomass produced on the year following treatments end (to evaluate residual effect of treatments). Results were species dependent. Mean clipped-off biomass increased with defoliation intensity in *T. crinita* and *D. californica*. However, defoliation intensity negatively affected clipped-off biomass trend in *T. crinita* and the production of *P. vaginatum* and *T. crinita* during “residual effect” evaluation. The three species responded positively at least in one response variable to the amount of rest periods in the grazing strategy. Our results are not fully consistent with the concept that forage production is more influenced by defoliation intensity than by grazing strategy: In two of the three species, grazing strategy presented greater impact on response variables than defoliation intensity. When significant “defoliation intensity × grazing strategy” was detected, intensity tended to be more detrimental as grazing strategy allows fewer rest periods. We observed a residual effect of treatments in the three species (generally, negative effect of defoliation intensity and positive effect of grazing strategies with more rest periods). Our results show that dormant season utilization and rest periods are beneficial for maximizing mean clipped-off biomass and ensuring clipped-off biomass trend. High defoliation intensities can maximize short-term clipped-off biomass, but it may produce negative residual effects and trends.

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Introduction

Defoliation intensity and timing are two of the most important factors in determining the plants’ response to grazing. In livestock systems, these factors can be managed by adjusting the stocking rate (which affects the consumed percentage of aboveground biomass produced annually) and applying a grazing strategy (which determines the temporal and spatial distribution of animals in the field, and hence the periods of grazing and rest) (Briske et al., 2008; Distel, 2013).

Most grazing and clipping studies indicate that defoliation adversely affects primary productivity (Belsky, 1987; Milchunas and Lauenroth, 1993; Oesterheld et al., 1999; Ferraro and Oesterheld, 2002). While plant productivity generally decreases with defoliation intensity, the proportion of removed biomass increases (Parsons et al., 1983) and then there is a tradeoff between maximizing plant growth and sustainability (at lower intensities) and maximizing the proportion of biomass removed by grazing animals (at greater intensities; Briske et al., 2008).

Several authors have indicated that plant and livestock production is more influenced by the stocking rate than the grazing strategy (Van Pollen and Lacey, 1979; O’Reagain and Turner, 1992; Holechek et al., 1998; Briske et al., 2008). Briske et al. (2008) found insufficient evidence to support that rotational-intensive-grazing strategies (involving days to weeks of deferment after short grazing periods) achieve a productive advantage over the continuous grazing strategy. However, as Briske et al. (2008) and other authors indicate, allowing periods of long deferment (nongrazing during part of the growing season) or rest (nonuse for 12 consecutive mo, as defined by Howery et al., 2000) could be a useful tool to maintain or improve rangeland productivity (Holechek et al., 1999; Müller et al., 2007; Davies et al., 2014; O’Reagain et al., 2014).

☆ Funding for R. E. Quiroga, L. J. Blanco, and P. R. Namur was provided by INTA projects: PNPA-1126072, PNPA-1126074, CATRI-1233103, CATRI-1233205, and CATRI-1233206.

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https://doi.org/10.1016/j.rama.2017.09.002
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Interaction between grazing intensity and grazing strategy was less investigated in rangelands than improved pastures, maybe due to the greater complexity of conducting range experiments (Holechek et al., 1999; Schwinning and Parsons, 1999). Rangeland studies have generally not found an interactive effect between grazing intensity and grazing strategy on plant productivity (Cassels et al., 1995; Derner and Hart, 2007). However, evidence from individual plant experiments indicate that grasses can respond better to defoliation when there is a longer time interval between clippings (Oesterheld and McNaughton, 1991; Ferraro and Oesterheld, 2002). Then it is possible to expect that defoliation intensity differentially affects plants according to the timing of grazing and rest periods to which they are subjected (grazing strategy).

To add complexity, individual plants and plant communities can respond to disturbance with certain time lags. Climatic events or grazing can influence plants per months or years after its occurrence (Barnes, 1989; Fabricante et al., 2009; Taylor and MacLean, 2009; Sala et al., 2012), considering that this type of response is generally omitted in investigations.

In a long-term study conducted in the arid Chaco region of Argentina, we assessed by means of defoliation (the most important direct effect of grazing) the effect of different defoliation intensities and grazing strategies on three native grasses. We worked on monospecific plots of these species to include the effect of intraspecific competition between plants that may alter the response to defoliation (McNaughton, 1992). We evaluated the response of the species in terms of the clipped-off biomass (an estimate of yield to grazers, according to McNaughton et al., 1983) over the 6 yr of treatment application (Briske et al., 2008) and the residual effect of treatments 1 yr after its cessation (Barnes, 1989). The aim was to respond the following questions: 1) How does the clipped-off biomass of native grasses vary under different defoliation intensities and grazing strategies? 2) Is there a residual effect of defoliation intensities and grazing strategies in these species? 3) Is there an interactive effect between defoliation intensity and grazing strategy over the response variables? 4) Which factor (defoliation intensity or grazing strategy) has more influence on response variables?

Methods

Study Area

The investigation was performed at the "Instituto Nacional de Tecnología Agropecuaria" (INTA) La Rioja Experimental Station (lat 30°27′S, long 66°11′W) in northwestern Argentina, specifically the Arid Chaco ecological region (Morello et al., 1985). The region has a subtropical climate (Morello et al., 1985), with hot summers (20 − 25 days with >40°C temperatures) and mild winters (5 − 10 days with <0°C temperatures; Prohasca, 1959). Mean temperature is 26°C for the warmest month (January) and 11°C for the coldest one (July). In the study site, mean annual precipitation is 469 mm, with 80% occurring in the southern hemisphere warm season between November and March. The frost period is from June to August (Bazán, 1993). Vegetation growing season coincides with the warm season (Blanco et al., 2009), extending 3 − 6 mo between November and April according to the variation of the beginning and end of the rainy season. Vegetation goes dormant during the rest of the year—the cold and dry season (grasses do not grow during this period). For practical reasons, in this study we consider "year" as the period from September to August. Typical vegetation of the region is a subtropical xerophytic shrubland, with scattered trees and a patched herbaceous layer. The main trees are *Aspidosperma quebracho-blanco* and *Prosopis* spp. The most common shrubs correspond to the *Larrea, Mimozyganthus,* and *Senna* genera. The herbaceous layer is composed of mainly C4 perennial grasses of the *Aristida, Digitaria, Pappophorum, Setaria,* and *Trichloris* genera (Morello et al., 1985; Blanco et al., 2009). Predominant soils are coarse textured, with low organic matter content (<1.5% of soil mass) and neutral to basic pH (Gómez et al., 1993). At the study site, soil was classified as *Typic Torriortent* (SAGyP–INTA, 1990).

Study Species

We studied three native forage grasses: *Pappophorum vaginatum* (Buckley), *Digitaria californica* ([Benth.] Henr.) and *Tricholoris crinita* ([Lag.] Parodi). They are C4 perennial bunchgrasses of summer growth. According to Peterson et al. (2007), *P. vaginatum* and *T. crinita* present an amphitropical disjunct distribution, occurring in two broad regions centered in subtropical arid and semiarid rangelands of South and North America. In addition to these environments, *D. californica* is also present in Central America and the Caribbean (Vega and Rúgolo de Agrasar, 2005; Sánchez-Ken, 2012).

Experimental Approach

A completely randomized block design (with six replicates) was established in a previously existing pasture of each species. In each one, we applied a factorial experiment evaluating 3 defoliation intensities and 4 grazing strategies, resulting in 12 defoliation treatments. Experimental units (plots) had 0.75 m^2 (1.5 m long × 0.5 m wide) and were separated by edges of 0.5 m. Each species was planted separately by seeds in the summer of 1997, on a previously cleared and disked site. Used seed was collected from nearby rangeland areas. After establishment, until the beginning of the experiment (2002 − 2003), pastures were grazed every dormant season by cows at moderate grazing intensity (leaving a stubble height of 10 − 15 cm). At the beginning of the experiment, the pasture of each species had a mean density of 22 − 23 plants.m^{-2}.

As mentioned, stocking rate is the main management determinant of the grazing intensity (i.e., defoliation intensity, the percentage of aboveground biomass produced annually that is consumed by animals). For its part, grazing strategy is the main determinant of the temporal and spatial distribution of animals over an entire area (subareas receiving grazing or rest) (Briske et al., 2008; Distel, 2013). Distribution of animals according to a rotational grazing strategy implies that subareas subjected to grazing in one period of time have higher animal density than the overall density of the entire area, or than a continuously grazed area with the same overall animal density (Howery et al., 2000). As has been recognized, even continuous grazing is not a continuous process, because it involves a succession of discrete defoliation events at the bite-patch scale, each followed by a regrowth period (Morris, 1969; Parsons et al., 2001). We considered these concepts to conduct our experiment. We used percentages of tissue removal as surrogates of overall grazing intensity (Holechek and Galt, 2000), and temporal distribution of defoliation (intra-annually and interannually) as a surrogate of grazing events for the different grazing strategies (Schwinning and Parsons, 1999). Periods of increased animal density for a grazing strategy were simulated by increasing proportionally defoliation frequency, while during periods of rest we did not apply defoliation. To investigate grass response to grazing, a grazed paddock could be considered as a collection of small-sized patches (Schwinning and Parsons, 1999). We are confident that our experimental approach was able to simulate what occurs with patches of the studied species in paddocks subjected to different grazing intensities and strategies.

Treatments

Defoliation treatments began in October 2002 and ended in July 2008 for *P. vaginatum* and *D. californica.* For *T. crinite,* treatment began in December 2003 and ended in June 2009 (during 6 yr in each species). These periods of time were considered adequate to assess trends in grazing studies (Biondini and Manske, 1996).

We simulated defoliation intensity by clipping plants to different stubble height (Oesterheld, 1992; Holechek and Galt, 2000). In a previous study, Derner et al. (1994) found that the stocking rate but not the grazing strategy affects the stubble height in *Schizachyrium scoparium* (a C4 perennial bunchgrass, dominant on the North American tallgrass prairie). In each species we determined the clipping heights in the season previous to the beginning of the experiment, quantifying the aboveground biomass distribution through plant height (Oesterheld, 1992) (sampling 5 − 10 representative plants per species from surrounding areas to each trial). Selected clipping heights corresponding to the removal of ~70%, ~50%, and ~30% of the annual aboveground biomass production (dry matter) in each species were 5, 11, and 20 cm *(P. vaginatum);* 8, 15, and 25 cm *(D. californica);* and 6, 14, and 24 cm *(T. crinita)*. Estimations along the 6 yr of treatments corroborated the effectiveness of the clipping heights to achieve the desired biomass removal percentages (defoliation intensities) in the different grazing strategies (Table 1; estimation methodology and aboveground biomass removal percentages for each study year are shown in Appendix A). This is an important point because it shows that plants did not change significantly the aboveground biomass vertical distribution in response to treatments.

Simulated grazing strategies were 1) continuous grazing, 2) dormant season grazing, 3) two-paddock rest-rotation, and 4) three-paddock rest-rotation. A description of each strategy (according to Howery et al., 2000) and how it was simulated experimentally by clipping is presented as follows. In this work, the term “grazing strategy” is used instead of “grazing system.” This is because the latter makes reference to grazing management that considers both periods of grazing and nongrazing (Society for Range Management, 1998), so it includes our “two-paddock rest-rotation” and “three-paddock rest-rotation” treatments but excludes our “continuous grazing” and “dormant season grazing” treatments.

1. Continuous grazing: Animals graze all the time over the same area. According to Derner et al. (1994), tillers of grasses are defoliated on average two or three times per year under continuous grazing. To simulate this in our study, we applied that amount of defoliations in each of the 6 yr of treatment application. For this, we applied clippings every 12 wk (~84 d): once at the beginning of the growing season, once in the middle (in years with a long growing season), and once at the end of it (Table 2).
2. Dormant season grazing: Dormant season grazing is applied after the end of the growing season, when plants are not in active growth. In our region, this grazing management becomes important since the use of deferred (over the entire growing season) paddocks is encouraged when part of the ranch has been planted with pastures (e.g., *Cenchrus ciliaris*) that animals can graze in the growing season (Blanco et al., 2005). In our study, to simulate the dormant season grazing, we clipped the plots each year once during the dormant season (in May to August; see Table 2), avoiding the use of clippings in the last part of the dormant season (September − October) when winds increase (Kunst, 2011) and hence the fall of grass tissues.
3. Two-paddock rest-rotation (2PRR):
   Two-paddock rest-rotation is a one-herd, two-paddock, 2-yr rest-rotation strategy. Each paddock is grazed over 1 entire yr (including the growing season), and the following year is left to rest. To simulate this, we considered that animal density in the paddock where animals are grazing is twice the animal density of the continuous grazing. During the years in which defoliations were applied along the growing season, plots were clipped at a time interval of 6 wk (~42 d, half the time of the continuous grazing), while in the years of rest, plots were clipped only once during the dormant season (see Table 2).
4. Three-paddock rest-rotation (3PRR):
   Three-paddock rest-rotation is a one-herd, three-paddock, 3-yr rest-rotation strategy. Each paddock is grazed over one entire year (including the growing season), and the following 2 yr is left to rest. This strategy exhibits similarity with the “Santa Rita” grazing strategy described by Martin and Severson (1988). To simulate this, the years in which defoliations were applied along the growing season, plots were clipped at a time interval of 4 wk (~28 d, one-third of the continuous grazing). In the years of rest, plots were clipped once during the dormant season (see Table 2).

In our experiment, as in arid and semiarid grazed rangelands, recuperation of plants between defoliation events depends on water availability (Reynolds et al., 2004). This aspect does not invalidate our experimental approach (rests and defoliation at distinct time intervals according to grazing strategy) because water shortage could limit regrowth in the same manner for the distinct grazing strategies, maintaining relative differences in effective time for regrowth among them. Something similar happens in rangelands grazed under different grazing strategies (Howery et al., 2000; Briske et al., 2008; Teague et al., 2008).

Response Variables

For the 6 yr of treatment application, clipped-off biomass (an estimate of yield to grazers, McNaughton et al., 1983) in each plot was oven dried (65°C, 72 h) and weighed. We then calculated 1) the mean clipped-off biomass over the 6 yr of treatment application ($g.m^{-2}year^{-1}$; considering September to August annual periods); 2) the slope ($\boldsymbol{b}$) of clipped-off biomass over the 6 yr (temporal trend [Blanco et al., 2009; Quiroga et al., 2009; Fensholt and Rasmussen, 2011; Peng et al., 2012]; a measure of the mean change in clipped-off biomass per year) by lineal regression analysis ($\boldsymbol{y} = \boldsymbol{a} + \boldsymbol{b} * \boldsymbol{x}$) between annual values of clipped-off biomass ($\boldsymbol{y}$; $g.m^{-2}year^{-1}$) and time ($\boldsymbol{x}$; yr 1 − 6). Before the obtaining this slope ($\boldsymbol{b}$), to minimize the effect of interannual precipitation variability (Blanco et al., 2009), values of annual clipped-off biomass were divided by the annual precipitation (mm) (Prince et al., 1998) and then rescaled by multiplying with the mean annual precipitation of the 6 yr. Annual clipping yield corrected by this methodology and the corresponding slope are shown for each species and treatment in the Appendix B. Mean clipped-off biomass during the 6 yr of treatment application can be considered as an indicator of the “current benefit” obtained from the pastures, while the trend of clipped-off biomass in that time can be considered as an indicator of pasture sustainability (Dıaz-Solis et al., 2003).

To estimate the residual effect after the 6 yr of treatment application, all the plots were left without any manipulation during the seventh year (Barnes, 1989), at end of which the number of inflorescences was counted ($number.m^{-2}yr^{-1}$; a proxy of seed production) and the

Table 1
Mean defoliation intensities (% of aboveground biomass removal) for each clipping height over 6 yr of treatment application in each species and simulated grazing strategy. Methodological details in Appendix A.

	Pappophorum vaginatum			*Digitaria californica*			*Trichloris crinita*		
Grazing strategy	5 cm	11 cm	20 cm	8 cm	15 cm	25 cm	6 cm	14 cm	24 cm
Dormant season	73	50	35	75	56	28	68	45	25
3-paddock rest-rotation	68	52	34	65	48	29	73	54	30
2-paddock rest-rotation	68	53	38	67	43	32	73	53	32
Continuous	73	54	38	66	54	32	73	52	32
Mean	71	52	36	68	50	30	72	51	30

Table 2
Clipping dates to simulate the different grazing strategies in **A,** *Pappophorum vaginatum* and *Digitaria califórnica*, 2002—2003 (yr 1) to 2007—2008 (yr 6); and **B,** *Trichloris crinita*, 2003—2004 (yr 1) to 2008—2009 (yr 6). Years consider September—August periods.

A

Grazing strategy	2002-2003	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008
Dormant season	May 3	Aug 11	Aug 12	Jul 6	Aug 30	Jul 22
3-paddock rest-rotation	Nov 6 Dec 4 Jan 2 Jan 30 Feb 27 Mar 26 Apr 24	Aug 11	Aug 12	Dec 16 Jan 14 Feb 11 Mar 11 Apr 8	Aug 30	Jul 22
2-paddock rest-rotation	Nov 6 Dec 18 Jan 30 Mar 13 Apr 24	Aug 11	Nov 15 Dec 28 Feb 8 Mar 22 May 3	Jul 6	Dec 11 Jan 23 Mar 5 Apr 18 May 31	Jul 22
Continuous	Nov 6 Jan 30 Apr 24	Nov 7 Feb 2 Apr 26	Nov 15 Feb 8 May 3	Dec 15 Mar 11	Dec 11 Feb 28 May 24	Dec 18 Mar 11 May 30

B

Grazing strategy	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009
Dormant season	May 2	Jul 30	Jul 6	Jul 27	Jul 31	Jun 30
3-paddock rest-rotation	Jan 12 Feb 9 Mar 8 Apr 7	Jul 30	Jul 6	Dec 11 Jan 8 Feb 6 Mar 8 Apr 4 May 2 Jun 4	Jul 31	Jun 30
2-paddock rest-rotation	Jan 12 Feb 23 Apr 7	Jul 30	Dec 16 Jan 31 Mar 14	Jul 27	Nov 27 Jan 8 Feb 19 Apr 1 May 13	Jun 30
Continuous	Jan 12 Apr 7	Dec 14 Mar 8 May 31	Dec 16 Mar 14	Dec 11 Mar 8 May 29	Nov 27 Feb 19 May 13	Jan 5 Mar 31 Jun 24

aboveground biomass production (g.m^{-2}yr^{-1}) was assessed by harvesting the plots at soil level, retaining the tissues produced in the year (green and senesced-yellowish tissues) and discarding tissues produced in previous years (senesced-gray tissues). Aboveground biomass produced in the seventh year was oven dried (65°C, 72 h) and weighed.

At beginning of the experiment, basal area was measured in each plot, for its possible use as covariate.

Data Analysis

Mean and trend (slope) of clipped-off biomass (first 6 yr), inflorescence, and aboveground biomass production during residual effect evaluation (seventh yr) were analyzed using mixed models in each species separately (PROC MIXED, SAS; SAS Institute, 2011). Defoliation intensity, grazing strategy, and their interaction were considered as fixed effect factors; while blocks were considered as random (Littell et al., 1996). Basal area measured at the beginning of the experiment was used as covariate only for the mean clipped-off biomass of *D. californica* because it was significant only for this. Comparison of means was performed with the LSD test ($\alpha = 0.05$) using the macro developed by Saxton (1998).

Precipitations During the Study Period

During study, precipitations were highly concentrated within the growing seasons: 78%—97% of the annual precipitation occurred between November and March (Fig. 1). Mean duration of periods between rain events within the growing seasons was 7 d (min. = 1 d; max. = 28 d; 5th percentile = 1 d; 50th percentile = 6 d; 95th percentile = 18 d). Mean precipitation per rain event was 16 mm (min. = 0.5 mm; max. = 250 mm; 5th percentile = 0.8 mm; 50th percentile = 8 mm; 95th percentile = 55 mm). Mean annual precipitation during the 6 yr of treatment application was 401 mm.yr^{-1} in *P. vagimatum* and *D. californica* (2002—2003 to 2007—2008) and 374 mm.yr^{-1} in *T. crinita*

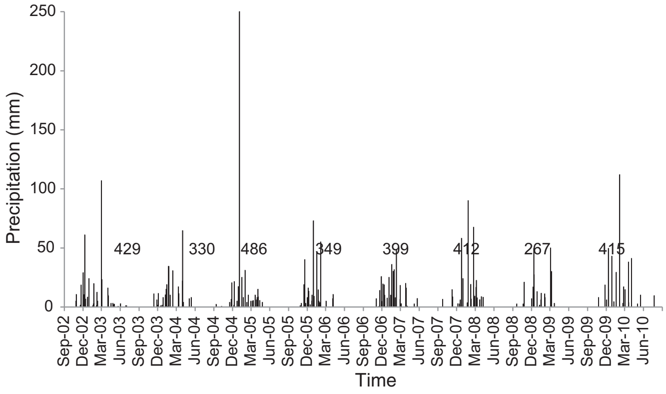

Figure 1. Precipitations during the study at INTA La Rioja Experimental Station. Vertical lines represent daily amounts. Numbers over each rainy season are annual precipitation values, considering September to August periods.

(2003 − 2004 to 2008 − 2009). Precipitation during the year of residual effect evaluation was 267 mm.yr^{-1} in *P. vagimatum* and *D. californica* (2008 − 2009) and 415 mm.year^{-1} in *T. crinita* (2009 − 2010).

Results

Pappophorum vaginatum

In *P. vaginatum*, there was interactive effect between defoliation intensity and grazing strategy on the mean clipped-off biomass ($P = 0.0475$; Fig. 2a). Under dormant season grazing, higher yield was achieved at high defoliation intensity. Meanwhile, in the 3PRR strategy higher yield was obtained at moderate defoliation intensity, and in the 2PRR strategy this goal was achieved at low intensity. Mean clipped-off biomass did not vary with defoliation intensity in the continuous grazing strategy. Overall effect of grazing strategy was significant ($P = 0.0141$; higher yields under dormant season grazing), but not that of defoliation intensity ($P = 0.5185$; see Fig. 2a).

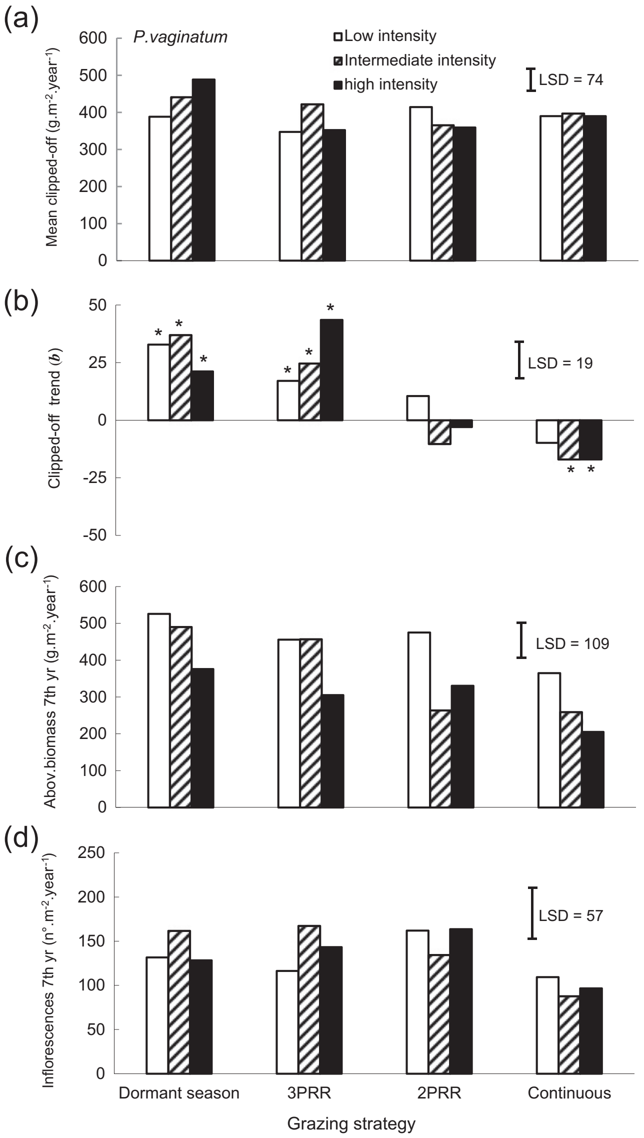

Figure 2. Response of *P.vaginatum* to different defoliation intensities and grazing strategies: (a) mean clipped-off biomass (g.m^{-2}year^{-1}); (b) clipped-off biomass trend (***b***, the slope of a lineal regression analysis between annual values of clipped-off biomass (***y***; g.m^{-2}year^{-1}; values corrected by precipitation variability, see section *Response variables* in *Methods*) and time (***x***; year 1 to 6); (c) aboveground biomass (g.m^{-2}year^{-1}) and (d) inflorescence (number.m^{-2}year^{-1}) productions during the year after treatments end. Least significant difference (LSD) for means comparison is showed for each variable.

Grazing strategy was the most important factor determining clipped-off biomass trend of *P. vaginatum* during treatment application ($P < 0.0001$; Fig. 2b). This trend was positive in dormant season grazing and the 3PRR strategy, neutral in the 2PRR, and negative under continuous grazing. The significance of the "defoliation intensity × grazing strategy" interaction ($P = 0.0203$) was due to a change in the order of clipped-off biomass trends of the defoliation intensities according to grazing strategies. For example, in the 3PRR strategy, high-defoliation intensity showed the most positive trend and low-defoliation intensity showed the less positive trend; however, under continuous grazing, it was reversed, showing high-defoliation intensity the most negative trend (together with the intermediate intensity) and low defoliation intensity the less negative one (see Fig. 2b). No overall effect of defoliation intensity ($P = 0.6784$) was observed on this variable.

We did not find significant "defoliation intensity × grazing strategy" effect on any of the two variables measured 1 yr after treatment end in *P. vaginatum* ($P = 0.0764$ for aboveground biomass production, Fig. 2c; $P = 0.3813$ for inflorescence production, Fig. 2d). But aboveground biomass production of this species on the seventh year was affected by defoliation intensity ($P < 0.0001$) and grazing strategy ($P < 0.0001$): increasing at lower-defoliation intensities and in grazing strategy with more rest years. Inflorescence production varied according to the grazing strategy ($P = 0.0073$) but not with defoliation intensity ($P = 0.8545$), showing grazing strategies with rest periods ~50% more inflorescences than the continuous strategy (see Fig. 2d).

Digitaria californica

Interaction between defoliation intensity and grazing strategy was significant in determining mean clipped-off biomass of *D. californica* ($P = 0.0001$; see Fig. 3a). Defoliation intensity showed a more positive effect on mean clipped-off biomass as more rest periods had the grazing strategy. Higher yield was obtained in the dormant season grazing at high-defoliation intensity, while under continuous grazing it was achieved at intermediate-defoliation intensity. There were significant effects of defoliation intensity ($P < 0.0001$) and grazing strategy ($P = 0.0003$): in general, mean clipped-off biomass tended to be lower at low-defoliation intensity and higher under dormant season grazing (see Fig. 3a).

In *D. californica,* only grazing strategy showed a significant effect on clipped-off biomass trend ($P = 0.0182$; see Fig. 3b). In general, there were neutral trends in the 3PRR and 2PRR strategies and negative trends in the dormant season grazing (except with low-defoliation intensity) and continuous grazing. Neither the defoliation intensity ($P = 0.3112$) nor the interaction of this with the grazing strategy ($P = 0.5967$) showed significant effects (see Fig. 3b).

In *D. californica*, "defoliation intensity × grazing strategy" interaction showed no significant effect on variables measured 1 yr after treatment ended ($P = 0.5827$ for aboveground biomass production, see Fig. 3c; $P = 0.7107$ for inflorescence production, Fig. 3d). Aboveground biomass production on the seventh increased with the years of rest in the grazing strategy ($P = 0.0353$). However, defoliation intensity did not show significant effect on this variable ($P = 0.3502$). Inflorescence production did not vary with defoliation intensity ($P = 0.1723$) or grazing strategy ($P = 0.0914$) (see Fig. 3d).

Tricholoris crinita

In *T. crinita*, mean clipped-off biomass increased with defoliation intensity ($P < 0.0001$). However, neither the grazing strategy ($P = 0.0708$) nor the interaction of this with the defoliation intensity ($P = 0.1624$) significantly affected this variable (Fig. 4a).

An interaction occurred between defoliation intensity and grazing strategy on the clipped-off biomass trend of *T. crinita* ($P = 0.0021$; see

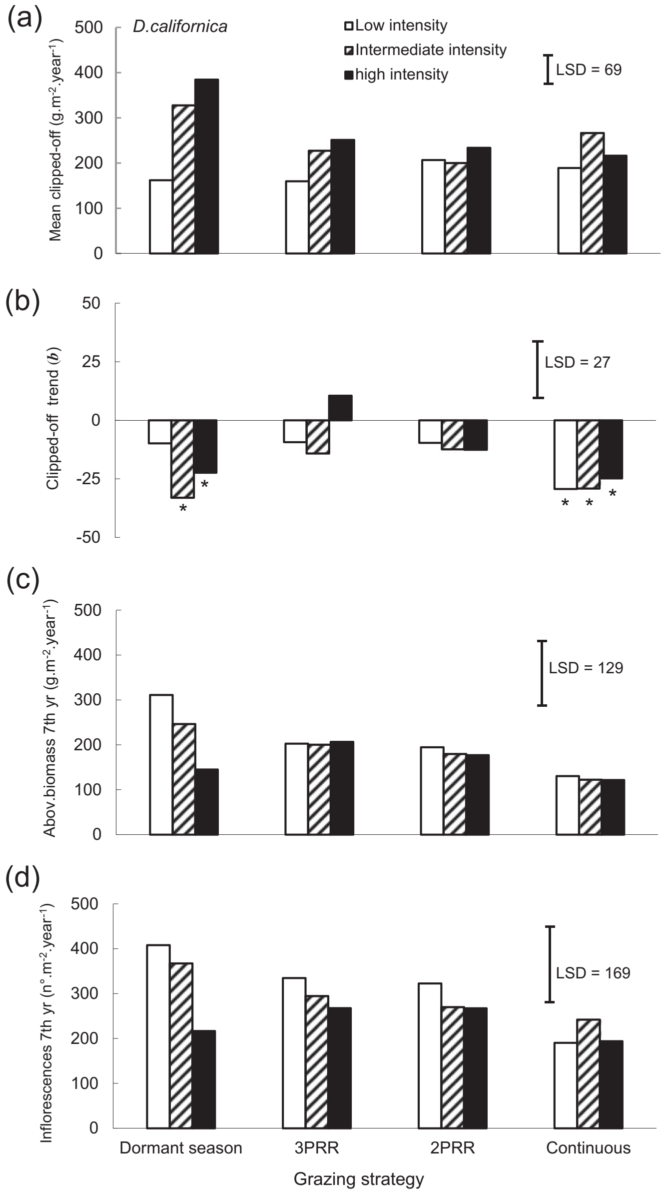

Figure 3. Response of *D.californica* to different defoliation intensities and grazing strategies: (a) mean clipped-off biomass (g.m^{-2}year^{-1}); (b) clipped-off biomass trend (***b***, the slope of a lineal regression analysis between annual values of clipped-off biomass (***y***; g.m^{-2}year^{-1}; values corrected by precipitation variability, see section *Response variables* in *Methods*) and time (***x***; year 1 to 6); (c) aboveground biomass (g.m^{-2}year^{-1}) and (d) inflorescence (number.m^{-2}year^{-1}) productions during the year after treatments end. Least significant difference (LSD) for means comparison is showed for each variable.

Fig. 4b). In this sense, the negative effect of defoliation intensity on the trend of clipped-off biomass tended to disappear by increasing rest years in the grazing strategy (see Fig. 4b). In general, there was a positive effect of rest periods in the grazing strategies ($P < 0.0001$) and a negative effect of defoliation intensity ($P < 0.0001$) on this variable.

Interaction between defoliation intensity and grazing strategy showed no significant effect on variables measured on *T. crinita* 1 yr after treatment ended ($P = 0.8998$ for aboveground biomass production, see Fig. 4c; $P = 0.9639$ for inflorescence production, see Fig. 4d). There was residual effect of defoliation intensity on the seventh yr's aboveground biomass ($P = 0.0018$) and inflorescence ($P < 0.0001$) productions: In both variables the high-defoliation intensity showed lower values than intermediate- and low-defoliation intensity. Grazing strategy did not show a significant effect on these variables ($P > 0.30$ in both cases).

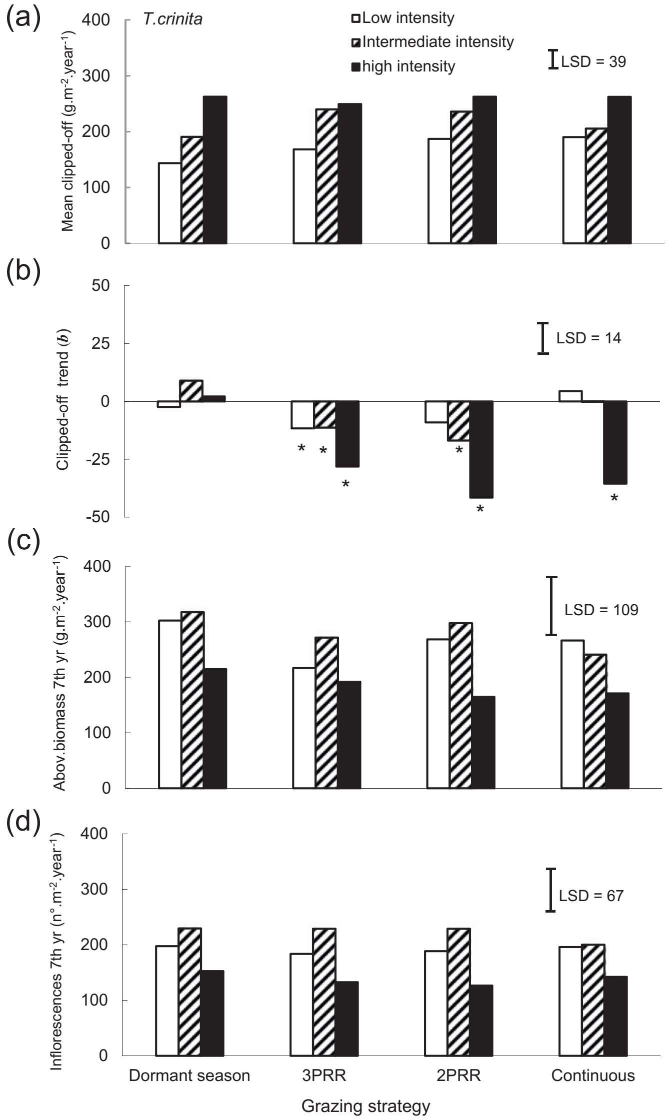

Figure 4. Response of *T.crinira* to different defoliation intensities and grazing strategies: (a) mean clipped-off biomass (g.m^{-2}year^{-1}); (b) clipped-off biomass trend (***b***, the slope of a lineal regression analysis between annual values of clipped-off biomass (***y***; g.m^{-2}year^{-1}; values corrected by precipitation variability, see section *Response variables* in *Methods*) and time (***x***; year 1 to 6); (c) aboveground biomass (g.m^{-2}year^{-1}) and (d) inflorescence (number.m^{-2}year^{-1}) productions during the year after treatments end. Least significant difference (LSD) for means comparison is showed for each variable.

Discussion

We found different results for variables related to current yield (mean clipped-off biomass), sustainability (clipped-off biomass trend), or residual effect of treatments (inflorescence and aboveground biomass productions 1 yr after treatments end) (Table 3). In this sense, Briske et al. (2008) and Davies et al. (2014) highlighted the importance of long-term studies because short-term experiments can sometimes give a partial perspective of the effect of grazing treatments.

Grazing Strategy

Three species responded positively, as measured by any of the response variables, to the number of rest periods provided by the grazing strategy (see Table 3). Consistently, Müller et al. (2007) showed in a simulation study that long rest periods could play an indispensable role on the sustainability and productivity of arid and semiarid grazing rangelands. Intensive rotational grazing (with short deferment periods)

Table 3
Synthesis of the effects of defoliation intensity, grazing strategy (expressed by the number of rest years), and their interaction, over the mean clipped-off biomass, clipped-off biomass trend (yr 1 − 6), and aboveground biomass production (seventh yr) 1 yr after treatment end (for simplicity we have not included inflorescence production on the seventh year, but their inclusion would not change results pattern). Signs indicate: (+) positive effect, (−) negative effect, (n.s.) nonsignificant effect, (intermediate) higher values at intermediate levels, and (X) significant 'defoliation intensity × grazing strategy' interaction. The last row indicates which factor (defoliation intensity vs. grazing strategy) had a greater impact on each variable, showing estimated values of effect sizes (the product between the *F* value and the degrees of freedom, taken from the statistical analysis; Fritz et al., 2012) when both factors were significant.

	Pappophorum vaginatum			*Digitaria californica*			*Trichloris crinita*		
	Mean clipped-off biomass	Clipped-off biomass trend	Aboveground biomass production on the seventh year	Mean clipped-off biomass	Clipped-off biomass trend	Aboveground biomass production on the seventh year	Mean clipped-off biomass	Clipped-off biomass trend	Aboveground biomass production on the seventh year
Defoliation intensity	n.s.	n.s.	−	+	n.s.	n.s.	+	−	−
Number of rest years in the grazing strategy	+	+	+	+	Intermediate	+	n.s.	+	n.s.
"Defoliation intensity × grazing strategy" interaction	X	X	n.s.	X	n.s.	n.s.	n.s.	X	n.s.
"Defoliation intensity vs. grazing strategy" importance	S > I	S > I	S > I (39 vs. 31)	I > S (32 vs. 22)	S > I	S > I	I > S	I > S (47 vs. 43)	I > S

has not demonstrated superiority over continuous grazing (Briske et al., 2008), but it is recognized that (longer) rest periods are valuable to improve or maintain rangeland productivity (Briske et al., 2008; Teague et al., 2013; O'Reagain et al., 2014). Holechek et al. (1999) found that rotational grazing has been more beneficial to forage species in humid sites than semiarid and arid areas. However, our results obtained in a semiarid site of NW Argentina provide evidence of the benefit of dormant season utilization and rest periods on C4 perennial grasses. In a 10-yr remote sensing study realized in the same region, Blanco et al. (2009) found that paddocks grazed under a 2-paddock rest-rotation strategy have a more positive trend in "normalized difference vegetation index" (an estimate of vegetation productivity) than a paddock grazed continuously, both at the same moderate stocking rate. These results, obtained at different scales, support the suggestion that variables related to productivity trend or residual effect of treatments (often omitted in investigations) are sensitive to detect the impact of grazing strategies (Davies et al., 2014).

Positive effect of rest periods over grasses productivity could be due to the plants' 1) basal area increase, 2) productivity increase per unit of basal area, or 3) density increase (e.g., if rest periods cause higher plant recruitment and/or lower plant mortality). In this respect, measurements carried out at the end of the experience in two of the three species (Appendix C) showed that in *P. vaginatum* plants, basal area and density were not affected by the grazing strategy, defoliation intensity, and their interaction; in *D. californica,* plant density did not vary with treatments, but basal area increased with the number of years of rest in the grazing strategy (Table C.1, Appendix C). This suggests that in *P. vaginatum,* differences are due to changes in plant productivity (per individual and per unit of basal area), while in *D. californica,* at least some of the differences between grazing strategies are explained by the higher basal area of plants receiving more rests.

Teague et al. (2008) suggested that discrepancies between experimental results that did not show any advantage of rotational over continuous grazing and the advocacy of commercial ranches to rotational grazing (Briske et al., 2008) are partially due to the smaller scale, rigidity, and simplifications implemented in research experiments. Briske et al. (2011) pointed out that discrepancies between both perspectives are because the implementation of rotational grazing in ranches increases the "intensity of management" and, hence, the possibility of adapting to contingencies, without necessarily stimulating ecological functions such as plant or animal production. Importantly, our experiment with no differences in management intensity and adaptability to contingencies between treatments showed a better response of the species to grazing strategies with rest periods than to the continuous grazing strategy without rests. Even more, as we discuss later, we encountered that the effect of grazing strategy was on several occasions greater than the effect of grazing intensity, and that both factors can interact in some situations (see Table 3).

Defoliation Intensity

Defoliation intensity effect strongly varied depending if variables were related to current yield (mean clipped-off biomass), sustainability (clipped-off biomass trend), or residual effect of treatments (inflorescence and aboveground biomass productions 1 yr after treatment ends). Although higher defoliation intensity presented higher mean clipped-off biomass during treatment application in *D. californica* and *T. crinita,* it negatively affected the clipped-off biomass trend in *T. crinita* and production in the year after treatment end of *P. vaginatum* and *T. crinita* (see Table 3).

In a review article, Holechek et al. (1999) found that heavy stocking consistently caused a downward trend in rangeland ecological condition, while light stocking caused an upward trend and moderate stocking caused a slight improvement. Also, in another review focused on northern Australia, O'Reagain et al. (2014) found that moderate stocking rates determined, in the long term, higher range condition and economic profitability than high stocking rates—the latter showing negative trends.

Our results highlight the trade-off between maximizing forage harvest in the short term and achieving a sustainable harvest along the time. In the short term, higher defoliation intensities can yield more harvested biomass. However, in the long term, this can be reversed due to the negative temporal trend of primary productivity at high intensities (Briske et al., 2008). In this sense, Parsons et al. (1983) demonstrated in pastures of *Lolium perenne* that high percentages of harvested biomass by high stocking rates are not synonymous with high primary productivity, which in turn was higher at lower stocking rates. Meanwhile, Oesterheld and McNaughton (1991) pointed out that the effect of grazing can be visualized differently depending on the response variable considered, expecting more negative effects of defoliation intensity on primary productivity than on the biomass harvested by herbivores.

Interaction between defoliation intensity and grazing strategy

In cases where there was significant "defoliation intensity × grazing strategy" interaction (see Table 3), it was observed that defoliation intensity tended to have a more negative effect as the grazing strategy had fewer rests. As described by O'Reagain et al. (2014), our results suggest that a heavy stocking rate that causes pasture deterioration under continuous grazing may be less harmful if it is applied under a rest-rotation strategy, which indicates that adverse effects of stocking rate could be mitigated to some extent by providing rest periods. This could be so because the recovery of plant vigor and reserve-substances under rest would allow plants to exhibit a better response to upcoming defoliations.

As an exercise, if we consider the clipped-off biomass trends obtained in the three species under the different defoliation intensities and grazing strategies, there are only two defoliation intensity-grazing strategy combinations that are sustainable (trend positive or neutral) for the three species: 2PRR at low-defoliation intensity and dormant season use at low-defoliation intensity (Figs. 2b, 3b, and 4b). The other 10 combinations produce negative trend in at least 1 of the 3 species. Our results further indicate that continuous grazing at high-defoliation intensity is the worst combination for rangeland conservation.

Importance of Defoliation Intensity versus Grazing Strategy

Our results are not consistent with the concept that herbage productivity or rangeland condition is more influenced by defoliation intensity than grazing strategy (Van Pollen and Lacey, 1979; Holechek et al., 1998; Briske et al., 2008). Indeed, in two of the three studied species (*P. vaginatum* and *D. californica*), grazing strategy presented greater impact on response variables than defoliation intensity. *T. crinita* was the unique species in which defoliation intensity has been more influential than grazing strategy (see Table 3).

Rest years in the grazing strategy produced at least some positive effect (and no negative effect) on the three species: the four response variables measured in *P. vaginatum,* two of the response variables in *D. californica* (mean clipped-off biomass and aboveground biomass production on the seventh yr), and in the clipped-off biomass trend in *T. crinita* (species less affected by grazing strategies). Meanwhile, defoliation intensity produced a positive or negative effect depending on the species and response variable: increased mean clipped-off biomass in *D. californica* and *T. crinita* but decreased clipped-off biomass trend in *T. crinita* and aboveground biomass production the year after treatments ended in *P. vaginatum* and *T. crinita* (in this species it also reduced inflorescence production that year).

Experiment Limitations

Some aspects that can be seen as limitations of the experimental approach are mentioned at continuation, as well as the points that can be seen as benefits of this methodology.

We applied clippings instead of grazing with animals. This simplification neglects the potential impact of animal trampling, dungs, and urine, but instead it does include the main effect of grazing on plants, which is defoliation (Kohler et al., 2004). We strongly believe that this methodological simplification allowed us to increase the control over the factors under study and to minimize the experimental error, something difficult to achieve in grazing experiments.

We used small and monospecific pasture plots. This means that the (spatial and botanic) heterogeneity of extensive paddocks was not considered in the study. However, we evaluated three of the main forage grasses of the Arid Chaco region over 7 yr, so as to take an important temporal variability into consideration. Also, we worked on plant stands (~17 plants per plot of 1.5 m × 0.5 m), not with individual plants, and then incorporated the effects of intraspecific plants coexistence (e.g., canopy closure, shading) that influence plant response to defoliation (McNaughton, 1992).

Management Implications

Results show that defoliation intensity is not the only important issue to consider when managing forage grasses. The importance of applying grazing strategies with rest periods is an important finding of our study. Our results show that dormant-season utilization and rest periods are beneficial for maximizing "current" clipped-off biomass and ensuring clipped-off biomass trend over time. High-defoliation intensity can maximize current clipped-off biomass, but this goes against sustainability or produces a negative residual effect on the grasses. The negative impact of high-defoliation intensities can be at least partially alleviated by permitting rest periods in the grazing strategy. Results suggest that the worst management practice for grass perdurability is to combine continuous grazing with high-defoliation intensities. It is also important to consider possible particular responses of different grass species.

Acknowledgments

We thank Enrique Orionte for promoting the study of native forage grasses; Bernardino Andrada for collaborating on pasture planting; Ariel Herrera, Emanuel Luna Toledo, Diego Teruel, Alicia Sancho, German Berone, Nico Zarate, and Tito Flores for assistance at different stages of field work; Martín Oesterheld; and two anonymous reviewers for suggestions that improved the manuscript.

Supplementary data

Supplementary data to this article (Appendices A, B and C) can be found online at https://doi.org/10.1016/j.rama.2017.09.002.

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