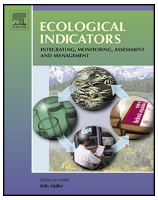
Ecological Indicators 63 (2016) 100–109

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



High impact grazing as a management tool to optimize biomass growth in northern Argentinean grassland

Ditmar Bernardo Kurtz[a,b,*], Folkard Asch[a], Marcus Giese[a,1], Christian Hülsebusch[c,2], Maria Cristina Goldfarb[b], Jose Francisco Casco[b]

[a] *Institute for Crop Production and Agroecology in the Tropics and Subtropics, University of Hohenheim, Garbenstr. 13, Stuttgart, Baden-Württemberg, Germany*
[b] *National Institute of Agriculture (INTA), Estación Experimental Corrientes, ruta 12km 1008, CC 57, CP 3400, Corrientes, Argentina*
[c] *German Institute for Tropical and Subtropical Agriculture (DITSL), GmbH, Steinstraße 19, D-37213, Witzenhausen, Germany*

ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form 26 October 2015
Accepted 28 October 2015

Keywords:
Cattle
Grazing management
Herd effect
Standing dead biomass
Trampling

ABSTRACT

Grasslands are the main source of feed for cattle in Argentina. Standing dead biomass accumulation threatens efficient resource use. The effect and timing of high impact grazing by cattle as a management tool to remove excess standing dead biomass was studied in grasslands of North Eastern Argentina. High impact grazing (HIG) was introduced monthly on adjacent paddocks over the course of the year and its effects were studied for 12 months following the treatment. Dynamics of biomass re-growth and accumulation of green and standing dead biomass were studied. HIG generally improved the green to total biomass ratio and reduced the overall biomass in the paddocks. Strong seasonal dynamics in the biomass growth rates strongly influenced the effects of timing of the HIG. All sub-plots subjected to HIG showed a growth pattern anti-cyclic to control, with an active growth phase during autumn when the biomass in the control sub-plots decreased. Best results in terms of standing dead biomass reduction and dead to green biomass ratios were achieved after HIG in winter. HIG in autumn, however, reduced fodder availability and reduced next year's grassland's productivity. We propose strategically (carefully) timed HIG not only as an alternative method to reduce standing dead biomass, but also as a pathway to sustainable intensification by providing green forage at levels equal or even higher than those achieved under continuous traditional grazing.

1. Introduction

Regular disturbances such as fire and continuous grazing have shaped Argentina's grassland structure (Carnevali, 1994). In the northern province of Corrientes, having a strong tradition of cattle ranching, net primary productivity (NPP) of C_4 grasses is high in summer but relatively low in winter (Bernardis et al., 2005b; Martín et al., 2011; Royo Pallarés et al., 2005). Therefore, farmers stock their rangelands adjusted to the availability of winter fodder, which in turn results in very low stocking rates (Calvi, 2010). As a consequence, high standing dead biomass pools build up in large grassland areas in north-western Corrientes (Kurtz et al., 2010). Standing biomass decreases net photosynthesis and energy capture decreasing net production; nevertheless it accumulates annually, independent of the season (Fidelis et al., 2013) and acts not only as a grazing deterrent (Balph and Malecheck, 1985; Moisey et al., 2006) but also reduces live weight gain of large herbivores through decreased palatability and low overall forage quality (Mingo and Oesterheld, 2009). Due to these reasons, the overall animal production for northern Argentinean grasslands is low (Royo Pallarés et al., 2005). Recently published data indicated that over the last 60 years cattle live weight gain neither not change in Corrientes (Calvi, 2010) nor or in Argentina (Elizalde and Riffel, 2014; Hidalgo and Cauhépé, 1991), suggesting that a considerable production potential of these rangelands remains unutilized.

There is a wide range of possible treatments to reduce unproductive and low quality standing dead material. It comprises from mechanical elimination e.g. with knife-rollers, choppers,

---

* Corresponding author at: National Institute of Agriculture (INTA), Estación Experimental Corrientes, Ruta Nacional 12 km 1008, CC 57, CP 3400, Corrientes, Argentina. Tel.: +54 3794 231011; mobile: +54 91168001896.

E-mail addresses: kurtz.ditmar@inta.gob.ar (D.B. Kurtz), fa@uni-hohenheim.de (F. Asch), m.giese@uni-hohenheim.de (M. Giese), c.huelsebusch@ditsl.org (C. Hülsebusch), goldfarb.maria@inta.gob.ar (M.C. Goldfarb), casco.jose@inta.gob.ar (J.F. Casco).

[1] Tel.: +49 0711 459 22574.

[2] Tel.: +49 05542 607 29.

http://dx.doi.org/10.1016/j.ecolind.2015.10.065
1470-160X/© 2015 Elsevier Ltd. All rights reserved.

mowers and plows (Adema et al., 2004), targeted weed grazing (Frost et al., 2012), goat grazing (Lovreglio et al., 2014), and very often the use of fire (Bernardis et al., 2008; Fernández et al., 2011; Toledo et al., 2014). However, both fire and mechanical options have their disadvantages, namely increased burning risk (Fidelis et al., 2013; Thomas, 2006), bush encroachment (Dudinszky and Ghermandi, 2013), reduced species recruitment and weed germination (Franzese and Ghermandi, 2012), biodiversity loss (Azpiroz et al., 2012; Podgaiski et al., 2014), soil compaction (Hamza and Anderson, 2005; Jung et al., 2010; Schrama et al., 2013) and reduced water infiltration (Chyba et al., 2014). Nevertheless, fire is the most frequent and easy-to-use management tool in tropical grasslands and savannas (Oesterheld et al., 1999; Pausas and Ribeiro, 2013). Recently, burning has been forbidden both in Argentina (Argentina, 2009) and in the Corrientes Province (Corrientes, 2004).

High impact grazing (HIG) or the “herd effect” was proposed as a management option for restoring and maintaining grassland ecosystem functions (Savory, 1983, 2005) and as a means of improving the plant productivity (Savory and Parsons, 1980). Although sometimes controversially discussed (Briske et al., 2013; Teague et al., 2011), HIG has been shown to stimulate plant growth in some grassland ecosystems (McMillan et al., 2011) and create productive grazing lawns with high fodder quality (Cromsigt and Olff, 2008; Hempson et al., 2014; McNaughton, 1984).

HIG has multiple effects; it removes shading by dead biomass, including plant defoliation, nutrient removal and re-distribution through excreta, enhancing nutrient cycling and the mechanical effect of trampling. Although most of the aforementioned effects and issues are known, information of HIG effects on above ground biomass dynamics is surprisingly scarce and for some grassland ecosystems not considered so far. Up to date, the herd effect method generated a strong controversy in the scientific community (Briske et al., 2008, 2011, 2013; Dunne et al., 2011; Joseph et al., 2002). Only few studies analysed the effects of HIG on the above ground biomass; Jacobo et al. (2000, 2006) found positive effects of rotational grazing to control standing dead material; Striker et al. (2011) found for flooded grasslands that the Graminiods share was increased after HIG, while the aboveground net primary productivity (ANPP) was not significantly affected. Since most grassland ecosystems are characterized by pronounced climate seasonality, the timing (i.e. HIG in spring, summer, autumn, or winter) will likely affect biomass growth dynamics during the months following HIG. If properly timed, we assume considerable shifts in green to dead biomass ratio and rangeland productivity and thus positive effects on animal production as well.

It has not been investigated to date if HIG could be a serious alternative management practice for Northern Argentinean grasslands to control standing dead biomass and promote plant growth. The results will be relevant for developing strategies within the concept of sustainable land use intensification with regards to both environmental stability and raising productivity of agro-ecosystems (Garnett et al., 2013).

2. Materials and methods

2.1. Study area

The study was carried out at the Corrientes INTA Research Station (lat 27°40′01″S, long 58°47′11″W), in the Empedrado Department, 30 km South of Corrientes city, Capital of the Corrientes Province, Argentina. Mean elevation at the site is 69 m above sea level, and slopes are less than 0.1%. Local mean annual precipitation is about 1300 mm. There is a slight seasonality of rains; most of precipitation occurs in autumn (33% from March to May) and summer (30% from December to February) and less in spring (24% from September to November) and winter (13% from June to August). The average annual temperature is 21 °C. The annual temperature amplitude of monthly means ranges from 25.6 °C in January to 15.5 °C in July. The mean temperature during the experiment was similar to the average mean temperature. Precipitation amount during the experimental period varied only slightly between years, from June 2012 to May 2013, total precipitation was 1345 mm, and evapo-transpiration 1150 mm. From June 2013 – May 2014, precipitation was 1233 mm and evapo-transpiration 1107 mm (Fig. 1)

Soils have a sandy-loam texture and belong to the Treviño series (Aquic Ariudoll, Escobar et al., 1996) which covers approximately 37,250 ha in north-western Corrientes. Soils remained humid or very humid for most of the time every year, mostly due to both, the high precipitation and the clay layer located at approximately 40–90 cm depth (Bt horizon). The pH varied from 5.6 to 6.0, up to 7.0 to 7.4 below the Bt layer. Soil organic matter varied from 1.2 to 1.7% in the upper part, being as low as 0.3% at 90 cm (Escobar et al., 1996).

2.2. The dominant vegetation

Dominant tussock species were paja colorada (*Andropogon lateralis* Nees), paja amarilla *Sorghastrum setosum* (Griseb.) Hitchc. (ex *S. agrostoides* Speg. Hitchc.) and *Paspalum plicatulum* Michx. Among grass bunches, other short grasses develop, pasto horqueta (*Paspalum notatum* Flügge), *Axonopus affinis* Chase, *Eleocharis nodulosa* (Roth) Schult., *E. viridans* Kük. ex. Osten. and *Leersia hexandra* Sw. are the most frequent grass and grass-like species. Legumes are rather infrequent, with *Desmodium incanum* DC. being the most widely spread perennial legume and *Vicia epetiolaris* Burk. being the annual most frequent species growing and flowering in late winter and spring (Vanni and Kurtz, 2005).

2.3. Experimental layout

The experiment was established on a 24 ha natural grassland area which is part of the research facility of the Institute of Technical Agriculture (INTA) Corrientes. Before, the area was traditionally managed with continuous grazing at an intensity of 0.5 animal units per ha. Four adjacent paddocks of 6 ha each were separated with permanent electric fences. Three of them were used as replicates (R1–R3) for the HIG treatment experiment, and the fourth paddock was defined as control with continuous grazing with no HIG. The HIG treatment followed a monthly sequence; therefore each replicate paddock was divided into 12 sub-plots of 0.5 ha each, used for monthly HIG. The experiment started in July 2012, when the first sub-plot (50 m width, 100 m length) was enclosed with mobile/temporal electric fences and subjected to three days of HIG. For that purpose a mixed 75-animal herd of Braford, Hereford, and Brahman cattle breeds was used, representing an instantaneous grazing intensity of 150 animals ha^{-1} (approximately 30,000 kg of animal biomass ha^{-1}). During the first day the herd was allowed to graze ad libitum and the second day the cows were moved/driven around within the sub-plot to ensure an impact as homogeneous as possible until all vegetation was trampled down. After HIG, the mobile sub-plot fences were removed and the HIG herd was driven to the remaining two 6 ha paddocks to carry out the HIG at the particular sub-plots. All four 6 ha paddocks were continuously grazed throughout the experiment with 3 non-lactating cows each, to resemble the average stocking rate of 0.5 animal unit ha^{-1} in Corrientes Province (Calvi, 2010; Kurtz and Ligier, 2007). These cows were also crossbreeds Braford, Hereford, and Brahman. According to mean temperature, monthly precipitation, daily reference evapo-transpiration and relative humidity the impact month were classified to represent an annual season namely spring (September, October, November),

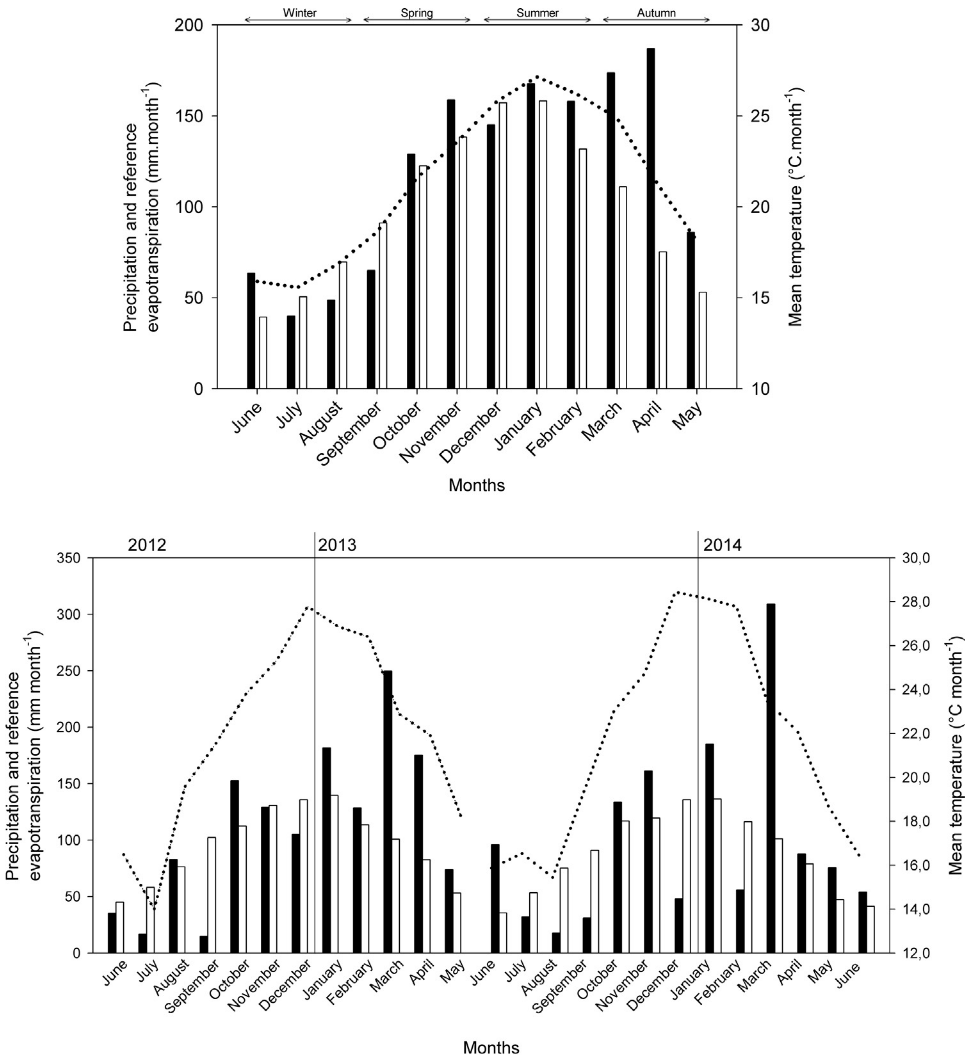


Fig. 1. Monthly climate patterns and seasons from INTA Corrientes meteorological data, period 1968 to 1998 (upper right) and during the experiment from 2012 to 2014 (bottom right). The dotted line indicates mean air temperature (°C). White bars indicate reference monthly evapo-transpiration and black bars depict monthly precipitation (mm).

Table 1
Monthly climate variables which define the seasons in the study area, calculated from INTA Corrientes meteorological data, period 1968 to 1998.

Season Months	Monthly mean temperature (°C)	Monthly Precipitation (mm)	Daily evapo-transpiration (mm)	Monthly relative humidity (%)
Winter June, July and August	16.1 (0.7)	50.8 (14)	1.7 (0.5)	41.9 (3.2)
Spring September, October and November	21.3 (2.5)	104.7 (41.3)	3.9 (0.8)	47.2 (4.4)
Summer December, January and February	26.4 (0.7)	138 (24.7)	5 (0.2)	52.3 (3.2)
Autumn March, April and May	21.4 (3.4)	150.4 (44.2)	2.6 (0.9)	47.1 (0.7)

summer (December, January, February), autumn (March, April, May), and winter (June, July, August) (Table 1, Fig. 1).

2.4. Biomass sampling

Aboveground biomass was harvested completely at two 1 m^2 sampling areas per sub-plot near the ground level. Aboveground biomass was sampled every month between February 2013 and June 2014 and separated into green and dead material. Monthly biomass re-growth was measured using two protective cages per sub-plot. The cages were placed onto the freshly cut m^2 of the particular sub-plot and harvested the next month. The plant material was oven-dried at 75° until constant weight.

2.5. Statistic analysis

We analysed the effects of HIG applied every month compared to the control areas without treatment. The experiment was set up as a randomized block design with three repetitions (R1–R3). For biomass comparison, a linear mixed model for repeated measures using maximum likelihood (REML) in time with independent heteroscedastic errors was used for biomass. Months of harvest were considered as the fixed effects. For the random effects, sub-plots were declared as the stratification criteria, so that it was explicitly stated the correlation of measured data coming from the same sub-plot. The model takes into account the month of data acquisition order, as harvest time was equidistant, the structure corAR1 was applied (Piepho et al., 2004). Different biomass fractions were analysed, monthly biomass re-growth (BRG), standing green biomass (SGB), standing dead biomass (SDB) and standing total biomass (STB) as dependent variables. The comparison of means was tested when a significant *F*-value was achieved; then the least significant difference (LSD) post hoc analysis was applied. To explore how the time after seasonal impact influenced the biomass pools accumulation, we used a set of models using the different biomass fractions (BRG, SGB, SDB and STB) as dependent variable and months after high impact grazing (MAI) as independent variable. Statistical significance of all tests was $p < 0.05$, if not stated differently. We used the software InfoStat (v.2014) for the statistical analyses. The cows where weighed before and after the experiment. Analysis of variance (ANOVA) was used to analyse the treatment effects on live weight gain.

3. Results

3.1. Biomass dynamics

Compared with the control area, HIG had no effect on monthly biomass re-growth (BRG) (Fig. 2). There was no interaction between the harvest season and the HIG treatment ($p = 0.2898$). However, season significantly influenced BRG ($p < 0.0001$), i.e. winter showed the lowest monthly re-growth (30 g m^{-2}), while growth rates in summer (73 g m^{-2}), autumn (64 g m^{-2}) and spring (60 g m^{-2}) were significantly higher.

Fig. 3 shows the standing biomass (STB) dynamics of HIG treated sub-plots subdivided by impact timing (winter, spring, summer, autumn) and control sub-plots harvested during the whole 23-month sampling period. We found no seasonal effects on the residual biomass after trampling (Fig. 3). Our calculations indicate that on average the instantaneous effect of HIG reduced the standing green and dead biomass by 95% (±1%), measured STB before and after HIG showed that it was reduced from 1970 g m^{-1} in spring, from 1680 g m^{-1} in summer, from 1770 g m^{-1} in autumn and from 2370 g m^{-1} in winter to approximately 100 g m^{-1}. Over the entire experimental period STB was significantly lower at the different HIG treatments (Fig. 3).

STB dynamics at the control sub-plot followed a seasonal pattern with clear maxima in November and December and minima from April to August but always above 1000 g DM m^{-2}. HIG sites showed a STB between 200 and 800 g DM m^{-2}. Active growth phases for both control and HIG were observed from September to January (spring and summer); thereafter total biomass of the control sub-plots decreased by about 40% in the period from February to August (autumn and winter). In contrast, sub-plots under HIG independent of the impact timing, showed an extended growth period in autumn, from February to June. With exception of the HIG in autumn the STB increased by 850 g m^{-2}, while the control lost biomass or stagnated at roughly 1000 g m^{-2}.

3.2. Impact timing

Fig. 4 shows the biomass dynamics after HIG in spring, summer, autumn and winter. The figure shows total and standing dead biomass of HIG treated and control sub-plots over a period of 13 months; where the difference between the two curves, represents the amount of green biomass in the respective sub-plots.

$\text{HIG}_{\text{winter}}$ resulted in two growth phases with one strong biomass increase in spring and the other one in autumn (Fig. 4a).

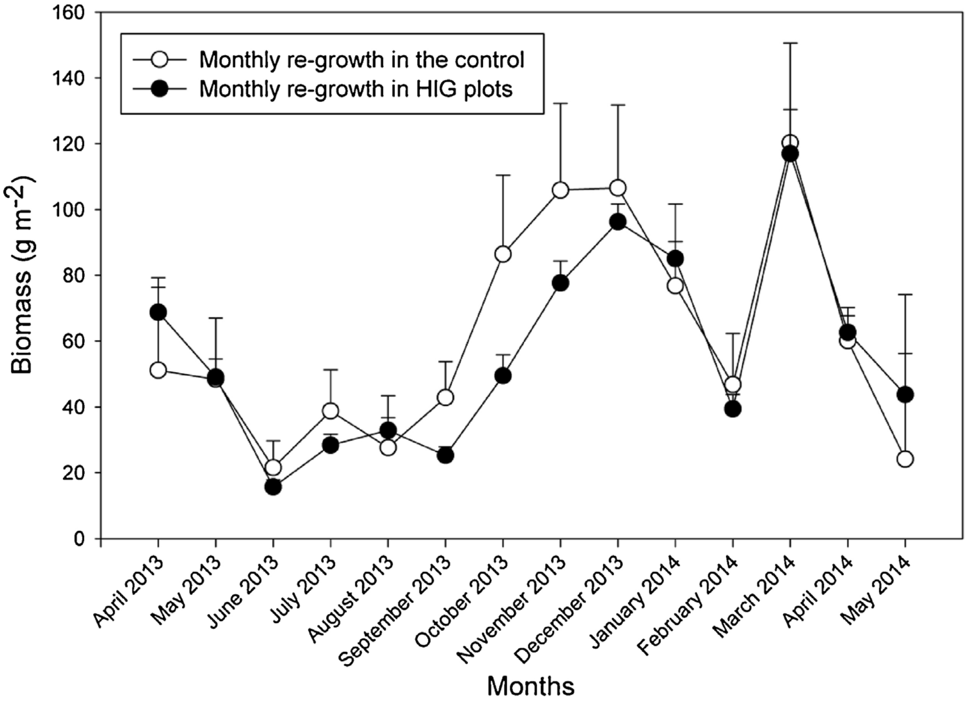


Fig. 2. Grassland dynamics, monthly re-growth in control and in the high impact grazing (HIG) sub-plots. Al variables expressed in g m^{-2}. Error bars indicate the standard error of the means ($p < 0.05$).

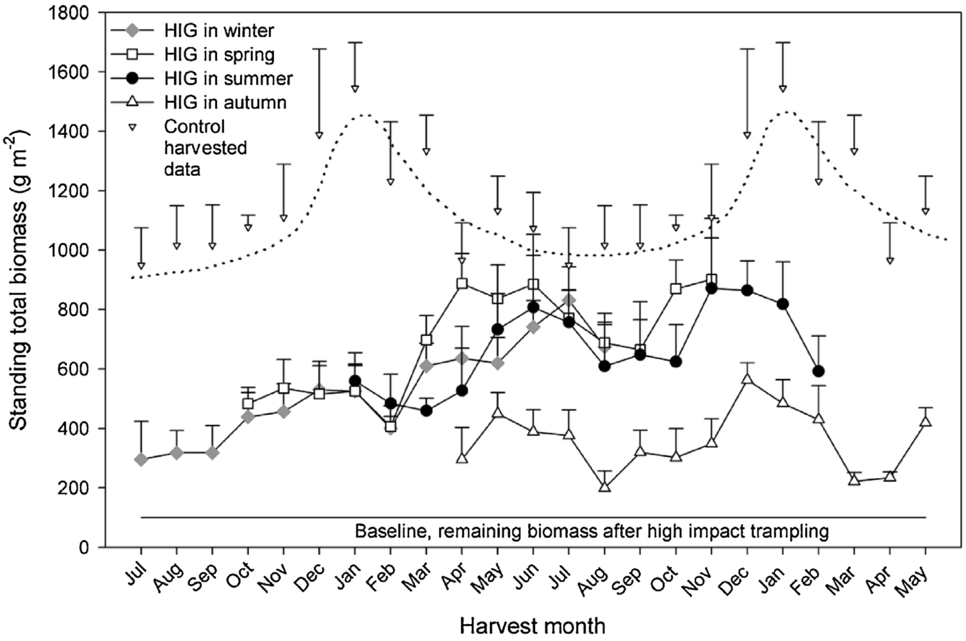


Fig. 3. Standing total biomass (STB) after the high impact grazing (HIG) in winter, spring, summer and autumn compared to STB harvested in the control. STB of every impact season is the average STB of the impact months classified accordingly. For example winter HIG is the average STB of the months classified and treated by HIG in winter (e.g. June, July and August) measured at the particular month. For better comprehension biomass dynamics of control was eye fitted (dotted line).

In contrast we found only one active growth phase in spring for the control site. The STB accumulation in spring was faster after $\text{HIG}_{\text{winter}}$ compared to the control (slope $b = 258\,\text{g}\,\text{m}^{-2}$ vs. $196\,\text{g}\,\text{m}^{-2}$ month), as shown by the slope of the regression of STB over time, representing the growth rate (Fig. 4a). While the second growth phase at $\text{HIG}_{\text{winter}}$ increased the aboveground biomass by around $500\,\text{g}\,\text{m}^{-2}$, the control sub-plots lost dry matter between 300 and $400\,\text{g}\,\text{m}^{-2}$.

$\text{HIG}_{\text{spring}}$ triggered an extended active growth phase into autumn with increasing aboveground biomass (up to $1000\,\text{g}\,\text{DM}\,\text{m}^{-2}$) until seven months after impact (Fig. 4b). During the same time the control sub-plot showed decreasing biomass from 1500 to $1000\,\text{g}\,\text{m}^{-2}$. 10–12 months after the impact both control and $\text{HIG}_{\text{spring}}$ resumed growth again during the following spring. Through the year the largest share of the biomass in the control was of very low quality with SDB varying from 62 to 84% compared to 34 to 74% in the HIG sub-plots. Moreover, SGB was not significantly different ($277\,\text{g}\,\text{m}^{-2}$ vs. $252\,\text{g}\,\text{m}^{-2}$) between control and HIG sub-plots, respectively.

$\text{HIG}_{\text{summer}}$ also promoted growth, the first growth phase during the autumn (this phase was again absent in the control sub-plots where STB showed a negative trend) and a second one in spring. The autumn growth phase resulted in a sharp increase in STB ($b = 137.1\,\text{g}\,\text{m}^{-2}$ month), which peaked at about $800\,\text{g}\,\text{m}^{-2}$ (Fig. 4c). The second growth phase, in spring, started in September and occurred in both, HIG and control sub-plots.

The $\text{HIG}_{\text{autumn}}$ did not trigger a second active growth of biomass in the year but resulted in an extended growth phase from September to March in parallel with the control sub-plots. During this period, STB accumulated from about $1000\,\text{g}\,\text{m}^{-2}$ to about $1400\,\text{g}\,\text{m}^{-2}$ in the control sub-plots and from about $300\,\text{g}\,\text{m}^{-2}$ to about $700\,\text{g}\,\text{m}^{-2}$ in the $\text{HIG}_{\text{autumn}}$ sub-plots (Fig. 4d). Across all seasons the absolute amount of green standing biomass in the HIG sub-plots matched in most cases the amount of green biomass in the control sub-plots. In addition, due to a much higher accumulation of SDB in the control sub-plots the share of green biomass was higher in the HIG sub-plots for as at least as long that one year after the HIG (Fig. 5). Green biomass share of the control sub-plots was highest during summer with a peak value of around 30% of the total biomass. For most parts of the year, the share of green biomass was lower and fluctuating roughly between 20 and 25%. In the HIG sub-plots the share of green biomass peaked once or twice depending of the HIG season and reached values of up to 60% of the total biomass. Throughout the year the proportion of green biomass in the HIG sub-plots was on average 20% higher than in the control sub-plots. In combination with the generally lower amounts of total biomass in the HIG sub-plots, the available biomass was better more palatable and more easily accessible to the cows in the HIG sub-plots.

4. Discussion

4.1. The effect of high impact grazing on grassland dynamics

The monthly vegetation re-growth showed a clear seasonal pattern, which is typical for C_4 dominated grasslands, where low growth rates coincide with periods of low temperature and low radiation (Knapp and Medina, 1999; Martín et al., 2011; Ötztürk et al., 1981; Royo Pallarés et al., 2005). The accumulated biomass re-growth was barely 8% higher in the control sub-plot ($857\,\text{g}\,\text{m}^{-2}$) compared to the HIG sub-plots ($791\,\text{g}\,\text{m}^{-2}$). Neither over-compensatory growth as reported by McNaughton (1979, 1983) nor a reduced productivity following the impact was observed in this study as growth rates remained similar between HIG and control sub-plots indicating a rather resilient rangeland in response to grazing disturbance. This could have been due to three factors, (i) relatively more of the biomass was trampled down instead of grazed or, (ii) the nutrient cycles were not accelerated by the additional faeces deposition, and last but not least (iii), the intercalary and protected apical meristems were not lost by HIG and could recover easily after shoot removal (Heckathorn et al., 1999).

On the other hand, we found that HIG reduced the standing total (STB) and standing dead biomass (SDB). We can confirm that the effects on grassland biomass dynamics depend strongly on the season when HIG was applied (McNaughton, 1983). HIG showed a

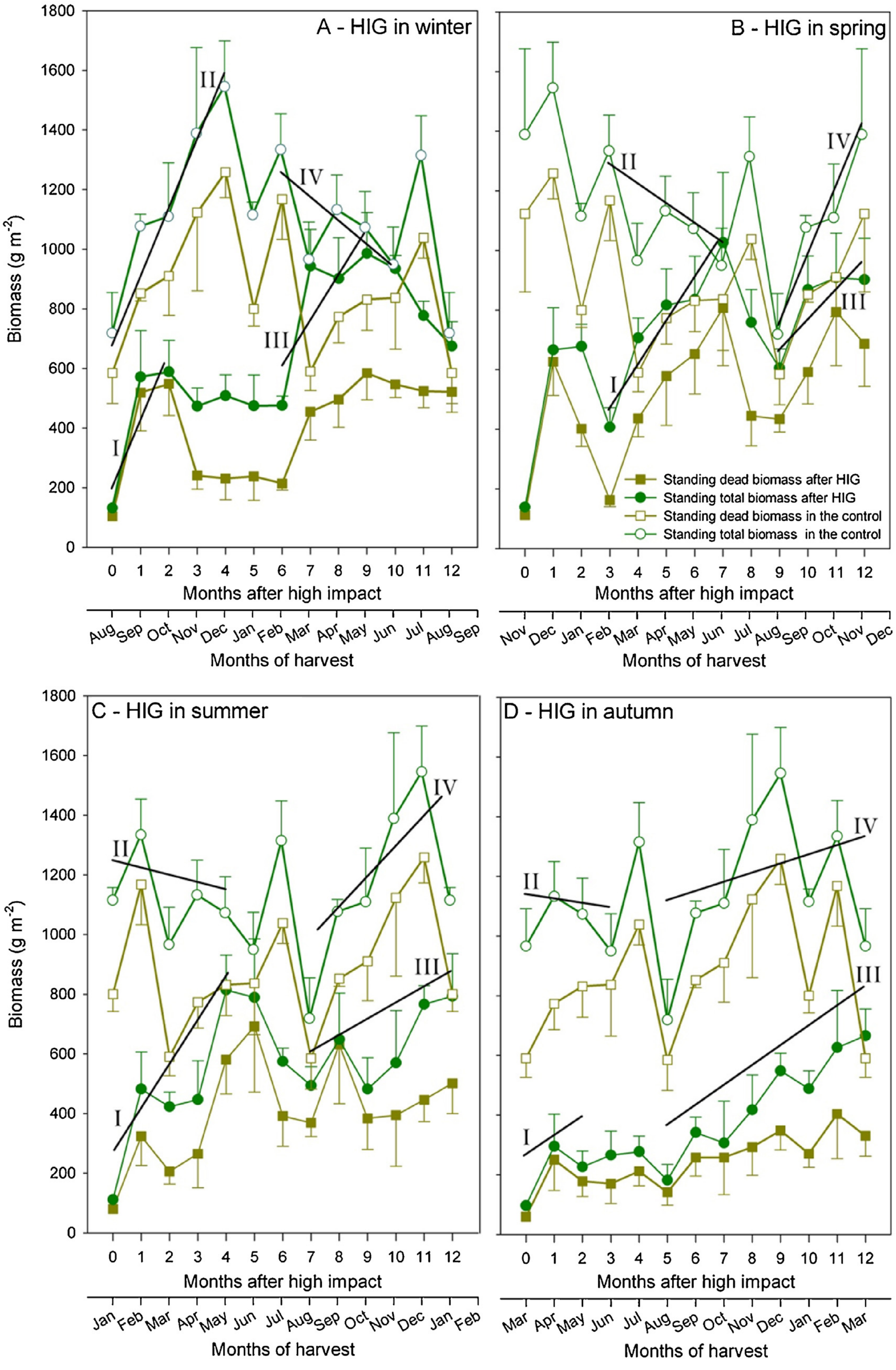


Fig. 4. Total and dead biomass dynamics after high impact grazing (HIG) applied in four different seasons. Exemplary shown for August, HIG_{winter} (A), for November HIG_{spring} (B), for January HIG_{summer} (C) and for March HIG_{autumn} (D). The difference between curves indicates the green biomass. For each HIG season the regressions were calculated considering the STB, one month after HIG and at the time the maximum achievable STB was harvested; while in the control and for comparativeness the regression was calculated considering the STB during that same period of time. The rate of biomass accumulation changed with the month of HIG occurrence as follows, AI. $y = 258.4x + 152.3$ ($r^2 = 0.775$); AII. $y = 196.5x + 578.4$ ($r^2 = 0.954$); AIII. $y = 148.9x + 603.5$ ($r^2 = 0.661$); AIV. $y = -66.2x + 1289.9$ ($r^2 = 0.452$). BI. $y = 92.9x + 681.9$ ($r^2 = 0.686$); BII. $y = 196.5x + 484.9$ ($r^2 = 0.902$); BIII. HIG, $y = 136.9x + 603.5$ ($r^2 = 0.661$); BIV. $y = -66.2x + 1289.9$ ($r^2 = 0.452$). CI. $y = 55.4x + 487.1$ ($r^2 = 0.6$); CII. $y = 104.8x + 792.6$ ($r^2 = 0.472$); CIII. $y = 137.1x + 181.3$ ($r^2 = 0.755$); CIV. $y = -28.5x + 1209.9$ ($r^2 = 0.113$). DI. $y = 88.9x + 504.6$ ($r^2 = 0.908$); DII. $y = 37.9x + 986.2$ ($r^2 = 0.1273$); DIII. $y = 65.4x + 218.1$ ($r^2 = 0.924$); DIV. $y = -10.9x + 1057.6$ ($r^2 = 0.026$).

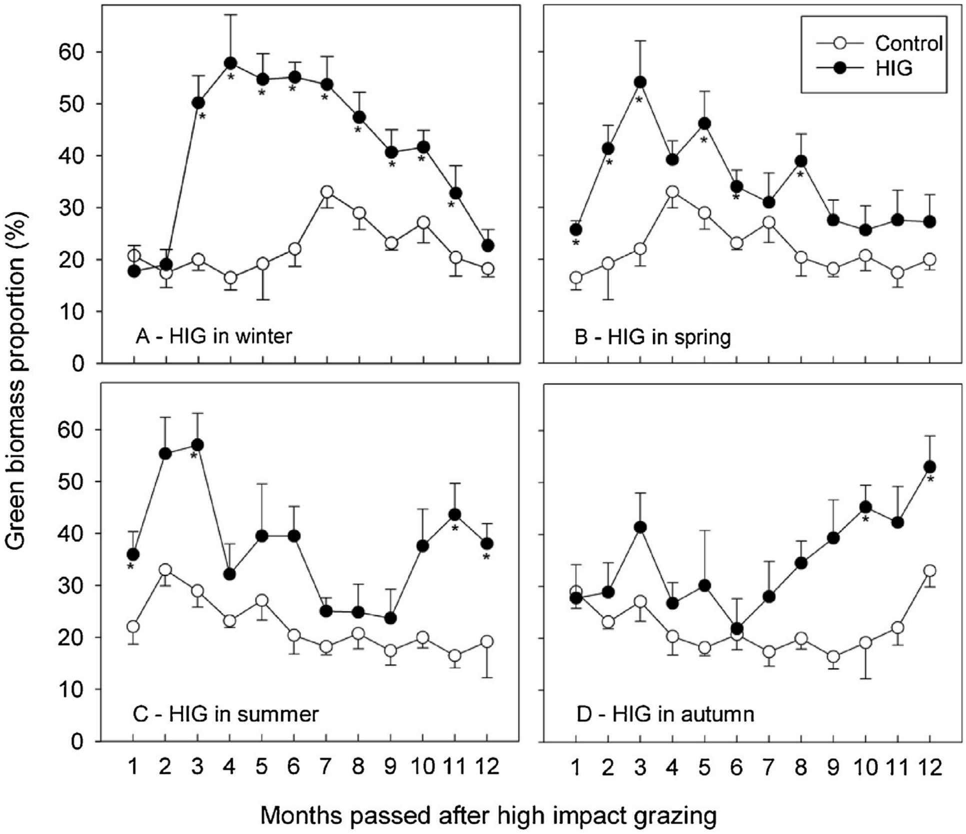


Fig. 5. Green proportion of the grassland biomass and time passed after HIG, which was applied in four different seasons. Exemplary months are shown, August for HIG in winter (A), November for HIG in spring (B), January for HIG in summer (C) and March for HIG in autumn (D). Error bars indicate the standard error of the means ($p < 0.05$).

different growth pattern anti-cyclic compared to that of the control, with an active growth phase during autumn when the biomass in the control sub-plots decreased. The declining trend of STB in the control sub-plots was indeed negative in autumn due to strong SDB biomass decay, whereas the response to HIG was active tillering that built up new biomass as most of the biomass was previously removed or trampled down.

In the untreated control sub-plots as a result of the seasonal growth, STB accumulated from spring to summer and decreased approaching the end of the growing season in late autumn until the end of the winter in August. The negative rate of STB accumulation was not only directly related to the climatic conditions, particularly to the low temperature (Long, 1999), but also, we assume likely due to less light interception due to the shade produced by the biomass. It is well documented that an open canopy and low light interception is essential for high photosynthetic rates in C_4 plants (Heckathorn et al., 1999; McMillan et al., 2011; Ötztürk et al., 1981) and consequentially for biomass production (Heckathorn et al., 1999; Pearcy et al., 1981). During autumn and winter control sub-plots suffered from a combination of high amounts of STB shading the lower canopy leaves and decreasing temperatures. As the decreasing temperatures affect both the HIG and the control sub-plots equally, it is likely that the better light penetration in the HIG sub-plots induced the active growth observed in autumn in the HIG sub-plots improving the ratio between SGB and SDB. This is supported by the biomass re-growth results showing a similar growth potential of control and HIG sites throughout the year after biomass was removed (Fig. 2).

Compared to HIG in winter, summer or spring (STB accumulation between ~400 and 800 g m^{-2}), HIG in autumn produced exceptionally low STB (~200–600 g m^{-2}) (Fig. 4d). Two major effects may have been the cause of this. On one hand, seasonal variations in temperature induce C_4 plants to allocate resources to below-ground organs before grasses senesce when temperatures decrease towards winter. It is highly likely that the HIG towards the end of the growing season in autumn impeded the allocation of photosynthates to roots (Knapp and Medina, 1999). Therefore, the HIG in autumn, by destroying all present biomass, interfered with root resources allocation which translated into low growth on the following growing season. $\text{HIG}_{\text{autumn}}$ could have been amplified by water logging resulting in soft water saturated soil horizons (Striker et al., 2011). High rainfall and low potential evapo-transpiration during autumn indeed resulted in water-logging during HIG on our experimental sites. Therefore HIG mainly due to trampling during times of water-logging has likely triggered stalks injury and serious root damage (Dunne et al., 2011; Striker et al., 2006), responsible for the reduced growth during the next spring and even summer.

Clearly the grasses are more sensitive to HIG in autumn, when soils were and normally are waterlogged, but if it had been applied in a less damaging manner at this time of year damage would likely have been considerably less. Also in a management system only a small part of the whole management would be receiving HIG treatment at this time of year. So if different areas of the grazing whole were subjected to HIG each year this would not be a problem.

In general, the control sub-plots offered a mixed bunch of green and huge amounts of deterrent standing dead grass hardly accessible for the cows (Balph and Malecheck, 1985; Moisey et al., 2006). Green proportion in control sub-plots barely reached 30% in autumn; they had, on average, only 22% green biomass (of ~800–1600 g m^{-2} STB) through the year. In contrast, the proportion of green biomass was higher in HIG sub-plots. For example, the share of green biomass was on average above 38% and 42% after HIG in winter and summer, respectively (Fig. 5). Moreover, it seems that by removing SDB and preventing shading we also prolonged leaf longevity (McNaughton, 1983), as was shown by the share of green biomass in HIG and control sub-plots (Fig. 5). HIG reduced STB by around 95%; nevertheless, seasonality and variable weather such as wet or dry conditions altered grassland STB incorporation to the soil. HIG under muddy conditions with water logging, led to more biomass incorporation into the soil compared to dry conditions, where biomass was trampled to the soil surface. However, several months after HIG we did not observe any significant effects on biomass dynamics. Finally, there was a clear trade-off; in general less forage was harvested in HIG sub-plots compared to the control, nevertheless after HIG the grassland produced a more stable availability of palatable green biomass throughout the year (Fig. 5). Independently of when HIG was done and compared to the control, the senesced grassland biomass was rejuvenated (McNaughton, 1983). Moreover, the results of the present study suggest better foraging conditions for grazers resulting from the reduction of SDB.

The proportion of SGB (SGB/SDB ratio) should be further explored to function as indicator for the positive effects of HIG. Although the amount of SGB produced was less when HIG was applied in summer or autumn compared to the winter or spring impact, the positive effects for the winter and spring period (the most difficult period for animal nutrition) are of higher relevance for the overall productivity of the land use system. HIG at any time of the year increased the SGB/SDB ratio which consequentially enhanced energy capturing during winter and early spring periods when grass growth is normally light limited by the SDB.

4.2. *Implications for range management and meat production*

Despite the fact that overall biomass was reduced, the amount of palatable biomass (SGB) in the HIG sub-plots was still sufficient to feed cows throughout the year. For example, during the first three months after HIG in winter, grassland had enough green biomass (~170 kg biomass ha^{-1}) to feed 0.5 A.U. which is the normal stocking rate in the Province (considering a theoretical daily feed intake of 12 kg dry matter or 3% of life weight of a 400 kg cow). Nevertheless after HIG in spring, summer or autumn, the available SGB was between 2 and 6 times more than needed at that stocking rate. On the other hand, control sub-plot produced 4–10 times the amount of green biomass at that stocking rate, but was barely accessible due to the huge volume of deterrent SDB. Even though not conclusive, our results clearly show that cows' weight increased significantly more on the grasslands subjected to HIG than on the control sub-plots. All sub-plots were constantly grazed by cows which at the beginning had the same live weight (232.8 kg, sd = 18.3 kg). Weighed again, about a year later, at the end of the experiment cows on control sub-plots weighted 282.3 kg (sd = 19.1 kg) whereas those in HIG sub-plots gained 30% more live weight (400.9 kg, sd = 86.7, Fig. 6).

Grazing was less efficient in the control since cows probably spent more time and energy searching for forage (Abdel-Magid et al., 1987; Heckathorn et al., 1999). Our calculations indicate that cows could have consumed at least 20% more biomass after HIG than in the control (data not shown). The HIG, with monthly time intervals and on adjacent areas, produced a combination of areas of low, but high quality biomass and areas of high bulk but low quality biomass, which enhanced ruminant resources utilization (Hempson et al., 2014) and could have determined the higher live weight gain. Reasons remain speculative, but the results are suggesting either a better availability due to the less proportions of deterrent SDB as a result of HIG, or an improved nutritious quality of the sward or both. Prior research in the region showed that the chemical composition of different grass species was most nutritious up to two months after clipping (Casco and Bernardis, 1992, 1993, 1994; Bernardis et al., 1997). Fodder quality analysis will reveal whether HIG was able to improve the nutrient content of the grasses or not. Our results suggest that impact grazing in (late) winter would result in most beneficial rangeland properties with regard to biomass re-growth dynamics, green to dead proportions and extended growth periods. An impact during autumn, however, could (i) significantly reduce the fodder availability during the winter and (ii) jeopardize the next years productivity due to the threat of serious root destruction in water logged soils unless management mitigates this impact as mentioned earlier. Our results confirm that strong disturbances towards the end of the winter, such as fire for example, maximally increase the share of green biomass in the grassland (Bernardis et al., 2005a, 2008; Fernández et al., 2011; Martín et al., 2011).

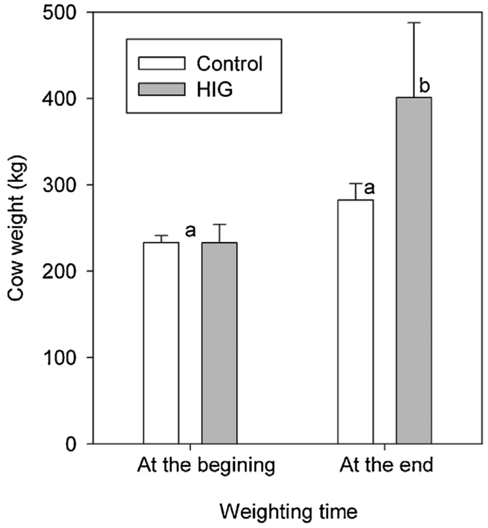


Fig. 6. Live weight (kg) of the cows at the beginning and at the end of the 2013–2014 period, in both control and treated sub-plots. The figure shows the weight means and the vertical bars indicate the standard deviation. Means with a common letter are not significantly different ($p > 0.05$).

We are aware that, further in depth studies of HIG as a management tool are needed to improve our understanding of the plant–animal interactions and to use this potentially beneficial quasi-natural disturbance mechanism (Cromsigt and Olff, 2008; Hempson et al., 2014; McNaughton, 1984) to increase resource use efficiency and productivity of rangeland ecosystems.

5. Conclusions

We provide first hand evidence of a HIG management alternative for Argentinean ranchers in order to reduce the unproductive and grazing deterrent standing dead biomass. HIG effect on the biomass pools lasted for several months thereby increasing the green to dead biomass ratio. Timing of the HIG is most important and should consider the natural seasonal dynamics of the grassland ecosystem. Best results in terms of standing dead biomass reduction and dead to green ratios were achieved with HIG in winter. HIG in autumn, however, could reduce fodder availability and reduce next year's grassland's productivity. Irrespectively of the season applied HIG produced an extended growth phase which lasted until the next autumn. This growth response has not been observed or reported up to now for the region, and should be explored for the potential to improve the fodder availability for cattle right at the beginning of the winter. Dead to green biomass ratios as a result of HIG should be further analysed to function as an indicator for improved pasture management.

In addition our results contribute to a better understanding of ecosystem disturbance mechanisms with potential to be used for enhanced rangeland management. HIG could be a valuable alternative for range managers seeking not only for a different method to reduce dead biomass pools, but also working towards a sustainable intensification providing green forage at levels equal or even higher than those achieved under continuous traditional grazing.

Acknowledgements

We especially thank the support staffs of the INTA Corrientes Research Station in Argentina for their help during the field work. This research was jointly supported by the Centre for Agriculture in the Tropics and Subtropics (TROZ), the National Institute of Agriculture (INTA) and the German Academic Exchange Service (DAAD) with funds of the Federal Ministry of Economic Cooperation and Development (BMZ) of Germany and the Foundation Fiat Panis. This research was supported through a scholarship from the Food Security Centre (FSC) from the University of Hohenheim, which is part of the DAAD program "exceed". The concepts, the ideas and the framework for this research were developed in cooperation with GrassNet, a DAAD founded research-educational network. We also would like to thank the two anonymous reviewers and the journal editor for their helpful comments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2015.10.065. These data include Google maps of the most important areas described in this article.

References

Abdel-Magid, A.H., Trlica, M.J., Hart, R.H., 1987. Soil and vegetation responses to simulated trampling. J. Range Manag. 40, 303–306.

Adema, E.O., Buschiazzo, D.E., Babinec, F.J., Rucci, T.E., Gomez Hermida, V.F., 2004. Mechanical control of shrubs in a semiarid region of Argentina and its effect on soil water content and grassland productivity. Agric. Water Manag. 68, 185–194.

Argentina, 2009. In: Argentina, S.y.C.d.D.d.l.N. (Ed.), Ley de presupuestos mínimos de protección ambiental para el control de actividades de quema. Senado y Cámara de Diputados de la Nac. Argent., p. 2.

Azpiroz, A.B., Isacch, J.P., Dias, R.A., Di Giacomo, A.S., Fontana, C.S., Palarea, C.M., 2012. Ecology and conservation of grassland birds in Southeastern South America: a review. J. Field Ornithol. 83, 217–246.

Balph, D.F., Malecheck, J.C., 1985. Cattle trampling of crested wheatgrass under short duration grazing. J. Range Manag. 38, 2.

Bernardis, A.C., Casco, J.F., Goldfarb, M.C., 1997. Valor nutritivo de *Schizachyrium paniculatum* bajo tres frecuencias de corte. Rev. Argent. Producción Anim. 1, 150.

Bernardis, A.C., Fernandez, J.A., Céspedes Flores, F., Goldfarb, M.C., Casco, J.F., 2008. Efecto de la quema prescripta de un pastizal sobre el balance de CO$_2$. Agrotecnia.

Bernardis, A.C., Goldfarb, M.C., Fernández, J.A., Casco, J.F., 2005a. Acumulación estacional de biomasa aérea de un pastizal bajo distintas frecuencias de quema prescripta en el N.O. de Corrientes, Argentina. Rev. Científic. Agropecuari. 9 (2), 133–139.

Bernardis, A.C., Roig, C.A., Bennasar Vilches, M., 2005b. Productividad y calidad de los pajonales de *Sorghastrum setosum* (Griseb.) Hitchc. en Formosa, Argentina. Agric. Técni. 65, 177–185.

Briske, D.D., Bestelmeyer, B.T., Brown, J.R., Fuhlendorf, S.D., Polley, H.W., 2013. The Savory method can not green deserts or reverse climate change. Rangelands 35, 72–74.

Briske, D.D., Derner, J.D., Brown, J.R., Fuhlendorf, S.D., Teague, W.R., Havstad, K.M., Gillen, R.L., Ash, A.J., Willms, W.D., 2008. Rotational grazing on rangelands: reconciliation of perception and experimental evidence. Rangel. Ecol. Manag. 61, 3–17.

Briske, D.D., Sayre, N.F., Huntsinger, L., Fernandez-Gimenez, M., Budd, B., Derner, J.D., 2011. Origin, persistence, and resolution of the rotational grazing debate: integrating human dimensions into rangeland research. Rangel. Ecol. Manag. 64, 325–334.

Calvi, M., 2010. Evolución de la ganadería correntina. Ser. Tecni. 47. INTA, Corrientes, pp. 1–28.

Carnevali, R., 1994. Fitogeografía de la Provincia de Corrientes. INTA – Gobierno de la provincia de Corrientes, Corrientes.

Casco, J.F., Bernardis, A.C., 1992. Caracterización del valor nutritivo de *Paspalum notatum* L. bajo tres frecuencias de corte. In: III Reunión de Comunicaciones Cient. y Tecni., Corrientes, p. 55.

Casco, J.F., Bernardis, A.C., 1993. Caracterización del valor nutritivo de *Paspalum plicatulum* bajo tres frecuencias de corte. In: IV Reunión de Comunicaciones Cient. y Tecni., Corrientes, p. 58.

Casco, J.F., Bernardis, A.C., 1994. Caracterización del valor nutritivo de *Andropogon lateralis* bajo tres frecuencias de corte. In: V Reunión de Comunicaciones Cient. y Tecni., Corrientes, p. 61.

Chyba, J., Kroulík, M., Kristof, K., Misiewicz, P.A., Chaney, K., 2014. Influence of soil compaction by farm machinery and livestock on water infiltration rate on grassland. Agron. Res. 12, 59–64.

Corrientes, 2004. Ley 5590. In: Corrientes, H.S.y.H.C.d.D.d.l.P.d. (Ed.), Honor. Senado y Honorable Cámara de Diputa. de la Provincia de Corrientes. , pp. 1–11.

Cromsigt, J.P.G.M., Olff, H., 2008. Dynamics of grazing lawn formation: an experimental test of the role of scale-dependent processes. Oikos 117, 1444–1452.

Dudinszky, N., Ghermandi, L., 2013. Fire as a stimulant of shrub recruitment in Northwestern Patagonian (Argentina) grasslands. Ecol. Res. 28, 981–990.

Dunne, T., Western, D., Dietrich, W.E., 2011. Effects of cattle trampling on vegetation, infiltration, and erosion in a tropical rangeland. J. Arid Environ. 75, 58–69.

Elizalde, J., Riffel, S., 2014. Eficiencia más allá del stock. http://www.pregonagropecuario.com/cat.php?txt=5641 (accessed 28.11.14).

Escobar, E.H., Ligier, H.D., Melgar, R., Matteio, H., Vallejos, O., 1996. Mapa de suelos de la Provincia de Corrientes 1:500.000. INTA, Corrientes.

Fernández, J.A., Schroeder, M.A., Goldfarb, M.C., Bernardis, A.C., 2011. Efecto de la frecuencia de quema prescripta sobre la composición mineral de los pastizales en el Nordeste Argentino. Ecol. Apl. 10, 23–29.

Fidelis, A., Lyra, M.F.d.S., Pivello, V.R., 2013. Above- and below-ground biomass and carbon dynamics in Brazilian Cerrado Wet Grasslands. J. Veg. Sci. 24, 356–364.

Franzese, J., Ghermandi, L., 2012. Effect of fire on recruitment of two dominant perennial grasses with different palatability from semi-arid grasslands of NW Patagonia (Argentina). Plant Ecol. 213, 471–481.

Frost, R., Walker, J., Madsen, C., Holes, R., Lehfeldt, J., Cunningham, J., Voth, K., Welling, B., Davis, T.Z., Bradford, D., Malot, J., Sullivan, J., 2012. Targeted grazing: applying the research to the land. Rangelands 34, 2–10.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable intensification in agriculture: premises and policies. Science 341, 33–34.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res. 82, 121–145.

Heckathorn, S.A., McNaughton, S.J., Coleman, J.S., 1999. 9 – C4 Plants and herbivory. In: Sage, R.F., Monson, R.K. (Eds.), C$_4$ Plant Biology. Academic Press, San Diego, pp. 285–312.

Hempson, G.P., Archibald, S., Bond, W.J., Ellis, R.P., Grant, C.C., Kruger, F.J., Kruger, L.M., Moxley, C., Owen-Smith, N., Peel, M.J.S., Smit, I.P.J., Vickers, K.J., 2014. Ecology of grazing lawns in Africa. Biol. Rev., 1–17.

Hidalgo, L.G., Cauhépé, M.A., 1991. Effects of seasonal rest in aboveground biomass for a native grassland of the flood Pampa, Argentina. J. Range Manag. 44, 471–475.

Jacobo, E.J., Rodríguez, A.M., Bartoloni, N., Deregibus, V.A., 2006. Rotational grazing effects on rangeland vegetation at a farm scale. Rangel. Ecol. Manag. 59, 249–257.

Jacobo, E.J., Rodríguez, A.M., Rossi, J.L., Salgado, L.P., Deregibus, V.A., 2000. Rotational stocking and production of Italian Ryegrass on Argentinean. Rangel. Ecol. Manag. 53, 483–488.

Joseph, J., Molinar, F., Galt, D., Valdez, R., Holechek, J., 2002. Short duration grazing research in Africa. Rangelands 24, 9–12.

Jung, K.-Y., Kitchen, N.R., Sudduth, K.A., Lee, K.-S., Chung, S.-O., 2010. Soil compaction varies by crop management system over a claypan soil landscape. Soil Tillage Res. 107, 1–10.

Knapp, A.K., Medina, E., 1999. 8 – Success of C4 photosynthesis in the field: lessons from communities dominated by C4 plants. In: Sage, R.F., Monson, R.K. (Eds.), C4 Plant Biology. Academic Press, San Diego, pp. 251–283.

Kurtz, D.B., Ligier, H.D., 2007. La carga ganadera real en la Provincia de Corrientes. Rev. Tierra Correntina Corrientes.

Kurtz, D.B., Schellberg, J., Braun, M., 2010. Ground and satellite based assessment of rangeland management in sub-tropical Argentina. Appl. Geogr. 30, 210–220.

Long, S.P., 1999. 7 – Environmental responses. In: Sage, R.F., Monson, R.K. (Eds.), C$_4$ Plant Biology. Academic Press, San Diego, pp. 215–249.

Lovreglio, R., Meddour-Sahar, O., Leone, V., 2014. Goat grazing as a wildfire prevention tool: a basic review. iForest – Biogeosci. For. 7, 260–268.

Martín, B., Galleano, V., Spiller, L.C., Vilche, M.S., Montico, S., 2011. Evaluación de la productividad primaria de un pastizal templado en Santa Fe, Argentina. Arch. Zootecni. 60, 965–975.

McMillan, B.R., Pfeiffer, K.A., Kaufman, D.W., 2011. Vegetation responses to an animal-generated disturbance (*Bison Wallows*) in Tallgrass Prairie, The America. Midl. Nat. 165, 60–73.

McNaughton, S.J., 1979. Grazing as an optimization process: grass-ungulate relationships in the Serengeti. Am. Nat. 113, 691–703.

McNaughton, S.J., 1983. Compensatory plant growth as a response to herbivory. Oikos 40, 329–336.

McNaughton, S.J., 1984. Grazing lawns: animals in herds, plant form, and coevolution. Am. Nat. 124, 863–886.

Mingo, A., Oesterheld, M., 2009. Retention of dead leaves by grasses as a defense against herbivores. A test on the palatable grass *Paspalum dilatatum*. Oikos 118, 753–757.

Moisey, D.M., Willms, W.D., Bork, E.W., 2006. Effect of standing litter on rough fescue utilization by cattle. Rangel. Ecol. Manag. 59, 197–203.

Oesterheld, M., Loreti, J., Semmartin, M., Paruelo, J.M., 1999. Grazing, fire, and climate effects on primary productivity of grasslands and savannas. In: Walker, L.R. (Ed.), Ecosystems of Disturbed Ground. Elsevier Science, pp. 287–306.

Ötztürk, M., Rehder, H., Ziegler, H., 1981. Biomass production of C_3- and C_4-plant species in pure and mixed culture with different water supply. Oecologia (Berl) 50, 73–81.

Pausas, J.G., Ribeiro, E., 2013. The global fire–productivity relationship. Global Ecol. Biogeogr. 22, 728–736.

Pearcy, R., Tumosa, N., Williams, K., 1981. Relationships between growth, photosynthesis and competitive interactions for a C_3 and C_4 plant. Oecologia (Berl) 48, 371–376.

Piepho, H.P., Büchse, A., Richter, C., 2004. A mixed modeling approach for randomized experiments with repeated measure. J. Argon. Crop Sci. 190, 230–247.

Podgaiski, L.R., da Silva Goldas, C., Ferrando, C.P.R., Silveira, F.S., Joner, F., Overbeck, G.E., de Souza Mendonça, M., Pillar, V.D., 2014. Burning effects on detritivory and litter decay in Campos grasslands. Austral. Ecol. 39, 686–695.

Royo Pallarés, O., Berretta, E.J., Maraschin, G.E., 2005. The South American Campos Ecosystem. In: FAO (Ed.), Grasslands of the World. FAO, Rome, Italy, p. 535.

Savory, A., 1983. The Savory grazing method or holistic resource management. Rangelands 5, 155–159.

Savory, A., 2005. Manejo holístico. Un nuevo marco metodológico para la toma de decisiones. Secretaria de Medio Ambiente y Recursos Naturales, Instituto Nacional de Ecología, Fondo Mexicano Para la Conservación de la Naturaleza, Fundación para Fomentar el Manejo Holístico de los Recursos, AC.

Savory, A., Parsons, S.D., 1980. The Savory grazing method. Rangelands 2, 234–237.

Schrama, M.J., Cordlandwehr, V., Visser, E.W., Elzenga, T., de Vries, Y., Bakker, J., 2013. Grassland cutting regimes affect soil properties, and consequently vegetation composition and belowground plant traits. Plant Soil 366, 401–413.

Striker, G.G., Insausti, P., Grimoldi, A.A., León, R.J.C., 2006. Root strength and trampling tolerance in the grass *Paspalum dilatatum* and the dicot *Lotus glaber* in flooded soil. Funct. Ecol. 20, 4–10.

Striker, G.G., Mollard, F.P.O., Grimoldi, A.A., León, R.J.C., Insausti, P., 2011. Trampling enhances the dominance of graminoids over forbs in flooded grassland mesocosms. Appl. Veg. Sci. 14, 95–106.

Teague, W.R., Dowhower, S.L., Baker, S.A., Haile, N., DeLaune, P.B., Conover, D.M., 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass Prairie. Agric. Ecosyst. Environ. 141, 310–322.

Thomas, H.S., 2006. Rangeland wildfires can be good or bad. Rangelands 28, 12–16.

Toledo, D., Kreuter, U.P., Sorice, M.G., Taylor Jr., C.A., 2014. The role of prescribed burn associations in the application of prescribed fires in rangeland ecosystems. J. Environ. Manag. 132, 323–328.

Vanni, R.O., Kurtz, D.B., 2005. Nueva variedad y precisiones taxonómicas para el Género *Vicia* (*Leguminosae*) en el Norte de la Argentina. Darwiniana 43, 216–231.