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Management of grassland/savannas encroached by woody plants in South American Semiarid Chaco: Ecological restoration vs. African grasses introduction

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Abstract. In Semiarid Chaco, two management approaches for woody plant-encroached grassland/savannas were evaluated: ecological restoration and the African grass introduction. An experiment with five treatments was carried out: 1) reference community (Ref_Eco; a grassland/savanna in good state, used as standard of comparison); 2) grassland/savanna encroached by woody plants (Woody_Encr; the woody state of grassland/savannas); 3) roller chopping of the encroached ecosystem, followed by grazing suppression and prescribed fire (Roll_Fire; aimed at inducing grassland/savanna ecological restoration); 4) roller chopping of the encroached ecosystem, with instantaneous seeding of *Megathyrsus maximus* cv. Gatton Panic and grazing suppression (Roll_Gatton Panic), and 5) roller chopping of the encroached ecosystem, with instantaneous seeding of *Cenchrus ciliaris* cv. Buffel Texas and grazing suppression (Roll_Buffel Texas). The last two treatments aimed to obtain new highly productive grassy states for ranching through the introduction of these African grasses. The results suggested that Ref_Eco (average herbaceous biomass [HERB]=7196.9 kg DM/ha) was dominated by shade intolerant and fire tolerant grasses, and it had good soil quality and good utilitarian range condition. Regarding Ref_Eco: a) in Woody_Encr (HERB=2192 kg DM/ha), the vegetation structure, plant composition and the utilitarian range condition were altered, but it still had good soil quality and abundant native grass populations; b) in Rol_Fire (HERB=6591.6 kg DM/ha), both the vegetation structure and good utilitarian range condition were restored, plant composition was not restored and the good soil quality was kept, and c) Roll_Gatton Panic and Roll_Buffel Texas (HERB=10972.1 and 7450.8 kg DM/ha, respectively) resulted in new grassy states integrated by native and exotic grasses with good utilitarian range condition and good soil quality. In this study case, the ecological restoration of the encroached ecosystems would be both ecologically and productively viable. So, probably the introduction of African grasses to improve ranching was not necessary.

[Keywords: prescribed fire, roller chopping, grazing suppression, plant species composition, vegetation structure, utilitarian range condition]

Resumen. Manejo de pastizales/sabanas lignificados del Chaco Semiárido Sudamericano: Restauración ecológica vs. implantación de pasturas africanas. Dos enfoques de manejo de pastizales/sabanas lignificados fueron evaluados: la restauración ecológica y la implantación de pasturas africanas. Se realizó un experimento con cinco tratamientos: 1) comunidad de referencia (Ref_Eco; pastizal/sabana en buen estado, usado como estándar de comparación); 2) pastizal/sabana lignificado (Woody_Encr; estado lignificado de los pastizales/sabanas); 3) rolado del ecosistema lignificado, seguido por supresión del pastoreo y fuego prescripto (Roll_Fire; objetivo: inducir la restauración ecológica del pastizal/sabana); 4) rolado del ecosistema lignificado con siembra instantánea de *Megathyrsus maximus* cv. Gatton Panic y supresión del pastoreo (Roll_Gatton Panic), y 5) rolado del ecosistema lignificado, con siembra instantánea de *Cenchrus ciliaris* cv. Buffel Texas y supresión del pastoreo (Roll_Buffel Texas). Los dos últimos tratamientos buscaron obtener nuevos estados graminosos muy productivos para la ganadería mediante la implantación de esas pasturas africanas. Los resultados sugirieron que Ref_Eco (biomasa herbácea promedio [HERB]=7196.9 kg MS/ha) estuvo dominado por gramíneas intolerantes a la sombra y tolerantes al fuego, y tuvo calidad del suelo buena y condición utilitaria del pastizal buena. Comparado con a Ref_Eco: a) en Woody_Encr (HERB=2192 kg MS/ha), la estructura de la vegetación, la composición de plantas y la condición utilitaria del pastizal fueron alteradas, pero éste todavía tuvo calidad del suelo buena y poblaciones de gramíneas nativas abundantes; b) en Roll_Fire (HERB=6591.6 kg MS/ha), la estructura de la vegetación y la condición utilitaria del pastizal fueron restaurados, la composición de plantas no fue restaurada y la calidad del suelo buena fue preservada, y c) Roll_Gatton Panic y Roll_Buffel Texas (HERB=10972.1 y 7450.8 kg MS/ha, respectivamente) resultaron en nuevos estados graminosos integrados por pastos nativos y exóticos con calidad del suelo buena y condición utilitaria del pastizal buena. En este estudio, la restauración ecológica del ecosistema lignificado sería ecológica y productivamente viable. Por lo tanto, probablemente la implantación de pasturas africanas para mejorar la producción ganadera no fue necesaria.

[Palabras clave: fuego prescripto, rolado, supresión del pastoreo, composición de especies de plantas, estructura de la vegetación, condición utilitaria del pastizal]

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Introduction

Arid and semiarid grassland/savannas are a source of multiple ecosystem services highly valued for society, both at local and global scale (Easdale 2021). These ecosystems are under grazing and are not fit for intensive agricultural practices due to an inappropriate rainfall regime or poor soil quality. Usually, they have been overgrazed and that fact has deeply altered them (Aronson et al. 1993; Gibson et al. 1995; Archer et al. 2017). Therefore, initiatives oriented to regulate the use and restore these ecosystems are desirable.

Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed (Society for Ecological Restoration International Science and Policy Working Group 2004). Normally, it aims to stop threats and to reestablish vegetation structure, species composition and ecological, productive and sociological ecosystem functions (McDonald et al. 2016). In arid and semiarid regions of the southern hemisphere, the complete ecological restoration of historic native ecosystems (those that existed before the intensification of disturbances) may not be achieved, due to: 1) it is rarely possible to precisely determine which original ecosystems were there and what was the complete list of native species, and 2) often, the alteration of the ecosystem evolved so far that the irreversibility thresholds were crossed (e.g., seed bank of key species finished, soil A horizon severely altered or eliminated). Concomitantly, the complete ecological restoration may have prohibitive costs or be practically impossible (Aronson et al. 1993; Allen 1995; Bestelmeyer 2006; Archer et al. 2017; Coppock et al. 2017; Evans et al. 2017). Two types of ecological restoration have been proposed: a) the *sensu stricto* ecological restoration that aims at complete ecosystem recovery; and b) the *sensu lato* ecological restoration that simply aims to halt the degradation and to redirect the disturbed ecosystem in a trajectory resembling those presumed to have prevailed prior to the start of disturbances (Aronson et al. 1993). Despite these differences, the primary goal of both types of ecological restoration is to conserve native biodiversity and ecosystem structure and dynamics (Aronson et al. 1993).

In ecological restoration, the reference ecosystem is a key concept that represents the comparison standard for altered biotic communities (Aronson et al. 1993; McDonald et al. 2016), and it normally coincides with the historic native ecosystem (Aronson et al. 1993). Often, it is assumed that the reference ecosystem maximizes the ecosystem services, the biodiversity and soil conservation and the management options (Bestelmeyer et al. 2003, 2010). In the Americas, historic native ecosystems can be established as those the European colonizers found at their arrival, and its definition requires to consider the natural variation of both the biotic community and ecosystem functioning (Bestelmeyer et al. 2003, 2010). However, the historic native ecosystems commonly disappeared and cannot be reliably estimated from historic records. As a consequence, they are usually estimated under the assumption that the most palatable plant species dominated on them (Bestelmeyer et al. 2003).

In South American Semiarid Chaco, overgrazing and the concurrent reduction/suppression of grassland fires (intensified by drought) have been identified as the main causes of a grassland/savanna massive woody plant encroachment occurring since the early 1900s (Morello and Adamoli 1974; Adamoli et al. 1990). Usually, it is observed: 1) a substantial increase in shrub cover (a substantial increase in tree cover occurs with overgrazing for more than 50 years); 2) an impoverishment of the utilitarian range condition due to the reduction of perennial forage grasses and the excessive woody cover that complicates accessibility and animal management, and 3) alterations in plant diversity and functional types (Morello and Saravia Toledo 1959; Coria et al. 2021). In contrast, woody plant diversity is less affected by woody plant encroachment (Coria et al. 2021). In extreme alteration cases, there is a severe soil erosion and perennial grasses communities are replaced by annual broadleaf herbs or annual grasses with little forage value and very low productivity (Morello and Saravia Toledo 1959; Adamoli et al. 1972; Díaz 2015).

In the Semiarid Chaco area of Argentina, the main approach of woody plant encroachment management aims to improve ranching production and consists in reducing/eliminating the woody cover by means of roller chopping, and to simultaneously seed African forage grasses. Roller chopping consists in woody plants crushing using a roller chopper (i.e., metallic drum >2 m width and armed with blades) pulled by tractors or bulldozers. Generally, the resulting herbaceous stratum has a mix of African grasses with variable proportions of native grasses, and the increase in the stocking rate is notable (up to 400-500%) (Fumagalli and Kunst 2002). Low/medium intensity roller chopping preserves both a significant part of native vegetation and soil properties (Kunst et al. 2016; Rejžek et al. 2017). This intensity is achieved by using relatively small machinery (e.g., small tractors and roller chopper <2.5 m width) and concentrating the treatment on shrubs (height <3 m).

In the region, the *sensu stricto* ecological restoration of grassland/savannas may not be possible in most of the cases. Instead, when irreversibility thresholds in superficial soil quality and native grass populations have not been crossed (Aronson et al. 1993; Allen 1995; Bestelmeyer 2006; Coppock et al. 2017; Puthod et al. 2020), a *sensu lato* ecological restoration would be a more realistic goal. So, in the last scenario, a new grassy estate and in a better utilitarian range condition would be achieved through a management that utilizes in sequence: 1) low/medium intensity roller chopping to reduce woody plant competition; 2) grazing suppression during one or two growing seasons to favor the herbaceous biomass productivity (fine fuel), and 3) the application of prescribed fire to reduce woody plant competition again, and stimulate the re-sprout, germination and flowering of grasses (Kunst et al. 2003a,b, 2008; Coria et al. 2021).

The objective of this study was to compare the effects on vegetation structure, plant composition and utilitarian range condition of two management approaches on woody plant-encroached grassland/savannas: 1) the *sensu lato* ecological restoration, and 2) the introduction of the African grasses *Megathyrsus maximus* cv. Gatton Panic and *Cenchrus ciliaris* cv. Buffel Texas. The hypothesis stated that returning from a woody to a grassy state is effectively promoted by an appropriate disturbance regime when soil and native grass populations are not too altered. The predictions (P) were that if the encroached ecosystem still has a good superficial soil quality and abundant native grass populations, then: P1) a new grassy state with native species and in better utilitarian range condition (it means, the *sensu lato* ecological restoration) will occur in the short term by a sequential utilization of low/medium intensity roller chopping, grazing suppression and prescribed fire, and P2) the application of low/medium intensity roller chopping with both simultaneous seeding of African grasses and grazing suppression, in the short term will result in new grassy states with native and exotic grasses and in good utilitarian range condition. Figure 1 schematizes both predictions.

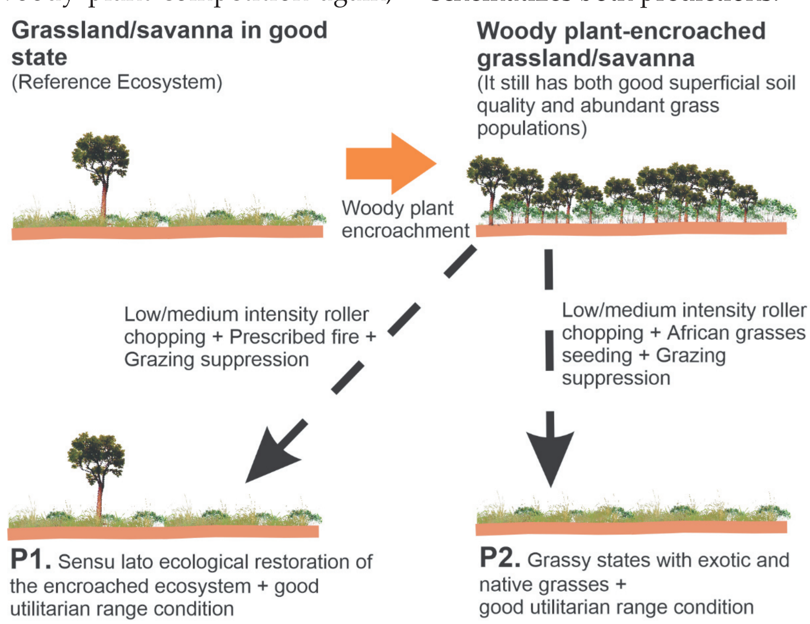


Figure 1. Management of woody plant encroachment in grassland/savannas of the Semiarid Chaco. If the encroached ecosystem still has good superficial soil quality and abundant native grass populations, predictions P1 and P2 can occur.

Figura 1. Manejo de la lignificación en pastizales/sabanas del Chaco Semiárido. Si el pastizal/sabana lignificado todavía conserva una calidad del suelo superficial buena y poblaciones de gramíneas nativas abundantes, entonces las predicciones P1 y P2 pueden ocurrir.

Materials and Methods

Study area

The study was conducted at F. Cantos Experimental Ranch, belonging to Santiago del Estero Agricultural and Livestock Experimental Station, Instituto Nacional de Tecnología Agropecuaria (INTA), Argentina (coordinates of the ranch vertices: 27°59′6.94′′ S - 64°24′9.38′′ W; 28°1′23.62′′ S - 64°24′41.25′′ W; 28°3′18.64′′ S - 64°14′15.14′′ W; 28°1′0.19′′ S - 64°13′53.01′′ W) (Figure 2). The site belong to the ecoregion of Dry Chaco, Semiarid Chaco sub-region (Morello et al. 2012). The altitude is ~200 m a. s. l. The climate is subtropical semiarid with warm and wet summers and dry and cold winters (Boletta et al. 2006). The average annual precipitation is 587.1 mm and the average temperature is 20.1 °C. Most of the study area is located within the geomorphological unit Bajada Distal del Piedemonte Subandino Pampeano and the soils are Haplustolls (Prieto Angueira 2016).

At local scale (200 m - a few kilometers), the soft topographic gradient defines three characteristic ecological sites: 1) highland ecological sites, at high topographic positions, originally occupied by tall hardwood forests; 2) midland ecological sites, at medium topographic positions, originally occupied by open tall forests, and 3) lowland ecological sites, at low topographic positions, originally occupied by grassland/savannas, where this study focused on. The current grassland/savannas have isolated trees of *Schinopsis lorentzii* and *Aspidosperma quebracho-blanco*, and abundant shade intolerant and fire tolerant grasses such as *Elionurus muticus*, *Schizachyrium tenerum*, *Heteropogon contortus* and *Pappophorum pappiferum*. In woody plant-encroached grassland/savannas, *Vachellia aroma*, *Prosopis nigra*, *Geoffroea decorticans* and *Schinus* sp. are abundant. Soils are Typic Haplustolls (Anriquez et al. 2005).

Figure 2a corresponds to the study area and it was obtained from air photographs in 1960. It can be seen that grassland/savannas (light-colored areas) were abundant in lowland ecological sites (red polygons). Figure 2b corresponds to an actual satellite image (August 2019). By comparing both figures, it can be observed that, in the central part of the study area, large surfaces of grassland/savannas have been encroached by woody plants (dark green areas in Figure 2b).

Experimental design

This study was carried out at lowland ecological sites in the Bajada Distal del Piedemonte Subandino Pampeano geomorphological unit of the F. Cantos Experimental Ranch. Between December 2016 and April 2019 (that includes three growing seasons: 2016/2017, 2017/2018 and 2018/2019), an experiment with five treatments was performed. Each treatment had eight experimental units (plots of 20x20 m each). Once the experiment was completed, all vegetation and soil variables were measured between April and May 2019.

The first treatment (reference ecosystem; from now on, Ref_Eco), was an area covered by grassland/savannas considered in good state based on the gathered empirical and scientific information. Its objective was to estimate the historic native grassland/savanna and serve as standard of comparison. Ref_Eco was located in a patch of lowland ecological site almost entirely covered by grassland/savannas (1259 ha). The available satellite images show that the grassy state existed at least since 1960 until today (previous to 1960, there are not available images) (Figure 2a and 2b). Inside this patch, Ref_Eco (yellow polygon in Figure 2b) was an area of 6 ha historically isolated from livestock grazing (more than 1850 m away from the watering point).

The rest of the treatments were located in a patch of lowland ecological site originally covered by grassland/savannas and currently completely encroached by woody plants (586 ha). Available remote images show that the grassy state existed at least since 1960 (previous to this year there are no images available) until 1988/2000, when woody plant encroachment was consolidated. Woody state is likely the result of both overgrazing and fire suppression since 1989, intensified by a severe drought occurring during 1988/99 (Kunst et al. 2012; Ledesma et al. 2018). Within the selected area, two smaller areas (area 17.5 ha and 3 ha, respectively) were used due to the presence of roads and fences that ensure grazing suppression (light-blue polygon in Figure 2b). Inside these fenced areas, the rest four treatments were: a) Woody_Encr: it was a woody plant-encroached grassland/savanna which did not receive any disturbance during the experiment (included grazing). Its objective was to represent the woody state of native grassland/savannas; b) Roll_Fire: it was a woody plant-encroached grassland/

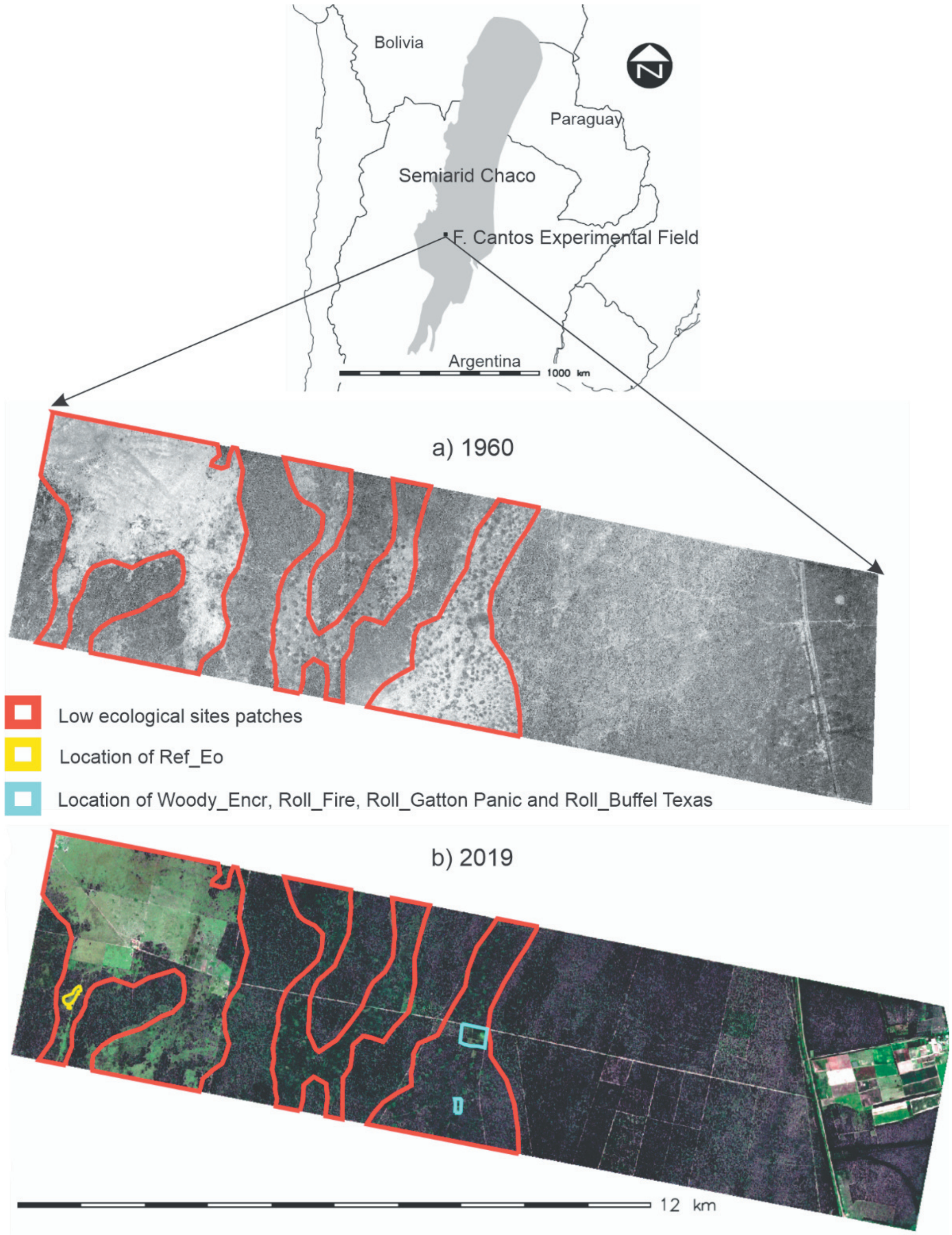


Figure 2. Management of woody plant encroachment in grassland/savannas in Semiarid Chaco. Study area, F. Cantos Experimental Ranch. a) Ancient air photographs (1960). It is appreciated that grassland/savannas (light areas) predominated in lowland ecological sites (red polygons). b) SENTINEL satellite image from August 2019. It is appreciated that in the central part, grassland/savannas were encroached by woody plants (dark green areas). The yellow polygon contains the Ref_Eco treatment. The light-blue polygon contains the Woody_Encr, Roll_Fire, Roll_Gatton Panic and Roll_Buffel Texas treatments.

Figura 2. Manejo de la lignificación en pastizales/sabanas del Chaco Semiárido. Área de estudio, Campo Experimental F. Cantos. a) Mosaico de fotografías aéreas antiguas (1960). Se aprecia que los pastizales/sabana (áreas claras) predominaron en los sitios ecológicos bajos (polígonos rojos). b) Imagen satelital SENTINEL de agosto de 2019. Se aprecia que los pastizales/sabanas del área central se lignificaron (color verde oscuro). El polígono amarillo contiene al tratamiento Ref_Eco. El polígono celeste contiene a los tratamientos Woody_Encr, Roll_Fire, Roll_Gatton Panic y Roll_Buffel Texas.

savanna that received a specific management inducing the *sensu lato* ecological restoration of the historic native grassland/savanna. Initially, in December 2016 a roller chopping concentrated on shrubs (height ≤3 m) was applied using small machinery (100 hp tractor, roller chopper width=2.5 m and weight ~900 kg). The machine was passed in the same place four times, and the intensity of the disturbance was considered medium since the soil was superficially moved and the shrub cover was almost completely crushed. After this initial disturbance, the herbaceous biomass was left to accumulate during two growing seasons without grazing, and, afterwards, an intense prescribed fire was applied. Prescription was as it follows: average herbaceous biomass >3000 kg DM/ha, air temperature 20-30 °C, wind speed 12-25 km/h, air humidity 25-35% and length flame >3 m (Kunst et al. 2003b). After the fire, grazing exclusion continued on one more growing season; c) Roll_Gatton Panic: it was a woody plant-encroached grassland/savanna that received a specific management to obtain a new highly productive grassy state through the introduction of the African grass *Megathyrsus maximus* cv. Gatton Panic (from now on Gatton Panic). This exotic grass is highly productive, shade and fire tolerant and adapts to an annual precipitation >500 mm (Ledesma et al. 2017). In December 2016, a roller chopping was applied with a simultaneous seeding of 12 kg/ha of Gatton Panic seed. This roller chopping had the same features as the one applied in Roll_Fire. However, this seeding failed probably due to the high temperatures and lack of rain during January/February 2017. So, in March 2018 the treatment was roller chopped (two passes at the same place) and 12 kg/ha of Gatton Panic seed were simultaneously seeded again. Grazing was all-time excluded, and d) Roll_Buffel Texas: this treatment had the same features as Roll_Gatton Panic, with the unique difference that the African grass *Cenchrus ciliaris* cv. Buffel Texas (from now on Buffel Texas) was seeded instead of Gatton Panic. The Buffel Texas is moderately productive, shade intolerant and fire tolerant, growing with an annual precipitation >300 mm (Ledesma et al. 2017).

In this experiment, both the roller chopping and prescribed fire had the objective of reducing woody plant competition and increasing environmental resource availability (space, sunlight, soil nutrient and water) for herbaceous plants. Livestock grazing suppression had the objective of maximizing the herbaceous biomass productivity. In order to better understand the experiment, Table 1 summarizes the treatments and Supplementary Material-Figure S1 shows photographs of the experiment.

Vegetation attributes

The following measurements were made in each experimental plot, avoiding the first 2 m from the border.

Herbaceous stratum and litter. The initial grass density (it means, prior to the beginning of the experiment) was measured by counting the observed plants in a metallic frame of 0.25 m^2. The number obtained was multiplied by four to refer to plants/m^2. At the end of the experiment, total and per species herbaceous biomass and litter biomass were obtained by the gravimetric method (collection and drying of materials at 60 °C until constant weight) (Bonham 1989), with four subsamples per experimental plot (the same former metallic frame). The presence-absence of each species was also registered using 10 subsamples per experimental plot (same former metallic frame). The sampling was performed at the end of the growing season (April) when it occurs the maximum expression of herbaceous productivity and diversity (Aronson et al. 1993).

Woody stratum. At the end of the experiment, the woody stratum was measured by the modified point quadrat method (Passera et al. 1983). In each experimental plot, two transect with length=15 m each were installed. In each transect, 50 sample points (separated each by 30 cm) were evaluated using a telescopic cane with length=5 m. In each point, it was registered: 1) the number of touches between the cane in vertical position with plant organs, discriminating between shrubs (height ≤3 m) and trees (height >3 m), and 2) the species names and the highest touches (m). Later, the following attributes were obtained: a) total woody cover (touches/transect), counting the total number of touches; b) shrub and tree cover (%), from the percentage of sample points where there were touches with each type of cover; c) woody stratum height (m), averaging the highest touches, and d) woody cover per species (touches/transect), counting the respective touches.

Table 1. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Synthesis of treatments.

Tabla 1. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Síntesis de los tratamientos.

Shorten name	Main characteristics	Objective/interpretation
Ref_Eco	Grassland/savanna in good state. It did not receive any disturbances during the experiment	It was the reference ecosystem (Figure 1). It estimated the historic native grassland/ savannas and served as standard of comparison
Woody_Encr	Grassland/savanna encroached by woody plants. It did not receive any disturbances during the experiment	To represent the woody state of historic native grassland/savannas (Figure 1)
Roll_Fire	Woody plant-encroached grassland/savanna that received medium intensity roller chopping, prescribed fire after two growing seasons and grazing suppression during the entire experiment	To induce the *sensu lato* ecological restoration of the grassland/savanna encroached by woody plants (Figure 1, P1)
Roll_Gatton Panic	Woody plant-encroached grassland/savanna that received medium intensity roller chopping, seeding of Gatton Panic grass and grazing suppression during the entire experiment	From a grassland/savanna encroached by woody plants, to obtain a new highly productive grassy state by means of the introduction of Gatton Panic exotic grass (Figure 1, P2)
Roll_Buffel Texas	Woody plant-encroached grassland/savanna that received medium intensity roller chopping, seeding of Buffel Texas grass and grazing suppression during the entire experiment	From a grassland/savanna encroached by woody plants, to obtain a new highly productive grassy state by means of the introduction of Buffel Texas exotic grass (Figure 1, P2)

Environmental variables

Annual precipitation (mm/year). It was obtained for the 2016/2019 period through the meteorological database of F. Cantos Experimental Ranch, which has provided a complete monthly data series since 1988. Annual precipitations were weighted as 'below normal', 'normal' or 'above normal' depending on whether their values correspond respectively to the first, second or third tercile of the data series (SMN 2019).

Superficial soil quality. It was evaluated for the first 20 cm of soil, which is the A soil horizon thickness in the study area (Angueira et al. 2007). The following semiarid region relevant indicators were measured (Bono et al. 2012; Lorenz 2016; Taleisnik and Lavado 2017): pH and electric conductivity (EC; dS/m) (Jackson 1976), organic matter (OM; %) (Norma IRAM- 29571-2-SAGPyA 2011), total nitrogen (TN; %) (Norma IRAM- 29572-1-SAGPyA 2011) and bulk density (BD; kg/dm^3) (Lorenz 2016). Per each experimental plot, it was taken: 1) a compound soil sample (four subsamples) in a plastic bag to measure pH, EC, OM and TN, and 2) one soil sample using a metallic cylinder (100 cm^3) to measure BD.

Average fire focuses (AFF) (fire focusses/year). It is the number of fire focusses per year/total number of years. It was estimated in the period 2003-2019 for both: a) the patch of lowland ecological site covered by grassland/savannas, and b) the patch of lowland ecological site covered by woody plant-encroached grassland/savannas (see 'Study area' and 'Experimental design'). The number of fire focuses was obtained from the 'Fire Database' which, by means of images from the Satellite AQUA M-T (Sensor MODIS), forms temporal data series of fire focusses throughout the years (INPE 2020). For each fire focus, the day and time of occurrence and geographic location with an average precision ~400 m, are provided. The detection threshold is determined by fire focuses of 30 m width and 1 m long, or larger. Only those fire focusses, whose location and radius of 400 m were completely inside the studied patches, were considered (arbitrary criterion based on the average precision of locations).

Total woody cover (touches/transect). This variable was obtained by means of the modified point quadrat method (see 'Woody stratum'), and it estimates the capacity of the woody cover to intercept sunlight and decrease the availability of this environmental resource for the herbaceous stratum; more touches, more sunlight interception (Kunst et al. 2006).

Burned woody debris biomass (BWD) (t DM/ha). This variable was estimated only for the treatment that received prescribed fire (Roll_Fire) by means of the fallen woody material inventory method (Brown 1974), and by deducting the load of woody debris biomass pre- and post-fire. For each experimental plot, the woody debris was evaluated in three transect with length=5 m, prior and posterior to the fire.

Data analysis and interpretation

Initial grass density. To assess the initial situation of grass populations (before the beginning of the experiment, P1 y P2), a nonparametric estimation of the initial grass density (plants/m^2) and its confidence interval at 95% was performed. Resampling with the replacement bootstrap procedure (n=250) was utilized (Di Rienzo et al. 2013). The estimation obtained was compared with the reference value of 4-5 plants/m^{2,}, where equal or bigger values mean that grass populations are relatively abundant and anticipate quick and effective grass biomass responses to the management (Fumagalli and Kunst 2002).

Plant composition. To verify modifications in plant composition (P1 and P2), the species presence/absence was utilized to obtain the Chao-Jaccard nonparametric estimator of similarity in broadleaf herb, grass and woody plant composition among pairs of treatments (Colwell 2013). Values were multiplied by 100 to refer to the percentage of similarity. The similarity classes were: 0-39.9% (low), 40-69.9% (moderate) and 70-100% (high). The analyses were performed using the EstimateS 9.10.0 Software (Colwell 2013).

To evaluate the participation of exotic and native grasses in Roll_Gatton Panic and Roll_Buffel Texas, the average and standard deviation of grass biomass was obtained grouped according to the species status (i.e., native, naturalized and exotic) (Instituto de Botánica Darwinion 2017).

Vegetation structure, utilitarian range condition and total woody cover. The vegetation structure refers to the vegetation aspect or physiognomy. Its modification (P1 and P2) was evaluated through descriptor variables of several vegetal strata: shrub and tree cover (%), woody stratum height, and herbaceous and litter biomass.

Changes in pastoral suitability was evaluated using the utilitarian range condition concept (P1 and P2), understood as a description of the resources of the site with respect to livestock grazing (Muir and McClaran 1997). Three condition classes (good, fair and poor) were obtained using the following two valuable attributes for bovine production (Kunst et al. 2006; Díaz 2015): herbaceous forage biomass (kg DM/ha) (food estimator) and shrub cover (%) (accessibility estimator). The herbaceous forage biomass (HFB) was estimated by

$$HFB = PHB + (LPHB \times 0.5) \qquad \text{Equation 1}$$

where PHB is the palatable herbaceous biomass (kg DM/ha) and LPHB is the low palatable herbaceous biomass (kg DM/ha) (Kunst et al. 2006). The information of species palatability was obtained from the literature (Morello and Saravia Toledo 1959; Kunst et al. 1986, 1998; Díaz 2015; Ledesma et al. 2017).

Significant differences in vegetation structure variables, herbaceous forage biomass and total woody cover (environmental variable), were checked using one factor covariance analysis (factor=treatment), and the Bonferroni statistical for *a posteriori* tests (α=0.05). Before the analysis, in order to keep normality and homogeneity of residual variances, tree and shrub covers (%) were transformed using the arcsine method (suitable when the variable is a proportion), while the rest of variables were transformed by logarithmic method (Fowler and Cohen 1990). The pH, EC, OM, TN, BD and BWD variables were incorporated to the covariance analysis as co-variables. The INFOSTAT Software 2013 version was utilized (Di Rienzo et al. 2013).

Superficial soil quality. To evaluate superficial soil quality (P1 and P2), pH, OM and TN values were interpreted using the standards of Bono et al. (2012), while CE and BD, using the standards of Lorenz (2016). These standards are in Supplementary Material-Table S2.

Results

Environmental variables

Annual precipitations. They were considered normal in 2016 (565.9 mm), 2017 (534.5 mm) and 2019 (636.6 mm), and below normal in

2018 (447.8 mm). The precipitation deficit in 2018 was not extreme because the registered value represented 76.3% of the historic annual average (587.1 mm). Therefore, during this study, precipitation availability was considered relatively favorable for herbaceous plant productivity.

Average fire focuses. In the lowland ecological site covered by grassland/savannas, between 2003 and 2019, an AFF=1.24 fire focuses/year was obtained, SD=1.89. In the patch of lowland ecological site covered by grassland/savannas encroached by woody plants, and during the studied period, there were no fires (AFF=0 fire focuses/year).

Total woody cover. Regarding Ref_Eco, first, this environmental variable was significantly and substantially larger in Woody_Encr, and second, it was not significantly different in Roll_Fire, Roll_Gatton Panic and Roll_Buffel Texas (Figure 3).

Superficial soil quality. Ref_Eco had good superficial soil quality (optimal values of pH, EC, OM and BD, and medium content of TN) (Table 2). Coherently with P1 and P2, Woody_Encr had a good superficial soil quality (optimal values of all indicators) (Table 2). Finally, Roll_Fire, Roll_Gatton Panic and Roll_Buffel Texas maintained the good superficial soil quality after the disturbance application (optimal values of every indicator) (Table 2). See the interpretation of soil quality indicators in Supplementary Material-Table S2.

Burned woody debris biomass. In Roll_Fire, the average and standard deviation of BWD were 21.2 and 15.3 t/ha, respectively. For the rest of the treatments, the variable had value=0 because they were not burned.

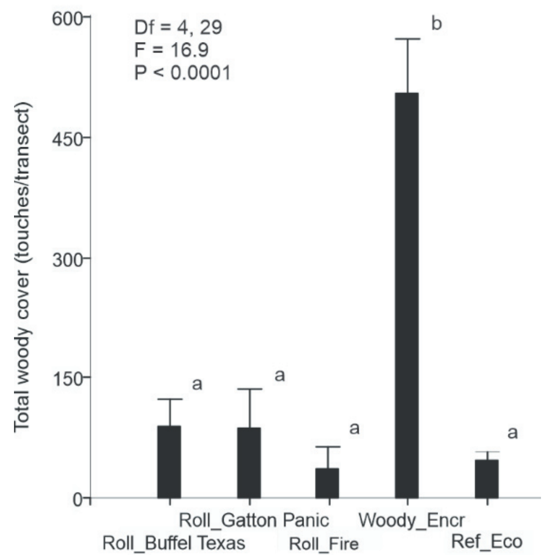


Figure 3. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Bars graphic (average+SD) for the total woody cover. The result of the covariance analysis is presented. Df=degrees of freedom, F=F statistical, α=0.05. Averages with common letters are not significantly different (Bonferroni Test).

Figura 3. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Gráfico de barra (media+desvío estándar) para la variable cobertura leñosa total. Se presenta el resultado del análisis de la covarianza. Df=grados de libertad, F= estadístico de la prueba F, α=0.05. Medias con letras comunes no son significativamente diferentes (prueba de Bonferroni).

Initial grass density

In all treatments, the estimated average of the initial grass density was above the reference value of 4-5 plants/m^2 (Table 3). So, regarding

Table 2. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Superficial soil quality indicators (average+SD) and interpretation according to Bono et al. (2012) and Lorenz (2016) standards.

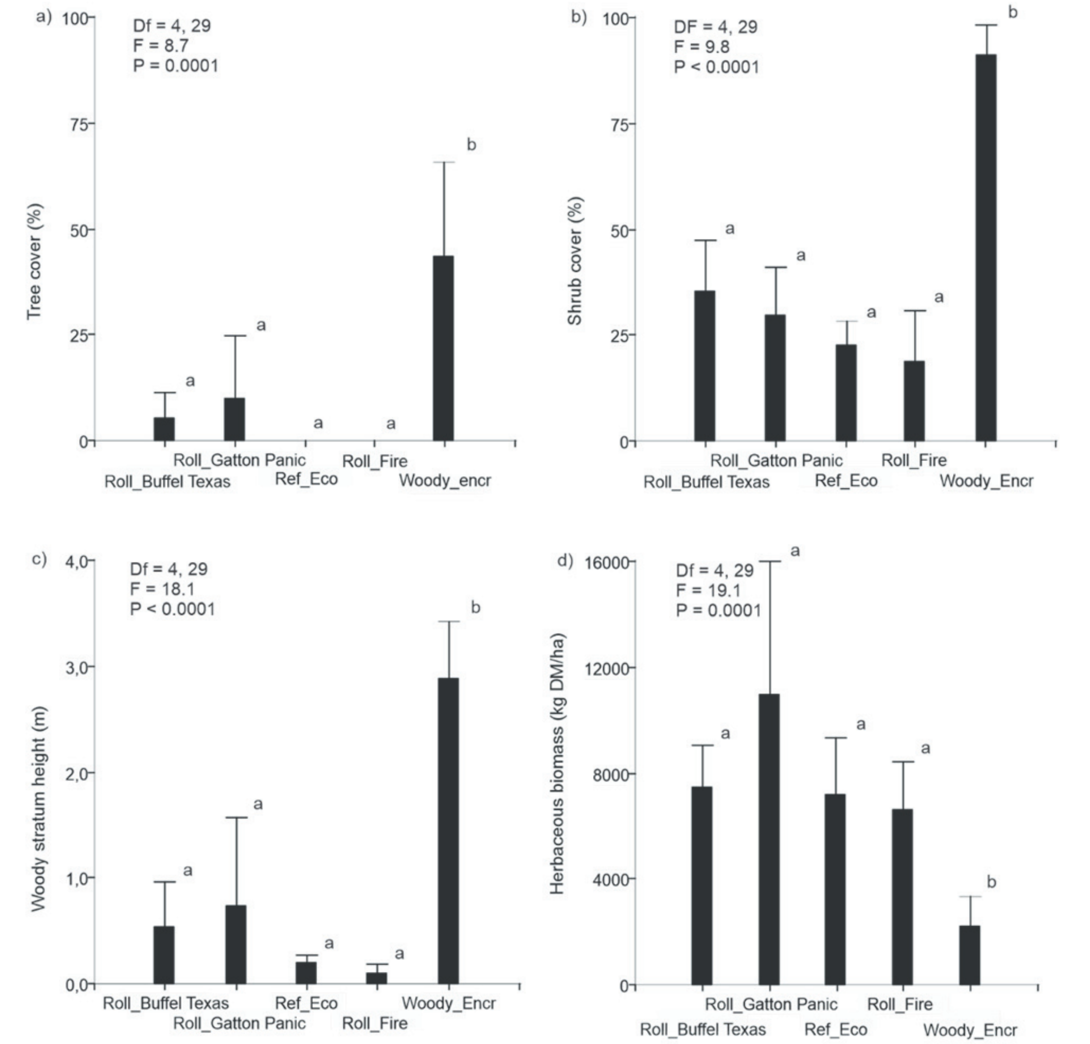
Tabla 2. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Indicadores de calidad del suelo superficial (media+desvío estándar) e interpretación según los estándares de Bono et al. (2012) y Lorenz (2016).

Treatment	EC (dS/m)	pH	OM (%)	TN (%)	BD (kg/dm^3)
Ref_Eco	0.31±0.07 (not saline, optimal)	6.9±0.08 (optimal)	2.33±0.52 (high, optimal)	0.1±0.02 (medium, sub-optimal)	1.12±0.1 (very low, optimal)
Woody_Encr	0.42±0.13 (not saline, optimal)	7.03±0.22 (optimal)	2.81±0.71 (high, optimal)	0.14±0.03 (high, optimal)	0.94±0.09 (very low, optimal)
Roll_Fire	0.57±0.09 (not saline, optimal)	7.31±0.2 (optimal)	3.15±0.84 (high, optimal)	0.15±0.03 (high, optimal)	0.98±0.13 (very low, optimal)
Roll_Gatton Panic	0.38±0.09 (not saline, optimal)	7.14±0.2 (optimal)	3.62±1.24 (high, optimal)	0.17±0.05 (high, optimal)	0.98±0.11 (very low, optimal)
Roll_Buffel Texas	0.5±0.18 (not saline, optimal)	7.24±0.22 (optimal)	3.41±1.03 (high, optimal)	0.17±0.03 (high, optimal)	0.98±0.1 (very low, optimal)

P1 and P2, in Roll_Fire, Roll_Gatton Panic and Roll_Buffel Texas the initial grass populations were abundant.

Vegetation structure

There was a significant effect of the treatment factor (P<0.05) for all vegetation structure



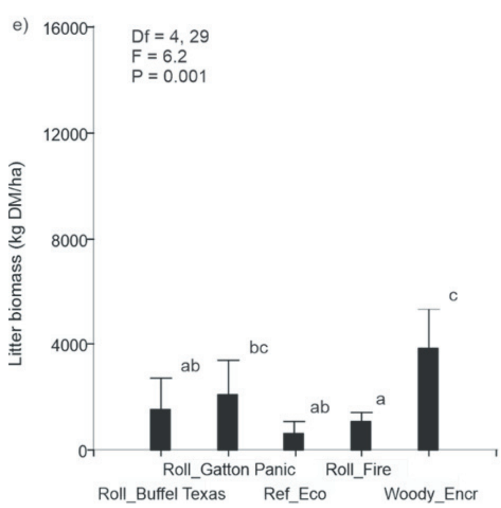


Figure 4. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Bar graphics (average+SD) for vegetation structural variables. The results of the covariance analysis are presented. Df=degrees of freedom, F=F statistical, α=0.05. Averages with common letters are not significantly different (Bonferroni Test).

Figura 4. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Gráficos de barras (media+desvío estándar) para las variables de estructura de la vegetación. Se presentan los resultados de los análisis de covarianza. Df=grados de libertad, F=estadístico de la prueba F, α=0.05. Medias con letras comunes no son significativamente diferentes (prueba de Bonferroni).

Table 3. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Estimated average and lower and upper bounds (95%) of the initial grass density.

Tabla 3. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Media estimada y limites inferior y superior (95%) de la densidad inicial de gramíneas.

Treatment	Estimated average (plants/m^2)	Lower bound (95%)	Upper bound (95%)
Ref_Eco	27.1	20.8	33.7
Woody_Encr	9.5	6.6	12.8
Roll_Fire	9.7	7.2	11.9
Roll_Gatton Panic	9.3	7.9	10.7
Roll_Buffel Texas	7.8	6.4	9.4

variables (Figure 4). In Woody_Encr regarding Ref_Eco, first, the shrub and tree cover, woody stratum height and litter biomass were significantly larger, and second, the herbaceous biomass was significantly lower (Figure 4). Coherently with P1 and P2, in Roll_Fire, Roll_Gatton Panic and Roll_Buffel Texas all vegetation structure variables did not significantly differ from Eco_Ref (a new grassy state was achieved) (Figure 4).

Species composition

The Chao-Jaccard estimator shows that, regarding the rest of treatments, Ref_Eco had the lowest similarity in broadleaf herb, grass and woody plant composition (Table 4, Table 5 and Table 6). So, Ref_Eco had the most singular species of plant community. Between Ref_Eco and Woody_Encr, the similarities in woody plant, broadleaf herb and grass composition were, moderate, moderate and low, respectively. The species lists are in Supplementary Material 3-Table S3 and Supplementary Material 4-Table S4.

The grass biomass results grouped according to species status are in Table 7. The most part in Ref_Eco corresponded to native species (78.5%), but a noticeable part corresponded to a naturalized species (21.5%, *Heteropogon contortus*). In Woody_Encr,

Table 4. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Similarity in broadleaf herb composition obtained by Chao-Jaccard estimator.

Tabla 4. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Porcentajes de similitud en la composición de hierbas de hoja ancha obtenidas a partir del estimador Chao-Jaccard.

Treatment	Treatment	Similarity (%)	Weighting
Ref_Eco	Roll_Fire	49.2	Moderate
Ref_Eco	Roll_Buffel Texas	49.6	Moderate
Ref_Eco	Roll_Gatton Panic	57.1	Moderate
Ref_Eco	Woody_Encr	64	Moderate
Roll_Buffel Texas	Woody_Encr	88.2	High
Roll_Fire	Woody_Encr	93	High
Roll_Buffel Texas	Roll_Gatton Panic	93.2	High
Roll_Gatton Panic	Woody_Encr	95.7	High
Roll_Buffel Texas	Roll_Fire	99.2	High
Roll_Gatton Panic	Roll_Fire	100	High

Table 5. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Similarity in grass composition obtained by Chao-Jaccard estimator.

Tabla 5. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Porcentajes de similitud en la composición gramíneas obtenidas a partir del estimador Chao-Jaccard.

Treatment	Treatment	Similarity (%)	Weighting
Ref_Eco	Roll_Gatton Panic	17.9	Low
Ref_Eco	Woody_Encr	27.9	Low
Ref_Eco	Roll_Fire	33.7	Low
Ref_Eco	Roll_Buffel Texas	44.2	Moderate
Roll_Gatton Panic	Roll_Fire	66.2	Moderate
Roll_Gatton Panic	Woody_Encr	67.8	Moderate
Roll_Buffel Texas	Roll_Gatton Panic	72.1	High
Roll_Buffel Texas	Woody_Encr	75.2	High
Roll_Fire	Woody_Encr	78.6	High
Roll_Buffel Texas	Roll_Fire	93.8	High

Table 6. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Similarity in woody plant composition obtained by Chao-Jaccard estimator.

Tabla 6. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Porcentajes de similitud en la composición plantas leñosas obtenidos a partir del estimador Chao-Jaccard.

Treatment	Treatment	Similarity (%)	Weighting
Ref_Eco	Roll_Gatton Panic	37	Low
Ref_Eco	Roll_Fire	46	Moderate
Ref_Eco	Roll_Buffel Texas	52	Moderate
Ref_Eco	Woody_Encr	65	Moderate
Roll_Gatton Panic	Woody_Encr	82	High
Roll_Gatton Panic	Roll_Fire	85	High
Roll_Buffel Texas	Woody_Encr	88	High
Roll_Fire	Woody_Encr	88	High
Roll_Buffel Texas	Roll_Fire	95	High
Roll_Buffel Texas	Roll_Gatton Panic	99	High

Table 7. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Grass biomass according to the species status (average+SD).

Tabla 7. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Biomasa de gramíneas según el status de las especies (media+desvío estándar).

Treatment	Exotic average	SD	Native average	SD	Naturalized average	SD
Eco_Ref	0.0	0.0	5446.3	3312.8	1487.5	1410.3
Woody_Encr	0.0	0.0	1835.9	2049.4	0.0	0.0
Roll_Fire	8.8	34.8	3764.3	2550.9	0.0	0.0
Roll_Buffel Texas	2444.8	3209.2	4327.5	3642.5	0.0	0.0
Roll_Gatton Panic	6685.8	9656.7	3177.9	2837.1	0.0	0.0

the 100% corresponded to native species. Consistently with P1 and P2, 1) in Roll_Fire, 99.76% corresponded to native species and a negligible part to an exotic species (0.24%, *Eragrostis cilianensis*); 2) Roll_Gatton Panic and Roll_Buffel Texas were unique treatments with appreciable participation of exotic grasses (in the first case, 100% corresponded to Gatton Panic and, in the second one, 99.94% corresponded to Buffel Texas), and 3) in both Roll_Gatton Panic and Roll_Buffel Texas there was also a high participation of native grasses (average >3000 kg DM/ha).

Utilitarian range condition

Ref_Eco had low shrub cover (Figure 4b) and high herbaceous forage biomass (Figure 5), which justify its utilitarian range conditions. In Woody_Encr regarding Ref_Eco, the shrub cover was significantly higher (91.2%) (Figure 4b) and the herbaceous forage biomass was significantly lower (Figure 5). Despite that, in Woody_Encr, the herbaceous forage biomass was moderate (1817.5 kg DM/ha). Woody_Encr is classified as in poor utilitarian range condition, being its excessive shrub cover its main limitation. Regarding Ref_Eco, in

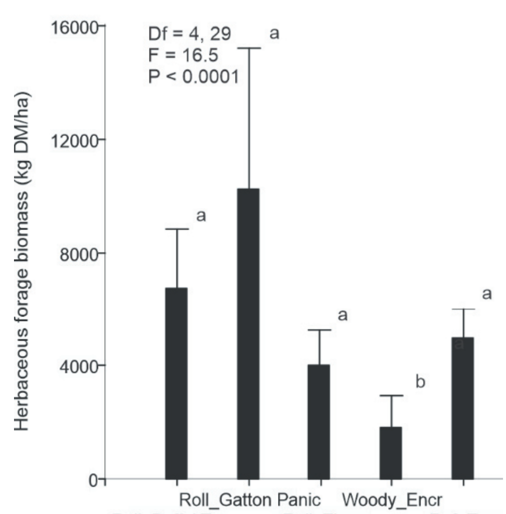


Figure 5. Experiment in lowland ecological sites, F. Cantos Experimental Ranch, Semiarid Chaco. Bars graphic (average+SD) for the herbaceous forage biomass. The result of the covariance analysis is presented. Df=degrees of freedom, F=F statistical, α=0.05. Averages with common letters are not significantly different (Bonferroni Test).

Figura 5. Experimento en sitios ecológicos bajos, Campo Experimental F. Cantos, Chaco Semiárido. Gráfico de barra (media+desvío estándar) para la forrajimasa herbácea. Se presenta el resultado del análisis de la covarianza. DF=grados de libertad, F=estadístico de la prueba F, α=0.05. Medias con letras comunes no son significativamente diferentes (prueba de Bonferroni).

Roll_Fire, Roll_Gatton Panic and Roll_Buffel Texas, the shrub cover and the herbaceous forage biomass did not differ significantly (Figure 4b and Figure 5). Therefore, the last three treatments were classified as in a good utilitarian range condition, which agrees with P1 and P2. Despite the lack of significant differences, the very high herbaceous forage biomass average in Roll_Gatton Panic is notable (10213.7 kg DM/ha). For example, it was a little more than twice the average of Roll_Fire (Figure 5). However, at the same time, Roll_Gatton Panic had an herbaceous forage biomass variability (SD=5011.9 kg DM/ha) far above the rest of treatments.

Discussion

The reference ecosystem

In this study, several facts reflected that the reference ecosystem utilized (Ref_Eco) represented a well conserved grassland/savanna and in consequence an acceptable standard of comparison. On one hand, between 2003 and 2019, the patch that contained Ref_Eco had periodic fires (AFF=1.24 fire focuses/year). Additionally, for this same patch, between 1925 and 1996, by means of dendrochronological methods, an average fire frequency of 0.18 fires/year was determined (Bravo et al. 2010). As a consequence, the available data indicate that for the most part between 1925 and 2019 the patch containing Ref_Eco had recurrent fires. This would have maintained the grassy state over time and favored grassland/savanna adapted plants (shade intolerant and fire tolerant) (Ripley et al. 2015; Archer et al. 2017; Coria et al. 2021). Coherently with the former, in Ref_Eco, the three most abundant grasses were shade intolerant and fire tolerant (*Elionurus muticus*, *Heteropogon contortus* and *Pappophorum pappiferum)* (Kunst et al. 1998) and they represented 83.3% of the total herbaceous biomass . On the other hand, in Ref_Eco, the good superficial soil quality, the high herbaceous forage biomass (4959.4 kg DM/ha) and the good utilitarian range condition would be the results of a low historical grazing intensity (Abril and Bucher 1999; Bestelmeyer et al. 2003; Díaz 2015; Coria et al. 2021). The herbaceous forage biomass even surpassed other grassland/savannas in good utilitarian range condition from nearby areas (1789-3071 kg DM/ha) (Kunst et al. 2006).

The grassland/savanna encroached by woody plants

The results suggested that the encroachment of woody plants substantially altered the characteristics of grassland/savanna vegetation. In Woody_Encr compared with Ref_Eco, 1) the woody stratum height, shrub and tree cover and litter biomass were significantly higher (1340.0%, 305.6%, 4350.0% and 511.6%, respectively); 2) the herbaceous biomass was significantly lower (69.5%); 3) the similarity in woody plant, broadleaf herb and grass composition were respectively moderate (65%), moderate (64%) and low (27.9%), and 4) the utilitarian range condition was poor. However, in Woody_Encr, the moderate changes in woody plant composition were unexpected, because in a previous study this attribute was little affected by woody plant encroachment (Coria et al. 2021).

The low similarity in grass composition between Woody_Encr and Ref_Eco could be due to a prevalence of grasses adapted to shrubland/forests in the first (*Digitaria californica*, *Digitaria insularis*, *Gouinia latifolia*, *Gouinia paraguayensis*, *Setaria lachnea*, *Setaria* sp. and *Leptochloa pluriflora* represented the 96.2% of grass biomass); while in the second, grasses adapted to grassland/savannas prevailed (see first paragraph of this discussion). It is remarkable that in the patch where Woody_Encr was located, evaluations of the herbaceous stratum done between 1983 and 1988 (i.e., previous to woody plant encroachment) show an herbaceous plant composition adapted to grassland/savannas, where the *Elionurus muticus* grass was the most abundant species (average cover=67.3%; SD=36.5%) (unpublished data). Globally, this evidence suggests that woody plant encroachment would have promoted the replacement of grassland/savanna adapted grasses by other adapted to shrubland/forests (i.e., shade tolerant) (Archer et al. 2017; Coria et al. 2021).

The former analysis also highlights the importance of alterations in fire regimes and sunlight availability on grass composition. Normally, woody plant encroachment reduces or suppresses fire events and increases woody cover generating shaded habitats. In this study, the AFF analysis showed that in the patch where Woody_Encr was located there were no fires between 2003 and 2019. Kunst et al. (2012) reported that in this patch, the last fire occurred in the late 1990s. Additionally, compared with Ref_Eco, in Woody_Encr, the total woody cover (touches/transect) significantly higher (1002.5%) suggests the greater capacity of the last treatment to reduce the sunlight availability for grasses (Kunst et al. 2006).

Very noticeable and coherent with P1 and P2, the results suggested that, in this specific study, woody plant encroachment did not affect superficial soil quality (optimal values of all soil quality indicators in Woody_Encr) and did not finish native grass populations (initial grass density in Woody_Encr=9.5 plants/m^2); which would determine a high potential of *sensu lato* ecological restoration of the encroached ecosystems. In Woody_Encr, this favorable results would be because, on one hand, the historical overgrazing was not extreme (Morello and Saravia Toledo 1959; Adamoli et al. 1972; Díaz 2015) and, on the other hand, the high woody cover and litter biomass had a beneficial effect on physical, chemical and biologic soil properties (Anriquez and Albanesi 2008; Anriquez et al. 2008).

Sensu lato ecological restoration of the grassland/savanna encroached by woody plants

Consistently with P1, in Roll_Fire all vegetation structure variables did not differ significantly from Ref_Eco, suggesting that the management applied was able to restore the grassy state of the encroached ecosystem. This new grassy state would be explained by a conjunction of environmental and management factors. In first place, the high initial grass density (9.7 plants/m^2 in Roll_Fire), the good superficial soil quality in the encroached ecosystem, and the annual precipitation mostly normal, would have determined a great capacity of recovery of the herbaceous stratum. Later, the medium intensity roller chopping used would have been effective in reducing woody plant competition and, together with grazing suppression, would have allowed herbaceous plants to substantially increase their biomass (Kunst et al. 2012; Díaz 2015). During two growing seasons, the fine fuel accumulated allowed to applicate the prescribed fire, which reduced even more the competition of woody plants and benefit again herbaceous plants (Allen 2008; Scott et al. 2013). As a final result, in Roll_Fire the balance between woody and herbaceous plants was modified in favor of the latter.

The results also suggest that the short-term management applied in Roll_Fire would not restore the plant composition of the encroached ecosystems. This is due to, between Ref_Eco and Roll_Fire, the similarities in grass, broadleaf herb and woody plant composition that were low (33.7%), moderate (49.2%) and moderate (46%), respectively. We believe that to consider these attributes reasonably restored, these similarities should be high (≥70%).

It is interpreted that in Roll_Fire, the grasses that responded to the management were essentially the same shrubland/forest adapted species present in the predecessor encroached ecosystem. It is supported by 1) the prevalence of shrubland/forest adapted grasses in Roll_Fire (*Gouinia latifolia, Setaria lachnea* and *Leptochloa plutiflora* represented the 75.5% of the grass biomass), and 2) the high similarity in grass composition between Roll_Fire and Woody_Encr (78.6%). In Roll_Fire, the high achieved fine fuel load (>3000 kg DM/ha) suggests the feasibility of reconstructing the grassland/savanna normal fire regime (an event each three years, approximately) (Bravo et al. 2010). Future studies could check if with long-term practices like these, the abundance of grassland/savanna adapted grasses is increased.

Consistent with P1, between Ref_Eco and Roll_Fire there were no significant differences in shrub cover and herbaceous forage biomass, which justified a good utilitarian range condition in Roll_Fire. The high herbaceous forage biomass achieved in Roll_Fire (4010.6 kg DM/ha), representing 80.9% of the herbaceous forage biomass of Ref_Eco, is remarkable. So, the management applied would be beneficial for ranching.

In Roll_Fire, it is highlighted that the applied management did not affect the superficial soil quality (optimal values of all soil quality indicators). However, the soil quality indicator types utilized (chemical and physical) often respond slowly to disturbances. Therefore, a long term monitoring on them would be appropriate (Abril 2003; Cardoso et al. 2013; Bünemann et al. 2018).

As a global appreciation, the management applied in Roll_Fire was able to restore almost all ecosystem attributes to Ref_Eco levels, with the exception of plant composition (especially of grasses). Thus, in the context of this study, this management would have the potential to reasonably induce a *sensu lato* ecological restoration of the encroached ecosystems.

Introduction of African grasses to grassland/ savannas encroached by woody plants

In the Americas, the C4 African grasses introduced to improve ranching have often expanded and colonized natural areas at great speed, with effects in the ecosystem such as the increase of fire frequency, alterations in energy, nutrients and water fluxes, and the displacement of native species. (D'Antonio and Vitousek 1992; Williams and Baruch 2000; Marshall et al. 2012). In this study, the productivity of Gatton Panic (7044.3 kg DM/ha) and Buffel Texas (2444.8 kg DM/ha) was within the expected values for Semiarid Chaco (4300-8600 and 1500-4500 kg DM/ha, respectively) (De León 1998; Avila et al. 2014). Coherently with P2, a) in both Roll_Gatton Panic and Roll_Buffel Texas there was also a high participation of native grasses (3177.9 and 4327.5 kg DM/ha, respectively), then, there were truly mixes between native and exotic grasses, and b) both treatments achieved a good utilitarian range condition.

Surprisingly, both Roll_Gatton Panic and Roll_Buffel Texas were quite similar to the treatment designed to induce the encroached ecosystem restoration (i.e., Roll_Fire). Among these treatments, all variables of vegetation structure and the herbaceous forage biomass did not differ significantly, similarities in plant species composition were high in most of the cases and all indicators of superficial soil quality had optimal values. This suggests that the introduction of African grasses was friendly with both the superficial soil and native plant diversity of the encroached ecosystems. However, this appreciation is valid only for this study and it should be taken as preliminary because a precise valuation requires more long-term complex studies. On the other hand, due to the good utilitarian range condition achieved in Roll_Fire, the introduction of African grasses to improve ranching would not have been necessary. In Dry Chaco, it was emphasized that the utilization of African grasses must be restricted to the most degraded areas, due to the profitability of well managed natural grasslands (Díaz 2015).

Conclusions and management implications

This study suggested that the woody plant encroachment in grassland/savannas induced important changes in vegetation structure and plant composition (in native grasses, there was a replacement of species adapted to grassland/savannas by other adapted to shrubland/forests), and it impoverished the utilitarian range condition. However, the phenomenon would not have negatively affected the superficial soil quality nor finished the native grass populations, which would have determined a high potential of *sensu lato* ecological restoration of the encroached ecosystems.

The results also suggested that in these encroached ecosystems and with a mostly normal annual precipitation, 1) the combined use of medium intensity roller chopping, grazing suppression, and prescribed fire after two growing seasons would produce a new gassy state, where a) both the vegetation structure and good utilitarian range condition would be restored; b) the plant composition would not be restored, especially grasses; c) the good superficial soil quality would be kept, and d) a normal fire regime could be restored by means of prescribed fires. Therefore, this management would be capable of reasonably inducing a *sensu lato* ecological restoration of encroached ecosystems, and 2) the combined use of medium intensity roller chopping, grazing suppression and seeding of the African grasses Gatton Panic and Buffel Texas would produce new grassy states integrated by exotic and native grasses and in good utilitarian range condition. These new ecosystems would be friendly to both the superficial soil quality and the native plant diversity of the encroached ecosystems. However, this appreciation is valid only for this study and should be taken as preliminary because a precise valuation requires more long-term complex studies.

Globally, predictions 1 and 2 were supported, thus the hypothesis as well. Regarding management implications, in the studied encroached ecosystems, the *sensu lato* ecological restoration would be a viable ecological and productive alternative. For that reason, in similar cases, the introduction of African grasses to enhance ranching should be carefully evaluated because it might not be necessary.

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