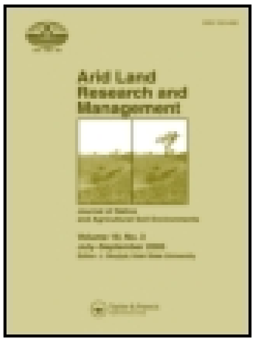

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Developing a prescription for brush control in the Chaco region, effects of combined treatments on the canopy of three native shrub species

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ABSTRACT

Shrub encroachment is frequent in grazing lands in the Chaco region, Argentina. Fire is used by cattlemen to reduce the dominance of the shrub stands, improve forage standing biomass and quality, and enhance grazing accessibility. In this research, we assessed the combined effect of roller chopping + fire on the plant canopy of three native shrub species, *Acacia gilliessi, Celtis ehrenbergiana*, and *Schinus bumelioides*. We used a randomized design, with three factors, year, burn dates, and fine fuel load. Before the burn, the area received a roller-chopping treatment. Canopy volume reduction was assessed using, $\text{DifV} = -1^*(V_i - V_a)$ and $\text{DifS} = -1^*(S_i - S_a)$, respectively, where $V =$ plant volume and $S =$ sprout number. Suffixes *i* and *a* represent measurements taken before the roller-chopping treatment and one growth season after the fire, respectively. Fire intensity, headfire residence time, woody residues, and initial plant volume were evaluated as covariates. Results indicate a negative fire effect on canopy volume and sprouting. *A. gilliesi* was more susceptible to fire than the other two species. High fine fuel load and high fire intensity generated a severe effect on sprout number. The same trend was observed for coarse fuels. The canopy volume reduction was greater in *A. gilliesi* than the other species, reaffirming its high susceptibility to fire. Head fires were faster in 2009 than in 2008 and in the late than in the early burn dates. These results suggest that mechanical + fire treatments can be useful management tools for controlling shrub encroachment in the western Chaco.

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Fire intensity; fuel load; roller chopping; sprouting shrubs

Introduction

Grasslands, savannas, and forests that have shifted to a shrub dominated state represent a severe limitation for livestock operations in the Argentine Chaco region, where cow-calf operations are an important economic activity (Adamoli et al. 1990). In this research, we explored the effect of the sequence roller chopping followed by fire on native shrub control and developed a prescription. The Chaco biome comprises northwestern Argentina, eastern Bolivia, and western Paraguay. Originally, its native vegetation was a mosaic of dry forests, grasslands, and shrublands with a component of woody deciduous and thorny species (Bucher 1982). These vegetation types were flammable according to fine

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fuel availability and climatic conditions. Increasing livestock introduction up to the 1940s modified the original plant communities (Adámoli et al. 1990), causing a reduction of availability of fine fuels and a change in fire regime, leading to a severe brush encroachment (Morello and Adamoli 1974).

Brush encroachment is an issue in the Chaco as well as in other arid and semiarid regions of the world (Asner et al. 2004; Eldridge et al. 2011; Lohmann et al. 2014). The effects of brush encroachment are different among ecosystems and vegetation units, by altering vegetation dynamics and changing habitat quality for wildlife species (Adámoli et al. 1990; Peterson and Reich 2001; Hamilton et al. 2004; Kunst et al. 2012; Hanberry, Kabrick, and He 2014). From a practical standpoint, woody encroachment reduces grass availability as well as obstructs visibility, and movements of livestock, wildlife, and personnel. The suitability of a pasture for the livestock industry is substantially diminished in severely encroached areas (Dacy and Fulbright 2009; Archer et al. 2011). On the other hand, shrubs have some positive aspects such as increments in soil C and N levels, typically restricted to the upper soil profile (Archer et al. 2011); shadow for livestock and refuge for wildlife, protection against soil erosion and can also act as nurse plants and facilitate herbaceous emergence (Al-Namazi, El-Bana, and Bonser 2016).

The knowledge of plant responses to disturbance is crucial for managing vegetation (Vesk, Warton, and Westoby 2004). According to Archer et al. (2011) there are four methods for controlling woody plant encroachment in semiarid regions, mechanical, chemical, fire, and biological. There are two strategies suggested in the literature for a successful shrub control, (a) "repetition" of a single disturbance (e.g., fire–fire, Peterson and Reich 2001); and/or (b) a "combination" of disturbances in sequence (e.g., mechanic-fire, Lohmann et al. 2014). The sequential mechanical treatments—fire has been successful in controlling shrub encroachment in others ecosystems (Paynter and Flanagan 2004; Vesk, Warton, and Westoby 2004; Thompson and Purcell 2016). In the Chaco region, there is available information only about the particular results of individual methods for controlling encroachment (Kunst et al. 2012). The roller chopping, a mechanical treatment designed to knock down and chop up brush and trees up to about 10 cm of main trunk diameter, promotes the subsequent growth of herbaceous species, and allows the application of prescribed fire as a "follow up" treatment (Kunst et al. 2012).

Prescribed burning is the planned use of fire to achieve precise and clearly defined objectives (Fernandes et al. 2013). A "prescription" is a rule or course of action to be followed to attain a practical objective, and should be based on scientific research and experience (Alexander and Thomas 2006). Shrub mortality induced by mechanical and fire treatments in the Chaco is usually low (Kunst et al. 2012). Therefore, a more certain appraisal of success of brush control should be based in the achievement of suitable changes in "plant architecture," "stand structure," or "coppicing" features (Peterson and Reich 2001). In practice, the objective should be to reduce sprout number and plant volume to a convenient size for cow-calf operations, without damaging other ecosystem services. There is information about mortality of native shrub species in the Chaco, but changes in plant structure have not yet been studied in detail (Kunst et al. 2001; Casillo, Kunst, and Ledesma 2006).

The hypothesis examined here was that the canopy volume and sprouting characteristics will vary according to, (a) species, fire susceptibility depends on plant physiology, plant structure and other tolerance traits (Drewa 2003); (b) prefire plant volume, the plant size influences on the bud bank size, reserves availability to resprout after fire (Pausas and Keeley 2014) and likelihood of survival; (c) burn dates, early burns (July) are usually less severe than late burns (October) due to drier meteorological conditions and greater fuel desiccation (Bravo et al. 2014; Kunst et al. 2015; Rissi et al. 2017); (d) amount and type of fuel (fine fuel and coarse fuels), the higher the fuel load, the more severe the fire effect on vegetation and soils is (Silberman et al. 2013). The objectives of this work were to assess the effects of the sequential roller chopping and fire at two burn dates (early and late fire season with different fuel load) on the plant canopy of three shrub species in the Chaco Region, Argentina.

Materials and methods

Study area

Research was conducted at the "Francisco Cantos" Experimental Ranch, belonging to Instituto Nacional de Tecnología Agropecuaria, Santiago del Estero, Western Chaco Region, Argentina (28° 03′S, 64°15′E). Climate is semiarid, with an annual average rainfall of 574 mm. Winters are cold and dry, and the summers warm and rainy (Boletta 1988). Mean annual temperature is 19.8°C, and the mean of the warmest (January) and coldest (July) months are 26.1 and 10.6°C, respectively. Freezing temperatures can occur from May to October, reaching extreme temperatures of −10 and −12°C (Torres Bruchmann, 1981).

At a scale ≈1:20,000, soil and vegetation types of the study area are located along a catena from the "upland" to the "lowland", that could be interpreted as upland, midland, and lowland ecological sites, respectively (Kunst et al. 2006). The former have coarse textured soils and sustain a hardwood forest of *Aspidosperma quebracho blanco* Schlecht and *Schinopsis lorentzii* Griseb. Engl, while the latter present more developed and finer textured soils, supporting a savanna of the bunchgrass *Elionurus muticus* Spreng. Kuntze. *A. quebracho blanco* is an evergreen hardwood species that may reach a height = 20 m and a diameter at breast height (DBH) = 80 cm. *S. lorentzii* is a hardwood deciduous species that sheds its leaves in early-spring (October), reaching a height = 25 m and a DBH = 1.50 m. *E. muticus* is a bunchgrass 0.5 m tall. "Parks" are located in the "midlands", between the other two topographic positions (Morello and Adamoli 1974). Soils of the upland and midland ecosites of the selected area were classified as Entic Haplustols, while those of the lowland were classified as Typic Haplustols (Anriquez et al. 2005).

We selected an area containing a midland ecological site, which was covered by a homogeneous, almost impenetrable shrub strata before the roller chopping treatment. Three native shrub species were considered for the study, *Schinus bumelioides* Johnst. (*Anacardiaceae*), *Celtis ehrenbergiana* (Klotzsch) Liebm. var. ehrenbergiana (Celtidaceae), and *Acacia gilliesii* Steud. (*Fabaceae*). Their individuals are characterized by a height <3.5 m, multistemed growth and thorny branches. These features represent a problem for grazing management.

The study area has not been burned since the late 1980s. The seeding of tropical grass species such as *Megathyrsus maximus* (Jacq) B. K. Simon & S. W. L. Jacobs var. Maximus. Cv Gatton is a widespread strategy to increase forage availability in the Chaco region (Kunst et al. 2015). This practice enhances standing forage up to 6000–8000 kg DM ha^{-1}.

Roller-chopping was applied one year before the experimental burns in the study area, without sowing of *M. maximus*. The objective of this previous treatment was to promote the growth of the herbaceous layer, therefore increasing the availability of fine fuel to perform the experimental burns. The quantity of woody residues (fuels with more than 2.5 cm diameter) also increased.

Experimental design

The experiment was performed in two successive years (2008 and 2009). In the study site, 120 plots of 2 × 2 m were randomly established. An individual of each species, located at the center of each plot was tagged and numbered. Sixty plots were burnt in each year, with five replications for each species, following Rissi et al. (2017). Treatments were, *burn date*; early (July); and late (October) in the fire season; and *fine fuel load* in two categories, (a) high, 8000 kg DM ha^{-1}, corresponding to the aboveground biomass in areas where *M. maximus* has been seeded and (b) low, 4000 kg DM.ha^{-1}, corresponding to the aboveground biomass in native grass, respectively. We added fine fuel in plots where the standing amount of fine fuel did not reach the target load (Drewa 2003). The load of woody plant residues (W, kg DM ha^{-1}) left by the roller chopping treatment was evaluated at each plot by method proposed by Brown (1974).

By manipulating fuel loads and burn date, we overcame limitations of research based on observations conducted after wildfires, in which intensity, rate of spread, severity, and other descriptors of fire behavior are usually unknown. This approach, by permitting changes in fire intensity and severity, is a useful tool to relate disturbance to the response of plant species (Drewa 2003).

Field measurements

Plant canopy

In the field, 1 month before and one growth season after the fire, respectively, we registered for each plant its height (H, m), average canopy diameter, estimated by two orthogonal diameters (m); and number of sprouts per plant (S, number). Using these data, plant volume (V, m^3) was calculated in the lab, assuming that the plant canopy presented the form of an inverse cone (Kunst et al. 2012). Changes in plant structure due to fire were assessed using the following formulas

$$\text{DifV} = -1 * (V_i - V_\text{a}); \quad (1)$$
$$\text{DifS} = -1 * (S_i - S_a). \quad (2)$$

Suffixes *i* and *a* represent measurements taken before the mechanical treatment and one growth season after the fire, respectively. Plant volume and number of sprouts are features that influence the suitability of the vegetation of a paddock for livestock grazing, the larger the plant volume and sprout number near the ground, the larger the obstruction for livestock and personnel movement. Sprouting is a mechanism by which a species persists after a disturbance such as fire, herbivory, or mechanical treatment (Pausas and Keeley 2014). Species tolerate fire due to that ability, a trait determined by the development, protection and resourcing of a viable bud bank (Wright and Bailey 1982; Casillo, Kunst and Ledesma 2006; Bravo, Kunst and Grau 2008; Clarke et al. 2012). Heat released by fire, depending on the season and fuel load, may also increase soil temperature and reduce sprout number

(Wright and Clarke 2007). The mean DifS is also an indicator of the vigor and success of resprouting (Malanson and Trabaud 1988).

Fire behavior

We conducted the burns using drip-torches, setting a head fire perpendicular to the dominant wind direction, usually N-NE. In fire science, the concept of fire behavior is used to characterize a fire event (Alexander 1982). Estimated fire behavior features were

- Fire intensity (I) represents the energy released by fire and was estimated by flame length (Alexander 1982, formula 3).

$$I\left(\mathrm{kW\,m^{-1}}\right) = 259.83*\mathrm{LL}^{2.174}, \tag{3}$$

where LL (m) is the average flame length, visually estimated by two independent observers (Ryan and Noste 1985). It was assumed that the longer the flame lengths, the greater heat released and the greater the fire intensity (Alexander 1982).

- Residence time. The time taken by the fire front to run through a plot (tt, minutes), and the time taken to achieve the total consumption of the fuels (tf, minutes) were also recorded. These parameters give a hint of fire severity; the greater residence time, the more severe effect on vegetation and soil (Wright and Bailey 1982; Stoof et al. 2013).

Statistical analysis and interpretation

Year, burn date, fine fuel load, and W, are surrogates for external factors influencing the fire environment; while flame length, tt and tf indicate fire behavior, respectively. Species, Vi and Si represent intrinsic factors such as plant vigor and size. Vi and the prefire number of sprouts (Si) are considered indicators of plant vigor and may denote the size of the bud bank, suggesting more meristematic tissue in crown and roots (Malanson and Trabaud 1988).

To characterize differences in fire behavior, flame length, W, tt, and tf were analyzed using ANOVA with fuel load, year and burn date and their interactions as independent variables.

The effect of fire was assessed using two approaches. First, we individually assessed the differences with zero of the LSMeans of DifV and DifS, for each species, using *t*-tests. If either DifV or DifS = 0, >0, or <0, then fire effect on a specific plant attribute was interpreted as nil, beneficial and/or harmful, respectively. This analysis gave us a general understanding of fire effects. To analyze better the relationships among the prefire plant structural features and fire effects, we constructed graphs of DifV and DifS versus the means of Vi and Si, classified by classes, considering all species (Hodgkinson 1998). Four Vi classes were considered, I, from 0 to 0.4 m^3; II, from 0.41 to 0.8 m^3; III, 0.81 a 1, 2 m^3; and IV, from 1.21 to 1.6 m^3. For Si the classes were I, from 0 to 10 sprouts; II, from 11 to 20 sprouts; III, from 21 to 30 sprouts. The range of Vi and Si for each species were defined empirically by visually assessing the graphics.

Changes in DifV and DifS were also assessed in an ANCOVA with a randomized design with these plant features as dependent variables, and year, burn date, species, and fine fuel load as independent variables. Year is a classification factor representing annual climatic variability, which is quite high in the Chaco region, with a significant influence on fire severity (Dale et al. 2001). Burn date was the treatment representing the seasonal variation of fuels and atmospheric conditions. Both could influence on the resprouting number due to annual plant resource allocation (Hmielowski, Robertson, and Platt 2014; Robertson and Hmielowski 2014). Fine fuel load is a treatment related to the amount of energy stored in the biomass and it is an estimator of fire intensity. Species is a classification factor representing the intrinsic features of an individual such as its flammability, plant architecture, volume, that may affect fire resistance. The initial plant features (Vi and Si) and fire descriptors (flame length, W, tt, and tf) were used as covariates. DifV and DifS were transformed to ranks by nonparametric method to fulfill ANOVA assumptions (Conover 1980). Since the dependent variables were a combination of the plant attributes used as independent variables, its collinearity was assessed using the variance inflation factor (VIF), with a threshold of 10% (Neter, Wasserman, and Kutner 1983).

The procedures FREQ, REG, TTEST, and GLM of the SAS University package were used for mathematical calculations (SAS Institute Inc 2015). Independent variables as well as covariates were considered significant if $p < 0.05$. In all statistical analysis, nonsignificant interactions were removed.

Results

The roller-chopper crushed all the aboveground organs of the plants, and was characterized as a disturbance of high severity. However, no plants were killed, and they sprouted profusely. Before the fire, mean plant height was 1–1.2 m considering all species (SD = 0.19 cm). Mean Si was 7.5 for *S. bumelioides*, 9.7 for *A. furcatispina* and 10.6 for *C. ehrenbergiana* with significantly differences among them ($p < 0.001$). Sprout average diameter was <1 cm. Mean W varied according to species, *S. bumelioides* and *C. ehrenbergiana* presented a larger mean W than *Acacia gilliessi* (30,306, 25,368, and 16,851 kg. ha^{-1}, respectively, $p < 0.0002$).

Accumulated rainfall recorded during the growth period before the fire season was greater in 2008 than 2009, while the number of days with freezing temperatures were larger in the latter year (Table 1). Mean air temperatures observed during the burns were milder and less variable in 2008. On the other hand, air relative humidity and wind speed in 2009 were less than in 2008 (Table 1).

Table 1. Weather conditions and time variables of experimental burns conducted on July and October, in two years 2008 and 2009 in the "Francisco Cantos" Experimental Ranch, INTA Santiago del Estero, Chaco region, Argentina.

	Year			
Variables	2008		2009	
Accumulated rainfall mm[1]	514		357	
Number of freezing days[2]	30		43	
Timing of burn	Early	Late	Early	Late
Day and time of the burns	July 17 (between 9:50 and 12:50)	October 24 (between 10:15 and 15:50)	July 29 (between 11:45 and 16:25)	October 20 (between 9:15 and 15:15)
Air Temperature (°C)[3]	24–27.1	26.6–28	15.5–24	25.6–38.2
Air Relative humidity (%)[3]	48–38	56–50	29–19	37–23
Wind speed (km h^{-1})[3]	3.7–2.8	3.4–2.4	1.3–2	0.9–7.3

[1]Rainfall reported corresponds to the amount recorded during the active growth season of plants before each experiment, October to April. INTA Experimental Ranch meteorological station.
[2]Air temperature below 0°C.
[3]Air temperature, air relative humidity, and wind speed registered at mid-flame height, during the day of the burns using a portable psychrometer and anemometer.

Table 2. Fire behavior parameters during burns according to year, timing of burn, and fuel load. Francisco Cantos' Experimental Ranch, INTA Santiago del Estero Experimental Station. Standard deviation between brackets.

Year	Burn date	Fuel load	Mean flame length (m)	Mean fire intensity k W m	tt	tf
2008	Early	High	2.54 (0.71)	2155.06	61.47 (16.6)	288.62 (141.65)
		Low	1.59 (0.64)	855.08	56.4 (16.67)	332 (278.89)
	Late	High	2.22 (0.51)	1567.87	53.79 (19.03)	443.21 (251.57)
		Low	1.73 (0.54)	960.91	54.31 (17.81)	504.33 (342.06)
2009	Early	High	3.19 (0.46)	3309.85	34.5 (7.6)	553.21 (99.61)
		Low	2.17 (0.52)	1492.88	42.79 (17.58)	563.5 (67)
	Late	High	3.94 (0.65)	5294.16	23.2 (9.47)	247.2 (53)
		Low	3.14 (0.55)	3229.74	25.93 (8.52)	285.27 (59.2)

References: Fuel load: high: 8000 kg DM ha^{-1}; low: 4000 kg DM ha^{-1}.
Fire intensity calculated using formula = 259.83*(Flame length)$^{2.174}$.
tt = time taken by the fire front to run through a plot (seconds).
tf = time required to achieve the total consumption of the fuels (seconds).

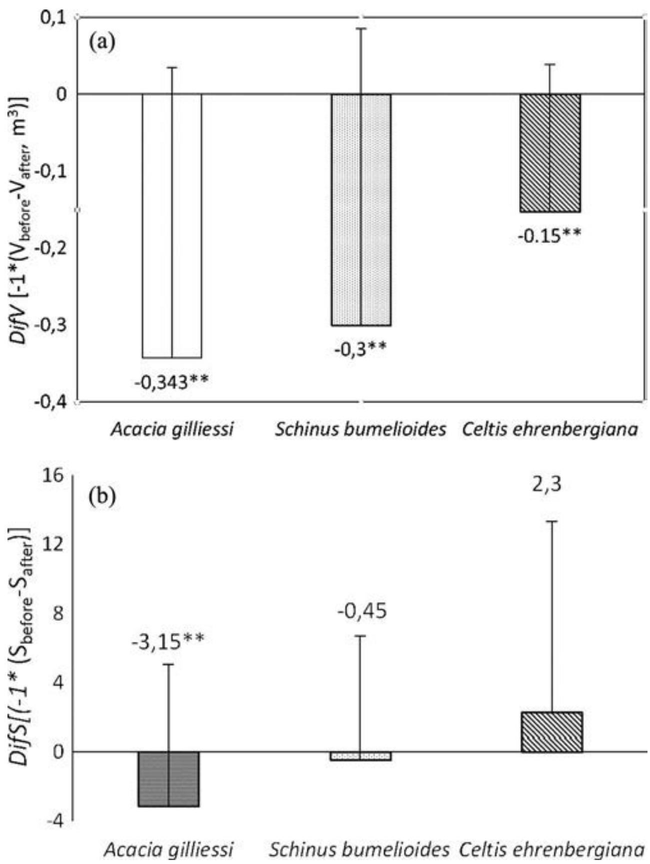

Figure 1. Effect of fire on DifV (a) and DifS (b) in three native shrub species of the Chaco region, Argentina. Differences with zero of LS means of DifV and DifS, according to species. **Significant differences from zero, two-tailed *t*-test, $\alpha = 0.05$. Francisco Cantos' Experimental Ranch, Santiago del Estero, Argentina.

Fire behavior

Fine and coarse fuel consumption was total. Average flame length ranged from 1.59 to 3.9 m (Table 2). Flame length was significantly influenced by year ($p < 0.0001$), burn date ($p < 0.0028$), fuel load ($p < 0.0001$), and by the interactions year*burn date ($p < 0.0001$), and burn date*fuel load ($p < 0.0649$). Mean flame length was longer in, (a) in 2009, (b) in the late burn date, and (c) in the plots with high fine fuel load. W did not affect flame length. I was greater in 2009 than in 2008. In 2009, the highest I was registered in the late burn date and in the high fine fuel load plots. In 2008, I was similar in the two burn dates, it was higher in the early burn date with high fine fuel.

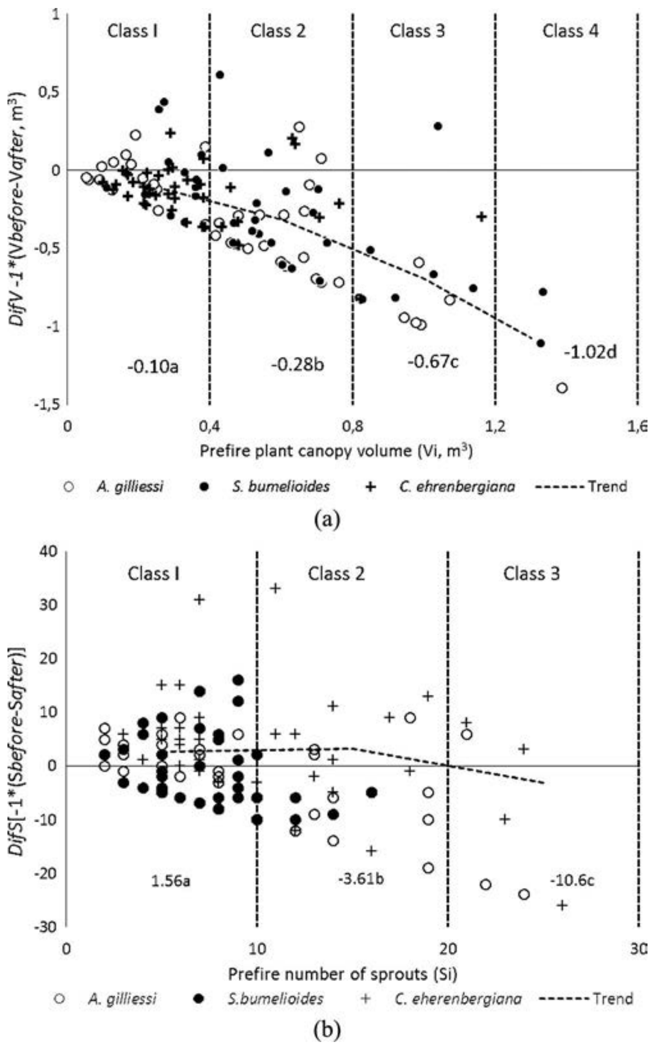

Figure 2. (a) Effect of prefire canopy volume (Vi, m^3) and (b) prefire sprout number (Si) on DifV (m^3) and DifS, respectively, in three native species of the Chaco region, Argentina. LSMeans by size class. Means followed by the same letter are not significantly different. Francisco Cantos' Experimental Ranch, Santiago del Estero, Argentina.

Mean tt varied according to year ($p < 0.0001$); burn date ($p < 0.0008$), and species ($p < 0.0528$). Fire spread was faster in 2009 than in 2008; in the late date than in the early burn date (Table 2). Mean tt observed in *C. ehrenbergiana* plots (40.10 seg; SD, 19.42) was shorter than those observed in *A. gilliesii* (44.18 seg; SD, 20.08) and in *S. bumelioides* 48.15 seg; SD, 20.21). Fine fuel load and W did not affect tt.

Tf was affected by burn date ($p < 0.04$), species ($p < 0.0001$), and W ($p < 0.0001$). Mean tf was longer in the early than in the late burn date (Table 2). Tf was positively associated to W ($R^2 = 0.24$). Tf was longer under *S. bumelioides* (506.73 seg; SD, 239.08) and *C. ehrenbergiana* (422.79 seg; SD, 183.84) than under *A. gilliesii* (278.70 seg; SD, 182.26) canopies.

Fire effects

The aboveground structure of all plants was totally killed by the fire and they resprouted from the root crown. The mean DifV was significantly different from zero in the three species (Figure 1). *A. gilliesii* presented a more negative value of DifV than *S. bumelioides* and *C. ehrenbergiana* (Figure 1a) indicating a more harmful effect of fire for the former. The mean DifS of *C. ehrenbergiana* was positive while other species increased number of sprouts after fire (Figure 1b). DifV presented a negative association with Vi ($ß = -0.79$, $R^2 = 0.45$, VIF < 10% Figure 2a). Four Vi classes can be observed in the relationship, each one with distinct pattern of DifV (Figure 2a), class I shows an indifferent, even positive, fire effect with a mean reduction of Vi of 0.10 m^3, mainly in *A. gilliesii* and *S. bumelioides*; while class IV (Vi > 1.2 m^3) shows a mean decrease ≈1.0 m^3 in the three species (Figure 2a). Mean DifS was significantly influenced by Si, with a $\beta = -0.57$, but showed a low, $R^2 = 0.13$ (Figure 2b). However, the negative relationship is enhanced when Si is visually classified in three categories (Figure 2b), plants with Si < 10, presented a mean DifS > 0, suggesting either a neutral or even a beneficial fire effect. On the other hand, plants with Si > 20 showed a reduction of Si ≈ −10, indicating a reduction of sprouts after fire. This pattern varies according to species, *A. gilliesii* displayed $R^2 = 0.33$, with $\beta = -0.77$, while *C. ehrenbergiana* and *S. bumelioides* showed negative trend, but with a smaller magnitude of β.

Table 3. Fire effects on plant structure, assessed by differences before and after the fire in sprout number (DifS) and plant canopy volume (DifV) of *Acacia gilliessi*, *Celtis ehrenbergiana*, and *Schinus bumelioides*. "Francisco Cantos" Experimental Ranch, Santiago del Estero, Argentina.

Source of variation	DifS	DifV
	$P < F =$	
Treatments		
Year	0.28	0.04
Burn date	0.33	0.22
Species	0.0129	0.0745
Fine fuel load	0.14	0.2
Year*species	0.045	0.89
Species*fine fuel load	0.48	0.6
Covariables		
Flame length (m)[1]	0.77	0.58
Prefire sprout number[1]	0.007	0.12
Prefire volume (m^3)[1]	0.95	<0.0001
W (woody residues)[1]	0.15	0.018

[1]Covariables.

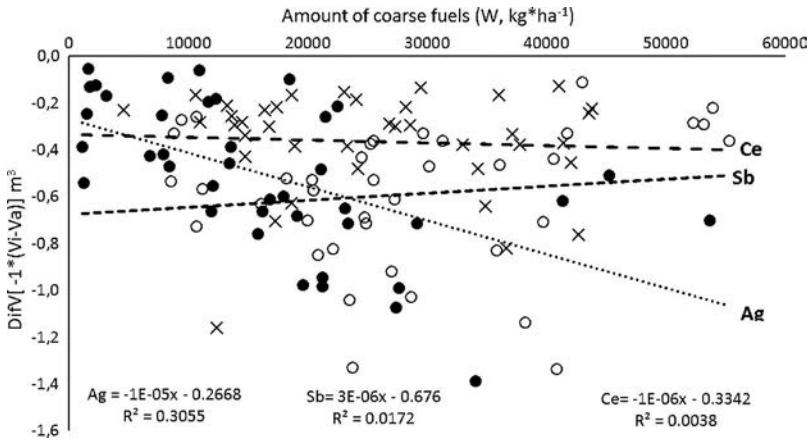

Figure 3. Effect and trend of amount of fuel (W, less than 2 cm of diameter) on canopy volume reduction (DifV, m^3) of three native shrub species of the Chaco region, Argentina, observed one growth season after the fire. Markers: Ag and full circles: *Acacia gilliessi*; Sb and empty circles: *Schinus bumelioides*; Ce and crosses: *Celtis ehrenbergiana*.

Year only influenced DifV ($p = 0.04$), mean DifV was −0.32 in 2009 versus −0.21 in 2008 (Table 3). Species affected mean DifS, ($p = 0.0129$) and DifV ($p = 0.0745$). The interaction year*species also affected DifS ($p = 0.045$). Mean DifS was lowest in 2008 (−1.28) than in 2009 (0.46).

Covariable W affected DifV ($p = 0.018$) and to a lesser extent DifS ($p = 0.15$). The effect of W was significant in *A. gilliessi* (Figure 3). The sign of the relationship was negative in both cases. Si significantly influenced DifS ($p < F = 0.007$) while Vi significantly influenced DifV ($p < F < 0.0001$, Table 3). These results agree with the analysis of structural relationships prefire and postfire by classes.

Discussion

In our experiment, fires were characterized as very intensive according to the observed flame lengths. They were within the range reported in range fires in the Chaco and other semiarid areas (Trollope 1984; Kunst et al. 2001, 2012). Differences in fire intensities between years were likely due to the low amount of rain in the previous rainfall season, and the resulting low air relative humidity and fuel moisture during the next fire season (Bravo et al. 2014). The interactions year*burn date and fuel load*burn date contradict the observation of Kunst et al. (2001) that fires at the early time may show lower intensity (low flame length) than those lit at the late time, because of high air relative humidity and fuel moisture. There was a difference in mean wind speed between years (Table 1), a fact that may have also a stronger influence on fire behavior than the fuel moisture in grass fuels, as suggested by Cheney and Sullivan (2008).

The large amounts of W registered in this study agree with reports in the literature, where mechanical treatments are used previously to other practices of brush control and fuel reduction (Bossard and Rejmanek 1994, Paynter and Flanagan 2004, Kreye et al. 2014). W likely increased the heat released, and positively influenced tt, an indicator of fire residence time, suggesting a potential increase of smoldering and fire severity (Kreye et al.

2014). The large Tf magnitudes observed also indicate longer residence times and confirm the high fire severity (Keeley 2009).

The height and volume reached by the plants after the mechanical treatment agree with the magnitude of the growth reported in the literature for species of *Acacia* and *Celtis* (Wright and Bailey 1982; Casillo, Kunst, and Ledesma 2006). Mean DifV and DifS were significantly less than, or near zero in all species, indicating a strong negative fire effect on plant structure. As suggested by the magnitude of the differences of the mean DifV and DifS among species, *A. gilliesi* was more susceptible to fire than *S. bumelioides* and *C. ehrenbergiana*. The probable cause of these differences is an intrinsic feature as well as the plant phenological status at the burn date. The amount of carbohydrates reserves in roots and crowns, a crucial physiological condition is a key issue, sprouting should be least vigorous when carbohydrate reserves are the lowest, near regrowth (Robbins and Myers 1993). The effect of the fire on mean DifV was significantly greater in October than in July for *A. gilliessi* and *S. bumelioides*. In the Chaco region the late burn date coincides with the spring rains, the onset of the annual cycle of growth. Probably, *A. gilliessi* likely began the transport of the reserves up, toward flowers and leaves, leaving roots, and crown with a low carbohydrate concentration. Therefore, fire had a more severe impact on its sprouting ability. In the late timing (October), weather conditions were drier than in the early time (July), thereby the impact of the fire was more severe on the shrub volume. There was no significant effect of timing of burn on DifV for *C. ehrenbergiana*. Individuals of this species were senescent at both burn times (July and October). Probably, the root and crown content of carbohydrates was high at the timing of burn, and the plants could sprout and grow readily after the burns. This species also presented the largest bud bank, as indicated by the positive magnitude of Si.

The negative relationships of DifV and DifS with Vi and Si in the three species, respectively, suggest that the plants may lose the ability to stand fire as their age increases, i.e., loose its ability to regrowth (Malanson and Trabaud 1988; Hodgkinson 1998; Robertson and Hmielowski 2014). Gurvich et al. (2005) reported this effect for Chaco native species. This result contradicts information in the literature reporting that small sized or younger plants are more sensible to fire (Wright and Bailey 1982). Probably, the latter information refers to mortality rather than to structural changes. In this study, Vi and Si were heterogeneous among the selected species, i.e., *C. ehrenbergiana* has the highest Si and lowest Vi, in *S. bumeloides* was the opposite and in *A. gilliesi* was intermediate. In future research, it would be appropriate to evaluate fire effects on shrubs with a high shoot number and high canopy volume combined.

A. gilliesii showed the most negative changes in size (DifV) and sprout numbers (DifS) after the burns, confirming the potential of fire to modify plant structure and suggesting that fire hampers the development of this species. Barchuk et al. (2006) reported that this species does not tolerate well the removal of apical buds by any disturbance. *A. gilliesii* is common in the upland ecological sites of the Chaco, where fire frequency is estimated to be lower than in the lowland sites, owing to the paucity of fine fuel load (Bravo, Kunst, and Grau 2008). On the other hand, although fire reduced the size of *C. ehrenbergiana*, it seemed to stimulate its resprouting ability and new growth, suggesting a large bud bank and confirming its high fire tolerance. *S. bumelioides* reaction was intermediate between the other two species.

The mean prefire Si of *C. ehrenbergiana*, larger than that of the other two species, suggests that this species is rather well prepared to face disturbances such as fire, in comparison with *A. gilliesii*. Timing of fire also influenced plant features, although its effect was somewhat obscured by the effect of W. The early date and the low fine fuel load presented the smallest DifS and DifV, suggesting that a fire in that time of the year and with a fine fuel load ≈5000 kg ha^{-1} would not have a large impact on the shrub community other than reducing plant size.

The high wood density of the native Chaco species, a property that makes them very useful as firewood (Bravo, Kunst, and Grau 2008) likely enhanced fire effects on the ecosystem, especially in *A. gilliesii. S. bumelioides*, belonging to the family *Anacardiaceae*, also has a high content of oils, phenols, and other chemical components that increase fuel flammability (Kunst et al. 2012). These characteristics give high flammability to the plant and high tolerance to fire.

Our first hypothesis, related to differences in fire effect among species, was accepted. *A. gilliesi* was the most affected species, while *S. bumelioides* was the less, respectively. Differences could be attributed to their physiology, structure, and other characteristics, such as bud-bank. Our second hypothesis is that plant size (≈volume) influences fire effects, and this study suggests that the larger the plant size in the three species studied, the larger the fire effect, reducing post fire volume, and resprouting ability.

Further hypothesis refers to the fire environment during the burn, a fact that permits to select a timing of fire within a specific year. Results indicate that both year and burn date significantly influenced fire behavior (e.g., flame length), but effects on the structure of shrub species were no detected. The intrinsic features of the species and plants (e.g., size, bud bank) were more important in determining fire effects. The influence of amount of fine fuel load on the structural features of the plants was marginal. Trollope (1984) reported that the minimum fuel load threshold required to achieve an acceptable shrub topkill is 2000 kg DM ha^{-1}, a quantity largely exceeded by the total fuel load in this experiment. This fact probably overrun all other fire effects.

Conclusion and management implications, prescription for shrub control

Despite of the nuisance caused to livestock operations, shrub species bring ecosystems services (e.g., nutrient inputs, water retention, habitat and food for wildlife, and protection from soil erosion) and valuable goods as firewood and forage (Peterson and Reich 2001; Lohmann et al. 2014). Therefore, "brush encroachment" cannot be considered a synonym of "land degradation" and control should be carefully planned (Eldridge et al. 2011; Archer and Predick 2014).

Which factors could be managed to achieve success in brush control in the Chaco region? Should prescribed fire be used? Paddocks should be roller-chopper before fire? Translated into a "prescription", prescribed fire should consider objectives, thresholds of fire intensities and severity as related to the likelihood of an escape; and ecological and production concerns. Other aspects to be taken into consideration in a prescribed burn, according to the literature are, (a) from a fire standpoint, fire behavior and amount of fuel; (b) from a point of view of vegetation management, timing of burn, species concerned, and features such as prefire plant size.

Fire effects varied among species, a fact that should be carefully considered. *S. bumelioides* and *C. ehrenbergiana* were somewhat indifferent while *A. gilliessi* was strongly affected by fire. Results indicate that fire should be applied on "old" plants to get results in volume. The reduction in number of sprouts was less marked.

It must be clear that there are not 100% effective methods for shrub control. Neither the roller chopping nor the burn produce a full plant death. The general objective of the burn should be to change structural features of the shrub species, i.e., to reduce volume and sprout number, to get a better accessibility for grazing rather than achieving full plant death. Therefore, we have to apply a management and not an eradication approach. A reduction of the shrub canopy volume by 50–70% should be considered a successful control. The "mechanism" of control of a shrub community by burning is complex, fire is a top-to-bottom disturbance, that "topkills" young individuals (Hoffmann and Solbrig 2003). Thus, fire may create a "bottleneck" in population structure by limiting recruitment of the small sized individuals into larger size classes, and reducing the potential of competition for resources such as sunlight (Hoffmann and Solbrig 2003; Wright and Clarke 2007; Robertson and Hmielowski 2014).

The specific use of fire in rangeland management sometimes could not be avoided, since it has beneficial effects in pasture quality and soil nutrients (Wright and Bailey 1982). Despite of the generation of woody residues, a fact that can be considered a setback, the mechanical disturbance is necessary to create fine fuel to allow fire spread. The sequential mechanical treatment-fire produced changes in the shrub structure suitable for livestock management, such as a significant reduction of canopy volume. In paddocks where the shrub canopy volume is high, (more than 1.2 m^3 per plant) and there are trees and shrubs with thick shoots (more than 5–7 cm diameter), rolling chopping should be applied taking into account guidelines such as, do not crush individuals with a main trunk diameter greater than 5 cm and/or remove woody residues (after mechanical treatment) with diameter more than 7 cm (1000 h fuels).

Although wind had a strong effect on fire intensity, information gathered in this research let us to conclude that in the Chaco region, fire behavior (intensity and severity) depend mainly on the amount of fine and coarse fuel rather than the weather environment of the burn. These aspects can be managed by the operator, wind speed could be predicted and the amount of fuel could be managed either by rest, or by grazing. In any case, the threshold (2000 kg DM ha^{-1}) suggested by Trollope (1984) should be reached before using prescribed fire.

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