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Article *in* Rangeland Ecology & Management · September 2016

DOI: 10.1016/j.rama.2016.08.003

Roberto J. Fernández
University of Buenos Aires

Esteban Jobbágy
National Scientific and Technical Research C…

Rangeland Ecology & Management 70 (2017) 225–229

Contents lists available at ScienceDirect

Rangeland Ecology & Management

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

Soil Physical Changes After Conversion of Woodlands to Pastures in Dry Chaco Rangelands (Argentina)☆

Patricio N. Magliano [a,*], Roberto J. Fernández [b], Eva L. Florio [a], Francisco Murray [a,c], Esteban G. Jobbágy [a]

[a] Grupo de Estudios Ambientales–IMASL, Universidad Nacional de San Luis and CONICET, D5700HHW, San Luis, Argentina
[b] IFEVA, Universidad de Buenos Aires, CONICET, Facultad de Agronomía, C1417DSE Buenos Aires, Argentina
[c] INTA, UEyDT San Luis, San Luis, Argentina

ARTICLE INFO

Article history:
Received 11 December 2015
Received in revised form 4 August 2016
Accepted 9 August 2016

Key Words:
Arid Chaco
deforestation
ecohydrology
land use/land cover change
water balance

ABSTRACT

The conversion of dry woody rangelands into pastures can alter key soil physical properties that regulate ecosystem water circulation and storage. Based on three paired stands of native woodlands and pastures established 20 years ago in the southern Dry Chaco (San Luis, Argentina), we described contrasts in five soil physical properties using a systematic sampling of soil patches (9 − 18 patches along a single transect within each of the three paired 1-ha stands). Compared with woodlands, pastures displayed flatter microtopography (mean ± standard deviation [SD]: 3.7 ± 0.34 vs. 5.0 ± 0.67% slope; $P < 0.05$), lower infiltration rate (mean ± SD: 71.6 ± 9.0 vs. 139.9 ± 37.2 mm h^{-1}; $P < 0.05$), and higher penetration resistance (mean ± SD: 4.2 ± 0.10 vs. 1.9 ± 0.17 kg cm^{-2}; $P < 0.01$) and bulk density (mean ± SD: 1.39 ± 0.05 vs. 1.16 ± 0.04 g cm^{-3}; $P < 0.0001$). On average, topsoil water content at field capacity was similar for both types of cover (mean ± SD: 16.3 ± 0.21 vs. 17.1 ± 1.12%, pastures and woodlands, respectively; $P = 0.29$). However, at similar bulk density values, pastures presented a ~20% reduction in volumetric water content at field capacity (16.3%) compared with woodlands (19.7%). The establishment of pastures led to more homogenous soils, with most variables having reduced spatial variability in comparison with woodlands. Our observations showed how the conversion of native woodlands to pastures produced strong physical changes in the soils of Dry Chaco and help to understand the mechanisms that are most likely influencing the surface-soil water dynamics of these, and perhaps other, dry rangelands.

Introduction

The replacement of native vegetation by planted pastures, aimed at increasing livestock production, takes place in many rangelands, particularly those dominated by woody plants (Breman and de Wit, 1983; Eberbach, 2003; Bestelmeyer et al., 2015). Although such conversion can reduce ecosystem net primary productivity (NPP), the increment in the fraction of NPP allocated aboveground and to high-quality and accessible forage for livestock typically raises the stocking capacity of the transformed ecosystem, at least in the near term (Blanco et al., 2005; Scott et al., 2006; Don et al., 2011; Marchesini et al., 2015). The removal of woody vegetation and the establishment of planted grasses not only involves a drastic vegetation shift but also an intensification of grazing and trampling plus the mechanical disturbances of soil preparation (Eberbach, 2003; Nyssen et al., 2004; Foley et al., 2005; Destain et al., 2016). By altering soil physical properties, these three factors (vegetation shifts, intensified livestock activity, and soil cultivation) can influence water circulation and storage, limiting long-term forage production (Breshears and Barnes, 1999; Piñeiro et al., 2010; Arnhold et al., 2015).

While machinery transit and livestock trampling after the establishment of pastures can compact soils and reduce their potential for water infiltration, the establishment of densely rooted grasses can have the opposite effect (Nyssen et al., 2004; Piñeiro et al., 2010; Wang et al., 2010; Don et al., 2011). Considering the high spatial heterogeneity of dry ecosystems, the outcome of these contrasting effects on soil physical properties and water cycling can be better assessed at the patch scale (Wilcox et al., 2003; Ludwig et al., 2005; Bisigato et al., 2009; Caldwell et al., 2012). The replacement of a patchy woody cover by a more homogeneous herbaceous one, combined with a more evenly and widespread distribution of animal transit, can reduce the high heterogeneity of rangelands (Kleb and Wilson, 1997; Bird et al., 2002; Muñoz-Robles et al., 2011; Magliano et al., 2015c); this, in turn, can affect water fluxes through increased net runoff, reduced surface water redistribution, and altered evaporation and transpiration partitioning (Bhark and Small, 2003; Bradshaw et al., 2007; Newman et al., 2010).

☆ This work was funded by the University of Buenos Aires (UBACyT 20020100100736), ANPCyT-Argentina (PICT 2014-2790), International Development Research Center (IDRC, Canada 106601-001), and Inter-American Institute for Global Change Research (IAI, SGP-CRA 2031, and CRN 3095), in turn supported by the US National Science Foundation (Grant GEO-0452325).

* Correspondence: Patricio N. Magliano, Grupo de Estudios Ambientales–IMASL, Universidad Nacional de San Luis and CONICET, D5700HHW, San Luis, Argentina. Tel.: +54-266-4520325; fax: +54-266-4422803
E-mail address: pnmagliano@gmail.com (P.N. Magliano).
URL: http://gea.unsl.edu.ar (P.N. Magliano).

http://dx.doi.org/10.1016/j.rama.2016.08.003
1550-7424/

The South American Dry Chaco, covering ~1 million km^2, is one of Earth's largest semiarid woodland-dominated rangelands, and is rapidly being converted to pastures and croplands (Baldi and Jobbágy, 2012; Le Polain De Waroux et al., 2016). In the past 30 years, the Dry Chaco has undergone a massive contraction of native woodlands, with estimated losses of 2.2% of the remnant vegetation per year, which exceeds global trends (Zak et al., 2004; Gasparri and Grau, 2009). In this paper we explore the effect of replacement of native dry woodlands by planted pastures on soil physical properties in southern Dry Chaco (San Luis, Argentina). More specifically, we characterize changes in microtopography, soil density and compaction, and water infiltration and storage capacities in three paired stands occupied by native woodlands and pastures planted 20 years prior to our sampling, both subject to the cattle grazing typical in these rangelands.

Material and Methods

The study was conducted during the spring-summer austral season of 2014 − 2015 in the southern edge of the Dry Chaco (Arid Chaco), in the province of San Luis in Argentina (33.5°S, 66.5°W). We worked on ranches originally covered by 7-m high woody canopies dominated by *Prosopis flexuosa* and *Aspidosperma quebracho-blanco* trees and *Larrea divaricata* shrubs. Landscape slope is < 1.5%. Soils are derived from Quaternary fine loess and, to a lesser extent, alluvial sediments (Pennington et al., 2000; Tripaldi et al., 2013). They are Typic Torriorthents with 53% sand, 15% clay, and 1.4% organic matter in the upper 10 cm of the profile (Peña Zubiate et al., 1998). Mean annual rainfall is 430 mm, concentrated in the spring-summer season (Magliano et al., 2015b). A large fraction of woodlands (~30%) has been converted to pastures by traditional deforestation or roller-chopping over the past 30 years (Boletta et al., 2006; Hoyos et al., 2013; Steinaker et al., 2016), raising cattle stocking rates from 0.05 to 0.2 animal units per ha (Ser Beef S.A., personal communication). We focused on *Cenchrus ciliaris* pastures (2012 − present), which formerly were *Eragrostis curvula* pastures (1995 − 2012), and woodlands before then. Pastures composed of these two species of grasses are common in the study region (Blanco et al., 2005; Carranza et al., 2012).

We worked on three paired stands (~1 ha each) covered by native woodlands and planted pastures. These stands presented similar soil texture, meteorological conditions, and land use history before 1995 (Peña Zubiate et al., 1998; Marchesini, 2011). Within each stand, we measured microtopography, infiltration rate, surface penetration resistance, bulk density (0 − 10 cm), and water content at field capacity (0 − 10 cm). Measurements were located along transects (one transect per stand). Each transect origin was randomly located, and three different orientations were set (west-east, southwest-northeast, and south-north) to avoid any directional topographic bias. Within each transect we performed a systematic sampling, using 2-m regularly spaced patches of 50 × 50 cm each. Due to the labor-intensive requirements for determinations of infiltration rate, bulk density, and water content at field capacity, and given their known spatial homogeneity (Marchesini, 2011), $n = 18$ patches per transect were measured in woodlands (36 m long) but only $n = 9$ patches per transect in pastures (18 m long).

Microtopography was determined by measuring height differences between the center of each patch and its four neighboring patches (situated 0.5 m away in the N, S, E, and W directions), using a Ziplevel Pro-2000 altimeter, with a 2-mm resolution (Technidea, Escondido, CA). In order to obtain a single value for each patch, we averaged these four values and converted altimetry units to degree units, by dividing the height difference by the distance to the center of neighboring patches (0.5 m). Infiltration rate was determined with the double-ring method at each patch (Eijkelkamp, Giesbeek, Netherlands); we report the infiltration rate value at saturated flux, a measure independent of prior soil water content (Wilson and Luxmoore, 1988). Penetration resistance is an easy to measure soil property, sensitive to vegetation changes. In this study we measured and averaged values from five randomly located points within each patch using an analogical penetrometer (Eijkelkamp, Netherlands); these are reported at dry soil conditions (soil water content = 5 − 7%) (Hillel, 1998; Zou et al., 2000). Bulk density and volumetric water content at field capacity (0 − 10 cm) were determined using the same field samples. For this purpose, we irrigated each patch with ~50 mm of water, immediately covering it with nylon film in order to avoid evaporation. Twenty-four hr later, we took bulk density samples from the upper 10 cm using the cylinder method (Hillel 1998; Grossman and Reinsch, 2002) and determined bulk density values in the laboratory by dividing the dry soil weight (drying for 72 hr at 105°) by the volume of the cylinder. We estimated the initial water content of each field sample as the water content at field capacity.

Differences in the five studied soil physical properties between woodland and pasture stands were assessed by analysis of variance (ANOVA) for a completely randomized design ($n = 3$). In addition, we constructed whisker plots to display the internal variability of each cover type; in this case we presented pooled data. All associations between paired soil variables were determined by simple linear regressions. In the case of penetration resistance data, we also assessed differences between vegetated and bare soil patches with ANOVA. For both cover types (woodland, pasture), "bare soil patches" were defined as those without vegetation and soil litter on the surface ($n = 10$), while "vegetated patches" were those presenting at least one grass individual in pastures and grass, shrub, tree or litter on the surface in woodlands ($n = 10$). Analyses were performed using R v.2.15 statistical software ("lm" function, package MASS) (www.r-project.org).

Results

Compared with native woodlands, pastures had a smoother surface and hosted harder and denser soils with lower infiltration rates but similar water storage capacities (Table 1). Soil physical properties of pastures displayed a general reduction in variability at the patch scale compared with woodlands (Fig. 1). Microtopography of pastures, in spite of its reduction with respect to the original woodlands, still displayed a larger slope (1.9%−6%) than the one at the landscape scale (< 1.5%), suggesting that horizontal surface water transport could remain restricted to the patch scale (Fig. 1A). Infiltration capacity under pasture was half of that observed in woodlands and also showed a reduction in variability; in particular, the high infiltration patches (> 100 mm hr^{-1}) found in woodlands were absent in pastures (Fig. 1B). While penetration resistance was doubled under the pasture compared with woodlands (Fig. 1C), both cover types showed a lower resistance where vegetation was present. Comparing vegetated versus bare soil patches, penetration resistance was 1.41 versus 2.41 kg cm^{-2} ($P < 0.01$) in woodlands and 2.88 versus 5.28 kg cm^{-2} ($P < 0.0001$) in pastures (Fig. S1). Pasture soils had higher and more homogeneous bulk density than woodland soils (Fig. 1D). The large gradient of bulk density values found in woodlands was negatively correlated with infiltration rate ($r = -0.43$; $P < 0.01$) and positively correlated with penetration resistance ($r = 0.62$; $P < 0.0001$). Water content at field capacity was similar for both cover types, but woodlands presented higher variability (Fig. 1E).

Table 1
Soil physical properties measured in woodland and pasture stands in southern Dry Chaco rangelands (province of San Luis, Argentina). Each value represents the mean and its spatial standard deviation ($n = 3$); *P values* are for statistical differences between vegetation types

	Woodland	Pasture	*P value*
Microtopography (% slope)	5.0 ± 0.67	3.7 ± 0.34	*< 0.05*
Infiltration rate (mm h^{-1})	139.9 ± 37.2	71.6 ± 9.00	*< 0.05*
Penetration resistance (kg cm^{-2})	1.9 ± 0.17	4.2 ± 0.10	*< 0.01*
Bulk density 0 − 10 cm (g cm^{-3})	1.16 ± 0.04	1.39 ± 0.05	*< 0.0001*
Water content at field capacity 0 − 10 cm (% volume)	17.1 ± 1.12	16.3 ± 0.21	*0.29*

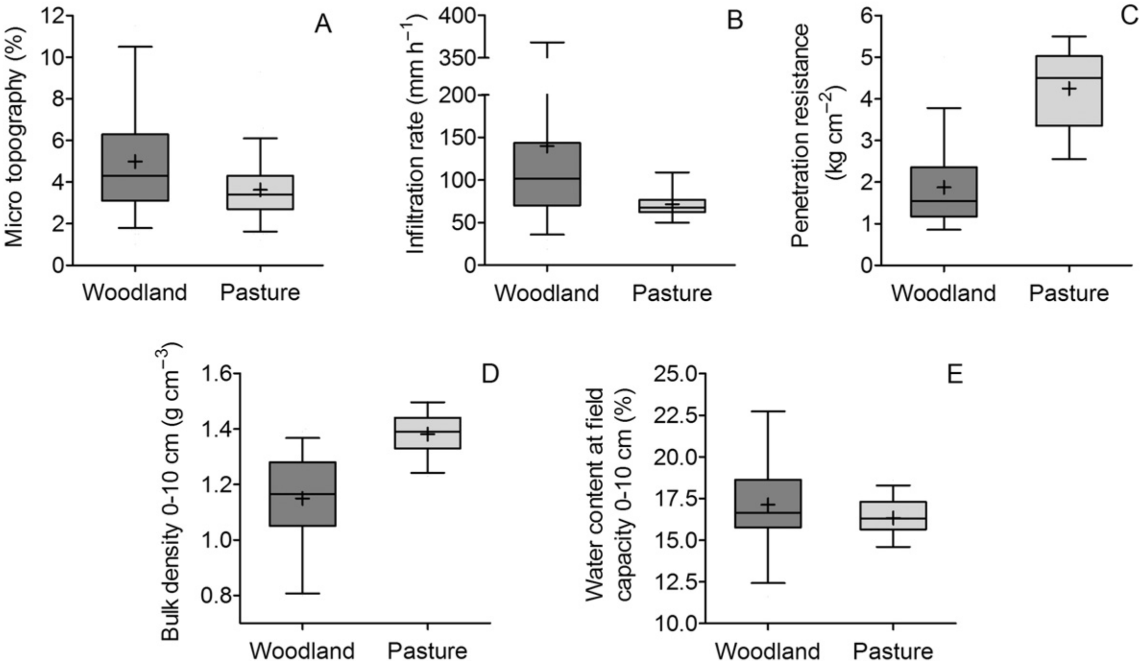

Figure 1. Soil physical properties measured in woodland and pasture stands in Dry Chaco rangelands. **A,** Microtopography, **B,** infiltration rate, **C,** penetration resistance, **D,** bulk density at 0 − 10 cm, and **E,** water content at field capacity at 0 − 10 cm. $n = 54$ (3 stands × 18 patches), except for pastures in **B, D,** and **E,** where $n = 27$ (3 stands × 9 patches). Whisker plots show percentile 95, first quartile, median, third quartile, and percentile 5 values; the *cross* represents the mean value.

Although water content at field capacity (0 − 10 cm) was the only soil variable that showed similar mean values for pastures and woodlands (see Table 1; see Fig. 1E), an important difference between both cover types emerged when this variable was examined as a function of bulk density (Fig. 2). We found a positive linear relationship between water content at field capacity and bulk density across the range that this variable displayed in woodlands ($y = 11.33\ x + 3.99$; $R^2 = 0.37$; $P < 0.0001$) (Fig. 2A). This means that, under the higher and less variable bulk density values of pastures, water content at field capacity was lower than what could have been expected on the basis of the relationship developed for the woodland (16.3% vs. 19.7%, for pasture and woodland, respectively) (Fig. 2B). Thus, at similar bulk density values, pastures presented a reduction of ~20% of water content at field capacity with respect to woodlands.

Discussion

The conversion of woodlands to pastures, aimed to increase livestock production, generated strong physical changes in the soils of the Dry Chaco rangelands studied here. The establishment of pastures flattened the surface and compacted the soil, decreasing its infiltration capacity and increasing its penetration resistance, while maintaining its water storage capacity. Overall, a general homogenization of soil physical properties was observed.

Soil compaction and surface smoothing after land use change suggest the detrimental effects of animal trampling and machinery transit are dominant over the potentially positive influence of denser grass roots (De Baets et al., 2007; Kyle et al., 2007). Although different degrees of soil compaction were found within the woodlands at the patch scale, compaction in the pasture was more widespread and led to a reduction in water holding capacity in comparison with woodland at similar bulk density values (Fig. 2). This can be explained by the likely destruction of soil aggregates (Horn et al., 1995; Håkansson and Lipiec, 2000) and associated reduction of macroporosity (pores that cannot store gravimetric water) but also of mesoporosity (pores that do store gravimetric water) (Hillel, 1998; Reichert et al., 2009).

The soil physical changes observed here, in addition to a lower transpiration capacity of pasture vegetation (Schlesinger and Jasechko,

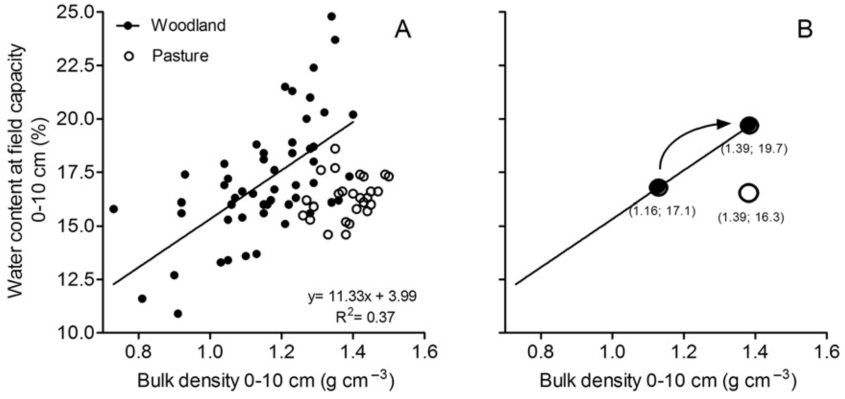

Figure 2. Water content at field capacity as a function of bulk density in the upper 10 cm of woodland *(black circles)* and pasture *(open circles)* soils of Dry Chaco rangelands. **A,** Equation and coefficient of correlation correspond to woodland ($y = 11.33\ x + 3.99$; $R^2 = 0.37$; $P < 0.0001$). **B,** Woodland and pasture mean data; *arrow* indicates the woodland water content at field capacity value obtained by replacing pasture bulk density mean value in the equation shown in **A.**

2014; Marchesini et al., 2015), could explain some of the ecohydrological shifts observed in the study region following woody vegetation replacement (Santoni et al., 2010; Nosetto et al., 2012; Amdan et al., 2013; Giménez et al., 2015; Magliano et al., 2016). The flatter microtopography found in pastures (see Table 1, Fig. 1) could explain the reductions of surface water redistribution at the patch scale found in the study area (Magliano et al., 2015a), which has also been observed in similar systems (Ludwig et al., 2005; Newman et al., 2010; Villegas et al., 2010). The reduction of infiltration rate in pastures could explain the increased net runoff losses at the stand scale found in many rangelands that underwent similar vegetation replacement (Devine et al., 1998; Reid et al., 1999; Turnbull et al., 2013).

Our results highlight the underlying soil physical mechanisms that potentially explain water flux alterations reported for many systems in which woody vegetation has been removed (Newman et al., 2006; Bradshaw et al., 2007; Marchesini et al., 2015). In addition, these observations support the need for long-term monitoring of both soil physical properties and water fluxes, which is urgent in rangeland areas like Dry Chaco, which depend on the conversion of woodlands to pastures for increased livestock production.

Management Implications

Although the replacement of woodlands by pastures in the Dry Chaco allows a fourfold increase of stocking rates, it is accompanied by the reduction of surface soil variability at the patch scale and an overall decline of water infiltration capacity. On the basis of our results, we propose to periodically measure infiltration rate, penetration resistance, and/or bulk density in those areas where native woody vegetation was replaced. These will help to detect incipient undesirable biophysical soil changes, such as soil compaction or loss infiltration capacity, which could alter the water balance of the region.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.rama.2016.08.003.

Acknowledgments

We are grateful to Ser Beef S.A. (especially Martin Ibarra, Alejandro Sánchez, and Nicolás Ríos Centeno) and Yeye Darvich for providing access to their ranches. Ricardo Páez and Raúl Giménez provided able and enthusiastic field assistance. We thank the REM editorial board and anonymous reviewers for greatly improving this manuscript.

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