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Effects of long-term grazing disturbance on the belowground storage of organic carbon in the Patagonian Monte, Argentina

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ABSTRACT

The objective of this study was to analyze the effect of grazing disturbance on the amount and the spatial distribution (vertical and horizontal) of root biomass and soil organic carbon (SOC) in order to evaluate whether grazing alters the belowground storage of organic carbon (C) in arid rangelands of the Patagonian Monte. We selected three representative sites (3 ha each) with low, moderate and high grazing disturbance located far, mid-distance and near the watering point, respectively, in rangelands submitted to sheep grazing for more than 100 years. We assessed the canopy structure and identified the four most frequent plant patch types at each site. We selected four replications of each patch type and extracted a soil sample (0–30 cm depth) underneath the canopy and in the middle of the nearest inter-patch bare soil area in winter and summer. We assessed the root and soil dry mass and the respective organic C concentration in each sample and then we estimated the total belowground organic C storage at each site. Total plant and perennial grass cover were lower with high than low grazing disturbance while the reverse occurred with dwarf shrub cover. High grazing disturbance led to the increase in total root biomass in the whole soil profile of patch areas and in the upper soil of inter-patch areas. SOC was higher in patch than in inter-patch areas at all sites but at both areas was reduced with high grazing disturbance. This was probably the result of the low total plant cover and the low and recalcitrant contribution of above and below-ground plant litter to soils at sites with high grazing disturbance. Accordingly, these changes did not result in variations in the total belowground organic C storage. We concluded that high grazing disturbance did not affect the total belowground organic C storage but led to changes in the spatial patterning of this organic C storage (i.e shifting from soil to roots).

1. Introduction

Soil is the largest storage of terrestrial organic carbon (C) in the biosphere (Lal, 2004a, 2011; Schlesinger, 1997). The total organic C storage is regulated mainly by primary production and decomposition processes which are controlled by biome type, environmental conditions, and management practices (Derner and Schuman, 2007; Zhao et al., 2004). In arid and semiarid ecosystems, these processes are strongly related to the amount and seasonal distribution of precipitation (Reynolds et al., 2004; Sala et al., 1988). Furthermore, low plant cover (<40–60%), the heterogeneous spatial distribution of plants, and the selective grazing by domestic herbivores could also control processes related to the input and output of soil organic carbon (SOC) in these ecosystems (Austin et al., 2004; Costa et al., 2012; Kröpfl et al., 2011). In these heterogeneous environments, the soil associated with plant patches concentrates SOC, microbial activity, and nutrients (Whitford, 2002). Since these arid ecosystems occupy more than 35% of the global land area, they are considered important storages of SOC (Lal, 2004b; Muñoz-Rojas et al., 2012a, 2012b).

In the Patagonian Monte, plant patches are dominated by shrubs and perennial grasses (Ares et al., 1990; Bertiller et al., 1991). Both plant functional groups (*sensu* Körner, 1993) differ in the height of adult plants, leaf lifespan, and rooting depth (Bertiller et al., 1991; Bucci et al., 2009; Rodríguez et al., 2007; Scholz et al., 2012). Shrubs display a wide variation in morphological and functional traits related to defenses against water shortage and herbivory (Bertiller et al., 1991; Moreno et al., 2010). Evergreen tall shrubs usually have long lasting tissues and deep root systems with large accumulations of secondary metabolites, and develop vegetative and reproductive growth coupled with high temperatures, independently from water inputs (Bertiller et al., 1991; Campanella and Bertiller, 2008; Coronato and Bertiller, 1997). Deciduous shrubs usually have structural defenses against water shortage and

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herbivory, dimorphic root system and develop vegetative and reproductive growth during periods with favorable water conditions (Bertiller et al., 1991; Campanella and Bertiller, 2008). Dwarf shrubs with shallow roots have large accumulations of secondary compounds in tissues which not only increase tolerance to water shortage but also provide resistance to herbivores (Grace, 1998). In contrast, perennial grasses are shallow-rooted species with low concentration of secondary compounds in their tissues, and display vegetative growth and reproductive activity coupled with precipitation inputs (Bertiller et al., 1991; Campanella and Bertiller, 2008). Accordingly, changes in the arrangement and abundance of plant species and/or plant functional groups induced by grazing disturbance could affect the contribution of roots and aboveground parts to litter with consequences on SOC (Angassa, 2012; Verlinden and Kruger, 2007).

In the Patagonian Monte, grazing was introduced at the beginning of the last century (Ares et al., 1990) and was typically organized in ranches of about 4 paddocks of 2500 ha each sharing a single permanent watering point. Since then, domestic herbivores have caused environmental impacts on ecosystem structure and function. The most conspicuous effects of long term grazing disturbance are the plant cover reduction and the replacement of perennial grasses by woody plants (Bertiller and Ares, 2011; Bertiller and Bisigato, 1998; Larreguy et al., 2012a). However, this notorious effect of grazing on aboveground cover is not always associated with reductions in the fine root biomass and SOC (Costa et al., 2012; Larreguy et al., 2012a; Milchunas and Lauenroth, 1993; Rodríguez et al., 2007). Some studies reported that grazing disturbance induced changes in the horizontal and vertical distribution of root biomass (Jackson et al., 2000; Schenk and Jackson, 2002), the reduction of SOC, and/or the redistribution of organic C storages from belowground towards plant canopies (Milchunas and Lauenroth, 1993). All of these changes affecting the quantity and distribution of SOC may have consequences on the total belowground organic C storage and biogeochemical cycles (Snyman, 2009; Zhao et al., 2009). These issues have been scarcely explored in grazed ecosystems although they are strongly related to ecosystem functioning. The capacity to predict and ameliorate the consequences of grazing disturbance on ecosystem function and global change depends in part on a better understanding of the distributions and controls of SOC and how vegetation changes (e.g. reduction of plant cover, plant species replacements) may affect the quantity and distribution of roots and SOC, and the total belowground organic C storage (Chapin and Ruess, 2001).

The objective of this study was to assess the total and the vertical and horizontal distribution of root biomass and SOC and quantify the total the belowground organic C storage in rangelands submitted to sheep grazing for more than 100 years in the Patagonian Monte. We hypothesized that the reduction of the total plant cover and the increase in cover of shrubs with shallow rooting depth and high concentration of chemical defenses induced by grazing disturbance lead to (1) increased amount and spatial heterogeneity of root biomass (root concentration underlying plant canopies and in the upper soil), (2) reduced concentration and spatial heterogeneity of SOC, and consequently, (3) little changes in the total belowground storage of organic C (C in root biomass + SOC).

2. Materials and methods

2.1. Study area

The study area is located in the Patagonian Monte. Mean annual temperature is 13 °C and mean annual precipitation is 188 mm (Barros and Rivero, 1982). Soils are a complex of Typic Petrocalcids-Typic Haplocalcids (del Valle, 1998; Soil Survey Staff, 1998) and vegetation is representative of the shrubland of *Larrea divaricata* Cav. and *Stipa* spp., characteristic of the southern portion of the Monte Phytogeographic Province, Argentina (León et al., 1998). Plant cover has a patchy structure dominated by shrubs and perennial grasses (Bisigato and Bertiller, 1997). The typical organization of ranches in paddocks led to the formation of extended piospheres of more than 1500 m around watering points where the spatial pattern and traits of plant species, and upper soil properties are modified by the frequent visit of grazers (Ares et al., 2003; Bertiller and Ares, 2011; Bisigato and Bertiller, 1997; Carrera et al., 2008; Larreguy et al., 2012b; Prieto et al., 2011; Bär Lamas et al., 2013). This study was conducted in La Esperanza wildlife refuge (42° 12′ 13.7″S, 64° 58′ 55.6″W; 92 m a.s.l.) of about 6.000 ha submitted to sheep grazing with a stoking rate of 0.11–0.14 sheep ha^{-1} since the beginning of the last century up to the year 2003 when this area was converted to a wildlife refuge and the stocking rate was gradually reduced (0.01 sheep ha^{-1} per year). In 2008, all domestic herbivores were removed.

Within La Esperanza, we identified an extended piosphere of about 2500 ha in which the site near the watering point had higher faeces count and plant and soil indicators of grazing disturbance than that far the watering point (Bär Lamas et al., 2013). In this piosphere, we delimited three sites (3 ha each, minimal area *sensu* Mueller-Dombois and Ellenberg, 1974) with low, moderate and high grazing disturbance located at far, mid, and near distances from the single permanent watering point, respectively (Ares et al., 2003; Bertiller and Ares, 2011). These sites were separated at least 1500 m from each other.

2.2. Climatic conditions in the study area

We registered the mean monthly air temperature and the daily precipitation with an automatic data recorder (21X Micrologger, Campbell Scientific) during the period March 2010–February 2011 located at the site with moderate grazing disturbance (42° 12′ 27.8″S, 64° 59′ 34.5″W; 94 m a.s.l.).

2.3. Canopy structure

Total and species plant cover were assessed at four randomly located 25-m linear transects by the line intercept method (Mueller-Dombois and Ellenberg, 1974) at each site (low, moderate and high grazing disturbance) in autumn 2010. We further assigned each species to one of the following plant functional groups: evergreen tall shrubs (ETS), shrubs more than 30 cm tall with evergreen leaves; deciduous shrubs (DES) shrubs more than 30 cm tall with drought deciduous leaves; dwarf shrubs (DS), shrubs less than 30 cm tall; and perennial grasses (PG) (Supplementary data Table 1). Perennial herbs (i.e. plants with leaves and aboveground stems dying at the end of the growing season but underground stems laying dormant until the next growing season) and annuals were present with a very low cover (<0.01%) at all sites and they were not included in the analysis. Additionally, at each transect, we assessed the number, the area, the height and the plant functional group composition of each intercepted patch (Mueller-Dombois and Ellenberg, 1974). These attributes were used to identify the 4 most frequent patch types at each site (Larreguy et al., 2012b). Plant patches were defined as discrete units of the spatial pattern of vegetation surrounded by bare soil, at least 20 cm from the nearest neighbor patch (Bisigato and Bertiller, 1997).

2.4. Soil sampling

Sampling was carried out in two contrasting seasons: winter 2010 and summer 2011. We randomly selected 4 plant patches of