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Are there any trade-offs between forage provision and the ecosystem service of C and N storage in arid rangelands?

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ABSTRACT

Changes in land use often increase the provisioning ecosystem services at the cost of decreasing the regulating services. Thus, the appropriation of primary production to optimize the supply of forage for livestock production may undermine C and N storage, essential to maintain the integrity of ecological systems and the biosphere. The aim of this work was to study this trade-off by estimating the effect of grazing intensity on two provisioning and regulating ecosystem services (forage supply and C and N storage, respectively) in a 300 km^2 Patagonian steppe. In areas with different historical sheep grazing regime (intensive, moderate and ungrazed), we estimated forage supply through the aboveground biomass of preferentially consumed species as well as total C and N storage in plants, through forage and non-forage aboveground biomass, litter and root biomass in the top 20 cm of soil. We found that forage supply and C and N storage were highest in moderately grazed areas and were positively correlated, indicating the absence of trade-offs between them. Grazing exclusion had no effect on total plant C and N, but decreased these stocks in green grass biomass in relation to moderate grazing. Intensive grazing decreased both provisioning and regulating services, markedly diminishing grass C and N stocks and grass forage compared to other conditions. Conversely, shrubs and roots were not influenced by grazing regime. This study provides evidence that in arid rangelands, an adequate grazing management could be a key control to complementarily maximize both provisioning and regulating ecosystem services.

1. Introduction

Change in land use is one of the major factors affecting terrestrial ecosystem structure (e.g., species composition, C and N stocks), functioning (i.e., community dynamics, primary productivity, decomposition), and ecological services provision (Sala et al., 2000; Millennium Ecosystem Assessment, 2005). The main environmental challenge is to sustain the capacity of ecosystems to provide goods and services meeting current and future human needs (DeFries et al., 2004; Millennium Ecosystem Assessment, 2005; Foley et al., 2005). Several authors stressed that in many ecosystems, trade-offs between regulation and provision ecosystem services are inevitable (DeFries et al., 2004; Millennium Ecosystem Assessment, 2005; Foley et al., 2005; Rodriguez et al., 2006; Bennett et al., 2009; Power, 2010; Raudsepp-Hearne et al., 2010). For example, increasing crop production (provisioning service) occurs at the expense of losses of regulation services such as carbon sequestration capacity and/or water quality regulation (Foley et al., 2005). In general, in rangeland ecosystems those trade-offs have not been thoroughly evaluated (but see Sala and Paruelo, 1997; Havstad et al., 2007) despite the generalized idea that domestic grazing promotes degradation and desertification (Ares et al., 2003; Reynolds et al., 2007).

In rangelands, the main provisioning service is forage supply for livestock production (kg dry matter ha^{-1} yr^{-1}) and the main regulating service is C sequestration and storage (kg C ha^{-1}) (Havstad et al., 2007; Yahdjian et al., 2015). Forage provision is the fraction of aboveground biomass that can be consumed by domestic herbivores, which in arid rangelands represents a small fraction of primary production (Golluscio et al., 1998; Oesterheld et al., 1999). In these lands, animal husbandry is an important activity in terms of cultural heritage, and grazing management reduces social impacts in comparison with other land uses (e.g., crop production, afforestation) (Havstad et al., 2007). Furthermore, rangelands represent a vast storage of C, both in soils and vegetation, containing 20–25% of the global terrestrial C

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(Havstad et al., 2007). Both services (forage provision and C sequestration) have a clear global and local impact on human societies and have been the target of many policy interventions in rangelands management; however, the existence of trade-offs between them remain poorly studied. Here we estimated forage provision and C and N sequestration under different grazing management alternatives in arid rangelands. In such areas, trade-offs between these services may occur, for example, when native vegetation is removed to plant pastures in order to optimize forage supply for livestock production. In general, this practice undermines C and N storage (FAO, 2010). On the other hand, grazing can change plant functional type composition, decreasing forage species and promoting a shrub encroachment which may maintain or increase C storage in non-forage shrubs (e.g., Van Auken, 2000) and thus generates the trade-off.

A singularity of arid rangelands is the relative contribution of vegetation and soil to total C storage. Even though soil is the main stock for C sequestration in rangelands (Lal, 2004; FAO, 2010), interestingly, as aridity increases C and N stocks in plant biomass and litter increase in importance compared to soil stocks. Carrera and Bertiller (2010) found that both plant cover and soil C and N stocks decrease along a gradient of increasing aridity, whereas the amount of aboveground litter does not change and woody cover with more recalcitrant material increases. Furthermore, decomposition rates of aboveground vegetation in arid temperate ecosystems dominated by woody species and perennial grasses, is usually slower than in mesic systems, and therefore the longevity of biomass stocks could be higher (Meentemeyer, 1978). On the other hand, the magnitude and importance of grazing effects on soil C and N stocks are elusive because of the direct and indirect effects of grazers, although such effect occurs mostly under heavy grazing pressure (Golluscio et al., 2009). There is also agreement that grazing reduces N availability (e.g., Golluscio et al., 2009). Nitrogen is a restriction in almost all water limited ecosystems (Hooper and Johnson, 1999; Yahdjian et al., 2011). Even though the ecosystem service associated with N per se is nutrient cycling, N availability and N stocks in plants is one of the key aspects for C sequestration (Piñeiro et al., 2010) and for quantity and quality of primary production and forage (West and Skujins, 1978; Burke et al., 1997). Herbivory may alter N cycling by selectively removing biomass, by physical disturbance and by excreting nutrient in feces and urine (Hobbs, 1996, 2006). In addition, herbivory may change plant litter quantity and quality through changes in species composition (Semmartin et al., 2004). In arid steppes, species promoted by grazing contain lower N levels than those diminished by this practice (Semmartin et al., 2004; Vivanco and Austin, 2006), which may involve N depletion in grazed fields.

Our objective was to study sheep grazing effects on (1) above and belowground C and N stocks in plants (regulating service), (2) forage biomass (provisioning service), and (3) the existence of trade-offs between both types of services in a mixed grass and shrub steppe. We specifically estimated forage fraction (within total plant biomass) under three grazing intensities in order to quantify the key provisioning service for livelihood of peasants and ranchers. The general hypothesis was that intensification of domestic grazing reduces the stock sizes of C and N and forage biomass due to selective defoliation. However, if grazing intensity is moderate, this reduction could be compensated because grazing can promote an optimization process (McNaughton, 1979), increasing productivity without a major reduction of more quality forage species, maintaining both types of ecosystem services provision and reducing trade-offs. Because of this optimization process, absence of domestic grazing will not necessarily increase forage, C and N stocks.

2. Materials and methods

2.1. Study site description

We worked in a grass-shrub steppe area of 300 km^2, including the Rio Mayo INTA Experimental Station and privately owned neighboring rangelands, in South Central Patagonia, Chubut province, Argentina (45° 24′ lat. S and 70° 15″ long. W). These ecosystems are devoted to wool production and have been grazed by sheep for more than one hundred years. Grazing management is extensive, arranged in very large paddocks (frequently around 2000–5000 ha), which are in general continuously grazed (Golluscio et al., 1998). Few dominant perennial grasses and shrubs contribute approximately 96% of the total biomass (Fernández et al., 1991) and mean aboveground net primary production is 56 $g\,m^{-2}\,y^{-1}$, half corresponding to grasses and half to shrubs (Jobbágy and Sala, 2000). Sheep and native herbivores are very selective and select their diet from the dominant grass and shrub species (Aguiar and Román, 2007).

2.2. Grazing treatments

We investigated three grazing managements: moderate and intensive grazing, both of which are continuous, and ungrazed (exclosure >20 years). Each management was represented by three replicates (different paddocks or fields). The moderately grazed situations are paddocks from the Experimental Station above mentioned, with a stocking rate of ~0.2 sheep ha^{-1}, during the last 20 years. The intensively grazed situations correspond to paddocks where the stocking rate during the last 20 years was ~0.4 sheep ha^{-1} (Cipriotti and Aguiar, 2005). In grazed fields we avoided areas near watering or fencing where sheep usually overgraze, making them unrepresentative of the average grazing intensity. The ungrazed condition was evaluated in three exclosures (installed in 1954, 1972, and 1983), for shrub biomass and belowground biomass estimation. Conversely, for destructive sampling needed to estimate grass aboveground biomass we only used the 1983 exclosure which was larger (>5 ha) than the rest, and included enough heterogeneity to reduce pseudoreplication effects. Furthermore, we confirmed that the three exclosures did not differ significantly in shrub and grass species densities. All study sites corresponded to the same plant community. Therefore, differences in species composition among treatments can be attributed to grazing historical effects (Cipriotti and Aguiar, 2005). The study was performed at the end of the growing season (peak of green biomass) during which annual rainfall was similar to an average year (i.e., 156 mm).

2.3. Estimation of regulating and provisioning services

We estimated the regulating service through the capacity of plants to sequester C and N in biomass. To estimate C and N concentrations we harvested and analyzed: (1) all aboveground green and standing dead biomass that was mostly explained by the dominant grass species (*Pappostipa speciosa* Trin. et Rupr., *Pappostipa humilis* Cav., *Poa ligularis* Nees ap. Steud and *Bromus pictus* Hook) and dominant shrub species (*Mulinum spinosum* (Cav.) Pers, *Adesmia volckmannii* Philippi and *Senecio filaginoides* De Candolle), (2) litter, and (3) roots in the top 20 cm of soil from three grazing intensities ($n = 3$). In the case of shrubs, we estimated C and N for main tissues: stem, lateral branches, and terminal twigs including leaves. Samples were homogenized and grounded before analysis. Elemental analyzer for C and N LECO TruSpec CN (St. Joseph, USA, 2004) was used. We estimated plants C and N stocks multiplying concentrations of C and N in each category of biomass (Table 1 in Appendix A) by specific aboveground green