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Livestock grazing modifies the effect of environmental factors on soil temperature and water content in a temperate grassland

I. Odriozola *, G. García-Baquero, N.A. Laskurain, A. Aldezabal

Department of Plant Biology and Ecology, Faculty of Science and Technology, University of the Basque Country, UPV/EHU, 48940 Leioa, Basque Country, Spain

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ABSTRACT

Grazing by large herbivores modulates the soil temperature and the water content as well as the quality of resources returned to the soil. Therefore, in order to predict the effects of grazing on complex interacting soil processes and plant production, an integrated approach is needed. We hypothesized that grazing accelerates nutrient cycling by increasing (i) soil temperature and fluctuations, (ii) water-holding capacity, and (iii) forage quality. To test this biological hypothesis, we conducted a field experiment simulating grazing abandonment conditions in semi-natural mountain grassland plots. Our results show that grazing accelerates soil processes through all three hypothesized mechanisms. Since grazing maintains a thin organic layer that provides less insulation to the soil, higher mean temperatures and large daily temperature fluctuations were recorded in grazed areas (less insulated); these daily fluctuations were as large as seasonal variation in the ungrazed plots. The response of the soil water content to grazing was complex. Although overall exclusion reduced the soil water content, particularly in coarse-textured soils, this trend was reversed during long periods of high solar radiation (i.e. high evaporation). Forage quality was reduced in all plots when grazers were excluded. Experiments attempting to realistically simulate grazing may benefit from these findings, particularly in very productive grasslands where the thickness of the organic layer increases rapidly under grazing exclusion.

1. Introduction

Grazing by large herbivores drives the main soil processes, such as nutrient cycling and microbial activity, as well as primary production (Bardgett and Wardle, 2003; Guitan and Bardgett, 2000; McNaughton et al., 1997a), through defoliation, trampling, and faeces–urine deposition. This occurs through the modulation of the soil's physical characteristics (temperature and water content) (Gass and Binkley, 2011; Greenwood and McKenzie, 2001) and the quality of the resources returned to the soil (Bardgett and Wardle, 2003; McNaughton et al., 1997b). For these reasons, in order to predict the effects of grazing on soil processes and plant production an integrated approach is needed (Butenschoen et al., 2011; Schrama et al., 2013a). The high rates of nutrient cycling measured under grazing conditions in temperate grasslands (Bardgett et al., 1998; Frank and Evans, 1997; McNaughton et al., 1997a; Semmartin et al., 2004) are probably a consequence of the combined effects of the abovementioned mechanisms; however, comprehensive studies are few (Schrama et al., 2013b).

Grazing (the consumption of plant biomass by livestock) modifies soil temperature over time, which, in turn, influences microorganism activity, the decomposition rate of organic matter, and nutrient cycling (Butenschoen et al., 2011). This occurs because the thickness of the soil organic layer affects the soil temperature (Aalto et al., 2013), with thicker organic layers providing more insulation. Under conditions of moderate to high stocking rates, more aboveground plant biomass is removed, and the incorporation of plant residues into the soil is reduced (Bilotta et al., 2007). Thus, dry matter accumulation is prevented and a thinner layer of plant litter is formed, which provides less insulation to the soil. Therefore, under grazing conditions, soil temperature is expected to be more variable and more dependent on environmental temperature than under non-grazing conditions (Gan et al., 2012; Zhao et al., 2011).

The effects of soil temperature on microbial biomass and activity depend on soil water availability (Poll et al., 2013). The consumption of plant biomass also affects the soil water content, with the counteracting effects of increased evaporation and reduced transpiration. Less insulated soils receive more solar radiation, which raises the temperature and increases evaporation; however, defoliation decreases the solar radiation intercepted by leaves and consequently decreases transpiration (Bremer et al., 2001). In addition, infiltration also affects the soil water content. In general, the way in which grazing as a whole affects the circulation, the retention capacity, and the availability of soil water may depend on interactions with the soil's physical and chemical properties (Greenwood and McKenzie, 2001), and environmental conditions. For example, compaction due to trampling is greater in fine-textured wet

* Corresponding author.
E-mail address: odrilarra@gmail.com (I. Odriozola).

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soils than in coarse-textured dry soils (Schrama et al., 2013a). Therefore, grazing is expected to increase the soil water-holding capacity, particularly in coarse-textured soils.

Soil temperature and moisture enhance microbial activity and biomass, if available substrates are not limiting (Frey et al., 2008). Grazing, too, may affect plant litter quality (Bardgett et al., 1998; Wardle et al., 2004). In temperate, highly productive grasslands (as those studied here), grazing results in an increase in species with a high nitrogen content and a low lignin content (Milchunas and Lauenroth, 1993; Semmartin et al., 2004). Generally, low carbon to nitrogen ratios promote nutrient release, thus accelerating nutrient cycling, whereas high ratios induce microbial immobilization (Semmartin et al., 2004). These effects are highly relevant to ecosystem functioning, because the amount of soil nitrogen derived from plant litter in grazed grasslands can be two to eight times greater than nitrogen derived from urine and faeces (Chaneton et al., 1996; Holland et al., 1992). Therefore, grazing is likely to promote plants with higher nitrogen to carbon ratios, consequently increasing forage quality.

Given that grazing accelerates nutrient cycling in temperate and productive grasslands (Bardgett et al., 1998; Frank and Evans, 1997; McNaughton et al., 1997a; Semmartin et al., 2004), we hypothesized that the mechanism involved in livestock grazing is a combination of increasing soil temperature and fluctuations, increasing water-holding capacity, and increasing forage quality. To test this biological hypothesis, we conducted an 'in situ' experiment simulating grazing abandonment conditions on a historically grazed semi-natural mountain grassland, and assessed the effects of grazing on the thickness of the organic layer, the soil thermal regime, the soil water content, and the forage quality.

2. Materials and methods

2.1. Study area

Experimental manipulations were carried out in the Aralar Natural Park (42°59′48″N, 2°06′51″W), an 11,000-ha protected area located in the Basque Country (Northern Spain). The vegetation in the Park is comprised of a mosaic of gorse-heather shrublands and grasslands, which support livestock (mainly 18,000 dairy sheep of the Latxa breed) that are managed in an extensive grazing system. The area has oceanic climatic conditions, with a mean annual temperature of 12.4 °C and an annual precipitation of more than 1400 mm. Despite the marked seasonality of the weather conditions at the site, drought periods are uncommon, as long periods without precipitation are unusual (Table 1). The area traditionally used by livestock (beef cattle, dairy sheep, and horses) occupies 2077 ha of the Park (18.9%), and its usage varies seasonally from May to November. Vegetation is mainly represented by native grasslands that are included in the Habitat Directive (European Commission, 2006). The most relevant vegetation type for livestock maintenance is *Jasiono-Danthonietum* grassland (code 6230, subtype a), primarily comprising *Festuca rubra* s.l., *Agrostis capillaris*, *Galium saxatile*, *Trifolium repens*, *Luzula campestris*, and *Cerastium fontanum*.

2.2. Experimental design

In order to simulate grazing cessation, four permanently fenced plots (50 × 50 m each) were erected in May 2005 at four experimental sites: Oidui (*Oid*), Igaratza (*Iga*), Alotza (*Alo*), and Uzkuiti (*Uzk*). Around each excluded plot (*E* level) we delineated a grazed plot (*G* level) where sheep, cattle, and horses were allowed to graze continuously during the vegetative period (from May to October or November). All four sites were located on a flat terrain, and differed only slightly in pH and elevation (except *Oid*), but more noticeably in soil texture and grazing intensity (Table 2). The thickness of the organic layer (defined as soil A horizon plus fresh litter), the soil temperature, the soil water content (as a measure of available moisture in $m^3\ m^{-3}$), and the forage quality were surveyed between 2010 and 2013 (after five to eight years of exclusion). There is a strong seasonal pattern in the Park (Table 1), so the effect of season was included in the analyses. January and February were used to represent winter, and July and August represented summer. The organic layer was measured in 2012; for this, we took 20 measurements in each experimental unit by digging a hole in the soil with a spade and directly measuring the organic layer using a metallic ruler. Soil temperature and water content were measured at 15 cm soil depth and at 2-hour intervals from April 2011 to March 2013, using Em50 data loggers connected to an ECH2O sensor system (Decagon Devices Inc., Pullman, WA, USA). Soil temperature data were only collected at two of the experimental sites (*Oid* and *Iga*). Forage sampling was carried out in July 2010, at the point of peak standing biomass. For this, three subsamples (1 m^2 each) were randomly collected to represent each experimental unit. The following variables were measured in % DM^{-1}: phosphorus (P), measured by a colourimetric determination technique; crude protein (CP), i.e. nitrogen content, measured by the Kjeldahl method and multiplied by 6.25; neutral detergent fibre (NDF), measured by the Weende method; and enzymatic digestibility (NDFcel), the enzymatic solubility of NDF in cellulase (Riveros and Argamentería, 1987). The first three relate to forage quality, and the fourth is a direct measure of digestibility.

2.3. Data analysis

To assess the differences in soil mean temperature and soil daily temperature variation between the *E* and *G* plots, four time series were decomposed into trend, regular, and irregular (random) components. We used an additive decomposition model for the time series (Montgomery et al., 1990; Makridakis et al., 1997). Each time series corresponded to a combination of site (*Oid* and *Iga*) and year (2011 and 2012), and they comprise the grazing period, which also represents the vegetative period. Prior to decomposition, graphical inspection confirmed that all the series could be considered as additive combinations of seasonal, trend, and irregular components (Gardner, 1985). This model can be expressed as: $X_t = m_t + s_t + W_t$, $t = 1, 2, 3,\ldots$ where m_t is the trend component, s_t is the seasonal (regular) component of period T that satisfies $s_t = s_{t+T}$ for all t and $s_1 + \ldots + s_T = 0$, and W_t is the irregular (random) component. Since we used daily temperatures, the seasonal component represented the daily oscillation in temperature. Consequently, a period of $T = 12$ (one record every 2 h) and a centred

Table 1
Mean temperature, precipitation, and solar radiation values for the study years and seasons. Data were collected from the weather station of San Miguel of Aralar (Navarra Government, 2014), located near the study area.

Year	Season	Temperature (°C)	Precipitation (l/m^2)	Solar radiation (W/m^2)
2011–12	Summer	13.4	85.4	191.1[a]
2011–12	Winter	−0.6	205.4	73.52
2012–13	Summer	14.5	86.3	206.2
2012–13	Winter	0.8	759.8[b]	60.8

[a] 2011–12 summer was very cloudy, the lowest solar radiation in last 11 years was recorded.
[b] 2012–13 winter was very rainy, hence the high precipitation recorded.