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The effects of land management (grazing intensity) vs. the effects of topography, soil properties, vegetation type, and climate on soil carbon concentration in Southern Patagonia

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ABSTRACT

Grazing is an economically important activity in Southern Patagonia's steppe and woodland ecosystems. In the past, emphasis has been on maximizing the provisioning capacity of these ecosystems with little concern for the longer term conservation of the ecosystem services related to climate regulation, like carbon sequestration. This is changing rapidly as livestock producers in the region work to develop a certification scheme for sustainable land management for Patagonians rangelands. This study is a scientific contribution towards this broader social objective in which we test whether soil C concentration in topsoil (10 cm depth) can be used as an indicator of rangeland condition. Data on climate, soil chemistry, topography, ecosystem type and stocking rates were obtained from the PEBANPA network of permanent plots database for 145 sites across Southern Patagonia. These variables were used as independent variables in a partial least squares regression in which top soil C was the dependent variable. The effects of land use (stocking rate) on top soil C were barely detectable at the regional scale in Patagonia. Top soil C was however strongly associated with other independent variables, notably soil chemistry and climate variables and also vegetation type. Thus, changes in land use management may not have a significant impact on soil carbon sequestration in these types of ecosystems. This may be because many factors interact to determine top soil C such that the footprint of overgrazing on top soil C is drowned out at the regional scale by other variables. This highlights the need for further work to develop indicators for sustainable land management in the region.

1. Introduction

Temperate grasslands are one of the largest biomes in the World occupying 9 million km^2 which represent 8% of Earth's terrestrial ice free surface (White et al., 2000). Disturbance to surface soils by activities such as livestock grazing can influence arid-land ecosystems in many ways including through the alteration of vegetation cover, soil physical properties, microbial communities, carbon cycling, nitrogen fixation and hydrologic properties (Schlesinger et al., 1990). In this context, rangeland livestock production using sustainable management practices is essential to support increasing human populations and lifestyles. Despite the extension and economic importance of rangelands in Santa Cruz there has been relatively little scientific focus on soil properties related to grazing in these ecosystems.

Soil carbon in grasslands and rangelands provides a range of important ecosystem services and functions, such as supporting the capacity of the land to sustain plant and animal productivity, maintaining and/or enhancing water and air quality, supporting human health and habitation (Karlen et al., 1997). The extension of rangelands and the impact of livestock grazing on ecosystem properties, and the need for sustainable grazing management to meet the demand of an increasing human population has been reported (Havstad et al., 2007; Kremen, 2005). However, this

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potential depends on how rangelands are managed for domestic animal grazing (Doran and Jones, 1996).

Over the last 70 years, degradation of the steppe (desertification) has occurred due mainly to an overestimation of the carrying capacity of these rangelands, inadequate distribution of animals in very large and heterogeneous paddocks, and year-long continuous grazing (Golluscio et al., 1998). Grazing impacts have led to substantial ecosystem modification, in particular an increase in bare ground and changes away from the original floristic composition (Bisigato and Bertiller, 1997; Peri et al., 2013), consistent with reviews that demonstrate that overgrazing may reduce aboveground Net Primary Production (ANPP) and change floristic composition in rangelands (Milchunas and Lauenroth, 1993; Oesterheld et al., 1999).

In response to the history of unsustainable large management in Patagonia, key stakeholders in the region have developed a certification scheme to promote sustainable land management practices (Borrelli et al., 2013). For certification and auditing purposes the standard developed a range of indicators to assess rangeland condition (see Borrelli et al., 2013 page 62). All of these indicators are qualitative and therefore open to interpretation. There is a definite need to develop quantitative measures of rangeland condition that can reflect the impacts of unsustainable grazing and land management practices in a way that is not subjective. In this context soil quality, and especially soil organic carbon (SOC), has been proposed as an integrative indicator of environmental quality, food security and economic viability (Monreal et al., 1998; Lal, 1999).

Grazing intensity on extensively managed grasslands may affect ecosystem C stocks (Piñeiro et al., 2010). Peri (2011) reported that C stocks in grasslands decreased from 130 Mg C ha^{-1} under low grazing intensity (0.10 ewe ha^{-1} yr^{-1}) to 50 Mg C ha^{-1} at a heavy stocking rate (0.70 ewe ha^{-1} yr^{-1}) mainly due to a decline in plant cover and loss of the organic layer of the soil and because of increased extension of bare areas and as a consequence of soil erosion by strong winds. Also, it has been documented in arid zones the importance of measuring grazing together with other environmental variables as drivers of soil C (Rabbi et al., 2015). In Patagonia, the influence of grazing on soil C interacting with environmental factors remains poorly understood, despite the vast area and the economic importance of grazing.

The objectives in this study where 1) to assess the potential for soil C concentration in topsoil to be used as an indicator of rangeland condition and therefore sustainable land management, and b) assess the extent to which environmental variables (vegetation type, topography, climate, soil chemistry) other than stocking rate influenced topsoil C concentration with the idea that any environmental variable that strongly affected soil C might be a candidate for use as a covariate that would facilitate efforts to relate soil C to rangeland condition.

2. Materials and methods

In Santa Cruz province (Argentinian Southern Patagonia), there are three main ecosystem types: *Nothofagus* forest, steppe and wetlands (mallines) which are found interspersed amongst the steppe vegetation. The native *Nothofagus* forest and woodland cover a narrow (100 km wide) but long (1000 km) strip of land. Southern beeches, lenga (*Nothofagus pumilio*), ñire (*Nothofagus antarctica*) and guindo (*Nothofagus betuloides*) are the dominant species covering 535,889 ha. The steppe ecosystem, mainly characterised by the presence of tussock (*Festuca*, *Stipa*), short grasses (*Poa*, *Carex*) and shrubs, covers 85% of the total area in Santa Cruz province and the main activity in this ecosystem is extensive sheep grazing.

The study was conducted in permanent plots established as part of PEBANPA network (Biodiversity and Ecological long-term plots in Southern Patagonia) (Peri et al., 2014). Measurements were made in 145 sites in Santa Cruz Province, across latitudinal (46° 00′–52° 23′ S) and longitudinal (65° 43′–73° 35′ W) transects, corresponding to temperature and rainfall gradients, respectively, which also capture the principal vegetation types of Patagonia (grass steppe, dwarf shrub steppe, shrub steppe, *Nothofagus* forest and wetlands) (Fig. 1). In Santa Cruz, rainfall decreases from 1000 mm to 200 mm yr-1 from west to east due to the Andes Mountains that act as an orographic barrier to moist winds coming from the west. A wide range of precipitation and soil characteristics in Patagonia results in deciduous *Nothofagus* forest in the west and the steppe vegetation in the east, and constitutes one of the most pronounced vegetation gradients on the planet. The climate in this region is dry, cold and windy. Temperatures are highest in December to February, and at a minimum in June–July. Summers are short, but with long days because of the latitude. The windiest season is from November until March. The predominant wind direction is from the south-southwest. Severe and frequent windstorms occur in spring and summer, with wind speeds over 120 km h^{-1}.

2.1. GIS derived independent variables

The climate parameters (Table 1) for each site were estimated from the WorldClim data set (Hijmans et al., 2005). WorldClim contains geographic surfaces for 19 different climatic parameters that describe rainfall, temperature and variation in those parameters at a resolution of 0.008333° (approximately 1 km). Solar radiation (W m^{-2}) was calculated from the Solar Radiation tool in ArcGIS version 9.3.1 (ESRI, California, USA), with topography data from the 3 arc second resolution NASA Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) of the globe (Jarvis et al., 2008). We also calculated another composite climatic variable for use in statistical analyses because this integrates climatic conditions highly relevant to plant growth. W* represents mean annual water availability (Wynn et al., 2006) (eqn (1)).

$$W^* = (MAP - Q/(r\ L)) + 4000 \tag{1}$$

where MAP is mean annual precipitation (mm/yr), Q is mean annual global solar radiation (J m^{-2} yr^{-1}), r is the density of liquid water at 25 °C (1000 kg m^{-3}), and L is the latent heat of evaporation of water at 25 °C (2.5 × 106 J kg $H2O^{-1}$).

A set of eleven topographic variables was derived from the SRTM DEM using an approach relatively unconstrained by the spatial resolution of the input DEM (Wood, 1996; Wang et al., 2010). In summary, a quadratic function was fitted to the elevation values within a 500 m diameter circular sample window around each sample location, and a set of indices was calculated from this surface to describe the topography around each sample location. Topographic variables were derived to represent slope, aspect, longitudinal curvature (LongC), cross-sectional curvature (CrossC), fuzzy memberships of the morphometric classes of ridges, valleys, pits, peaks and passes, the Compound Morphometric Terrain Index (CMTI), and the r^2 of the fitted quadratic function (Wang et al., 2010). Longitudinal curvature represents the rate of change of elevation along a channel or ridge. Cross-sectional curvature is the rate of change of elevation across the valley or ridge, and can be used to identify steep sided valleys or ridges. The fuzzy memberships of each morphometric class was calculated as a function of the distance of the processing location to that feature within the sample window (e.g. the axis of a ridge), divided by the radius of the sample window. Memberships are zero when the feature class is not found in the sample window. CMTI is an index derived from the fuzzy memberships of "ridge" (positive) and "valley" (negative) classes. Values of 1 are ridge tops, values of −1 are in valley centres,

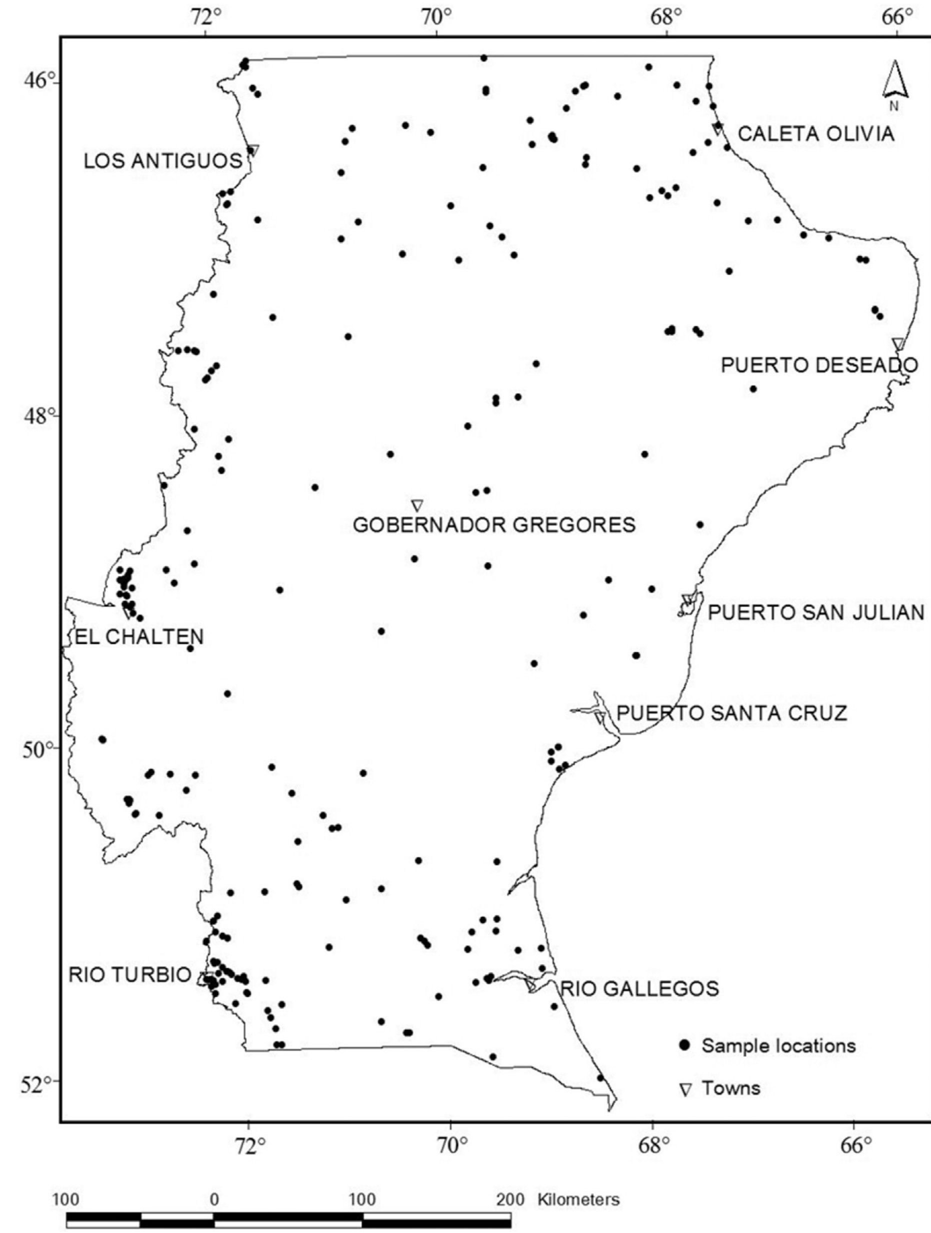

Fig. 1. Locations of sample sites considered in this analysis.

while values of 0 are along planar slopes at the scale analysed. Intermediate values between zero and the extremes have partial membership in the set of ridges or valleys and approximate upper, middle and lower slope positions. The r^2 acts as a measure of terrain complexity and roughness within the sample window as it measures the deviation of the observed terrain from the fitted quadratic function.

2.2. Grazing intensity

The intensity of grazing (mean sheep stocking rates) at each site was estimated by using long term animal registries at each station where permanent plots had been established. Also, we estimate an index represented as a ratio between animal requirements and mean pasture allowance in the main ecological areas in Santa Cruz Province (Central Plateau, Andean Vegetation, Humid Magellanic Grass Steppe, Mata Negra Matorral Thicket (*Juniella tridens* shrubland), Shrub steppe of Golfo San Jorge and Mountains and Plateaus, and Dry Magellanic Grass Steppe and Sub-Andean Grassland). Thus, the value of 1 means that the mean sheep stocking rate is adjusted to forage allowance (where grazing isn't advised for values below 100 Kg DM ha^{-1} in steppes and 600 Kg DM ha^{-1} in meadows) for adequate animal performance and conservation of grasslands. The estimation of carrying capacity is based on the biomass production of short grasses and forbs that grow in the space among tussocks of each ecological area and the requirements of 530 kg DM.yr^{-1} for 1 Corriedale ewe of 49 kg of live weight which represents a "Patagonian sheep unit equivalent (PSUE)" (Borrelli, 2001). The mean sheep stocking rates in this study varied from 0.05 to 1.60 ewe.ha^{-1}.yr^{-1}.

2.3. Soil

At each site, soil samples were collected from nine randomly

Table 1
A description of the WorldClim parameters (further detail available at http://www.worldclim.com, and in Hijmans et al., 2005).

Parameter	Description
BIO1	Annual mean temperature
BIO2	Mean diurnal range [mean of monthly (max. temp.−min. temp.)]
BIO3	Isothermality (BIO2/BIO7) (x 100)
BIO4	Temperature seasonality (standard deviation × 100)
BIO5	Max. temperature of warmest month
BIO6	Min. temperature of coldest month
BIO7	Temperature annual range (BIO5−BIO6)
BIO8	Mean temperature of wettest quarter
BIO9	Mean temperature of driest quarter
BIO10	Mean temperature of warmest quarter
BIO11	Mean temperature of coldest quarter
BIO12	Annual precipitation
BIO13	Precipitation of wettest month
BIO14	Precipitation of driest month
BIO15	Precipitation seasonality (coefficient of variation)
BIO16	Precipitation of wettest quarter
BIO17	Precipitation of driest quarter
BIO18	Precipitation of warmest quarter
BIO19	Precipitation of coldest quarter

selected points within three 20 m × 40 m quadrats using a hand auger (10 cm depth). Coarse root debris >2 mm from soil samples had been removed by sieving. To reduce the number of chemical analyses we pooled individual soil samples into combined samples. From the nine samples collected within each quadrat we created three composite samples so that each composite sample contained an equal proportion of soil from three auger holes ($n = 3$ for each site). The sample were finely ground to below 2 μm using a tungsten-carbide mill. Measurements of soil carbon (SOC) concentration were derived from the dry combustion (induction furnace) method using a LECO auto-analyzer (St. Joseph, USA), major cations (Na, Al, P, K, Ca), pH, percentages of clay, silt and sand. The pH of soil samples was determined with an electronic meter immersed in a 1:5 mixture of soil and deionised water. When appropriate, we cross-referenced soil carbon measurements against soil pH measurements to ensure that the soil samples were free of soil inorganic carbon and thus composed of SOC (after Donato et al., 2011).

2.4. *Data analysis*

We used a step-wise procedure to identify and remove explanatory variables that were collinear with other explanatory variables in the data set, following the method described by Fox (2002, p 216). Firstly, we calculated variance inflation factors (VIFs) for groups of related variables. For example the first group of variables included: % bare soil, % shrubs, % dwarf shrubs, % grasses, % Herbaceous vegetation and % trees. For this group of variables we calculated VIFs, identified the variable with the highest VIF score (% trees). We then deleted this variable and again calculated VIFs for the remaining variables. All remaining variables had VIFs or less than 10, which was recommended by Quinn and Keough (2002) as an acceptable level of collinearity. This procedure was then carried out with the following variables: radiation (MJ/m^2/yr), Evap (mm/yr) and mean annual water deficit (mm/yr) which showed no colinearity. Then we did the same for the climate variables obtained from Worldclim where various variables were deleted. After the iterative process of calculating VIFs and deleting the variable with the highest VIF score we obtained the following set of climate variables free from collinearity: Max Temperature of Warmest Month, Min Temperature of Coldest Month, Mean Temperature of Wettest Quarter, Mean Temperature of Driest Quarter, Precipitation of Wettest Month and Precipitation of Driest Month. The topographic variables were free of collinearity. For the soil properties % sand was deleted. Through this iterative process, we identified 40 explanatory variables free from collinearity. The explanatory power of these 40 variables on soil carbon concentration was then assessed using partial least squares regression (Appendix S1).

3. Results

Our analyses indicate that SOC concentration is heavily dependent on vegetation type (Fig. 2). The partial least squares regression produced a model that was an effective predictor of soil C in the regional data set presented here (Fig. 3, $R^2 = 0.75$). In this analysis stocking rate was only a moderately important predictor of soil C (see Row 1094 of 1150 of Appendix S1). In these Patagonian rangelands, climate (i.e. Mean Annual Climatic Water Deficit) and simple ecosystem classifications (i.e. grassland, steppe, Nothofagus forest) are much more important than land use management metrics (i.e. stocking rates) for prediction of soil carbon concentrations (see Fig. 4 and Rows 1078 to 1150 of Appendix S1).

4. Discussion

In the present study soil carbon concentration was mainly a function of climate, vegetation type and soil properties. These types of data are readily available and, as we have demonstrated previously (Ladd et al., 2013), the prediction and mapping of soil carbon is possible across large geographical regions using readily available data and without the need for large amounts of field work. However contrary to our initial hypothesis the effects of land management (grazing intensity) on soil carbon concentration was hardly detectable at the regional scale. The implications of which are discussed below. The fact that prediction of soil carbon is possible across the region should be useful if a carbon emissions offset market ever evolves for the carbon stored in the ecosystems in this region. The specific potential for carbon sequestration of a given site depends on a complex set of variables, including climatic conditions, soil features, productivity levels and past management, but suitable rangeland management can increase net carbon storage in grasslands and subsequent payment for C stocks (Conant et al., 2001; Follett and Reed, 2010). Quantification of SOC stocks

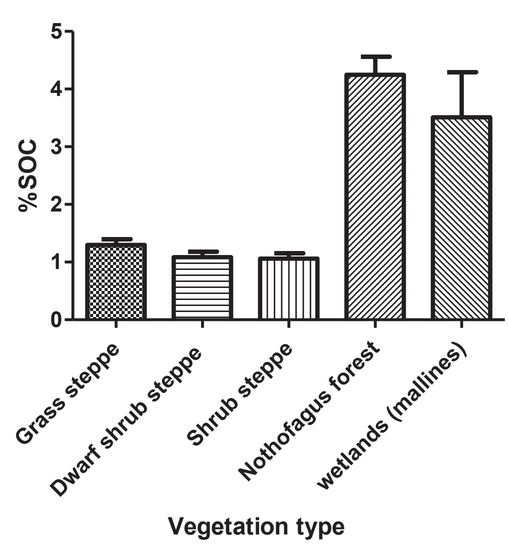

Fig. 2. Soil carbon concentration (%SOC) across vegetation types in Santa Cruz Province, Southern Patagonia.

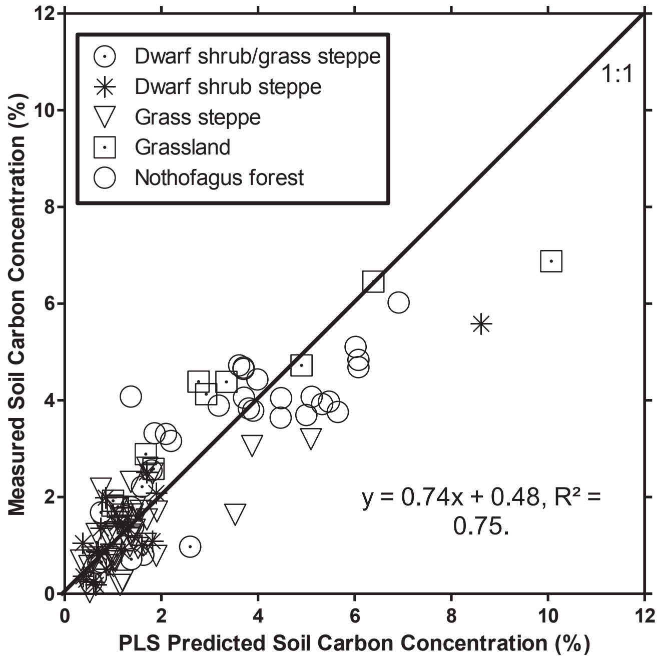

Fig. 3. The correlation between predictions of %C in soil from the PLS model and the measured values of %C in soil across the sites shown in Fig. 1. See Appendix S1 for statistical detail.

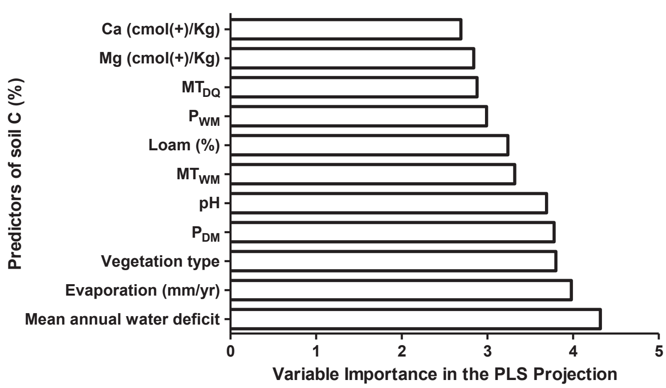

Fig. 4. Mean predictor importance for soil %C prediction. The 10 most important variables are shown in descending order. Soil properties (pH, Calcium and magnesium content and % loam), vegetation type, and climatic variables all affected % C in top soil. P_{DM} = precipitation in the driest month,. MT_{WM} = maximum temperature of the warmest month, P_{WM} = Precipitation of the warmest month and MT_{DQ} = mean temperature of the driest quarter.

could boost both carbon sequestration and biodiversity conservation to a greater extent than payment for carbon alone. Steinbeiss et al. (2008) suggested that higher biodiversity might lead to higher soil carbon sequestration in the long-term and therefore the conservation of biodiversity might play a role in greenhouse gas mitigation. Thus, effective C sequestration in grasslands demands a suitable grazing adjusted to local soil, climate and management features.

In extensively managed grassland it has been documented the importance of grazing intensity and frequency as the main management practices to affect soil C levels at paddock or plot level when comparing contrasting situations (Jones and Donnelly, 2004; Peri, 2011). At this spatial scale, Post and Kwon (2000) reported that the most significant factors affecting the direction and magnitude of change in soil C in response to management are the input rates of organic matter, the decomposability of organic matter inputs and changing physical protection through either intra-aggregate or organomineral complexes.

Contrary to our prediction, the effect of grazing on soil C concentration was hardly detectable at the regional scale in Patagonia. In Patagonian rangelands climate is much more important than land use management to support predictions of soil carbon concentrations. Also Rabbi et al. (2015) found by examining a very large dataset of C measurements across eastern Australia (1482 sites) that the differences in land use and management practice explained only 1.4% of total variation in C stocks across the whole data set, while climatic and soil related variables explained 64%. Similarly, McSherry and Ritchie (2013) in a multifactorial meta-analysis suggested that all factors in their analysis, including soil texture, precipitation, grass species composition, grazing intensity, sampling depth, and study duration, interacted in complex ways to determine effects of grazing on soil C. This is perhaps not surprising given that soil and soil properties are the result of many interacting factors: soil chemistry, vegetation type and climate being the most important in this region. In this context, in Patagonian grasslands, climate is important to consider. How grazing may affect soil C, and how this relationship may be impacted by expected changes in climate, such as an increased frequency of drought events is an important issue for future research because increased drought may turn Patagonian grasslands into sources of atmospheric C. Policy makers and land managers need to consider this complete context before they can fully understand the potential influence of grazing on soil carbon.

The only vegetation class for which long term grazing intensity explained any variance in soil carbon concentration was for the grass steppe ecosystem. This may be due to a decline in plant cover that favours soil erosion due to the regions strong winds, and as a result of high stocking rates and continuous grazing (Peri, 2011). A variety of management techniques that increase forage production for livestock, also have the potential to increase SOC. For example, Milchunas and Lauenroth (1993) reported that under certain conditions, grazing can lead to increased annual net primary production, particularly with moderate grazing in areas with a long evolutionary history of grazing and low primary production. An increase in carbon inputs generally results in important increases in soil microbial biomass and some of the more labile soil organic matter fractions (Herrick and Wander, 1998). These changes are eventually followed by an increase in soil organic matter, infiltration capacity and nutrient availability (Monreal et al., 1998). Initially, however, changes in these early warning indicators are not well correlated with differences in the standard indicators of sustainable land management due to the time lag involved. Another problem is that soil scientists often completely ignore relationships to many ecosystem functions, including biodiversity conservation. Although the environmental community generally recognizes that water quality frequently depends on soil quality, few people concerned with the environment are aware of the role that soils play in maintaining diverse, resilient plant and animal communities (Hillel, 1991). The results of this study highlight the need to further research to develop good indicators for certification schemes for sustainable grazing and land management in Patagonia's rangeland ecosystems which provide a wide range of ecosystem services including a sense of place or national identity in Argentina's south (Martinez Pastur et al., 2016). Better knowledge is needed on the linkage between biotic and landscape features. In this context, we must continue to search for quantitative variables (other than soil C concentration) that can be used to quantify sustainable land management and grazing impacts. Plant productivity, biodiversity, land-use change, meat production, habitat loss, incidence of invasive alien species and shrub encroachment are all possibilities

(Mace et al., 2012; Peri et al., 2013; Eldridge and Soliveres, 2015; Machovina et al., 2015). Also, it is important to strengthen the science-policy interface for biodiversity and ecosystem services for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jaridenv.2016.06.017.

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