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Impact of Extensive Grazing on Supporting and Regulating Ecosystem Services of Mountain Soils

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Livestock grazing impacts the ecosystems of high mountains and adjacent low-elevation regions as a result of the physical, chemical, and hydrological connectivity of soil. In particular, grazing may alter the ecosystem services provided by soil, such as carbon and organic matter accumulation, carbon storage, and water infiltration. The present study evaluated the relative contents of soil organic matter (SOM) and soil organic carbon (SOC) on soil in a human-induced grassland and an frequently grazed Abies religiosa *(Kunth) Schltdl. & Cham. forest in Nevado de Toluca, Mexico. It assessed carbon stocks in 2 different soil layers (0–5 cm and 5–25 cm), as well as soil compaction and water infiltration in both land uses. Results showed slightly lower SOM (21.7%) and SOC (12.6%) in soils on which livestock were grazed than in forest soils (25.7% for SOM and 14.65%, for SOC) at both depths and a greater bulk density of livestock soils (0.86 g cm^{-3}) than of forest soils (0.73 g cm^{-3}), particularly in the 0–5-cm layer (0.88 g cm^{-3}) of livestock soils. More than 40 years of livestock grazing has clearly impacted the capacity of soils to accumulate organic matter and organic carbon. However, carbon stocks and water infiltration were not significantly affected, as low carbon accumulation was compensated by changes in soil bulk density. These results indicate that extensive livestock ranching and resource conservation are not necessarily mutually exclusive in the study site. Direct and indirect mechanisms involved in the provision of the evaluated regulating services should be further studied, taking into account the highly variable social and environmental conditions of Nevado de Toluca. Management policies should also aim to maintain an equilibrium between livestock rancher needs and conservation of supporting and regulating ecosystem services that are highly relevant to the functioning of mountain ecosystems.*

Keywords: *High mountain systems;* Abies religiosa; *infiltration; saturated hydraulic conductivity; soil organic matter; carbon stocks; Mexico.*

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Introduction

Mountainous regions cover approximately 27% of the Earth's land surface, with ecosystem services and socio-ecosystems interacting dynamically along the elevational gradients of many of these regions. Productive human activities such as agriculture and livestock ranching in high-mountain systems can impact the ecosystem services produced at these elevations as well as the ecosystem services and adjacent socio-ecosystems located at lower elevations (Koellner 2009). Soil, in particular, is an important connector that links high-elevation ecosystems with those at lower elevations. The impact of human activities on the supporting (relative content of soil organic carbon [SOC] and soil organic matter [SOM]) and regulating ecosystem services (carbon [C] storage and water infiltration), is especially important, as these services support the provision of additional ecosystem services (Adhikari and Hartemink 2016).

Socio-ecological implications of livestock grazing are especially complex in high mountain systems. For example, livestock ranching represents an important source of livelihoods for communities, particularly indigenous communities (Valdivia et al 1996; Preston et al 2003; Gentle and Thwaites 2016), yet livestock grazing, depending on the number of livestock owned by landowners (livestock load), can have a significantly negative ecological impact on the ecosystem services provided by mountain soils (Steinfeld et al 2009). In high mountain systems, livestock ranching is mainly extensive: the livestock constantly move among different agroecological zones and consume a large diversity of plants (Byers 1996; Rota and Sperandini 2010), especially those that are most palatable. This constant grazing can modify the quality and quantity of organic matter that

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enters the soil (i.e., C inputs) and thus indirectly impact the physical and chemical properties of soils (Wardle et al 2004). This may reduce the productive capacity of soils (i.e., soil fertility, high C:N ratio), and alter other services regulated by SOM (e.g., water cycle, C storage, plant productivity) (Ellies et al 1996; Lal 2002, 2014; Liebig et al 2006; Klumpp et al 2009). Livestock grazing also directly affects soils due to constant trampling, which decreases the porous spaces in the soil and thus promotes compaction (Amésquita and Pinzón 1991; Klumpp et al 2009). Such changes can limit the movement of water and nutrients through soils, affecting plant production, water infiltration, and water recharge (Fleischner 1994; Dörner et al 2009; Keller and Hakansson 2010).

However, the extent of the impact of livestock grazing depends on the use intensity and management of foraging resources. Sustainable livestock practices, for instance, can simultaneously reduce the environmental impact of livestock ranching and satisfy local inhabitants' needs (Rodríguez and Jacobo 2012). Several practices for increasing the sustainability of livestock ranching (Uribe et al 2011) are establishing corrals, rotating between grazing areas, and cultivating forage crops as dietary supplements. However, the efficiency of these measures depends on specific site conditions, such as climate, animal load, and the growth rate of the plant species most frequently consumed by livestock, in addition to livestock ranchers' knowledge of such factors across space and time.

The Nevado de Toluca (NT) is the 4th highest mountain in Mexico (4680 masl). It has great local and regional importance because of its biodiversity and cultural heritage as well as the ecosystem services that it provides, including regulation of the water cycle, water provision for human consumption and agriculture, and provision of medicinal plants and wild edible mushrooms. These services offer benefits at local and regional scale to the inhabitants of this mountain region as well as to those of the city of Toluca (population nearly 870,000; INEGI 2015), which is at the foot of the mountain.

Approximately 5,297 people belonging to 54 *ejidos* (a communal land tenure system of Mexico) and 16 localities inhabit NT. *Ejidos* manage 59% of the NT area (31,842 ha). Local inhabitants have practiced agriculture, grazed livestock, and gathered non-timber forest products for many generations. However, these activities do not satisfy their daily needs, and many inhabitants have other livelihood strategies, such as rural tourism and trout farming. The present study focuses on the *ejido* of Agua Blanca. Extensive livestock ranching is practiced in this small mountain community located on the southeastern side of the NT volcanic cone at an elevation of approximately 3200 masl. This community forms part of a Protection Area for Flora and Fauna (PAFF), but livestock ranching is an important part of the lifestyle of many inhabitants since 1929, which is when they started using the land for agropastoral purposes after a national agrarian reform (RAN 1998). Although practiced at a small scale (on average only around 16 sheep owned per family), it contributes to strengthening the livelihoods of families; it also represents an economic security, particularly in cases of medical emergencies (Martínez-Hernández et al 2008; Hernández-Valenzuela et al 2016).

Livestock graze on human-induced grasslands during the dry season and are led into to the neighboring forest of *Abies religiosa* (Kunth) Schltdl. & Cham., during the rainy season (Esquivel-Domínguez and Estrada-Flores 2014). Until approximately 3 years ago, 25% of sheep owners also planted small plots of oats (50 to 100 m^2) as a livestock supplement, especially during the greatest forage shortage from November to January. However, more recent field observation and personal communication with local people showed that only a few shepherds plant oats, some as a monoculture and others in rotation with beans (*Vicia faba* L.). In general, sheep graze from 4 to 7 hours per day and are housed in corrals near landowners' houses in the afternoon/evening. However, serious legal restrictions have been imposed on the use of natural resources in NT since 2013: approximately 53,970 ha of the land are now protected by the National Commission of Natural Protected Areas (Comisión Nacional de Áreas Naturales Protegidas [CONANP]; Mastretta-Yanes et al 2014). CONANP reports that the PAFF of NT is one of the zones most impacted by livestock in the central region. In the area, heavy livestock grazing has led to fragmentation and loss of forest, hampering of native vegetation's regeneration, and loss of native species, counteracting the benefits of this Natural Protected Area (Candeau and Franco-Maass 2007). However, the impacts of extensive grazing on ecosystem services, such as soil organic matter accumulation, organic carbon storage, and water infiltration have not been explicitly considered. Such information can be used to inform management plans under a sustainability framework (Sánchez et al 2003; Vergara-Sánchez et al 2005).

The above context reveals the need to further evaluate and more comprehensively measure the impacts of extensive livestock ranching on the supporting and regulating ecosystem services of NT soils, especially those that maintain other important ecosystem services. In this way, more effective livestock practices and policies can be formulated to encourage the supporting and regulating ecosystem services conservation in the NT and to lessen poverty in the local communities. Therefore, the objective of the present study was to compare soil C stocks (i.e., SOM, SOC, and bulk density) and water infiltration of integrated livestock systems and *A. religiosa* forest soils in the Agua Blanca *ejido* in NT, with a view to improving our knowledge about the impacts of land use in these supporting and regulating mountain soil services.

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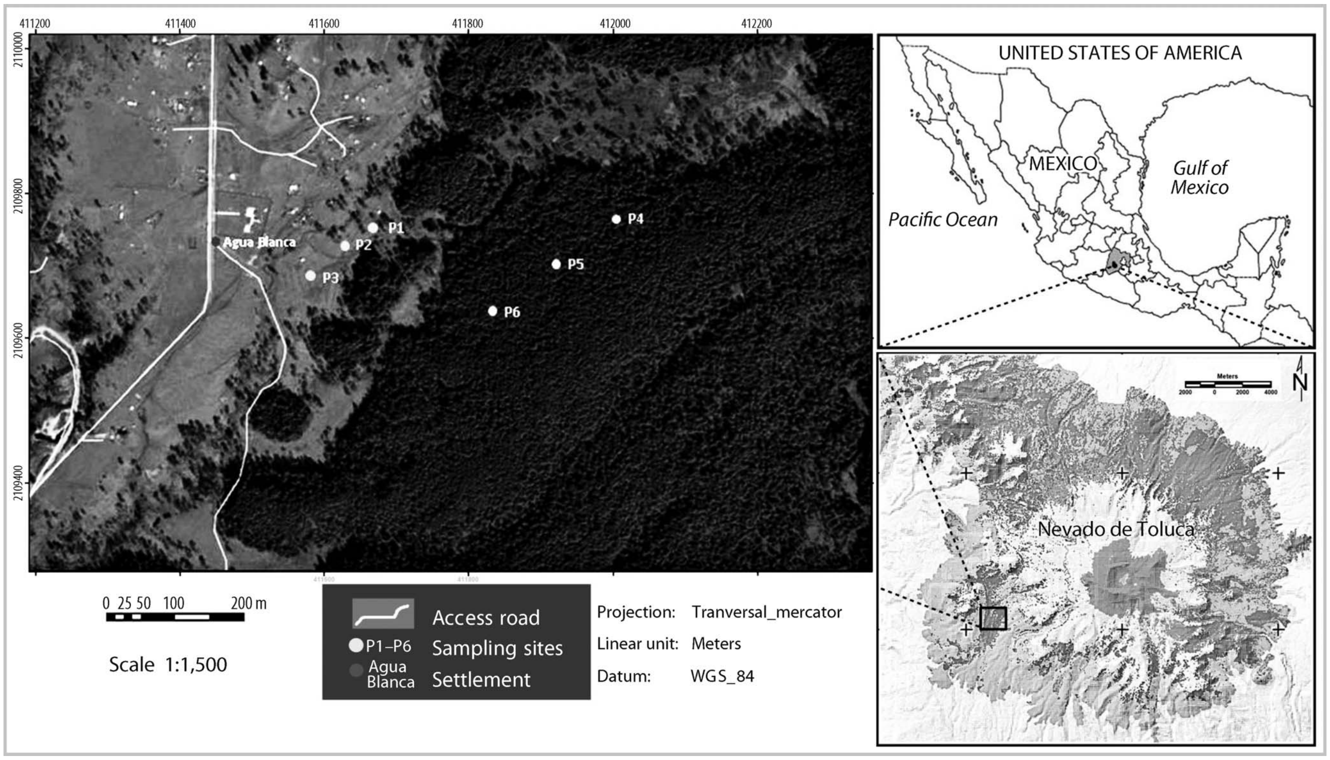
FIGURE 1 Location of study area, Protection Area for Flora and Fauna (PAFF) NT (top right). PAFF in a LANDSAT 8 image (2017) was combined with a digital elevation model and a classification of land cover (bottom right). Land cover and sampling sites: P1–P3 livestock; P4–P6 *Abies religiosa* forest (left). (Map by Farid Uriel Alfaro Ramírez)



Materials and methods

Study site

This work was carried out on 2 land uses, a human-induced pastureland and an adjacent forest of *Abies religiosa* used for grazing in the Agua Blanca *ejido* in NT. Although the cartographic records of 1972 already show the presence of this pastureland, the National Agrarian Registry (RAN 1998; Franco-Maass et al 2006) indicates that these lands were originally *A. religiosa* forest that were transformed as of 1929, when the land was redistributed as result of the agrarian reform, whose objective was to give greater weight to livestock activities. In this work the time of more than 40 years was used as a reference based on existing cartographic records. NT is located in the State of Mexico between 18°51′ and 19°19′ N and 99°38′ and 100°09′ W in the Trans-Mexican Volcanic Belt that crosses the central portion of Mexico (Figure 1). Cold climate dominates the NT region; average annual temperature ranges from −2 to 5°C. Average temperature in the coldest month is less than 0°C and in the warmest month ranges from 0 to 6.5°C. The region has a summer rainfall regime and frequent snowfalls in winter, mostly in January and February. Maximum extreme temperatures may reach 21°C in summer, while minimum extreme temperatures may decrease to −10°C in winter. Average annual rainfall varies from 200 to 1800 mm (Challenger and Soberón 2008), with greater rainfall from May to October; July is the rainiest month (García 1990). The dominant soil type is Andosol, although other types such as Phaeozem, Regosol, Cambisol, and Latosol are also present (Vargas 1984). The dominant ecosystems in the PAFF are temperate forests with tree species of the genera *Abies*, *Pinus*, and *Quercus* (3000 to 4100 m). High mountain grassland dominated by species of the genera *Festuca* and *Calamagrostis* is found at elevations of 4100 to 4500 m (Rzedowski 1978).

Overall, the land ownership system in NT area is collective, including 53–56 agrarian units. In some sites of the Agua Blanca *ejido*, only 67.5% of shareholders manage areas ranging from 0.25 to 2 ha, and 37.5% grow seasonal agricultural crops: oats (*Avena sativa*) and beans (*Vicia faba* L.). After harvest, livestock graze on the stubble (Martínez-Hernández et al 2014; Mastretta-Yanes et al 2014). There are 19 homes, none of which have electricity, a refrigerator, a washing machine, a personal computer, a landline, a cell phone, or Internet connection; 5% have an automobile, 5% have television, 26% have a radio, 26% have piped water, and 37% have a toilet.

Sampling design

A combined stratified and systematic sampling based on a 2 × 2 factorial design was applied in the present study. Two land uses (extensive livestock grazing on grasslands and in forest) were considered at 2 soil depths (0–5 cm versus 5–25 cm). The forest is one of the best-conserved *Abies religiosa* (H.B.K.) Cham. & Schltdl, (sacred fir) forests in the area (Mastretta-Yanes et al 2014). Community members of the

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ejido use human-induced grasslands that run parallel to the sacred fir forests close to the area where the community lives. These human-induced grasslands and the forest are therefore exposed to the same environmental conditions, elevation, etc. For each land use, 3 sites (used as repetitions in the statistical analysis; Figure 1) with the greatest possible environmental homogeneity were selected; the 3 grassland sites were parallel to the 3 forest plots. In each site, 3 nonexperimental plots of 12 m × 12 m were systematically established. Plots were divided into 9 quadrants of 4 m × 4 m, and the corners of each plot were delimited with wooden stakes.

Sampling and physicochemical soil analysis

Soil samples were taken once from each of the 9 quadrants per plot at depths of 0–5 cm and 5–25 cm with a cylindrical bore of 5 cm in diameter, resulting in a total of 54 samples per land use and 108 samples in total. Each sample was deposited in a plastic polyethylene bag that was labeled and placed in a cooler and then transported to the laboratory of the Institute of Rural Agricultural and Livestock Science (Instituto de Ciencias Agropecuarias y Rurales, ICAR) of the Autonomous University of the State of Mexico (UAEM). Once transported to the laboratory, the samples were dried at ambient temperature for 1 week and then sieved with a 2-mm mesh to separate their components (soil, rocks, and roots). The bulk density (BD) of the soil samples was calculated using the cylinder method (Elliot et al 1999). Soil fraction less than 2 mm in size was used to determine soil moisture, SOM, SOC, and pH. Moisture relative content (%) was determined using the gravimetric method (20 g of soil dried at 105°C for 48 h; Jarrel et al 1999). SOM (%) and SOC (%) were quantified by the modified Walkey and Black method (Nelson and Summers 1996). Soil pH was measured using the potentiometric method and a soil:distilled water ratio of 1:2. Finally, soil compaction was measured *in situ* at depths of 0–5 and 5–25 cm with a portable penetrometer (Turf-Tec Soil Compaction Tester), which measured resistance to soil penetration (MPa).

The following measurement was performed on additional soil samples taken from 3 of the preestablished quadrants in a diagonal pattern in each plot, beginning with the upper right quadrant. Unaltered samples were collected with a PVC pipe of 15 cm in length and 8 cm in diameter; samples were kept intact for the determination of hydraulic conductivity (*Ks*). Water infiltration in soil was indirectly measured by determining the saturated *Ks* (Morikawa-Sakura and Yoshitaka 2014), which showed the soil's capacity to conduct water under saturated conditions. In total, 18 soil samples, i.e., 9 per soil use (3 subsamples per plot), were collected to evaluate infiltration. The samples were placed in a cooler and transported to the Soil Physics Laboratory of the Postgraduate College, Montecillo Campus, where hydraulic conductivity was measured in saturated soils under a constant charge in a permeameter, which is based on the Darcy equation and reported in centimeters per hour (cm h^{-1}) (Klute and Dirksen 1986).

Statistical analysis

The data obtained for SOC and SOM relative content, C stocks (mg C ha^{-1}), soil moisture (%), BD (g cm^{-3}), and pH were used to perform a Kolmogorov-Smirnov normality test. When normality distribution was not fulfilled, a logarithmic transformation of the data was performed (Sokal and Rohlf 1994). One-way ANOVA was calculated considering a 2 × 2 factorial design (2 land uses × 2 soil depths), followed by a Tukey's multiple test comparison at a confidence level of 95%. Then, and given that the samples for measuring water infiltration were fewer than those for evaluating the other variables, and that all variables were not similarly evaluated at both depths, the data were also summed (mg C ha^{-1}) and averaged (BD, soil moisture, pH, SOM, and SOC) to compare all variables including infiltration in relation to land uses. Relationships between variables were independently evaluated for each soil depth and land use by determining the Pearson correlation coefficients. All statistical analyses were performed using the software SPSS Statistics 22.0.

Results

Soil organic matter, soil organic carbon, and infiltration per land use

In the present study, the SOC and SOM relative content (%), C stocks (Mg ha^{-1}) and water infiltration were measured in livestock pasture and forest sites as supporting and regulating ecosystems services of mountain soils. Results showed that SOC and SOM (Figures 2A, 2B) differed significantly ($P = 0.009$ in both cases) between the 2 evaluated land uses. SOC was significantly lower in the livestock pasture (12.6 ± 0.79%) than in the forest (14.65 ± 0.58%). Contrary to SOC relative content, the stocks were not significantly different between land uses (Figure 2C). Similarly to SOC, SOM was found to be lower in the livestock pasture (21.7 ± 1.37%) than in the forest (25.7 ± 0.88%). In addition, infiltration was found to be twice as high in the forest (Figure 2D), and soil compaction was greater in the livestock pasture (1612.66 ± 52.21 MPa; Figure 3C) than in the forest (1551.38 ± 28.73 MPa). Similarly, BD was significantly higher ($P = 0.013$) in the livestock pasture (0.86 ± 0.25 g cm^{-3}; Figure 3A) than in the forest soils (0.73 ± 0.06 g cm^{-3}). Finally, the pH ($P = 0.000$; Fig. 3B) had a value of 6.0 (± 0.12) and 5.34 (± 0.05) in the livestock pasture and forest, respectively.

Soil organic carbon, soil organic matter, and infiltration by depth

Results indicated that soil depth is an important factor that influences the regulating ecosystem services in each

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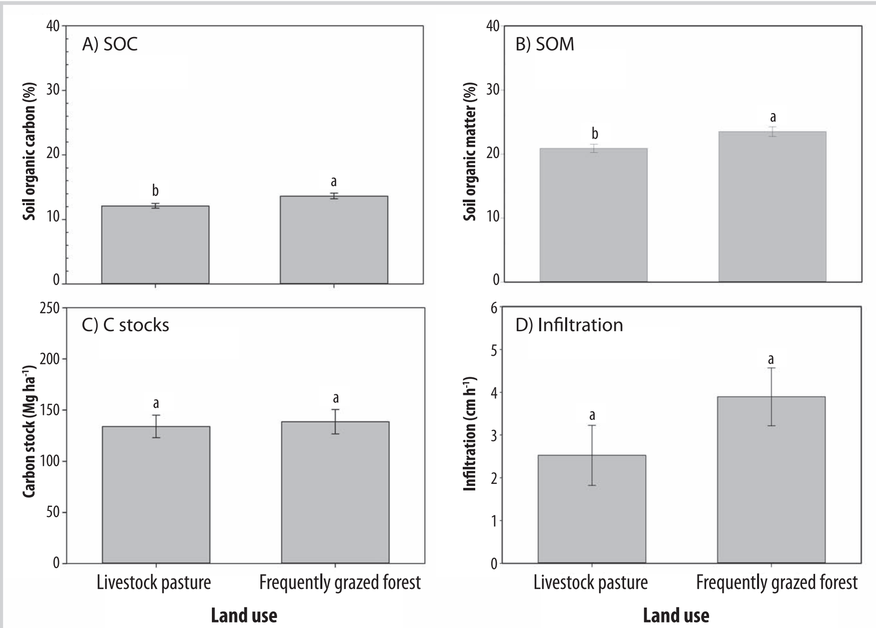
FIGURE 2 (A) Soil organic carbon, (B) soil organic matter, (C) carbon stocks, and (D) infiltration in soil under both land uses. Different letters indicate significant differences among land use means ($P \leq 0.05$).



land use. In this respect, SOC and SOM relative content (%) varied significantly according to soil depth and land use (Figure 4). For different soil depths of the same land use, significant differences ($P < 0.05$) were found in SOC relative content (%), with lower values at 5–25 cm (Figure 4A). There were also significant differences between the superficial layer of one land use and deeper soil of the other land use, with the same pattern of the lowest value in the deeper soil layer. SOM (Figure 4B) showed a significant difference between depths in the same land use with higher SOM in 0–5 cm soil layer than 5–25 cm. Differences between land use were recorded in the superficial soil layer with lower SOM in the livestock use.

With respect to C stocks (Mg ha^{-1}; Figure 4C), significant differences were recorded between the 2 depths in both land uses, with the C stocks triple the amount in the deeper layer of 5–25 cm in comparison to the surface layer of 0–5 cm (ca. 60 Mg C ha^{-1} in both land uses). Soil moisture (Figure 5A) was significantly lower in the layer of 5–25 cm (8.8 %) than in the surface layer in both land uses; meanwhile, BD (Figure 5B) was significantly greater in the layer of 0–5 cm in the livestock pasture (0.88 g cm^{-3}) than in the forest. The pH values were grouped at both soil depths. Significant differences in pH (Figure 5D) were found only between land uses; the livestock pasture was less acidic.

The relative content of SOC and SOM in addition to the C stocks, water infiltration, BD, and percentage moisture were related in different ways depending on soil depth and land use. In the livestock pasture, the Pearson correlation coefficient showed a significantly positive relationship between SOC and C stocks at both depths of 0–5 cm ($r = 0.728$) and 5–25 cm ($r = 0.800$), as well as between SOM and C stocks in the livestock soils (Table 1). The BD of livestock soil was negatively and significantly correlated with SOC and SOM relative content (%) in the soil layers of 0–5 cm ($r = -0.749$) and 5–25 cm ($r = -0.682$). Soil compaction in the livestock pasture also showed significant correlation with soil moisture in the soil layer of 5–25 cm ($r = 0.697$; Table 1). In the forest (Table 2), the BD was significantly related with C stocks (Mg C ha^{-1}) at both depths of 0–5 cm ($r = 0.779$) and 5–25 cm ($r = 0.955$), and water infiltration was inversely and significantly related ($r = -0.755$) with soil compaction.

Discussion

Livestock grazing in some natural ecosystems has affected the capacity of soils to provide a wide range of high-quality ecosystems services. In high mountain systems as well as in adjacent low-lying areas, soil fertility and soil health are of great importance to support other soil services (e.g., production, water flux, C storage). For this reason, the objective of the present study was to evaluate the relative content of SOC (and SOM), soil C stocks, and water infiltration under 2 land uses: livestock pasture (human-induced grassland) and *A. religiosa* forest in the PAFF of NT.

Effect of land use on soil organic carbon, soil organic matter, and infiltration

In the present study, SOC and SOM values were slightly lower in the livestock pasture (Figure 2A and 2B, respectively) than in the forest. These results are consistent with those reported by Cruz et al (2012) in zones near the present study area. But while Cruz et al found much higher differences in SOM content (27.1% at

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FIGURE 3 (A) Bulk density, (B) pH, (C) and soil compaction in soil under both land uses. Different letters indicate significant differences among land use means ($P \leq 0.05$).

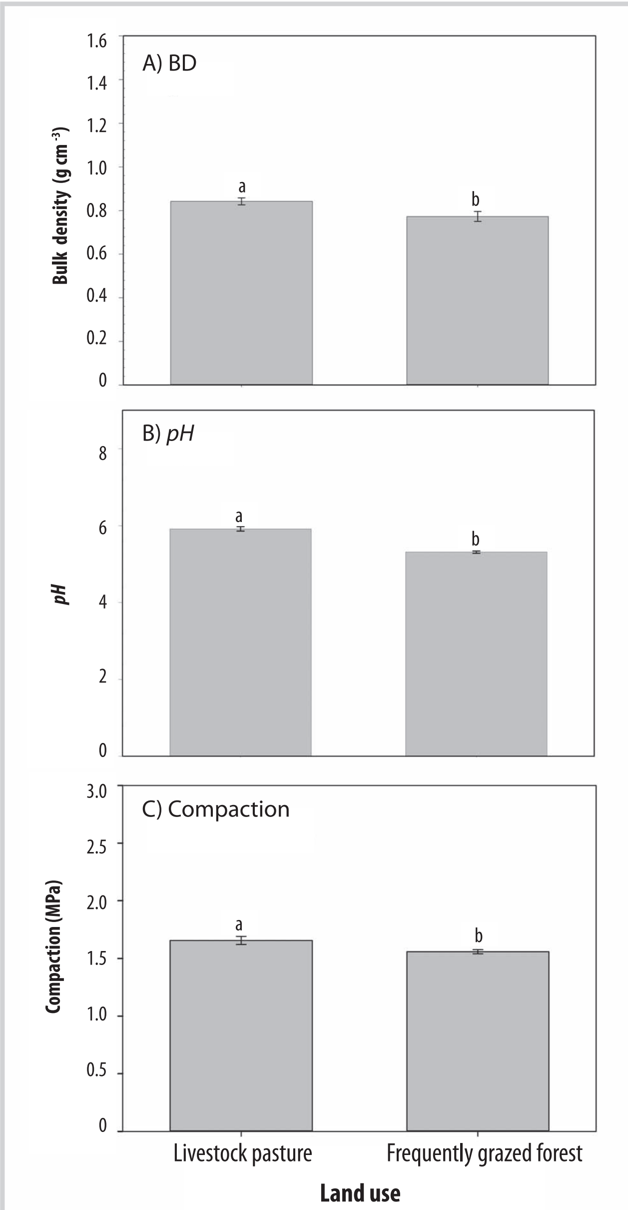
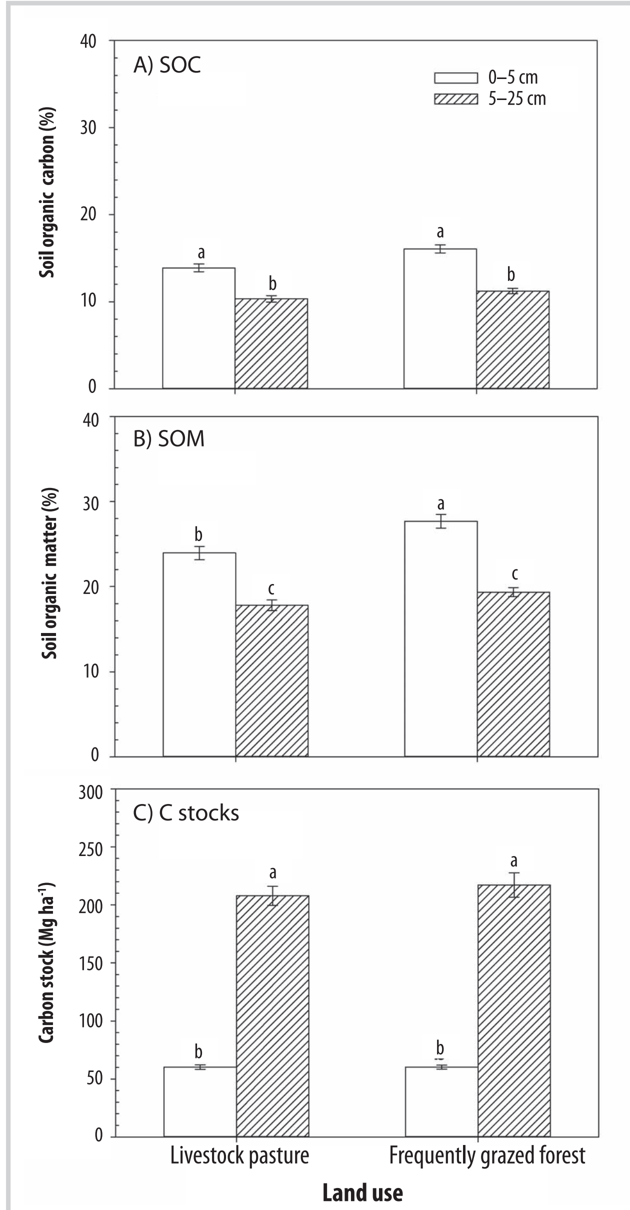


FIGURE 4 (A) Soil organic carbon, (B) soil organic matter, and (C) carbon stocks in 2 soil layers per land use. Different letters indicate significant differences among means ($P \leq 0.05$) of the interaction between soil depths and land uses.



10 cm of depth in forest soils *A. religiosa* versus 18.3% in grazed soils) and SOC (15.8% in forest versus 10.6% in grazed soils), the results of the present study showed only slight differences between forest and livestock grazing (Figure 3C). When considering SOC stocks per unit area (Mg C ha^{-1}), differences between land uses were not significant. This can partly be explained by the fact that C inputs and stabilization are very slow, and variation in C can generally be detected only after 10 to 15 years following land uses changes toward livestock (Swift 2001; Lal 2004). However, that would depend on soil type, livestock load, and vegetative cover type. Thus, both vertical and horizontal SOC distribution depend on plant functional types, i.e., grasses or forest trees, and their differences in SOM shoot/root allocation, with higher SOC in forest (50%) compared to grasslands (42%) in the upper 20 cm of soil (Jobbágy and Jackson 2000). Thus, in this study *A. religiosa* forest is characterized by a closed and shadowy canopy, which prevents the development of conspicuous shrubs and herbaceous strata and encourages abundant growth of lichens and mosses: these characteristics maintain lower temperatures and higher moisture levels, promoting the higher accumulation of SOM in the upper soil (Rzedowski 1978; Jobbágy and

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FIGURE 5 (A) Soil moisture, (B) bulk density, (C) pH, and (D) and soil compaction in soil under under both land uses. Different letters indicate significant differences among means ($P \leq 0.05$) of the interaction between soil depths and land uses.

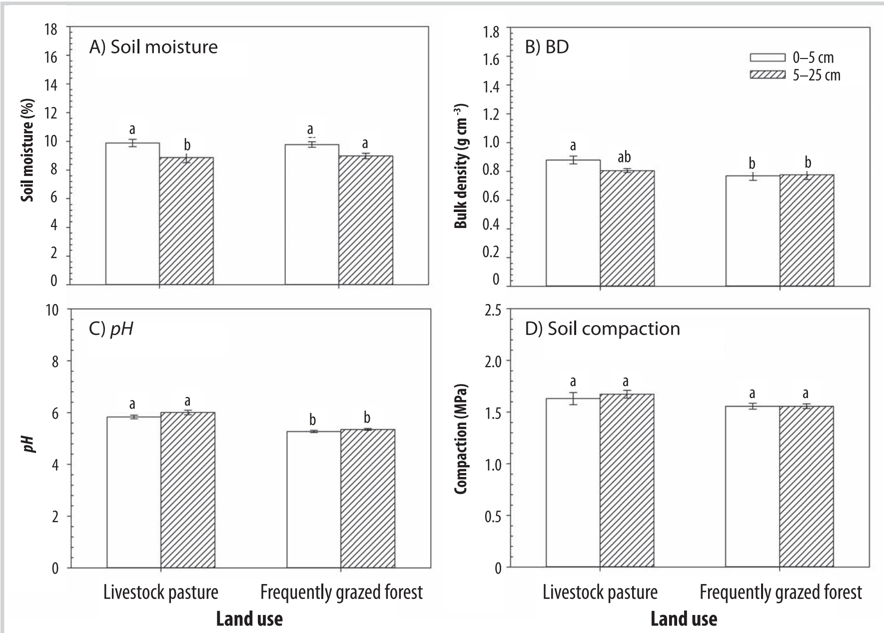

TABLE 1 Pearson's correlation matrix for supporting and regulating mountain soil services, as well as some physicochemical properties of livestock soils at 2 depths (0–5 and 5–25 cm).[a]

Variable	SOC (%)	C stocks (Mg ha^{-1})	Infiltration (cm h^{-1})	Compaction (MPa)	BD (g cm^{-3})	pH	Soil moisture (%)
Depth	0–5 cm						
SOC (%)	1						
C stocks (Mg ha^{-1})	**0.728***	1					
Infiltration (cm h^{-1})	−0.418	0.010	1				
Compaction (MPa)	0.176	−0.309	−0.543	1			
BD (g cm^{-3})	**−0.749***	−0.109	**0.723***	−0.537	1		
pH	−0.434	−0.283	0.620	0.011	0.269	1	
Soil moisture (%)	0.548	0.573	−0.041	−0.207	−0.210	−0.531	1
Depth	5–25 cm						
SOC (%)	1						
C stocks (Mg ha^{-1})	**0.800****	1					
Infiltration (cm h^{-1})	−0.383	−0.478	1				
Compaction (MPa)	−0.347	0.139	−0.159	1			
BD (g cm^{-3})	**−0.682***	−0.119	0.034	0.313	1		
pH	0.976	0.379	−0.547	−0.047	0.396	1	
Soil moisture (%)	−0.045	−0.016	−0.070	**−0.697***	0.123	0.368	1

[a] BD: bulk density; C: carbon; SOC: soil organic carbon.
*Significant at $\alpha = 0.05$ (2-tailed).
**Significant at $\alpha = 0.01$ (2-tailed).

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TABLE 2 Pearson's correlation matrix for supporting and regulating mountain soil services, as well as some physicochemical properties of forest soils at 2 depths (0–5 and 5–25 cm).[a)]

Variable	SOC (%)	C stocks (Mg ha^{-1})	Infiltration (cm h^{-1})	Compaction (MPa)	BD (g cm^{-3})	pH	Soil moisture (%)
Depth	**0–5 cm**						
SOC (%)	1						
C stocks (Mg ha^{-1})	−0.011	1					
Infiltration (cm h^{-1})	0.033	0.320	1				
Compaction (MPa)	−0.140	−0.422	**−0.755***	1			
BD (g cm^{-3})	−0.631	**0.779***	0.049	0.253	1		
pH	−0.464	0.359	−0.245	0.452	0.590	1	
Soil moisture (%)	0.583	−0.363	0.310	0.040	−0.593	−0.065	1
Depth	**5–25 cm**						
SOC (%)	1						
C stocks (Mg ha^{-1})	0.162	1					
Infiltration (cm h^{-1})	0.030	−0.200	1				
Compaction (MPa)	0.148	0.452	0.165	1			
BD (g cm^{-3})	−0.138	**0.955****	−0.201	0.212	1		
pH	−0.441	0.268	−0.413	0.347	0.400	1	
Soil moisture (%)	0.365	0.300	−0.057	0.538	0.195	0.457	1

[a)] BD: bulk density; C: carbon; SOC: soil organic carbon.
*Significant at $\alpha = 0.05$ (2-tailed).
**Significant at $\alpha = 0.01$ (2-tailed).

Jackson 2000; Rzedowski and Rzedowski 2001). At the same time, in the grasslands of the study site, grasses go through all stages of development and then senesce; then litter from senescent grasses is incorporated into the soil, suggesting that the livestock load in the study site is low.

Another study found a greater transference and accumulation of SOC in grazed alpine soils than in conserved alpine grasslands and even native forest soils (8.3 Mg ha^{-1} in grazed soils versus 2.1 Mg ha^{-1} in forest soils) (Andrade-Castañeda et al 2014). On the other hand, the significant reduction in SOC relative content (Figure 3A) and the greater BD in the livestock pasture of the present study indicate that livestock grazing simultaneously impacted both variables; however, the differences in the C stocks between both land uses are not clear because of the compensatory effect of BD, which is fundamentally related to SOC relative content (Walter et al 2016). In the surface soil layer (5 cm) of livestock soils of this study, high SOC (%; Figure 4A) and BD (Figure 5B) were recorded. According to Amésquita and Pinzón (1991), greater livestock loads lead to an increase in BD in the first 15 cm of soil. Moreover, several other studies (Amésquita and Pinzón 1991; Klumpp et al 2009; Keller and Hakansson 2010) have found a decrease in soil porosity as a result of livestock grazing and, as a consequence, a decrease in the flow of water from the surface soil layer to deeper layers. In the present study, the flow of water through infiltration was 1.6 times lower in livestock pasture soil (Figure 2D) than in forest soil. Accordingly, the regulating ecosystem service of soil C storage has not been significantly impacted after 40 years of livestock grazing, despite a corresponding significant reduction in SOM content and increased soil compaction (greater BD). This could be a result of the capacity of Andosol soils to recover from stressful events such as animal trampling, having higher resilience as confirmed *in situ* during fieldwork and in other studies (Martínez et al 2008; Dörner et al 2009).

Vertical variability of soil organic carbon, soil organic matter, and infiltration

Relative contents of SOC and SOM, such as C stocks at different depths (Figure 4) varied vertically between the livestock pastures and forestland. In both the livestock pasture and forest, significantly greater relative content of SOC and SOM were recorded at a depth of 0–5 cm than at 5–25 cm. However, overall, the average SOM values were lower in the livestock land use.

Contrary to the results for SOC relative content (%), C stocks were significantly lower in the surface soil layer (0–5 cm) and contained only 22% of the C stored in the first 25 cm of soil in both land uses of the *ejido* of Agua Blanca. The first 25 cm of soil is highly important in the conservation and storage of organic C in Andosol soils; in addition, this soil layer is significant for SOM accumulation and as an interface enabling the flow of water to greater depths. Changes in the upper layer are slow, according to Geissen et al (2009), who found that changing land use did not lead to the chemical degradation of soil, even after 15 years; while physical properties such as BD can experience drastic changes, as shown by high soil compaction at soil depths of 0–20 and 20–40 cm in permanent pastures. In line with the latter, Fernández-Rebollo et al (2015) and Bell et al (2011) reported that the trampling of sheep and goats only affects the first 10 cm of the surface soil layer. Hewins et al (2018) conclude that long-term livestock grazing may enhance SOC concentrations in shallow mineral soil and affirm that climate rather than grazing is the key modulator of soil C storage across northern grasslands.

Finally, in the present study, the evaluated variables were more stable between the soil layers in the forest, where C stocks were significantly related with BD. An inverse relationship between soil compaction and water infiltration also was found. Greater variability in evaluated variables was encountered between the soil layers of livestock soils with compaction, SOM, and SOC lower in the surface layer.

Environmental perspectives and implications

Impacts of livestock grazing on soils of the Agua Blanca *ejido* in NT, where extensive livestock ranching is practiced, indicate that soils can retain their capacity to store C and conduct water to deeper soil layers under certain conditions. This finding confirms that extensive livestock ranching maintains certain soil functions and ecosystem services in the long term in this region and possibly in other regions and ecosystems around the world (Piñeiro et al 2010). In zones with conditions similar to those of the present study area, economic reimbursement schemes compensate livestock ranchers for their contribution to maintaining ecosystem services and public environmental goods (Uribe et al 2011). Ultimately, the goal of such schemes is to encourage farmers to maintain or adopt sustainable grazing systems and to protect remaining forest ecosystems. In some respects, promoting extensive livestock ranching and forest conservation at the same time may seem contradictory, but the present study supports the merging of these perspectives. Nevertheless, critical and fundamental variables for guiding livestock management strategies such as SOM and BD should be further studied and identified to enable greater equilibrium between the needs of livestock ranchers and the maintenance of supporting and regulating ecosystem services of mountain soils along the elevational gradients of the high mountain systems.

Conclusions

In this study, results suggest that extensive livestock ranching in the *ejido* of Agua Blanca did not significantly affect some quality parameters of soils, despite more than 40 years of ranching activity. In particular, it did not affect the capacity of soils to store C and infiltrate water, because SOM and SOC content were compensated by an increase in bulk density. Previous research has argued either in favor of sustainable livestock ranching or in favor of the conservation of soil resources; the present research supports a convergence of the two recommendations. The results of this study showed that foraging resources might be sustainably used without notably affecting some of the ecosystem services provided by soil. In fact, livestock farmers could be eligible to receiving compensation under payment schemes for ecosystem services. However, the direct and indirect mechanisms that regulate soil ecosystem services should be further studied to better understand their impact on the quantity and quality of these ecosystem services along the elevational gradients. Additionally, attention should be placed on particular environmental conditions on high mountains like the Nevado de Toluca volcano.

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