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# Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil

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ABSTRACT

Grazing by domestic ungulates can have substantial impacts on forests in arid and semi-arid regions, possibly including severe loss of carbon from the soil. Predicting net livestock impacts on soil organic carbon stocks remains challenging, however, due to the dependence on animal loads and on soil and environmental parameters. The objective of this study was to better understand grazing effects on soil organic carbon in seasonal tropical dry forests of north-eastern Brazil (Caatinga) by quantifying carbon stocks of the upper soil profile (0–5 cm depth) and greater soil depths (>5 cm depth down to bedrock) along a gradient of grazing intensity while accounting for other influencing factors such as soil texture, vegetation, landscape topography, and water availability. We analysed soil organic carbon, soil clay content, altitude above sea level, soil depth to bedrock, distance to the nearest permanent water body, species diversity of perennial plants and aboveground biomass on 45 study plots located in the vicinity of the Itaparica Reservoir, Pernambuco, Brazil. Livestock (mainly goats and cattle) are unevenly distributed in the studied ecosystem, thus grazing intensity was accounted for based on the weight of livestock droppings per square metre and classified as no or light, intermediate, or heavy grazing. The mean soil organic carbon in the area was 16.86 ± 1.28 Mg ha$^{-1}$ C with approximately one-quarter found in the upper 5 cm of the soil profile (4.14 ± 0.43 Mg ha$^{-1}$ C) and the remainder (12.57 ± 0.97 Mg ha$^{-1}$ C) in greater soil depths (>5 cm). Heavy grazing led to significantly lower soil organic carbon stocks in the upper 5 cm, whereas no effect on soil organic carbon of the soil overall or in greater soil depths was detectable. The soil's clay content and the altitude proved to be the most relevant factors influencing overall soil organic carbon stocks and those in greater soil depths (>5 cm). Our findings suggest that grazing causes substantial release of carbon from Brazilian dry forest soils, which should be addressed through improved grazing management via a legally compulsory rotation system. This would ultimately contribute to the conservation of a unique forest system and associated ecosystem services.


## 1. Introduction

The accelerated increase in atmospheric $CO_2$ concentration is expected to cause severe global warming within the 21st century (IPCC, 2013). This trend can be slowed by combining a reduction in anthropogenic $CO_2$ emissions with the removal of $CO_2$ from the atmosphere (IPCC, 2013). Terrestrial ecosystems may work as efficient carbon sinks, which can significantly reduce atmospheric $CO_2$ concentration if properly managed (Boddey et al., 2012; Schils et al., 2008). Soils play a major role in the global carbon cycle—after the lithosphere and the oceans, the soil system is the third largest reservoir of C and accounts for approximately 2400 Pg C in the upper 2 m (Kirschbaum, 2000). In addition, the turnover rate of SOC[1] is known to be much lower than that of biomass carbon in vegetation, which highlights the relevance of soils as long-term carbon sinks (Post and Kwon, 2000).

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[1] SOC—soil organic carbon.

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Land-use change can cause a pronounced reduction in SOC stocks (Boddey et al., 2012; Post and Kwon, 2000; Schimel et al., 2001), albeit increases in SOC have also been reported (e.g., Boddey et al., 2012; Guo and Gifford, 2002). Carbon dioxide emissions through altered land use were estimated at 2–4 Pg $y^{-1}$ C during the 1990 s (Schimel et al., 2001). Consequently, scientific interest in the potential of different land-use options, including grazing regimes (e.g., Follett and Reed, 2010; Giongo et al., 2011), to foster C sequestration and to mitigate global warming has grown in recent decades.

Grazing may affect carbon sequestration in soils in different ways and directions. Herbivores such as cattle, sheep and goats reduce the amount of organic matter available for the formation of SOC by consuming and respiring aboveground biomass (e.g., Oesterheld et al., 1999; Piñeiro et al., 2010). Moreover, grazing may alter plant species composition (Manzano and Návar, 2000) and in some cases may reduce species diversity (Reeder and Schuman, 2002). This particularly holds for dry forests that can be severely impacted by grazing (Säumel et al., 2011; Stern et al., 2002). Studies reviewed by Piñeiro et al. (2010) revealed that grazing can favour species with lower net primary production, which may decrease the carbon input to the soil. However, the opposite can also occur when grazing favours highly productive species. In addition, root growth, and thus C input to the soil, may be enhanced by grazing (Derner et al., 2006; Piñeiro et al., 2010). A greater diversity, which may be a consequence of light grazing (e.g., Hart, 2001), often makes plant communities more productive due to species complementarity in resource use and positive interactions (Cardinale et al., 2007; Tilman et al., 2012).

SOC storage in soils is known to be related to other factors such as soil texture (e.g., Hassink, 1997; Rieger et al., 2014)—with a positive correlation of clay and silt concentrations to SOC (e.g., Burke et al., 1989; Jobbágy and Jackson, 2000)—and water availability, which can be lowered through herbivore trampling by compaction of macro-pores (Piñeiro et al., 2010). It has also been argued that losses of SOC can be regained by optimised management practices (Lal, 2004). However as SOC is related to soil texture, Wiesmeier et al. (2015) found that in degraded soils erosion leads to a loss of fine particles with an irreversible loss of the SOC sequestration potential.

Nitrogen availability, particularly the percentage of N-fixing legumes in vegetation, also plays a role in SOC generation (Piñeiro et al., 2010). Although the general underlying processes of higher carbon sequestration under N-fixing species still remain unexplained, Resh et al. (2002) found that N-fixing trees are capable of sequestering various types of soil carbon compared to non-N-fixers.

Due to the interplay of different drivers, grazing may cause a net increase or decrease in SOC stocks (e.g., Piñeiro et al., 2010; Wu et al., 2012). Generally consistent trends in grazing effects on SOC stocks include (1) a higher root content at grazed sites under very dry or wet conditions but lower root content at sites with intermediate precipitation (approximately 400–850 mm) and (2) increased bulk density on grazed sites (Piñeiro et al., 2010). Still, it remains challenging to reliably predict grazing impacts on an ecosystem's carbon balance.

The Caatinga in semi-arid north-eastern Brazil with an estimated cover of 600,000–900,000 $km^2$ (Sampaio, 1995), is one of the largest seasonal tropical dry forests of the world (Miles et al., 2006). This region is also one of the most densely populated semi-arid areas (Salcedo and Menezes, 2009) with about 27 million inhabitants (MMA, 2011). At present, about 46% of the area originally covered by Caatinga has already been deforested (MMA, 2011; Tiessen et al., 1998). Since the 18th century, livestock rearing has spread widely across the entire region (Sampaio, 1995). Nowadays, almost all forests are grazed to some extent by goats along with cattle, sheep (Tiessen et al., 1998) and donkeys (personal observation). As a consequence, many areas of the native Caatinga are severely degraded or even desertified due to deforestation as a result of slash-and-burn activities and overgrazing (Menezes et al., 2012). This often goes along with reduced soil carbon levels (Tiessen et al., 1998). As Caatinga soils are generally low in SOC content, sustainable agricultural productivity and food security depend on efficient soil conservation measures in the area (Maia et al., 2007; Tiessen et al., 1998).

Although numerous studies have analysed the impact of grazing on SOC dynamics, different grazing intensities have rarely been considered (Cierjacks and Hensen, 2004; Cierjacks et al., 2008), and knowledge of the mechanisms by which grazing affects SOC remains limited (Follett and Reed, 2010; Mayes et al., 2014). Moreover, the Caatinga is one of the least studied and most neglected Brazilian ecosystems (MMA, 2011; Santos et al., 2011). Consequently, more information on the impacts of grazing on these dry forest ecosystems is urgently required for a better understanding of their possible carbon sink functions and for appropriate land-use decisions.

The aim of this study was to assess the impact of different livestock grazing intensities on SOC stocks in the Caatinga located in the vicinity of the Itaparica Reservoir, Pernambuco, Brazil, while taking into consideration the soil's clay content, water availability, and vegetation. The hypotheses of this study were as follows: (1) SOC will decrease, particularly in the upper soil profile (0–5 cm in depth), at higher grazing intensities and (2) the inclusion of clay content, distance to the nearest permanent water body, vegetation parameters (aboveground biomass, perennial plant species diversity), depth to bedrock and altitude[2] will significantly improve statistical model predictions. Based on the results, we derive recommendations for adapted land-use practices which foster SOC storage in dry forests of north-eastern Brazil.

## 2. Materials and methods

### 2.1. Study area

The study area is located in semi-arid north-eastern Brazil. The plots were established in areas in the vicinity of the Itaparica Reservoir, within the municipalities of Itacuruba (city: 8°43′39.4″S, 38°41′05.2″W) and Floresta (city: 8°36′08.9″S, 38°34′15.4″W), Pernambuco. The Itaparica Reservoir is located in the sub-medium basin of the São Francisco River and is one of nine reservoirs along the São Francisco used for flood regulation and hydroelectric power generation (Romano and Garcia, 1999). The reservoir extends through two great landscape units, the Depressão Sertaneja (interior lowlands) and the Jatobá–Tucano Sedimentary Basin (Araújo Filho et al., 2013). A mosaic of degraded and recovering Caatinga dry forests covers more than 80% of the area (Schulz et al., unpublished). Vegetation varies greatly in height, density, and main life form (arboreal, shrubby–arboreal and shrubby). The main plant families of Caatinga forests are Fabaceae, Euphorbiaceae and Cactaceae (Tavares et al., unpublished; Sampaio, 1995; Fig. 1).

The climate is semi-arid with a pronounced dry season interrupted by a rainy season between November and April. The rainfall within the Caatinga region is generally irregular (Sampaio, 1995). In Itacuruba, the average annual rainfall over the last 25 years has been 391 mm, with a minimum of 88 mm and a maximum 748 mm (Sousa et al., 2013). Mean annual temperature ranges from 23 to 27 °C with high potential evapotranspiration between 1500 and 2000 mm per year (Sampaio, 1995). The combination of

[2] altitude above sea level.