



Grazing, forest density, and carbon storage: towards a more sustainable land use in Caatinga dry forests of Brazil

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Abstract

Grazing is the main land use in semi-arid regions of the world, and sustainable management practices are urgently needed to prevent their degradation. However, how different grazing intensities affect forest density and ecosystem functions is often not sufficiently understood to allow for management adaptations that safeguard the ecosystems and their functions in the long run. We assessed the aboveground carbon stocks and plant densities along a grazing gradient in the semi-arid seasonally dry tropical forest of north-eastern Brazil (Caatinga). On 45 study plots, we analysed the aboveground carbon stocks of the vegetation and determined forest density and recruitment as well as the population structure of the most abundant tree species. Grazing intensity was accounted for based on the weight of livestock droppings and classified as low, intermediate, or high. Mean aboveground carbon stock was $15.74 \pm 1.92 \text{ Mg ha}^{-1}$ with trees and shrubs accounting for 89% of the total amount. Grazing at high intensities significantly reduced aboveground carbon stocks of herbs but not of other plant functional types. Instead, aboveground carbon stocks of trees and shrubs were negatively related to altitude above sea level, which is a proxy for reduced water availability along with lower anthropogenic impact. The population structure of the most common tree species was characterised by abundant recruitment, irrespective of grazing, whereas the recruitment of less frequent woody species was negatively affected by grazing. Overall, our data imply that grazing and forage management need to be adapted, including the reduction of free-roaming livestock and storage of fodder, to maintain carbon storage and forest density.

Keywords Aboveground carbon stocks · Seasonally dry tropical forest · Ecosystem function · Semi-arid · Goats · Grazing intensity

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Introduction

Carbon sequestration and storage in aboveground biomass of terrestrial ecosystems is a pivotal ecosystem function. Forest ecosystems can work as carbon sinks, and tropical forests provide the largest global aboveground carbon stocks (AGCS), having more aboveground biomass than temperate and boreal forests (Köhl et al. 2015; Pan et al. 2011). Currently, more than 50% of the ice-free area of the earth has been affected by human activities that have substantially decreased the global forest cover (Hurt et al. 2011) and caused a net release of carbon (Pan et al. 2011). To counteract this process, protection and proper management of existing forests along with reforestation measures are needed.

Much of the work on carbon stocks has concentrated on the humid tropics, with tropical dry forests receiving much less scientific attention (but see Menezes et al. 2012; MMA 2010; Schulz et al. 2016). North-eastern Brazil's Caatinga is one of the largest seasonally dry tropical forests of the world with an area of about 780,000 km² (Schulz et al. 2017). About 27 million people live in the region (MMA 2011), which also makes it one of the world's most densely populated semi-arid areas (Salcedo and Menezes 2009). In 2011, the Brazilian Ministry of Environment (MMA 2011) published that about 46% of the area originally covered by Caatinga vegetation has been deforested. Together with slash-and-burn agriculture, overgrazing by introduced ungulates is considered the main driver of deforestation within the Caatinga (Leal et al. 2005) and has led to severe degradation or even desertification of many areas (Menezes et al. 2012). In addition, fuel wood extraction contributed to the degradation of the Caatinga (Albuquerque et al. 2008; Sampaio 1995), as firewood is the second most important energy source (Kengen et al. 2000). Nowadays, almost the entire area is grazed to some extent by cattle as well as goats, sheep (Tiessen et al. 1998), and donkeys (Marinho et al. 2016). However, current studies indicate an increase in forest cover in recent decades (Aide et al. 2012; Menezes et al. 2012; Schulz et al. 2017). Whether such trends are related to changes in grazing regimes, the abandonment of slash-and-burn agriculture or climatic changes remains largely unknown.

Grazing may directly affect AGCS as animals consume biomass. Moreover, repeated browsing of woody species, which is typical for goats, may reduce successful recruitment of trees (e.g. Bergmeier et al. 2010) and lead to over-aged stands and, in the long run, to stand opening (Cierjacks and Hensen 2004). Other livestock species such as cattle may, in contrast, create safe sites for the germination and establishment of trees and hence foster regeneration (Cierjacks et al. 2008). Given the different

feeding behaviours of livestock and the different responses and palatabilities of particular plant species, grazing may also alter plant species composition and vegetation structure (Fleming et al. 2016; González-Pech et al. 2015; Manzano and Návar 2000) with indirect effects on AGCS. Additionally, land clearing due to slash-and-burn activities or timber harvesting (e.g. Junior et al. 2013; Kauffman et al. 1993) leads to canopy opening that may subsequently affect the vegetation structure.

Although numerous studies have analysed the impact of grazing on carbon stock dynamics (e.g. Noretto et al. 2006), it is crucial to assess different grazing intensities to disentangle the underlying mechanisms and to guide appropriate land use decisions (Bailey and Brown 2011; Cierjacks and Hensen 2004; Cierjacks et al. 2008; Steffens et al. 2008). This is particularly true of land use adaptations in Caatinga ecosystems, due to their large extent and pronounced biodiversity (Leal et al. 2005). While the significance of the carbon stocks in the Caatinga has been acknowledged (e.g. Menezes et al. 2012), studies of how grazing affects carbon cycling in such systems remain scarce (Schulz et al. 2016). This study aims to fill this gap by analysing the effect of current grazing regimes on AGCS of different plant functional types along with forest density (including trees, shrubs, and cacti) within the Caatinga vegetation. As a model region, we worked in the vicinity of the Itaparica Reservoir, Pernambuco, Brazil, where an ample gradient from heavily grazed areas to less grazed preserved Caatinga areas can be found. A previous study conducted in this area revealed a negative impact of grazing intensity on soil organic carbon stocks (Schulz et al. 2016). However, altitude proved to be among the most important parameters influencing soil organic carbon stocks, possibly due to the underlying differences in water availability.

The hypotheses of the study were as follows:

(1) Grazing generally negatively affects aboveground carbon stocks. We expect a negative effect on the carbon stocks of smaller trees and shrubs due to grazing on woody parts. In contrast, the effect on emergent trees, cacti, and bromeliads is expected to be low due to the large size and the defence through thorns and spines, respectively. The highest effect of grazing is expected for herbaceous plants, although with the least overall impact. (2) Grazing negatively affects forest density and the recruitment of tree and shrub species in Caatinga vegetation. (3) Altitude is expected to show a negative correlation with aboveground carbon stocks, due to reduced water availability at higher elevations (Winter 2001), although a higher human impact is expected at low elevations (da Silva et al. 2014), especially near permanent streams (Revermann et al. 2016).

Based on our results, we derive recommendations for an adapted land management practice which will foster the carbon storage potential of dry forests of north-eastern Brazil.

Materials and methods

Study area

The study area is located in semi-arid north-eastern Brazil in the vicinity of the Itaparica Reservoir on the São Francisco River. Study plots were established 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 state. With a length of 2914 km, the São Francisco River is the major river of eastern South America, the fourth largest river system of the continent and the largest river located entirely within Brazil. The São Francisco River has been called the “river of national unity,” for it has long served as a line of communication between Brazil’s maritime and western regions and between the northeast and the southeast. The Itaparica Reservoir is one of the three major reservoirs along the São Francisco River used for flood regulation, hydroelectric power generation, irrigation farming, and drinking water supply (Braga et al. 2012; Romano and Garcia 1999). The construction of the dam was completed in 1988, and the subsequent filling of the reservoir forced about 10,400 households to migrate with a part of the population now living in irrigated areas within the former Caatinga forest (Cierjacks et al. 2016; Hagel et al. 2014), often with poor soils.

The native vegetation type, which still covers more than 80% of the study area, is Caatinga seasonally dry tropical forest (Schulz et al. 2017). These forests typically comprise a more-or-less continuous tree and shrub layer (average height in our study area ca. 2 m) with scattered emergent trees (tree height > 4 m), cacti, bromeliads, and, depending on rainfall events, a layer of herbaceous species. The most important plant families of Caatinga forests are Fabaceae, Euphorbiaceae, Cactaceae, which account for a major part of AGCS, and Malvaceae (Tavares et al. 2016; Sampaio 1995). *Poincianella pyramidalis* (Tul.) L.P. Queiroz (catingueira), *Poincianella microphylla* (Mart. ex G. Don) L.P. Queiroz (catingueira rasteira), and *Aspidosperma pyriforme* Mart. (pereiro) were the most abundant tree species in our study area. In total, we found 61 woody species of which at least 9 are known to be unpalatable for livestock (see Online Resource 1 for complete species list of woody species).

The climate is semi-arid with a pronounced rainy season between November and April. Rainfall is generally irregular with severe droughts occurring every 40–50 years (Sampaio 1995). The last drought in the study region started in 2010 and lasted until 2013. In Itacuruba, where climate data for the last 25 years are available, the average annual rainfall is 391 mm (Sousa et al. 2013). Yet, data of an associated study suggest that the precipitation rate is highly variable across the study

area (Guschal et al. unpublished). Mean annual temperature ranges from 23 to 27 °C with high potential evapotranspiration, between 1500 and 2000 mm per year (Sampaio 1995).

The geomorphology of the Caatinga area is characterised by smooth elevations between 300 and 500 m and few higher mountains and plateaus (900–1000 m; Sampaio 1995). Study plots were established in a minor range of 307 and 397 m. Despite a higher water availability at lower elevations, we do not expect pronounced climatic changes along the altitudinal gradient. Thus, we consider altitude in our study as a proxy for water availability with lower areas implying closer proximity to rivers with higher water availability (Winter 2001), and—due to a better accessibility—higher probability of recent and historic anthropogenic disturbances. To disentangle water availability effects from anthropogenic disturbance effects, we also considered the distance to the next farm or city in our study. Soils in the area are predominantly shallow, sandy, and rocky (Schulz et al. 2016) and have been classified as Planosols and Luvisols interspersed with Regosols and Leptosols (following the FAO classification system; Embrapa 2001a, b; Torres and Santos Pfaltzgraff 2014).

Land use

Access to water is generally limited, and irrigation farming is consequently only feasible in a few areas adjacent to the reservoir or major water courses (see Cierjacks et al. 2016; Schulz et al. 2017). Accordingly, the main land use type in the study area is livestock farming, mainly of small ruminants (Sampaio 1995; personal observations). The stocking densities reported by farmers who kept their animals in fenced areas with a rotating pasture system were as high as 2.3 livestock units ha⁻¹ (Schulz et al. 2016). Such values are substantially higher than the carrying capacity of the forests, which should not exceed 0.07–0.1 livestock units ha⁻¹ (Tiessen et al. 1998) when animals are kept only in fenced areas, and also higher than mean stocking densities observed in other Caatinga regions (e.g. 1.7 small ruminants ha⁻¹ in Tauá, Ceará; Schneider et al. 2012). Some farmers allow their livestock to roam freely in unfenced areas, particularly during periods of drought, to enlarge the grazing area. Moreover, the roaming behaviour of grazing animals is unknown. Hence, true stocking density and grazing intensities could not be inferred from the farmers’ information for most of the study area. Therefore, we used animal faeces weight per square metre (hereafter referred to as “grazing intensity”; Cierjacks and Hensen 2004; Schulz et al. 2016) as the indicator of recent animal presence and stocking density (Allen et al. 2011). In addition to uncontrolled animal browsing, cattle and sheep are fed with forage grass along with pods of the exotic tree species algaroba (*Prosopis juliflora* (Sw.) DC.). Especially during droughts, livestock are also fed with shoots of bromeliads and cacti collected in the dry forests (personal observation).

Study design

In 2012, we randomly established 45 study plots ($20 \times 20 \text{ m}^2$) within the Caatinga forest of which 30 were located within the municipality of Itacuruba and 15 in Floresta. Two stratification criteria were used to cover wide gradients of grazing intensity and water availability (for more details, see Schulz et al. 2016). (1) Plots were classified into three different grazing intensity classes based on a first visual assessment: heavy grazing intensity (plots located in fenced areas), intermediate grazing intensity (plots located in unused Caatinga forest but with visible signs of grazing such as trampled paths and livestock faeces), and preserved Caatinga (areas without clear signs of grazing). (2) The water availability classes comprised plots located at the lakeshore within 5 m of the high water level, plots along temporary water sources, and plots without any sign of surface water in the vicinity. A minimum of three plots was established for each combination of stratification criteria (45 plots overall) to obtain a balanced study design and a more or less even plot distribution across the study area (see Online Resource 2 for plot distribution across the study area and Online Resource 3 for plot examples). However, due to a high water availability in the proximity of the reservoir, the lakeshore is naturally used as farmland and attracts livestock in the unused Caatinga. Hence, the combination of permanent water and low grazing intensity did not exist.

The minimum distance between a plot and a road was 200 m, while all plots were located at least 300 m from each other, usually covering a distance of some kilometres. The position and altitude of each plot were determined using a handheld GPS (Garmin eTrex 30). The distance to the nearest city and farm was determined using satellite images provided by Google Earth (2013).

The final grazing intensities per plot used for statistical analyses were quantified using livestock faeces weight (Schulz et al. 2016). On each plot, six permanent subplots (each $2 \times 2 \text{ m}^2$) were established, and all faeces (goat/sheep, cow, donkey/horse) were collected, dried, and weighed twice (at the beginning of the study in 2012 and about 7 months later in 2013). Due to the similar values at both collection times, with a highly significant correlation ($r^2 = 0.87$), we used the mean dry weight of both to reclassify the plots according to their grazing intensity, as follows: (1) $< 5 \text{ g m}^{-2}$ = low grazing intensity, (2) $5\text{--}20 \text{ g m}^{-2}$ = intermediate grazing intensity, and (3) $> 20 \text{ g m}^{-2}$ = high grazing intensity (see Schulz et al. 2016 for further details). As we found a high correlation of faeces weight between two consecutive years with highly varying precipitation, we expect similar long-term patterns of animal presence in the area irrespective of the season and year (including 2014 when the herbaceous biomass was assessed). Goats are the main grazers within our study area, and hence, goat faeces were the most frequently collected faeces type (data not shown) while cow and donkey/horse faeces occurred

rather scarcely and were heterogeneously distributed across the study area. Consequently, analysing all faeces types together revealed the same effects on aboveground carbon stocks as goat faeces alone. We therefore included the faeces of all animal types together in the statistical analyses.

As a further grazing indicator, we recorded the number of woody plants with clear traces of grazing per plot ($20 \times 20 \text{ m}^2$). Plant damage and mean faeces weight were significantly positively related (GLM, $p = 0.0053$) which supports the assumption that faeces weight and grazing impact are positively related.

Aboveground carbon stock determination

The aboveground biomass was assessed separately for woody (including bromeliads) and herbaceous plants. The biomass of woody species and the long-term effect of grazing and browsing on woody species were evaluated on one $10 \times 10 \text{ m}^2$ subplot per plot using a non-destructive approach following Sampaio and Silva (2005). For all individuals with a diameter at ground level (DGL) $> 3 \text{ cm}$, we measured the circumference at ground level (Sampaio and Silva 2005). When branching occurred, all branches were measured individually even if the DGL of the particular branch was $< 3 \text{ cm}$ (Sampaio and Silva 2005). Then, the area for each branch was calculated and summed to yield a single basal area for each individual, assuming a circular shape of each branch. The basal area was used to calculate the resulting DGL (Cierjacks et al. 2008). In addition, plant height was measured from the top of the crown to ground level or, when plants showed a pronounced skewness, along the main growth axis. The biomass of each perennial plant individual was estimated using allometric equations provided by Sampaio and Silva (2005) and Sampaio et al. (2010) based on DGL. In cases where the equations required diameter at breast height, DGL was converted following Sampaio and Silva (2005).

In our study area, the tree species *Aspidosperma pyrifolium* is mostly characterised by a dwarfish growth compared to other Caatinga sites (personal observation). To account for this particular growth form, 30 individuals of *A. pyrifolium* were harvested, covering the common range in DGL values and heights found in the study area. For each individual, the perimeter at ground level and total height were measured in the field. Each tree was then cut at the base and if necessary cut into pieces for transportation. New equations were also developed for three cacti species. We measured crown projection area, DGL, or diameter of the thickest part along with height and collected 20 individuals of the common *Tacinga inamoena* (K.Schum.) N.P.Taylor & Stuppy (quipá), three individuals of the rarer *Tacinga palmadora* (Britton & Rose) N.P.Taylor & Stuppy (palminha), and three individuals of *Melocactus zehntneri* (Britton & Rose) Luetzelb.

A minimum of 15 individuals of each of the three bromeliad species *Bromelia laciniosa* Mart. ex Schult. & Schult.f., *Encholirium spectabile* Mart. ex Schult. & Schult.f., and *Neoglaziovia variegata* (Arruda) Mez were also collected. All plant samples were brought to the laboratory, dried at 55 °C to constant weight (at least 4 days), and afterwards weighed to determine the dry biomass. Allometric equations for *A. pyrifolium*, *T. inamoena*, *T. palmadora*, and *M. zehntneri* were developed following Sampaio and Silva (2005; see Online Resource 4 for equations). For bromeliads, the mean weight per rosette was calculated, which proved to be an easy and precise method (see Online Resource 4). The total biomass of bromeliads per plot was assessed according to the number of rosettes per subplot.

The biomass of herbaceous species was assessed twice on two 2 × 2 m² subplots per plot: once, under drought conditions in 2013 and a second time during the rainy season in 2014. Due to time constraints, the second data collection campaign was carried out on only 39 of the 45 plots. For biomass assessment, all herbaceous individuals in the subplot were harvested, dried, and weighed.

Allometric biomass and oven-dry biomass were converted into carbon stocks by multiplying by 0.5 (e.g. Cierjacks et al. 2010; Krankina and Harmon 1995; Peichl and Arain 2006). Carbon stocks of woody species were calculated per individual and then transformed to Mg per hectare. We calculated AGCS overall and for each plant functional group (emergent trees, trees and shrubs, cacti and bromeliads, and herbs) as each group is expected to be affected differently by grazing.

Allometric equations for large individuals are seldom developed as it would require the cutting of rare large trees. Hence, Sampaio and Silva (2005) stated that, for individuals with DGLs > 30 cm, biomass is likely to be overestimated. However, we included all individuals with DGL > 30 cm in our calculations of carbon stocks per hectare except for one individual of *Commiphora leptophloeos* (Mart.) J.B. Gillett due to its large size (diameter at ground level = 75 cm), which led to an extremely high carbon stock value (9.591 Mg) and was substantially higher than the mean carbon stocks of the other emergent trees (0.027 ± 0.005 Mg).

Perennial plant species were identified in cooperation with the herbarium Dárdano de Andrade Lima of the Agronomic Institute of Pernambuco, Recife.

Statistical analyses

Statistical analyses were performed using R version 3.2.3 (R core team 2015). The entire set of continuous variables was checked in terms of homogeneity, normality, and outliers (Zuur et al. 2010). All data were analysed using generalised linear models (GLMs) with quasi-Poisson distribution in order to meet statistical assumptions, to deal with outliers, and to avoid overdispersion (Zuur et al. 2010). Separate models were

fitted for the carbon stocks of each plant functional group (emergent trees, trees and shrubs, cacti and bromeliads, herbs in the dry season, herbs in the rainy season), forest density (all trees, shrubs, and cacti including saplings and emergent trees), carbon stocks per individual, population structure (*P. pyramidalis* and *P. microphylla* together, *A. pyrifolium*), and the recruitment of tree and shrub species without *P. pyramidalis*, *P. microphylla*, and *A. pyrifolium* (DGL > 3–10 cm). The distances to the nearest farmhouse and city were excluded from the full models because of a strong positive correlation with altitude (farmhouse: $R^2 = 0.5563$, $p < 0.0001$; city: $R^2 = 0.3972$, $p < 0.0001$) and a significantly worse performance of the variables distance to farmhouse and city compared to altitude (using the command “drop1()” during model selection process; Zuur et al. 2009). Stepwise backwards model selection was used to find the minimal adequate model (Crawley 2007). The full models comprised the explanatory variables altitude and grazing intensity (grazing classes based on faeces weight). Their interaction was also included due to a negative correlation between grazing intensity and altitude (GLM, $p = 0.0379$). Carbon stocks of cacti and bromeliads were analysed together due to their low abundance and consequently frequent zero counts. Herbaceous biomass was collected on 39 study plots with a small number of plots in the lowest grazing class. To obtain a balanced number of study plots per grazing class, the low and intermediate grazing classes were merged.

Results

Aboveground carbon stocks and forest density

The average AGCS were 15.74 ± 1.92 Mg ha⁻¹. Trees and shrubs (including emergent trees) contributed 89% to the total carbon stocks (Table 1). Emergent trees (height > 4 m) were found on 29 of 45 plots and contributed about 32% to the total AGCS found on the study plots. The mean carbon stock per emergent tree was on average five times larger than that of the smaller trees and shrubs. The mean number of individuals per hectare (trees and shrubs with DGL > 3 cm) was 2676 ± 218 (Online Resource 5). *P. pyramidalis*, *P. microphylla*, and *A. pyrifolium* were the most abundant tree species. They contributed 60% to the total carbon stocks (Table 1) and represented 75% of the individual trees and shrubs (only individuals with DGL > 3 cm) in the study area (see also Online Resource 5).

Aboveground carbon stocks related to grazing

Carbon stocks of herbaceous plant species after the first sufficient rainfall were significantly negatively affected by grazing intensity (Fig. 1). In contrast, we found no evidence of grazing impacts on carbon stocks overall or on any other

Table 1 Aboveground carbon stocks of Caatinga forests and different types of plants (means \pm standard error; SE) at different grazing intensities (high, intermediate, low). Carbon stocks of trees and shrubs were only calculated for individuals with diameter at ground level (DGL) > 3 cm. Carbon stocks of emergent trees (tree height > 4 m), smaller trees and shrubs, the most frequent tree species, cacti, bromeliads, and herbs are presented separately. Different lowercase letters indicate significant differences between grazing classes in generalised linear models. Height refers to the height of trees and shrubs with DGL > 3 cm, including emergent trees. Herbaceous biomass was sampled on 39 plots

	Mean \pm SE	Min	Max	Grazing intensity			No. plots with this plant type
				High	Intermediate	Low	
Overall carbon stocks (Mg ha ⁻¹)	15.74 \pm 1.92	0.87	72.16	18.35 \pm 3.44 (a)	13.97 \pm 2.48 (a)	12.08 \pm 1.59 (a)	45
Emergent trees, height > 4 m (Mg ha ⁻¹)	5.08 \pm 1.37	0	46.03	6.54 \pm 2.48 (a)	3.55 \pm 1.58 (a)	3.9 \pm 1.66 (a)	29
Trees and shrubs, height < 4 m (Mg ha ⁻¹)	8.89 \pm 1.23	0.22	34.88	10.19 \pm 1.81 (a)	8.35 \pm 2.54 (a)	6.53 \pm 1.23 (a)	45
Trees and shrubs, height < 4 m, without most abundant tree species <i>Poincianella pyramidalis</i> , <i>P. pyramidalis</i> , and <i>Aspidosperma pyrifolium</i> (Mg ha ⁻¹)	1.42 \pm 0.59	0	24.54	1.79 \pm 1.09 (a)	0.4 \pm 0.14 (a)	2.09 \pm 1.19 (a)	35
<i>P. pyramidalis</i> and <i>P. microphylla</i> , including emergent trees (Mg ha ⁻¹)	7.89 \pm 1.31	0	33.88	6.99 \pm 1.61 (a)	7.34 \pm 2.4 (a)	3.05 \pm 0.98 (a)	41
<i>Aspidosperma pyrifolium</i> , including emergent trees (Mg ha ⁻¹)	1.52 \pm 0.33	0	11.15	1.41 \pm 0.38 (a)	0.61 \pm 0.2 (a)	1.38 \pm 0.6 (a)	41
Bromeliads (Mg ha ⁻¹)	0.35 \pm 0.14	0	5.45	0.26 \pm 0.16 (a)	0.45 \pm 0.37 (a)	0.39 \pm 0.18 (a)	11
Cacti (Mg ha ⁻¹)	0.44 \pm 0.21	0	9.34	0.65 \pm 0.41 (a)	0.27 \pm 0.12 (a)	0.19 \pm 0.09 (a)	34
Herbs, dry season (Mg ha ⁻¹)	0.0025 \pm 0.0008	0	0.027	0.0014 \pm 0.0005 (a)	0.0032 \pm 0.0018 (a)	0.0041 \pm 0.0021 (a)	28
Herbs, rainy season (Mg ha ⁻¹)	1.12 \pm 0.13	0.02	3.29	0.8 \pm 0.14 (a)	1.42 \pm 0.21 (b)		39
Carbon stock per tree/shrub individual, height < 4 m (kg)	4.02 \pm 0.67	0.23	21.61	4.28 \pm 0.89 (a)	4.65 \pm 1.56 (a)	2.39 \pm 0.42 (a)	45
Carbon stocks per emergent tree, height > 4 m (kg)	21.10 \pm 6.62	0.51	230.13	33.68 \pm 12.77 (a)	9.46 \pm 3.69 (a)	8.46 \pm 2.18 (a)	29
Trees/shrub height (m)	2.06 \pm 0.13	0.84	4.96	1.8 \pm 0.11 (a)	2.35 \pm 0.31 (b)	2.25 \pm 0.25 (ab)	45

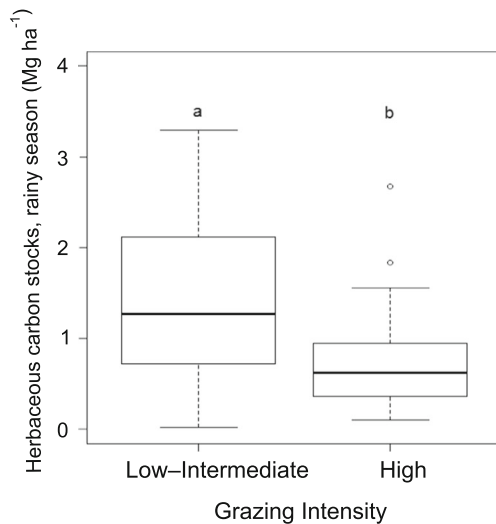


Fig. 1 Carbon stocks of the herbaceous layer of Caatinga forests during the rainy season at different grazing intensities. Different lowercase letters indicate significant differences (GLM, p grazing = 0.0285)

plant functional type studied. Also, mean carbon stock per tree/shrub individual was not significantly related to grazing intensity (see Table 1).

Forest density and population structure related to grazing

Densities of cacti and bromeliads and the overall forest densities (including trees, shrubs, and cacti; individuals ha^{-1}) were not related to different grazing intensities. However, emergent trees were significantly more abundant at low grazing intensity compared to high intensity, whereas trees and shrubs with DGL > 3 cm (without counting emergent trees) had the lowest abundances at intermediate grazing (see Online Resource 5).

The total density of the most abundant tree species was not affected by grazing intensity (Online Resource 5). They also showed a large number of individuals in the smallest diameter classes, which indicates sufficient recruitment in the *Poincianella* species and *A. pyrifolium* irrespective of grazing (Fig. 2, Online Resource 5). Accordingly, we found no

significant differences in the number of individuals in the smallest diameter classes (> 0–3 and > 3–10 cm; Online Resource 5) across grazing intensities.

However, grazing negatively affects the recruitment of Caatinga tree and shrub species without the most abundant tree species *Poincianella pyramidalis*, *P. microphylla*, and *Aspidosperma pyrifolium* (Online Resource 5).

Carbon stocks and population structure related to altitude

The carbon stocks of trees and shrubs (without emergent trees) as well as the carbon stocks per tree/shrub individual were significantly negatively related to altitude (Fig. 3). In contrast, the carbon stocks of cacti and bromeliads together were significantly positively related to altitude (GLM, p altitude = 0.0320).

The numbers of the smallest individuals of *P. pyramidalis* and *P. microphylla* (DGL > 0–3 cm; > 3–10 cm) were significantly negatively related to altitude (DGL > 0–3 cm; GLM, p altitude = 0.0047; DGL > 3–10 cm; GLM, p altitude = 0.0123), whereas the number of bromeliad rosettes and the number of tree and shrub individuals with DGL > 3–10 cm (without the most abundant tree species) were significantly positively related to altitude (GLMs, p < 0.0001). The overall forest density (all trees, shrubs, and cacti including saplings and emergent trees), however, showed no significant correlation with altitude.

Discussion

This study analysed the grazing impact of domestic ungulates (mainly goats) on aboveground carbon stocks and the recruitment of tree and shrub species within the Caatinga, a seasonally dry tropical forest area. We could not detect a negative effect on total AGCS or regeneration of the most frequent tree species. In contrast, we found a negative effect of grazing on the recruitment of less abundant tree and shrub species (DGL

Fig. 2 Population structure (diameter classes) of the most important tree species. **a** *Poincianella pyramidalis* and *P. microphylla* and **b** *Aspidosperma pyrifolium* at different grazing intensities. The diameter class “> 20 cm” includes trees with a diameter at ground level up to 76 cm

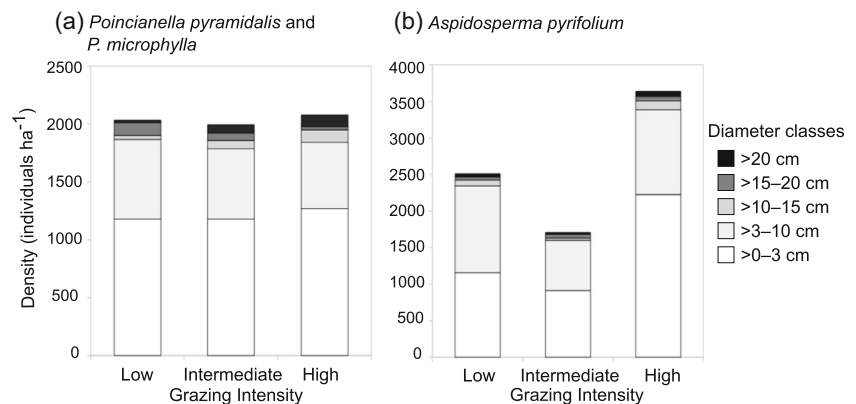
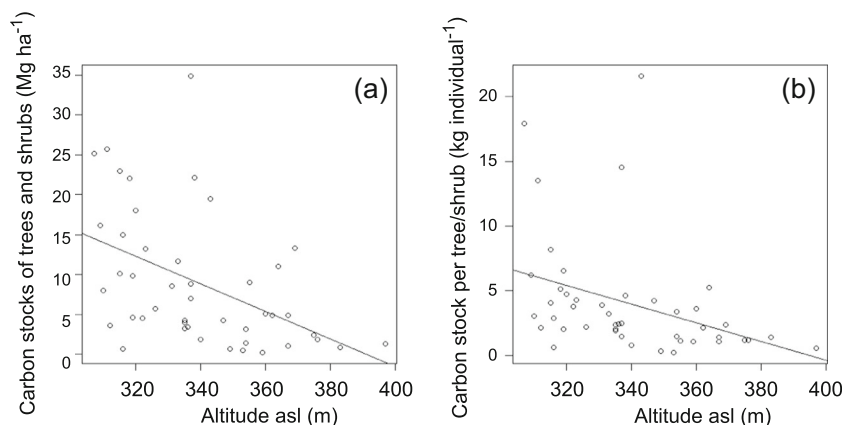


Fig. 3 **a** Carbon stocks of trees and shrubs (without emergent trees; GLM, p altitude = 0.0014). **b** Carbon stocks per tree/shrub individual (without emergent trees; GLM, p altitude = 0.0151) in Caatinga vegetation at different altitudes



> 3–10 cm) which implies a species turnover through grazing, which may reduce the resilience of the ecosystem if overgrazing by goats persists (see e.g. Ibáñez et al. 2007; Kyriazopoulos et al. 2009). As the forests in our study area show a similar vegetation structure and species composition as other Caatinga areas, our findings may also contribute to land use adaptations in other areas of north-eastern Brazil.

Aboveground carbon stocks and forest density

Our study provides further evidence that, despite their rather small AGCS per hectare compared to other ecosystems (e.g. Prentice et al. 2001; see Online Resource 6), Caatinga forests play an important role as carbon sinks due to their large spatial extent. If the average values from this study are used, without considering grazing or altitude effects, the Caatinga vegetation, which covers approximately 780,000 km² (Schulz et al. 2017), can be estimated to store about 1.23 Pg C.

Studies of the Caatinga region have found a wide range of values for AGCS. We found generally low values (on average about 16 Mg ha⁻¹) compared to some studies of Caatinga forests (see Sampaio and Costa 2011; Tiessen et al. 1998), but comparable or even higher than in other areas (e.g. Rodal et al. 2008; Santana and Souto 2006; see Online Resource 6). AGCS determined in our study were similar to soil organic carbon stocks in the same area (see Schulz et al. 2016). The AGCS of herbaceous plants were also in the lower range of data reported from other Caatinga areas and varied considerably between dry and wet years (Online Resource 6). The low AGCS of herbaceous plants in particular may be attributed to the last drought in our study area (2010–2013). Furthermore, e.g. the study of Freitas et al. (2012) on herbs was carried out in Caatinga areas undergoing regeneration that had not been exposed to grazing for at least 2 years, and hence AGCS are expected to be higher compared to grazed areas.

The mean number of trees and shrubs with DGL > 3 cm in the study area was within the range of other Caatinga studies, while the mean tree height was lower (Online Resource 6).

The reason for the overall low AGCS, forest density, tree height, and high number of tree individuals with small diameters may be a matter of particularly unfavourable conditions such as low precipitation (Amorim et al. 2005; Sampaio 2010) which is supported by the high percentage of poorly vegetated areas in the São Francisco Valley compared to other Caatinga areas (Schulz et al. 2017). In addition, although we failed to prove a direct effect of the current grazing regime on overall AGCS, historic grazing may have led to an opening of the vegetation which, in turn, led to soil erosion (see Schulz et al. 2016). The fact that the forest area showed a significant increase in vegetation cover between 2001 and 2010 (Schulz et al. 2017) also suggests that overgrazing was more severe in the past than in recent times. The negative effects on plant growth are exacerbated by low water availability (low rainfall, high evapotranspiration, and low soil water retention capacity due to the shallow depth and infiltration problems of Planosols; see FAO 2001). Additionally, several tree species (e.g., *A. pyrifolium*, *P. pyramidalis*) are known to be cut (personal observations) for many purposes (firewood, charcoal, timber, popular medicines; e.g. Albuquerque et al. 2005; Lucena et al. 2007) which may have further reduced AGCS in our study area—again, presumably at a higher rate in past decades compared to the current situation.

Impact of grazing on aboveground carbon stocks

In accordance with our first hypothesis, grazing significantly affected the AGCS of herbaceous plants. Herbaceous species, and in particular grasses, are known to be mainly consumed at the beginning of the rainy season (Pfister and Malechek 1986). This may be the reason why we observed a grazing impact exclusively after the rainy season. Overall, the carbon stocks of the herbaceous layer represented only a small percentage of the ecosystem's carbon storage, but the lack of herbaceous vegetation is nevertheless important as it may exacerbate soil erosion in many places.

In contrast to our hypotheses, carbon stocks of trees and shrubs were not significantly affected by grazing. Goats,

which are the main livestock in the study area according to the collected faeces, feed mainly on the foliage of woody species. Overall, leaves make up 68–86% of the diet of livestock, depending on the type of livestock and season, but only about 10% of the total leaf biomass is actually consumed by livestock (Araújo Filho 2013). Additionally, the leaves of many Caatinga tree species, e.g. *P. pyramidalis*, are not palatable when green (e.g. Araújo Filho 2013; Pfister and Malechek 1986), and most of the foliage is consumed during the dry season as litter (Araújo Filho et al. 1998; Araújo Filho 2013; Pfister and Malechek 1986) with no direct effect on trees. Goats also feed on the bark of trees or cacti (Araujo et al. 2010), but trees or cacti with recently damaged trunks were only observed occasionally (personal observations). The high share of senescent leaf material in the diet of livestock may be the reason why grazing showed no clear negative impact on overall AGCS in our area. On the contrary, the overall carbon stocks and the carbon stocks of emergent trees and of trees and shrubs together were even higher in heavily grazed areas, although not significantly. Plots with high grazing intensities were often located at low elevations and often in the vicinity of the lake—areas that are expected to have easily accessible groundwater. A higher nutrient input (manure) may additionally enhance plant growth.

Fruits and flowers are also important food sources (Pfister and Malechek 1986). Although they were not taken into account when analysing AGCS, the consumption of fruits may alter species composition. For example, the pods of the abundant exotic tree species *Prosopis juliflora* (Sw) DC are frequently consumed and dispersed by livestock (Sena et al. unpublished). Consequently, a long-term species turnover along with reduced diversity of perennial plant species is a known consequence of the current grazing regime (Schulz et al. unpublished).

Despite the missing impact on AGCS, livestock is known to enhance soil erosion due to the consumption of leaf litter, which is important for soil protection (Pfister and Malechek 1986) and accumulation of soil organic matter. Accordingly, grazing has been shown to result in reduced soil carbon stocks (Schulz et al. 2016). Furthermore, the recently increasing forest cover points to historic overgrazing and loss of AGCS in the area which cannot be directly related to the recent grazing intensities. Grazing thus conflicts with many conservation goals, but at the current intensities not with the ecosystem function of aboveground carbon storage.

Impact of grazing on forest density and population structure

Overgrazing is known to significantly reduce the number of trees and tree recruitment (Cierjacks and Hensen 2004). In our study, the current grazing regime negatively affected the recruitment of less frequent tree and shrub species (DGL > 3–

10 cm). On the other hand, the highest grazing intensity was accompanied by the highest numbers of young trees of the most abundant tree species (DGL < 3 cm; Fig. 2), a lower number of emergent trees, and a higher number of trees with DGL > 3 cm (without emergent trees; Online Resource 5). Again, high grazing intensity is frequently found adjacent to the lake which seems to promote tree recruitment. The abundant recruitment is also in line with a recent analysis of the entire Caatinga region, which revealed overall increasing forest cover (Schulz et al. 2017), possibly related to less intense land use (timber harvest or slash-and-burn agriculture) during recent decades. Unfortunately, there are no written records or photographs that reliably document historic land use, albeit oral information from older landowners, farmers, and residents supports this view. Still, this assumption is substantiated by the fact that in degraded areas scattered exceptionally large individuals of *A. pyriformium* were found, while the majority of these trees were characterised by small size (often < 100 cm in height, data not shown) suggesting a former vegetation structure that was less dense with fewer large trees. However, this view requires further studies on historical land use in the study area.

The overall grazing impact on the most abundant tree species *P. pyramidalis*, *P. microphylla*, and *A. pyriformium* is low due to their low palatability. *A. pyriformium* is generally not a forage species, e.g. causing abortions in goats (Souza Lima and Soto-Blanco 2010), while the leaves of the *Poincianella* species are mainly consumed as litter (Araújo Filho 2013). The effect of grazing on the biodiversity of Caatinga vegetation is investigated in another study (Schulz et al. unpublished).

Other studies, however, have found a negative effect of grazing at the given livestock densities e.g. on soil organic carbon stocks (Schulz et al. 2016), plant (Schulz et al. unpublished), or anuran diversity (Guschal et al. unpublished). Moreover, Althoff et al. (2016) expect a pronounced decrease in Caatinga aboveground and belowground carbon stocks within this century if climate changes as predicted. They calculated a loss of 650 Tg of C for the whole Caatinga due to climate change—considering an area of approx. 500,000 km², while other studies assign a larger area to Caatinga ecosystems (e.g. Schulz et al. 2017; 780,000 km²). Marengo et al. (2014) go farther, predicting a social crisis within the semi-arid north-eastern Brazil due to climate change and the related water shortage.

Altitude and additional drivers of carbon stocks, forest density, and population structure

Carbon stocks of trees and shrubs along with carbon stocks per individual were significantly negatively related to altitude (Fig. 3). As the difference in altitude between the plots was low (only about 100 m), altitude can be regarded as proxy for

different parameters, such as water availability (Winter 2001), anthropogenic impacts (da Silva et al. 2014; Revermann et al. 2016), and soil characteristics (Navar et al. 2014; Scheffer and Schachtschabel 2010). We assume a higher water availability at lower elevations caused by a reduced distance to groundwater (Winter 2001) and thus expect higher AGCS, despite a high grazing intensity in these areas as the effect of heavy grazing on established trees and shrubs appeared to be low. Additionally, the negative correlation between altitude and the carbon stocks of trees and shrubs may be partially attributed to the policy of protecting large shade trees in fenced areas (personal observation), which are more frequently located at lower altitudes. Altitude can also be considered an indicator for human presence, with areas at higher elevation likely seeing a lower probability of recent and historic anthropogenic disturbances (da Silva et al. 2014). To disentangle effects of human presence from those of water availability, we also tested the correlation between AGCS and the distance to the nearest farm or city, which we expected to be positive. Our analyses, however, revealed that altitude was always preferred to the distances in the statistical models (data not shown).

Several cacti and bromeliad species [e.g., *Cereus jamacaru* DC. (mandacaru), *Encholirium spectabile* (macambira)] are also used as livestock fodder, especially during droughts (Alves et al. 2009; Araujo et al. 2010; personal observations). Accordingly, we frequently found zero counts of macambira in the vicinity of farms which may indicate intense harvesting (Guschal et al. unpublished). Interestingly, the abundance of bromeliads and the AGCS of cacti and bromeliads together were significantly positively related to altitude. This implies that reduced tree growth in the course of water shortage allows for the spread of other plant functional types which are highly adapted to extreme climatic conditions. Consequently, water availability seems to be a more important factor in shaping vegetation structure and carbon allocation than the current land use.

Conclusion and implications for land use management

Since many farmers in arid regions strongly depend on livestock husbandry, understanding associated ecological impacts is vital for developing sustainable land use regimes. Our study showed that the major part of the aboveground carbon stocks was not significantly affected by grazing in the Caatinga. Yet, grazing at the given intensities negatively affects the recruitment of Caatinga tree and shrub species (excluding the most abundant tree species *Poincianella pyramidalis*, *P. microphylla*, and *Aspidosperma pyriformis*). Further, grazing has been proved to threaten soil organic carbon stocks (Schulz et al. 2016), and plant (Schulz et al. unpublished) and anuran diversity (amphibians; Guschal et al.

unpublished). Moreover, ongoing climate change is expected to further reduce the ecosystem productivity and the potential for animal husbandry. To safeguard ecosystem functions and ensure sustainable fodder production, adaptations to current management practices are therefore still needed. We recommend a forage and grazing management that makes use of a rotation system, thereby reducing free roaming of livestock and stocking density. During the dry season, livestock fodder should be supplied by fodder plants grown in wetlands and irrigation fields (see Cierjacks et al. 2016) and preserved and stored as silage or hay. Another important step is to raise awareness and provide information to local farmers (Liniger et al. 2017). Changes in grazing management should be combined with a network of protected areas (Louhaichi et al. unpublished) to facilitate the migration of native flora into expanding but species-poor forests (Schulz et al. 2017) and to promote the recovery of historically degraded Caatinga vegetation, a process which will take a long time (e.g. Althoff et al. 2016).

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