

Land-Use Effects on Plant Biodiversity and Carbon Cycling in Seasonally Dry Tropical Forests in North-Eastern Brazil

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„Was lange währt, wird endlich gut“
deutsches Sprichwort

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This thesis is based on four published articles.

- (1) Schulz K, Guschal M, Kowarik I, Almeida-Cortez JS, Sampaio EVSB, Cierjacks A (2019) Grazing reduces plant species diversity of Caatinga dry forests in north-eastern Brazil. *Applied Vegetation Science*. <https://doi.org/10.1111/avsc.12434>
- (2) Cierjacks A, Pommeranz M, Schulz K, Almeida-Cortez JS (2016) Is crop yield related to weed species diversity and biomass in coconut and banana fields of northeastern Brazil? *Agriculture, Ecosystems & Environment* 220: 175–183. <https://doi.org/10.1016/j.agee.2016.01.006>
- (3) Schulz K, Guschal M, Kowarik I, Almeida-Cortez JS, Sampaio EVSB, Cierjacks A (2018) Grazing, forest density, and carbon storage: towards a more sustainable land use in Caatinga dry forests of Brazil. *Regional Environmental Change* 18:1969–1981. <https://doi.org/10.1007/s10113-018-1303-0>
- (4) Schulz K, Voigt K, Beusch C, Almeida-Cortez JS, Kowarik I, Walz A, Cierjacks A (2016) Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil. *Forest Ecology and Management* 367:62–70. <https://doi.org/10.1016/j.foreco.2016.02.011>

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Summary

Tropical forests are generally known for their high biodiversity and importance as carbon sinks. However, in contrast to tropical rainforests, scientific research on seasonally dry tropical forests remained scarce, although they account for 42% of all tropical forests worldwide. Seasonally dry tropical forests are highly threatened by anthropogenic disturbances, such as deforestation and overgrazing. Degradation and biodiversity loss are often consequences, possibly amplifying climate change as the dry forests lose their functions as carbon sinks. To counteract these processes, sustainable land management strategies, which maintain or even enhance ecosystem functions and services of these ecosystems but safeguard the livelihoods of the local population at the same time, are urgently needed.

The seasonally dry tropical forests of north-eastern Brazil are called 'Caatinga'. The term refers to both the landscape covering the semi-arid part of Brazil and the unique vegetation characterised by deciduous trees and shrubs (often with thorns or spines), cacti, and bromeliads. Since the European colonisation in the 18th century, the Caatinga has been considerably altered. Today, it is considered one of the most threatened ecosystems of Brazil. Still, this ecosystem is hardly known to the international science or public.

The main economic sector in the Caatinga region is livestock husbandry (mainly goats but also cattle and sheep) due to the semi-arid climate with frequent droughts. Goats are typically kept in fenced areas in the dry forests. Besides high stocking densities, free roaming animals aggravate the degradation of this ecosystem. Within the study area, the São Francisco River was dammed in 1988 to provide water and hydropower to the Brazilian population. The Itaparica Reservoir was formed. The flooding required the resettlement of about 10,400 households. Most of these people received land in the newly established 'agrovilas' (agricultural settlements) in the irrigation schemes near the reservoir. Here, typical crop species are perennial plants such as coconut, banana, guava, and mango and annual crops such as onion and

melon. Common problems in the irrigation schemes are a high usage of agrochemicals and an improper irrigation, often leading to salinisation of the soils.

The present thesis analyses the effect of different land-use practices and intensities on plant diversity and organic carbon stocks with the aim to derive sustainable land-use options. The data assessment in the Caatinga dry forests was carried out in the municipalities of Itacuruba and Floresta on 45 permanent plots (20 m × 20 m). On each plot, grazing intensity was quantified by collecting, drying, and weighing animal droppings on six subplots (each 2 m × 2 m) per plot. The diversity of perennial plant species was recorded by counting all individuals or the number of bromeliad rosettes respectively within the 20 m × 20 m plot. Herbaceous species were assessed after the first sufficient rainfall on a subset of 36 plots (due to time constraints) with four subplots (each 2 m × 2 m) per plot using the Braun-Blanquet cover-abundance scale. Organic carbon stocks (above- and belowground) were assessed within the same study plots. Aboveground carbon stocks of woody plants (including cacti and bromeliads) were assessed on one subplot (10 m × 10 m) per plot. The circumference at ground level was measured for all trees, shrubs, and cacti with a diameter at ground level > 3 cm. Based on these circumference values, allometric equations were used to estimate the biomass of each plant. New equations were developed for certain cacti and bromeliad species and for the tree species *Aspidosperma pyrifolium*. The carbon stocks of herbaceous species were assessed on two subplots (each 2 m × 2 m) per plot. All herbaceous biomass within these subplots was harvested, dried, and weighed. All biomass values were multiplied by 0.5 to obtain carbon stock values. For analysing soil organic carbon stocks, three samples of the topsoil (0–5 cm in depth) and samples of two soil profiles (topsoil to bedrock) were taken in each Caatinga plot.

The assessment of plant diversity and carbon stocks was extended to 21 crop fields (banana, coconut) within the irrigation schemes Apolônio Sales and Icó-Mandantes, in the municipality of Petrolândia, to cover the entire gradient of land use within the study area. Two study plots (each 5 m × 5 m) were established per crop field (one in the centre and one at the field edge). On these plots, vegetation relevés of weed species were carried out (cover-abundance scale according to Braun-Blanquet). Further, crop plants were measured (circumference at breast height and plant height) to estimate the biomass per crop plant. The biomass of weed species was determined on two subplots (each 0.5 m × 0.5 m) per plot. Here, all plants with a plant height < 1 m were harvested, dried, and weighed. Soil organic

carbon stocks within the crop fields were determined by analysing two samples of the topsoil per study plot.

The study results reveal that the present land use has detrimental effects on the plant diversity and organic carbon stocks of the Caatinga dry forests. In total, 140 plant taxa including morphospecies were found within the study plots. The species richness and the Shannon and Simpson indices of the woody vegetation (including cacti and bromeliads) were significantly higher on plots with no/low grazing intensity compared to the heavily grazed plots (Chapter 2). The number of herbaceous species was also significantly higher on plots with no/low grazing. Aboveground carbon stocks were generally low (about 16 Mg ha⁻¹; Chapter 4) and the aboveground carbon stocks of herbaceous species were significantly reduced by grazing (1.42 Mg ha⁻¹ vs. 0.8 Mg ha⁻¹; no/low grazing vs. high grazing). In contrast, no effect of grazing was found on the aboveground carbon stocks of the woody vegetation (10.42 Mg ha⁻¹ vs. 16.75 Mg ha⁻¹) or the overall forest density (12,667 individuals ha⁻¹ vs. 8961 individuals ha⁻¹). However, the recruitment of tree and shrub species (excluding the most abundant tree species) was significantly negatively affected by grazing (1266 individuals ha⁻¹ vs. 327 individuals ha⁻¹; Chapter 4). Moreover, high grazing pressure significantly reduced soil organic carbon stocks in the topsoil (7.02 Mg ha⁻¹ vs. 3.39 Mg ha⁻¹; Chapter 5).

Besides grazing, altitude was the most important parameter in most of the statistical analyses of the dry forest areas with significant effects on plant diversity (positive), aboveground carbon stocks (negative), and soil organic carbon stocks (positive). Yet, due to the relatively small variation in altitude, pronounced climatic changes along the altitudinal gradient are not expected. Instead, altitude is rather assumed to be an indicator of accessibility to water (groundwater and surface water), with areas at lower altitude showing a better water availability due to runoff and a closer proximity to permanent streams. In addition, lower areas are considered to be associated with a higher probability of historical and recent human activities due to a better access to land and water, which most likely causes the observed differences in vegetation and soil organic carbon stocks.

Since the establishment of the Itaparica Reservoir, irrigation farming is a novel land-use option within the study area. Here, albeit a greater potential to sequester carbon (mean aboveground carbon stocks: 20.79 Mg ha⁻¹) and a high weed diversity (77 species; Chapter 3), the species assemblage showed only few similarities with the Caatinga dry forest plots (Chapter 2 & 6). However, the data on crop yield imply

a mostly significant positive relationship between crop yield and weed diversity, while no evidence was found that the use of herbicides or insecticides increases crop yield (Chapter 3). These findings point to a high potential for organic farming in semi-arid north-eastern Brazil.

The present study presents the first comprehensive overview on the impact of the current land use on the vegetation and carbon stocks in an area of Caatinga dry forests in north-eastern Brazil. These novel insights are of crucial importance for the development of sustainable land management options. Based on the findings of this thesis as well as of further studies of the overall research project INNOVATE, a set of recommendations for an adapted land use was developed, which safeguards both the preservation of the Caatinga ecosystem and their functions as well as the livelihoods of the rural populations. These recommendations were presented to and discussed with stakeholders and subsequently incorporated into a guidance manual. The most important recommendations are:

- Grazing should be performed at low animal loads (≤ 1 goat/sheep per hectare) to support a high vegetation cover.
- Species-rich Caatinga areas must be efficiently protected as source and stepping-stone habitats (preferably areas in wetland ecosystems, lake shores, or rocky outcrops) to facilitate the recovery of species-poor and degraded areas.
- The conversion from Caatinga dry forests to agrarian land should aim at a sustainable production of perennial crops, including the cessation of chemical herbicides and insecticides and the preference of organic fertiliser (goat manure).
- Field margins should be preserved as they play a major role for agrarian diversity and provide habitats for pest predators, both leading to higher crop yields.

Resumo

Em geral, as florestas tropicais são conhecidas por seus altos níveis de biodiversidade e pela importância como sumidouros de carbono. Entretanto, ao contrário do que é observado na floresta tropical úmida, a pesquisa científica em florestas tropicais sazonalmente secas permaneceu escassa, embora elas representem 42% de todas as florestas tropicais do mundo. As florestas tropicais sazonalmente secas estão sob forte ameaça de distúrbios antropogênicos, como desmatamento e sobrepastoreio. As consequências disso costumam ser degradação e perda de biodiversidade, que possivelmente contribuem para ampliar as mudanças climáticas enquanto as florestas secas perdem a função de sumidouros de carbono. Para contrabalançar esses processos, é necessário adotar urgentemente estratégias de gerenciamento de solo que mantenham ou até mesmo aprimorem as funções e os serviços ecossistêmicos desses locais enquanto protegem a subsistência da população local.

As florestas tropical sazonalmente secas do Nordeste do Brasil são chamadas de “Caatinga”. O termo refere-se tanto à paisagem observada na região semiárida do Brasil quanto à vegetação singular, caracterizada por árvores e arbustos decíduos (muitas vezes com espinhos), além de cactos e bromélias. Desde a colonização europeia no século 18, a Caatinga passou por alterações consideráveis. Hoje, ela é considerada como um dos ecossistemas mais ameaçados do Brasil. Apesar disso, esse ecossistema é praticamente desconhecido pelo público e pela ciência fora do país.

A principal atividade econômica na região da Caatinga é a criação de animais, principalmente cabras, mas também gado e ovelhas, sendo a prática decorrente do clima semiárido e que enfrenta secas frequentes. Normalmente as cabras são mantidas em áreas cercadas nas florestas secas. Além das altas densidades dos rebanhos, os animais com livre circulação agravam a degradação desse ecossistema. O Rio São Francisco foi represado em 1988 na área do estudo para fornecer água e energia hidrelétrica para a população brasileira. O reservatório de Itaparica foi

formado. A inundação exigiu o reassentamento de aproximadamente 10.400 famílias. A maioria das pessoas recebeu terras nas agrovilas recém-estabelecidas nos perímetros irrigados próximos ao reservatório. Nesses locais, as espécies habitualmente cultivadas são plantas perenes, como coco, banana, goiaba e manga, além de culturas anuais, como cebola e melão. O uso exacerbado de agrotóxicos e uma irrigação inadequada, que frequentemente resulta na salinização dos solos, são problemas comuns nos perímetros irrigados.

Nesta tese, o efeito de diferentes práticas e intensidades de uso do solo sobre a diversidade vegetal e os estoques de carbono orgânico é analisado visando a obtenção de opções sustentáveis de uso do solo. A avaliação de dados em florestas secas da Caatinga foi realizada em 45 parcelas permanentes (medindo 20 m x 20 m cada) nos municípios de Itacuruba e Floresta. Em cada parcela, a intensidade do pastoreio foi quantificada mediante a coleta, secagem e pesagem das fezes dos animais em seis subparcelas (medindo 2 m x 2 m cada) por parcela. A diversidade de espécies vegetais perenes foi registrada com a contagem de todos os indivíduos e do número de rosetas de bromélias nas parcelas de 20 m x 20 m. As espécies herbáceas foram avaliadas após a primeira chuva de volume suficiente em um subconjunto de 36 parcelas (devido a limitações de tempo) com quatro subparcelas (medindo 2 m x 2 m cada) por parcela, usando a escala de abundância de cobertura de Braun-Blanquet. Os estoques de carbono orgânico (acima e abaixo do solo) foram avaliados nas mesmas parcelas do estudo. Em cada parcela em vegetação de Caatinga, os estoques de carbono acima do solo de plantas lenhosas (inclusive cactos e bromélias) foram avaliados em uma subparcela (medindo 10 m x 10 m) por parcela. A circunferência no nível do solo foi medido para árvores, arbustos e cactos que tinham um diâmetro > 3 cm no nível do solo. Equações alométricas baseadas nessas circunferências foram usadas para estimar a biomassa de cada planta. Desenvolveu-se novas equações para determinadas espécies de cactos e bromélias e as espécies de árvores de *Aspidosperma pyrifolium*. Os estoques de carbono das espécies herbáceas foram avaliados em duas subparcelas (medindo 2 m x 2 m cada) por parcela. Toda a biomassa de herbáceas em cada subparcela passou por coleta, secagem e pesagem. Todos os valores de biomassa foram multiplicados por 0,5 a fim de obter os valores de estoque de carbono. Para a análise dos estoques de carbono orgânico no solo, três amostras da camada superior de solo (0 a 5 cm de profundidade) e amostras de

dois perfis de solo (da camada superior até o leito rochoso) foram coletadas em cada parcela na Caatinga.

A avaliação da diversidade vegetal e dos estoques de carbono foi ampliada para 21 campos de cultivo (banana, coco) nos perímetros irrigados de Apolônio Sales e Icó-Mandantes, no município de Petrolândia, a fim de abranger todo o gradiente de uso do solo na área do estudo. Duas parcelas do estudo (medindo 5 m × 5 m cada) foram estabelecidas por campo de cultivo (uma no centro e uma na borda do campo). Nessas parcelas, realizou-se um levantamento das espécies de ervas daninhas (usando a escala de abundância de cobertura de Braun-Blanquet). Adicionalmente, mediu-se as plantas cultivadas (circunferência na altura do peito e altura da planta) a fim de estimar a biomassa por planta cultivada. A biomassa das espécies de ervas daninhas foi determinada em dois subparcelas (medindo 0,5 m × 0,5 m cada) por parcela. Nesse caso, todas as plantas com altura < 1 m passaram por coleta, secagem e pesagem. Os estoques de carbono orgânico no solo dos campos de cultivo foram determinados por meio da análise de dois amostras da camada superior do solo por parcela do estudo.

Os resultados do estudo revelam que o uso atual do solo exerce efeitos prejudiciais sobre a diversidade vegetal e os estoques de carbono orgânico das florestas secas da Caatinga. Encontrou-se um total de 140 táxons vegetais, levando em conta morfoespécies, nas parcelas do estudo. A riqueza de espécies, e os índices de Shannon e de Simpson para as plantas lenhosas (inclusive cactos e bromélias), foram significativamente maiores em parcelas sem pastoreio/com baixa intensidade de pastoreio em comparação a parcelas com pastoreio intenso (Capítulo 2). O número de espécies herbáceas também foi significativamente maior em parcelas sem pastoreio/com baixa intensidade de pastoreio. Em geral, os estoques de carbono acima do solo foram baixos (aproximadamente 16 Mg ha⁻¹; Capítulo 4). Embora os estoques de carbono acima do solo para espécies herbáceas tenham apresentado redução significativa decorrente de pastoreio (1,42 Mg ha⁻¹ vs. 0,8 Mg ha⁻¹; sem pastoreio/baixa intensidade vs. pastoreio intenso), o pastoreio não exerceu efeito sobre os estoques de carbono acima do solo para a vegetação lenhosa (10,42 Mg ha⁻¹ vs. 16,75 Mg ha⁻¹) ou na densidade geral da floresta (12.667 indivíduos ha⁻¹ vs. 8961 indivíduos ha⁻¹). Entretanto, o pastoreio afetou negativamente de maneira significativa o recrutamento de espécies arbóreas e arbustivas (exceto para as espécies arbóreas mais abundantes; 1266 indivíduos ha⁻¹ vs. 327 indivíduos ha⁻¹; Capítulo 4). Além disso, a alta pressão

de pastoreio reduziu significativamente os estoques de carbono orgânico na camada superior do solo (7,02 Mg ha⁻¹ vs. 3,39 Mg ha⁻¹; Capítulo 5).

Além do pastoreio, a altitude foi o parâmetro mais importante na maioria das análises estatísticas das florestas secas, com efeitos significativos sobre a diversidade vegetal (positivo), estoques de carbono acima do solo (negativo) e estoques de carbono orgânico no solo (positivo). Entretanto, em decorrência da variação relativamente pequena na altitude, não esperamos alterações climáticas marcantes ao longo do gradiente de altitude. Em vez disso, espera-se que a altitude seja um indicador de acessibilidade à água (lençol freático e na superfície), com áreas em menores altitudes apresentando uma melhor disponibilidade hídrica decorrente do escoamento, além de maior proximidade em relação a cursos de água perenes. Adicionalmente, áreas mais baixas têm uma maior probabilidade de atividades humanas históricas e recentes por causa do melhor acesso a terras e água, sendo esse o provável motivo por trás das diferenças observadas na vegetação e nos estoques de carbono orgânico no solo.

A agricultura irrigada é uma opção recente de uso do solo na área do estudo, viabilizada pela criação do Reservatório de Itaparica. Nesse local, apesar de um maior potencial para o sequestro de carbono (média dos estoques de carbono acima do solo: 20,79 Mg ha⁻¹) e uma alta diversidade de ervas daninhas (77 espécies; Capítulo 3), a assembléia de espécies apresentou poucas semelhanças com as parcelas de floresta seca da Caatinga (Capítulos 2 & 6). Além disso, os dados de produtividade da colheita sugerem uma relação significativa e predominantemente positiva entre produtividade da colheita e diversidade de ervas daninhas, enquanto não foram encontradas evidências de que o uso de herbicidas ou inseticidas aumente a produtividade da colheita (Capítulo 3). Esses resultados indicam um alto potencial para a agricultura orgânica no Semiárido do Nordeste brasileiro.

Este estudo apresenta a primeira visão geral ampla sobre o impacto do atual uso do solo sobre a vegetação e os estoques de carbono em uma área de Caatinga no Nordeste brasileiro. Essas novas percepções são cruciais para o desenvolvimento de opções sustentáveis de gerenciamento do solo. Um conjunto de recomendações para o uso adaptado do solo foi desenvolvido com base nos resultados desta pesquisa, bem como em outros estudos do projeto de pesquisa INNOVATE, visando a proteção da preservação do ecossistema da Caatinga e de suas funções, além da subsistência da população rural. Essas recomendações

foram apresentadas e discutidas com as partes interessadas e, por fim, incorporadas em um manual de diretrizes. As recomendações mais importantes são:

- O pastoreio deve ser realizado com uma baixa carga animal (no máximo 1 ovelha/cabra por hectare) a fim de viabilizar uma alta cobertura vegetal.
- Áreas de Caatinga ricas em espécies precisam ser protegidas de maneira eficiente como habitats fonte e pontos de partida (de preferência áreas com próximos a rios e açudes, ecossistemas alagados ou afloramentos rochosos) a fim de facilitar a recuperação de áreas degradadas e com baixo número de espécies.
- A conversão de floresta seca da Caatinga em campo de agricultura deve visar a produção sustentável de culturas perenes, inclusive com a interrupção do uso de herbicidas e inseticidas químicos, além da preferência pelo uso de fertilizante orgânico (esterco caprino).
- As bordas do campo devem ser preservadas, já que elas desempenham um papel importante para a biodiversidade agrícola e fornecem habitat para os predadores de pragas, resultando em melhor produtividade da colheita.

Zusammenfassung

Tropische Wälder sind im Allgemeinen für ihre hohe Artenvielfalt und ihre Bedeutung als Kohlenstoffsinken bekannt. Die internationale Forschung und der Naturschutz haben sich jedoch bislang überwiegend auf tropische Regenwälder konzentriert. Obwohl tropische Trockenwälder 42% aller tropischen Wälder weltweit darstellen, blieben sie bislang weitestgehend unbeachtet. Anthropogene Beeinträchtigungen, wie das Abholzen der Wälder oder Überweidung, stellen die größten Gefahren für diese semi-ariden Ökosysteme dar. Typische Begleiterscheinungen sind Degradation und Biodiversitätsverlust. In der Folge kann es zu einer Verstärkung des Klimawandels kommen, da die Trockenwälder ihre Funktion als Kohlenstoffsinken verlieren. Daher sind nachhaltige Landmanagementstrategien dringend erforderlich, um zum einen die Funktionen und Dienstleistungen dieser Ökosysteme erhalten oder sogar zu verbessern, zum anderen aber auch, um die Lebensgrundlage der lokalen Bevölkerung zu sichern.

Die Trockenwaldgebiete im semi-ariden Nordosten Brasiliens werden als „Caatinga“ bezeichnet. Hierbei beschreibt der Begriff sowohl die Landschaft als auch ihre einzigartige Vegetation. Sie umfasst überwiegend sommergrüne Bäume und Sträucher, häufig mit Dornen oder Stacheln, sowie Kakteen und Bromelien. Seit der europäischen Besiedlung im 18. Jahrhundert ist die Caatinga stetigen Eingriffen durch den Menschen ausgesetzt. Heutzutage gilt die Caatinga als eines der gefährdetsten Ökosysteme Brasiliens. Dennoch ist dieses Ökosystem bislang kaum über die brasilianischen Grenzen hinaus bekannt.

Die Caatinga ist überwiegend ländlich geprägt. Aufgrund des semi-ariden Klimas ist die Haltung von Ziegen, teilweise auch Kühen und Schafen, der Hauptwirtschaftszweig in der Region. Die Ziegen werden typischerweise im Trockenwald innerhalb von eingezäunten Bereichen gehalten. Ein zu hoher Viehbesatz sowie freilaufende Tiere führen vielerorts zu einer fortschreitenden Degradation des Ökosystems. Dürren treten häufig auf und stellen eine permanente Bedrohung der Existenzgrundlage der Bauern dar. 1988 wurde der São Francisco im Untersuchungs-

gebiet aufgestaut, um die brasilianische Bevölkerung mit Wasser und Wasserkraft zu versorgen. Es entstand der Itaparica-Stausee. Im Zuge dessen mussten etwa 10.400 Haushalte umgesiedelt werden. Die Mehrheit dieser Personen erhielt Land in sogenannten „agrovilas“ (Agrarsiedlungen) in Stausee-Nähe. In diesen Gebieten wird Bewässerungslandbau betrieben. Kokosnuss, Banane, Guave und Mango sowie Zwiebel und Melone sind die häufigsten Feldfrüchte. Typisch für diese Gebiete ist ein hoher Einsatz von Agrochemikalien sowie eine unsachgemäße Bewässerung, die häufig zu einer Versalzung der Böden führt.

In der vorliegenden Arbeit wird der Einfluss verschiedener Landnutzungsformen und -intensitäten auf die Pflanzendiversität sowie die organische Kohlenstoffspeicherung mit dem Ziel untersucht, nachhaltige Landnutzungsempfehlungen abzuleiten. Die Datenerhebung in den Trockenwaldgebieten erfolgte in den Gemeinden Itacuruba und Floresta auf insgesamt 45 Daueruntersuchungsflächen (20 m × 20 m). Für jede Untersuchungsfläche wurde die Beweidungsintensität bestimmt. Hierfür wurden auf sechs Teilflächen (je 2 m × 2 m) pro Untersuchungsfläche alle Tierfaeces gesammelt, getrocknet und gewogen. Für die Bestimmung der Diversität holziger Pflanzen wurden alle Individuen innerhalb der 20 m × 20 m Fläche gezählt (inklusive Bromelien und Kakteen). Die Diversität der krautigen Pflanzen wurde nach dem ersten Regenereignis, aufgrund von zeitlichen Einschränkungen nur auf 36 der 45 Untersuchungsflächen, erhoben. Hier erfolgte die Datenerhebung auf jeweils vier Teilflächen (je 2 m × 2 m) pro Untersuchungsfläche nach der Methode von Braun-Blanquet (Artmächtigkeitsskala). Die Quantifizierung der Kohlenstoffvorräte (ober- und unterirdisch) erfolgte auf denselben Versuchsfeldern. Die Biomasse der holzigen Vegetation (inklusive Kakteen und Bromelien) wurde auf einer Teilfläche von 10 m × 10 m pro Untersuchungsfläche bestimmt. Hierzu wurde bei allen Bäumen, Sträuchern und Kakteen mit einem Durchmesser > 3 cm auf Bodenhöhe der Stammumfang gemessen. Anschließend wurde mit Hilfe von allometrischen Gleichungen die Biomasse pro Pflanze geschätzt. Für einige Kakteen- und Bromelienarten sowie die Baumart *Aspidosperma pyrifolium* wurden neue Formeln erstellt. Für die Bestimmung der krautigen Biomasse wurde auf zwei Teilflächen (je 2 m × 2 m) pro Untersuchungsfläche die gesamte krautige oberirdische Biomasse geerntet, getrocknet und gewogen. Alle Biomassewerte wurden mit 0,5 multipliziert, um Werte für die Kohlenstoffvorräte zu erhalten. Zur Bestimmung der Kohlenstoffvorräte im Boden wurden jeweils drei Proben des Oberbodens

(0–5 cm) sowie Proben von zwei Bodenprofilen (Oberfläche bis Grundgestein) je Untersuchungsfläche untersucht.

Um den gesamten Gradienten der Landnutzung abzudecken, wurde die Untersuchung der Pflanzendiversität und Kohlenstoffvorräte zusätzlich auf 21 Ackerflächen (Banane, Kokosnuss) innerhalb der Bewässerungsgebiete Apolônio Sales und Icó-Mandantes in der Gemeinde Petrolândia durchgeführt. Pro Feld wurden zwei Untersuchungsflächen (je 5 m × 5 m) eingerichtet (im Zentrum des Feldes und am Feldrand). Auf diesen Flächen wurden Vegetationsaufnahmen der Ackerunkräuter durchgeführt (Artmächtigkeitsskala nach Braun-Blanquet) sowie die Kulturpflanzen für die Bestimmung der Biomasse vermessen. Hierzu wurde der Stammumfang auf Brusthöhe sowie die Höhe der Pflanze bestimmt. Zur Bestimmung der Biomasse des Unterwuchses wurden auf zwei Teilflächen (je 0,5 m × 0,5 m) pro Untersuchungsfläche alle Pflanzen mit einer Höhe < 1 m geerntet, getrocknet und gewogen. Zur Bestimmung der Kohlenstoffvorräte im Boden wurden auf den Ackerflächen jeweils zwei Proben des Oberbodens genommen und analysiert.

Die Ergebnisse der Studie zeigen, dass sich die derzeitige Landnutzung signifikant nachteilig auf die Pflanzendiversität und die organischen Kohlenstoffvorräte der Caatinga Trockenwaldgebiete auswirkt. In den Untersuchungsflächen wurden insgesamt 140 Pflanzentaxa (inklusive Morphospezien) gefunden. Die Artenzahl sowie der Shannon- und Simpson-Index der holzigen Vegetation war auf den Flächen mit keiner/geringer Beweidung signifikant höher als auf den Flächen mit starker Beweidung (Kapitel 2). Die Anzahl krautiger Pflanzen war ebenfalls auf den Flächen mit keiner/geringer Beweidung signifikant größer. Die oberirdischen Kohlenstoffvorräte waren insgesamt gering (ca. 16 Mg ha⁻¹; Kapitel 4), wobei die oberirdischen Kohlenstoffvorräte der krautigen Pflanzen durch Beweidung signifikant verringert wurden (1,42 Mg ha⁻¹ vs. 0,8 Mg ha⁻¹; keine/geringe Beweidung vs. starke Beweidung). Im Gegensatz dazu wurden die oberirdischen Kohlenstoffvorräte der holzigen Pflanzen (10,42 Mg ha⁻¹ vs. 16,75 Mg ha⁻¹) ebenso wenig signifikant beeinträchtigt wie die Gesamtwalddichte (12.667 Individuen ha⁻¹ vs. 8961 Individuen ha⁻¹). Die Anzahl von Jungpflanzen (ohne die häufigsten Baumarten) hingegen wurde signifikant durch Beweidung verringert (1266 Individuen ha⁻¹ vs. 327 Individuen ha⁻¹; Kapitel 4). Darüber hinaus wurden die organischen Kohlenstoffvorräte im Oberboden signifikant durch starke Beweidung reduziert (7,02 Mg ha⁻¹ vs. 3,39 Mg ha⁻¹; Kapitel 5).

Neben der Beweidung war die Geländehöhe der wichtigste Parameter in den meisten statistischen Analysen der Trockenwald-Gebiete. Die Geländehöhe wies einen signifikant positiven Effekt auf die Pflanzendiversität, einen signifikant negativen Effekt auf die oberirdischen Kohlenstoffvorräte sowie einen signifikant positiven Effekt auf die organischen Kohlenstoffvorräte im Boden auf. Da aufgrund der geringen Unterschiede in der Geländehöhe keine ausgeprägten klimatischen Unterschiede entlang des Höhengradienten zu erwarten sind, ist in diesem Fall die Geländehöhe vermutlich ein Indikator für Wasserverfügbarkeit (Grund- sowie Oberflächenwasser). Flächen mit geringerer Geländehöhe weisen wahrscheinlich aufgrund des Abflusses von Niederschlagswasser sowie aufgrund einer größeren Nähe zu perennierenden Gewässern eine bessere Wasserverfügbarkeit auf. Es kann weiterhin davon ausgegangen werden, dass Flächen mit geringerer Geländehöhe aufgrund der Nähe zu perennierenden Gewässern sowie einer guten Erreichbarkeit stärker durch den Menschen geprägt wurden und werden. Dies führte vermutlich zu den beobachteten Unterschieden in der Vegetation und den organischen Kohlenstoffvorräten im Boden entlang des Höhengradienten.

Bewässerungslandwirtschaft ist eine relativ neue Landnutzungsform in dem Untersuchungsgebiet, die erst durch die Entstehung des Itaparica Stausees möglich wurde. Die Ackerflächen wiesen zwar ein größeres Potenzial für die Speicherung von Kohlenstoff (durchschnittliche oberirdische Kohlenstoffvorräte: 20,79 Mg ha⁻¹) sowie eine artenreiche Beikrautflora (77 Arten; Kapitel 3) auf, die Artzusammensetzung zeigte jedoch nur wenige Gemeinsamkeiten mit den untersuchten Trockenwaldgebieten (Kapitel 2 & 6). Die Daten deuten weiterhin einen positiven Zusammenhang zwischen der Diversität der Ackerunkräuter und dem Ertrag an. Im Gegensatz dazu gab es keinen Hinweis, dass sich der Einsatz von Herbiziden und Insektiziden positiv auf den Ertrag auswirkte (Kapitel 3). Diese Ergebnisse verdeutlichen, dass der semi-aride Nordosten Brasiliens ein großes Potenzial für ökologische Landwirtschaft aufweist.

In der vorliegenden Arbeit wird zum ersten Mal ein umfassender Überblick über die Auswirkungen der aktuellen Landnutzung auf die Vegetation sowie die Kohlenstoffvorräte in einem Caatinga-Gebiet im Nordosten Brasiliens gegeben. Diese neuen Erkenntnisse sind für die Entwicklung von Handlungsempfehlungen für eine nachhaltige Landnutzung von zentraler Bedeutung. Basierend auf den Forschungsergebnissen dieser und weiterer Arbeiten im Rahmen des Verbundprojektes INNOVATE wurde eine Reihe von Anpassungsvorschlägen erarbeitet, die sowohl

den Schutz der Caatinga und ihrer Ökosystemfunktionen, als auch die Sicherung der Lebensgrundlage der ländlichen Bevölkerung zum Ziel haben. Diese Empfehlungen wurden der lokalen Bevölkerung und Interessenvertretern in verschiedenen Workshops vorgestellt, diskutiert und abschließend in einem Handbuch zusammengefasst. Die wichtigsten Empfehlungen sind:

- Eine Beweidung der Trockenwaldgebiete sollte zum Schutz der Vegetationsdecke mit einem geringem Viehbesatz erfolgen (≤ 1 Ziege/Schaf pro Hektar).
- Artenreiche Caatinga-Gebiete (insbesondere Flussufer, Feucht- oder felsige Gebiete) müssen effektiv geschützt werden, um als Quell- und Trittsteinhabitate die Wiederbesiedlung artenarmer und degradierter Gebiete zu gewährleisten.
- Die Umwandlung von Trockenwald zu Ackerland sollte auf die nachhaltige Produktion von mehrjährigen Feldfrüchten abzielen. Hierbei sollte auf den Einsatz von chemischen Herbiziden und Insektiziden verzichtet werden. Organischer Dünger (Ziegendung) sollte gegenüber chemischem Dünger bevorzugt werden.
- Feldränder sollten geschützt werden. Sie sind zum einen für eine hohe Diversität der Ackerunkräuter von Bedeutung. Zum anderen stellen sie einen Lebensraum für biologische Schädlingsbekämpfer dar. Beides wirkt sich positiv auf den landwirtschaftlichen Ertrag aus.

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CHAPTER 1

General Introduction

Rationale of the study

Tropical forests are generally acknowledged for their high floral and faunal diversity (Santos & Almeida-Cortez 2009) and their importance as carbon sinks (Pan et al. 2011). However, while seasonally dry tropical forests (SDTF) represent about 42% of the tropical forest worldwide (Espírito-Santo et al. 2006), they received clearly less scientific attention and conservation efforts compared to other tropical ecosystems (Espírito-Santo et al. 2006; Leal et al. 2005; Santos et al. 2011). Human interventions such as deforestation and overgrazing are the main threat to SDTF (Leal et al. 2005), which are often accompanied by degradation and a loss of biodiversity. Hence, sustainable land management options are urgently needed to safeguard human livelihoods and to ensure ecosystem functions and services at the same time. However, scientific research which investigates the direct impact of land-use practices on ecosystems is scarce, yet of pivotal importance for the development of appropriate land-use measures.

The SDTF of north-eastern Brazil are called 'Caatinga'. The term refers to the landscape which covers about 70% of the Brazilian north-east (Queiroz et al. 2006) and 10% of the entire Brazilian territory (IBGE 2004). Moreover, the term 'Caatinga' also describes the unique vegetation of this area with nearly 4500 plant species (including relictual patches of humid forests and savannas; Siqueira Filho et al. 2012). About one-third of the 596 known woody species are endemic to the Caatinga (Araújo Filho & Crispim 2002). Yet, nowadays a high portion of the vegetation within the Caatinga is represented by alien plants, mainly forage grass species (Almeida et al. 2015).

With 27 million inhabitants and a population density of about 32 inhabitants per square kilometre, the Caatinga is one of the most densely populated semi-arid regions of the world (MMA 2011; Salcedo & Menezes 2009). The exploitation of the Caatinga began during the 18th century by European settlers (Araújo Filho et al. 1998; Sampaio 1995). Since then, livestock rearing spread widely across the Caatinga (Sampaio 1995) and is still the main land-use type in the region (Bakke et al. 2009; Tiessen et al. 1998). In 2015, 93% of all goats within Brazil (8.9 million heads) and 61% of all sheep (11 million heads) were bred in the north-east (IBGE 2015). This implies that nearly all forests are grazed to some extent (by goats, cattle, sheep, and donkeys), often exceeding the carrying capacity of the Caatinga (Tiessen et al. 1998; own observations). Overgrazing, however, is known to negatively affect plant diversity, population dynamics, and soil characteristics (Albuquerque et al. 2018). Besides livestock fodder, the Caatinga dry forests also supply several goods such as food, timber, charcoal, and medicinal plants (Lucena et al. 2007; MMA 2004). In rural areas, firewood is still the main energy source (Santos et al. 2014; own observations). Irrigation farming is carried out in areas with access to water. Here, problems such as salinisation and pests occur as well as an intense use of agrochemicals. Typical crop species are coconut, banana, guava, mango, onion, and melon.

Overall, 30–52% of the native Caatinga dry forests have been altered by human activities such as agriculture, livestock husbandry, and constructions (e.g., settlements, roads; MMA 2011; Leal et al. 2005; Tiessen et al. 1992). Consequences were desertification (MMA 2011; Menezes et al. 2012), biodiversity loss (Leal et al. 2005), and reduced soil carbon stocks (Tiessen et al. 1998). This is especially alarming, since the recovery of the vegetation takes a long time. Althoff et al. (2016) state that under the current climatic conditions, the native Caatinga vegetation needs more than 50 years to recover from cutting. Thus, the Caatinga is considered one of the most threatened ecosystems within Brazil (Espírito-Santo et al. 2009), with only 1% of the area being strictly protected ('Unidades de Proteção Integral'; categories Ia, II, III following IUCN classification; MMA 2017). However, this ecosystem has hardly been studied and remains largely unknown outside of Brazil.

Despite rather low carbon stock values, the Caatinga dry forests serve as important carbon sinks due to their large spatial extent. However, climate change with lower amounts of precipitation (Koch et al. 2015) may exacerbate the environmental

degradation and lead to a decrease in livestock and agricultural production together with a loss of the carbon storage potential (Althoff et al. 2016). This in turn may create a negative feedback loop by accelerating climate change as the forests lose their function as carbon sinks and emit sequestered carbon (Millennium Ecosystem Assessment 2005; Oyama & Nobre 2003). Marengo et al. (2014) even predict a social crisis for this region caused by these adverse conditions. Therefore, the protection of the Caatinga dry forests is of crucial importance (Pan et al. 2011; Prentice et al. 2001).

In the past, several studies assessed the plant diversity of the Caatinga (e.g., Ferraz et al. 2013; Maracajá et al. 2003; Rodal et al. 2008; Silva et al. 2014), while literature on carbon stocks in the Caatinga area remains scarce (Moura et al. 2016). Moreover, there is a lack of scientific research which analyses the effect of actual land uses and further environmental parameters on both biodiversity and carbon stocks. However, those studies are urgently needed to disentangle underlying mechanisms and derive recommendations for adapted land management measures which safeguard the livelihood of the local farmers but protect and possibly enhance ecosystems and their functions at the same time. The present study aims at closing this data gap by investigating the effect of different grazing intensities and irrigation agriculture on the native Caatinga vegetation and its potential to store organic carbon. Based on the findings of this study, recommendations for a sustainable land management have been derived, presented to and discussed with various stakeholders.

The INNOVATE project

This study was carried out within the research project INNOVATE (**I**nterplay among multiple uses of water reservoirs via **i**nnovative coupling of substance cycles in **a**quatic and **t**errestrial **e**cosystems). The INNOVATE project was one of twelve international research projects funded by the German Federal Ministry of Education and Research (BMBF) as part of the 'Sustainable Land Management' funding measure in the framework program 'Research for Sustainability' (FONA) with focus on stakeholder contact and practical solutions. The overall aim of INNOVATE was to develop management recommendations for an ecologically and socially sound development of the São Francisco River catchment area with focus on the Itaparica Reservoir and

semi-arid areas north of the reservoir. Research was carried out on macro-, meso-, and local scales by a team of multidisciplinary scientists funded by the BMBF as well as Brazilian funds. Based on the scientific research results of the present as well as associated studies, recommendations for a sustainable land management were derived. These measures were presented understandable for stakeholders including a series of workshops addressing various participants, several leaflets, and a guidance manual (for more information see Siegmund-Schultze 2017).

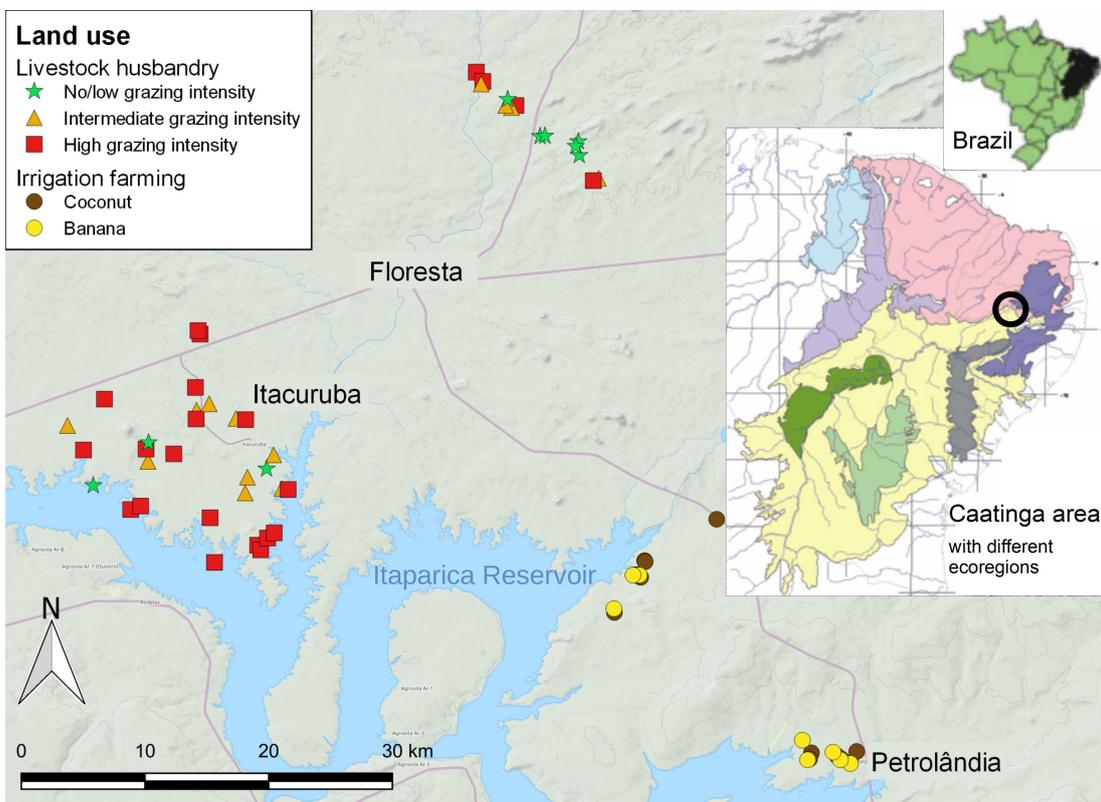


Figure 1.1 Plot distribution across the study area (municipalities of Itacuruba, Floresta, and Petrolândia). Different symbols indicate different land-use types. Map of study plots: © Thunderforest, Data © OpenStreetMap contributors, QGIS Development Team 2016 (<http://www.qgis.org>). Maps of Brazil and Caatinga: adapted after Velloso et al. (2002). Different colours in the Caatinga map refer to different ecoregions: Complexo de Campo Maior (light blue), Complexo Ibiapaba – Araripe (purple), Depressão Sertaneja Setentrional (pink), Planalto da Borborema (dark purple), Depressão Sertaneja Meridional (yellow), Dunas do São Francisco (dark green), Complexo da Chapada Diamantina (light green), and Raso da Catarina (dark grey).

Study area

Geographical setting

The study was carried out in the vicinity of the Itaparica Reservoir, in the federal state of Pernambuco, north-eastern Brazil. The Itaparica Reservoir is used for flood regulation, hydroelectric power generation, irrigation farming, and drinking water supply (Braga et al. 2012; Romano & Garcia 1999). The artificial lake was formed in 1988 after the construction of the Itaparica dam. The flooding required the resettlement of about 10,400 households (Hagel et al. 2014). Entire towns were relocated and fertile soils were lost. Many of the affected people received new land within the irrigation schemes which were established in former Caatinga dry forest areas (Hagel et al. 2015). The study sites were situated within the municipalities of Itacuruba and Floresta (Caatinga dry forests), and Petrolândia (crop fields) north of the reservoir (Figure 1.1).

Climate

The climate of the study area is semi-arid with a mean annual temperature of 23–27 °C and a rainy season between January and June (INMET 2018). The mean annual rainfall over the last decades was 371 mm (Itacuruba) and 514 mm

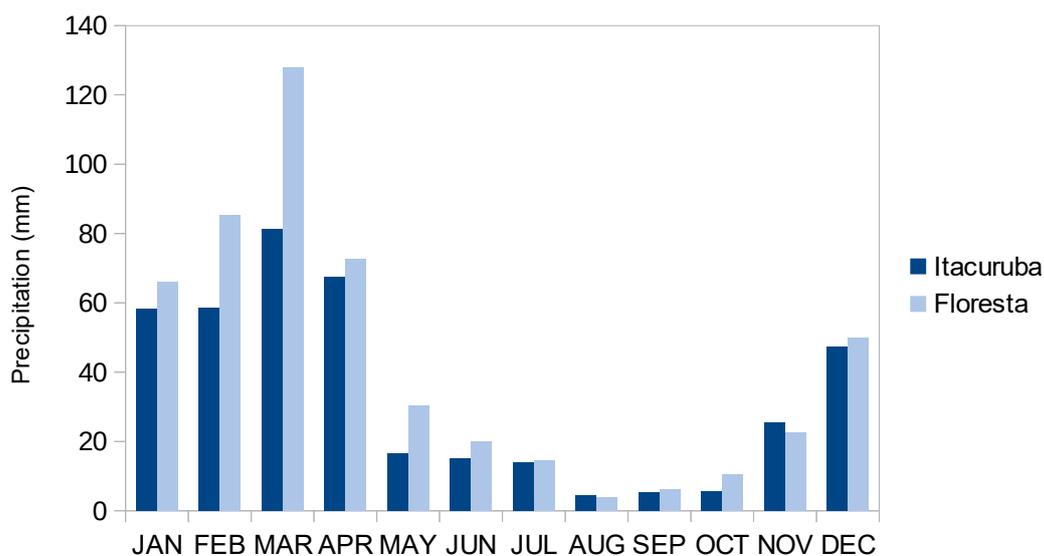


Figure 1.2 Mean precipitation per month recorded at the meteorological stations Itacuruba and Floresta (1911–1990; UFCG - DCA 2018).

(Floresta; Figure 1.2; UFCG - DCA 2018). Rainfall is generally very irregular and highly variable across the study area. Droughts are very common (Sampaio 1995) and part of our field campaign took place during the most recent drought which started in 2010 and lasted 3 years (INMET 2018).

Geology and soils

The geomorphology of the study area is characterised by smooth elevations between 300 and 500 m above sea level (a.s.l.) with scattered mountains and plateaus (900–1000 m a.s.l.; Sampaio 1995). The study plots were established between 304 m and 397 m a.s.l. The geology of the study area is composed of a Proterozoic crystalline basement (Sampaio 1995). Soils in our study area are mainly shallow, sandy, rocky, and poor in nutrients. They are classified as Planosols and Luvisols interspersed with Regosols and Leptosols (Itacuruba and Floresta; Embrapa 2001a,b; Torres & Santos Pfaltzgraff 2014), and Arenosols (Petrolândia; Araújo Filho et al. 2013). This diversity results in a complex mosaic of soils with extremely different characteristics, depths, and water availabilities (Sampaio 1995). The mean pH-value was 6.8 (Petrolândia).

Vegetation

Most of the study area was sparsely vegetated with shrubs, trees (average height about 2 m), scattered emergent trees (tree height > 4 m), cacti, and bromeliads. In many places, the study area appeared degraded. A dense, species rich forest vegetation was only found in preserved areas (Floresta) or in a great distance to settlements (Itacuruba). This observation is in line with a study by Barbosa Neto et al. (2015) who found a decline in vegetation cover between 1986 and 2010 for part of this study area (Itacuruba). The most important plant families found in the present study were Fabaceae, Euphorbiaceae, Cactaceae, which account for a major part of the aboveground carbon stocks (AGCS), and Malvaceae. Typically, Caatinga trees and shrubs are deciduous with small and pinnate leaves. Often, they exhibit thorns or spines (Prado 2003). The word 'Caatinga' derives from the native Tupi language and means 'white forest' (Leal et al. 2005) which depicts the white appearance of the forests during the dry season, when leaves are shed. The first field campaign

(2012/2013) coincided with a severe drought. Herb species were exclusively found along river margins and were heavily grazed by livestock. Therefore, the assessment of herbaceous plants had to be postponed. Only in 2014, after the first sufficient rainfall, the diversity and carbon stocks of herbaceous species could be assessed within the study plots.

Socio-economic setting and land use systems

The main source of income in the study area is livestock husbandry (mainly goats). However, there is no overall grazing management plan, limited economic resources of smallholders, and a lack of knowledge of innovative approaches and technologies. Water shortage (highly erratic rainfall events and droughts) is a permanent challenge for the local farmers due to low drought adaptations (Selge et al. 2015), often causing severe losses of livestock. High stocking rates and vast numbers of free roaming livestock (mainly goats and feral donkeys) presumably aggravate the land degradation of the Caatinga ecosystem.

Before the establishment of the reservoir, floodplain agriculture was an important economic sector in Petrolândia. After the construction of the Itaparica Dam, irrigation schemes were established as compensation measure to provide the population with arable land. Most of the resettlement of the rural population was concentrated in three areas: Icó-Mandantes and Barreiras (agrovila, housing in villages relatively distant from the fields) and Apolônio Sales (agricultural fields in close proximity to the houses). In contrast to livestock husbandry, irrigation farming achieves constant high crop yields independent from local rainfall (Selge et al. 2015). Coconut and banana represent 25% and 8% respectively of the cropped area in the investigated irrigation schemes. Along with further perennial crops (e.g., guava, mango), onion and melon are common crop species. Crop fields are commonly monocultures, except for the first three years after coconut planting when intercropping with peanut, beans, or manioc is carried out. Goat manure is often used as organic fertiliser, sometimes mixed with chemical fertilisers. Crop fields are irrigated throughout the year. Different irrigation techniques are used (drip, spray, and micro-spray). Typical problems are salinisation due to improper irrigation, intense use of agrochemicals, and pests such as whitefly (coconut fields). The Caatinga vegetation is usually removed before the establishment of the crop fields.

Alternative sources of income in the area are artisanal fishery, pisciculture, aviculture, and apiculture. In Itacuruba, an astronomical observatory is present and there is a controversially discussed plan to erect a nuclear power plant in the municipality. A public irrigation scheme was also planned, but finally suspended.

Objectives and chapter outline

The large seasonally dry tropical forests of north-eastern Brazil, known as Caatinga, are a particularly worrisome example of habitat transformations through land use. As a result, the Caatinga is now considered one of the most threatened ecosystems of Brazil. The main type of land use within the Caatinga dry forests is livestock farming, typically associated with overgrazing and vast numbers of livestock roaming unsupervised in the forests. In addition, irrigation farming is carried out in areas with access to water. Here, problems such as salinisation and pests occur together with an intense use of agrochemicals. The aim of this study is to analyse the effect of current land-use practices on the vegetation and organic carbon stocks within an area of Caatinga seasonally dry tropical forests and to develop recommendations for sustainable land management options. In particular, the objectives of this work are:

- (1) Analysing the Caatinga plant diversity and species assemblage along a gradient of land-use intensity (preserved Caatinga, intermediate grazing intensity, high grazing intensity, irrigation farming).
- (2) Quantifying organic carbon stocks (above- and belowground) in areas with different land-use intensities.

In order to identify the main drivers of Caatinga vegetation and organic carbon stocks, the study also aimed at:

- (3) Exploring the role of further environmental parameters such as proxies for anthropogenic influences, soil properties, and altitude.

This thesis is based on four scientific articles which were published in international peer-reviewed journals. The articles are followed by a synthesis which summarises and discusses the most important findings.

Chapter 2 Grazing reduces plant species diversity of Caatinga dry forests in north-eastern Brazil

The first article addresses the plant diversity of Caatinga dry forests. The alpha and beta diversity of herb species and of the tree and shrub layer are investigated with respect to grazing intensity (no/low, intermediate, high grazing). The data assessment was carried out in the municipalities of Itacuruba and Floresta on 45 permanent study plots. On each plot, grazing intensity was quantified by collecting, drying, and weighing animal faeces. The diversity of perennial plant species was recorded by counting individuals and the number of bromeliad rosettes. Herbaceous species were assessed after the first sufficient rainfall on a subset of 36 plots using the Braun-Blanquet cover-abundance scale. The data on plant diversity are analysed using generalised linear models (GLMs). Besides grazing intensity, the effect of further environmental parameters is analysed: water availability, soil parameters, cover of litter (%), cover of woody species (%; for herbs only), proxies for anthropogenic impacts (distance to the nearest farmhouse, city, and permanent stream), and altitude. Species composition and underlying environmental parameters are visualised using non-metric multidimensional scaling (NMDS). The hypotheses are: (1) Grazing negatively affects the diversity of woody and herbaceous plants, and (2) plant diversity is positively related to altitude above sea level and distance to the nearest farmhouse, city, and permanent stream as proxies of reduced long-term human presence.

Chapter 3 Is crop yield related to weed species diversity and biomass in coconut and banana fields of northeastern Brazil?

The second article draws attention to crop fields. In particular, the effect of weed diversity and biomass on the yield of two crop species (banana, coconut) is investigated. The data assessment was carried out within the irrigation schemes of Apolônio Sales and Icó-Mandantes in the municipality of Petrolândia. On 21 crop fields, two study plots were established, one in the centre and one at the field edge. Vegetation relevés of weed species were carried out according to Braun-Blanquet (cover-abundance scale). The biomass of weed species was determined on two subplots per plot. All plants with a plant height < 1 m were harvested, dried, and weighed. Moreover, the biomass of crop species was estimated by measuring the circumference at breast height as well as plant height of each crop plant. Soil

organic carbon stocks within the crop fields were determined by analysing two samples of the topsoil (0–5 cm in depth) per study plot. The statistical analyses include NMDS as well as generalised linear mixed models (GLMMs). This article addresses the following questions: (1) Are crop yield and crop plant biomass correlated with weed diversity and biomass, and if so, positively or negatively? (2) Which environmental and management variables influence crop yield, weed diversity, and biomass of crop plants and weeds? (3) Are there differences between the crop–weed relationships of coconut and banana fields?

Chapter 4 Grazing, forest density, and carbon storage: towards a more sustainable land use in Caatinga dry forests of Brazil

The third article elaborates on the vegetation of Caatinga dry forests. Aboveground carbon stocks of trees, shrubs, cacti, bromeliads, and herbs are quantified. Forest densities are assessed and the regeneration of the most abundant tree species (*Cenostigma pyramidale*, *Poincianella microphylla*, and *Aspidosperma pyriformium*) is investigated. The data assessment was carried out on a subplot of 10 m × 10 m on each of the 45 study plots. The circumference at ground level was measured for all standing perennial plants with a diameter at ground level > 3 cm. Based on these circumference values, allometric equations are used to estimate the biomass of each plant. For certain cacti and bromeliad species as well as the tree species *A. pyriformium*, new equations are developed. The carbon stocks of herbaceous species were assessed on two 2 m × 2 m subplots per plot on 39 of the 45 plots. All herbaceous plants within the subplots were harvested, dried, and weighed. Biomass values are multiplied by 0.5 to obtain carbon stock values. All data are analysed with respect to grazing intensity (no/low, intermediate, high; GLMs). Additionally, the variables altitude and distances to nearest farmhouse and city are also considered in the statistical analyses. The hypotheses of the study are as follows: (1) Grazing generally negatively affects aboveground carbon stocks. (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, although a higher human impact is expected at low elevations, especially near permanent streams.

Chapter 5 Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil

The fourth article draws attention to soil organic carbon (SOC) stocks of Caatinga dry forests. It provides quantifications of SOC stocks in different soil depths and analyses differences in SOC stocks with respect to varying grazing intensities along with further variables (clay content, altitude, plant diversity, aboveground biomass). It also provides a section about the classification of the grazing intensity classes used throughout this study. For the quantification of SOC stocks, on each of the 45 study plots, three samples (100 cm³) of the topsoil (0–5 cm in depth) were taken along the western edge of each plot. Additionally, two soil profiles were dug in the north-western and north-eastern corner of each plot. Soil samples (each 100 cm³) were taken every 10 cm down to bedrock. All soil samples were prepared in the laboratory and SOC content was determined by dry combustion. SOC stocks are calculated based on the SOC contents. The effect of the predictor variables on SOC stocks is analysed for each of the three soil compartments topsoil, greater soil depth, and overall soil using linear models. The hypotheses of the article are as follows: (1) SOC will decrease, particularly in the upper soil profile (0–5 cm in depth), at higher grazing intensities. (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 will significantly improve statistical model predictions.

Chapter 6 Synthesis

This chapter discusses the results of the preceding chapters with respect to the overall objectives of this work. The chapter also includes recommendations for an adapted land management of Caatinga dry forests and agricultural areas embedded in the Caatinga region.

References

- Almeida WR, Lopes AV, Tabarelli M, Leal IR (2015) The alien flora of Brazilian Caatinga: deliberate introductions expand the contingent of potential invaders. *Biological Invasions* 17:51–56. <https://doi.org/10.1007/s10530-014-0738-6>
- Albuquerque UP, Gonçalves PHS, Júnior WSF, Chaves LS, Silva Oliveira RC, Silva TLL, Santos GC, de Lima Araújo (2018) Humans as niche constructors: Revisiting the concept of chronic anthropogenic disturbances in ecology. *Perspectives in Ecology and Conservation* 16:1–11. <https://doi.org/10.1016/j.pecon.2017.08.006>
- Althoff TD, Menezes RSC, Carvalho AL, Siqueira Pinto A, Santiago GACF, Ometto JPHB, Randow C, Sampaio EVSB (2016) Climate change impacts on the sustainability of the firewood harvest and vegetation and soil carbon stocks in a tropical dry forest in Santa Teresinha Municipality, Northeast Brazil. *Forest Ecology and Management* 360:367–375. <https://doi.org/10.1016/j.foreco.2015.10.001>
- Araújo Filho JAD, Crispim SMA (2002) Associated grazing of cattle, sheep and goats at the semi-arid region of northeast Brazil. First Virtual Global Conference on Organic Beef Cattle Production Sept 2nd Oct 15th, 2002. University of Contestado, Concordia, Brazil
- Araújo Filho JC, Gunkel G, Sobral MCM, Kaupenjohann M, Lopes HL (2013) Soil attributes functionality and water eutrophication in the surrounding area of Itaparica Reservoir, Brazil. *Revista Brasileira de Engenharia Agrícola e Ambiental* 17:1005–1013
- Araújo Filho JAD, Leite ER, Silva ND (1998) Contribution of woody species to the diet composition of goat and sheep in Caatinga vegetation. *Pasture Tropicalis* 20:41–45
- Bakke IA, Bakke OA, Salcedo IH, Andrade AD (2009) In situ fodder production of *Mimosa tenuiflora* under pruning in native caatinga tropical dry forest in Brazil. *Tropical Grasslands* 43:178–187
- Barbosa Neto MV, Araújo MSB, Araújo Filho JC (2015) Avaliação do uso da terra, degradação dos solos e análise multitemporal da cobertura vegetal no Semiárido Pernambucano. In: XXXV Congresso Brasileiro de Ciência do Solo: o solo e suas múltiplas funções, 2–7 August 2015, Natal, pp 1–4
- Braga BPF, Gondim Filho JGC, Sugai MRVB, Costa SV, Rodrigues V (2012) Impacts of Sobradinho Dam, Brazil. In: Tortajada C, Altinbilek D, Biswas AK (eds) Impacts of large dams. A global assessment, Springer Berlin, Germany, pp 153–170
- Embrapa–Empresa Brasileira de Pesquisa Agropecuária, Ministério da Agricultura, Pecuária e Abastecimento (2001a) Mapa Exploratório-Reconhecimento de solos do município de Floresta, PE. Retrieved from <http://www.uep.cnps.embrapa.br/solos/pe/floresta.pdf>. Accessed Oct 2013
- Embrapa–Empresa Brasileira de Pesquisa Agropecuária, Ministério da Agricultura, Pecuária e Abastecimento (2001b) Mapa Exploratório-Reconhecimento de solos do município de Itacuruba, PE. Retrieved from <http://www.uep.cnps.embrapa.br/solos/pe/itacuruba.pdf>. Accessed Oct 2013
- Espirito-Santo MM, Fagundes M, Nunes YRF, Fernandes GW, Sánchez-Azofeifa GA, Quesada M (2006) Bases para a conservação e uso sustentável das florestas estacionais decíduas brasileiras: a necessidade de estudos multidisciplinares. *Unimontes Científica* 8:13–22

- Espírito-Santo MM, Sevilha AC, Anaya FC, Barbosa R, Fernandes GW, Sanchez-Azofeifa GA, Scariot A, Noronha SE, Sampaio CA (2009) Sustainability of tropical dry forests: two case studies in southeastern and central Brazil. *Forest Ecology and Management* 258:922–930. <https://doi.org/10.1016/j.foreco.2009.01.022>
- Ferraz JSF, Ferreira RLC, Silva JAA (2013) Analysis and uses of shrubs and trees by the Indians in an area of Caatinga in the municipality of Floresta, Itaparica region of Pernambuco, Brazil. In: Gunkel G, Silva JAA, Sobral MC (eds) Sustainable management of water and land in semiarid areas. Editora Universitária UFPE, Recife, Brazil, pp 165–185
- Hagel H, Hoffmann C, Doluschitz R (2014) Mathematical programming models to increase land and water use efficiency in semi-arid NE-Brazil. *International Journal on Food System Dynamics* 5:173–181. <https://doi.org/10.18461/ijfsd.v5i4.542>
- Hagel H, Huerta LRZ, Doluschitz R, Hoffmann C, Reiber C, Ferreira Irmão J (2015) The situation and perspectives of agricultural cooperatives in the surrounding area of the Itaparica reservoir in northeast Brazil. *Revista Brasileira de Ciências Ambientais (Online)* 36:168–178. <https://doi.org/10.5327/Z2176-947820151002>
- IBGE–Instituto Brasileiro de Geografia e Estatística (2004) Mapa de biomas e de vegetação. Retrieved from <http://www.ibge.gov.br/home/presidencia/noticias/21052004biomashtml.shtm>. Accessed Jan 2017
- IBGE–Instituto Brasileiro de Geografia e Estatística (2015) Produção da Pecuária Municipal volume 43, 2015 Brasil. Retrieved from https://biblioteca.ibge.gov.br/visualizacao/periodicos/84/ppm_2015_v43_br.pdf. Accessed Jul 2018
- INMET–Instituto Nacional de Meteorologia (2018). Retrieved from http://www.inmet.gov.br/portal/index.php?pr=home/page&page=rede_estacoes_auto_graf. Accessed Jun 2018
- Koch H, Biewald A, Liersch S, Azevedo JRG, Silva G, Kölling K, Fischer P, Koch R, Hattermann F (2015) Scenarios of climate and land-use change, water demand and water availability for the São Francisco River basin. *Revista Brasileira de Ciências Ambientais (Online)* 36:96–114. <https://doi.org/10.5327/Z2176-947820151007>
- Leal IR, Silva JMC, Tabarelli M, Lacher TE (2005) Changing the course of biodiversity conservation in the Caatinga of northeastern Brazil. *Conservation Biology* 19:701–706. <https://doi.org/10.1111/j.1523-1739.2005.00703.x>
- Lucena RF, Albuquerque UP, Monteiro JM, Cecília Fátima CBR, Florentino AT, Ferraz JSF (2007) Useful plants of the semi-arid northeastern region of Brazil—a look at their conservation and sustainable use. *Environmental Monitoring and Assessment* 125:281–290. <https://doi.org/10.1007/s10661-006-9521-1>
- Maracajá PB, Batista CHF, Sousa AD, Vasconcelos WD (2003) Levantamento florístico e fitosociológico do estrato arbustivo-arbóreo de dois ambientes na vila Santa Catarina, Serra do Mel, RN. *Revista de Biologia e Ciências da Terra* 3:1–13
- Marengo JA, Chou SC, Torres RR, Giarolla A, Alves LM, Lyra A (2014) Climate change in Central and South America: Recent trends, future projections, and impacts on regional agriculture. CCAFS Working Paper no. 73. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. Available online at: www.ccafs.cgiar.org

- Menezes RSC, Sampaio EVSB, Giongo V, Pérez-Marin AM (2012) Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. *Brazilian Journal of Biology* 72:643–653. <https://doi.org/10.1590/S1519-69842012000400004>
- Millennium Ecosystem Assessment (2005) *Ecosystems and human well-being: Desertification synthesis*. World Resources Institute, Washington DC, USA
- MMA–Ministério do Meio Ambiente (2004) *Estratégias para o uso sustentável da biodiversidade da caatinga*. In: Silva JMC, Tabarelli M, Fonseca MT, Lins LV (eds) *Biodiversidade da caatinga: áreas e ações prioritárias para a conservação*, Brasília, Brazil, Ministério do Meio Ambiente, Universidade Federal de Pernambuco, pp 329–340
- MMA–Ministério do Meio Ambiente (2011) *Subsídios para a elaboração do plano de ação para a prevenção e controle do desmatamento na Caatinga*. Ministério do Meio Ambiente, Brasília, Brazil. Retrieved from http://www.mma.gov.br/estruturas/203/_arquivos/diagnostico_do_desmatamento_na_caatinga_203_2_203_1.pdf. Accessed Sep 2015
- MMA–Ministério do Meio Ambiente (2017) *Caatinga*. Ministério do Meio Ambiente, Brasília, Brazil. Retrieved from <http://www.mma.gov.br/biomas/caatinga>. Accessed Mar 2017
- Moura PM, Althoff TD, Oliveira RA, Souta JS, Souta PC, Menezes RSC, Sampaio EVSB (2016) Carbon and nutrient fluxes through litterfall at four succession stages of Caatinga dry forest in Northeastern Brazil. *Nutrient Cycling in Agroecosystems* 105:25–38. <https://doi.org/10.1007/s10705-016-9771-4>
- Oyama MD, Nobre CA (2003) A new climate-vegetation equilibrium state for tropical South America. *Geophysical research letters* 30:2199. <https://doi.org/10.1029/2003GL018600>
- Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. *Science* 333:988–993. <https://doi.org/10.1126/science.1201609>
- Prado DE (2003) *As caatingas da América do Sul*. In: Leal IR, Tabarelli M, Cardoso da Silva JM (eds) *Ecologia e conservação da caatinga*. Universidade Federal de Pernambuco, Recife, pp 3–74
- Prentice IC, Farquhar GD, Fasham MJR, Goulden ML, Heimann M, Jaramillo VJ, Kheshgi HS, LeQuéré C, Scholes RJ, Wallace DWR (2001) The carbon cycle and atmospheric carbon dioxide. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) *Climate change 2001: The scientific basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp 185–237
- Queiroz JA, Trovão DMDBM, de Oliveira AB, de Oliveira ÉCS (2006) Análise da estrutura fitossociológica da Serra do Monte, Boqueirão, Paraíba. *Revista de Biologia e Ciências da Terra* 6:251–259
- Rodal MJN, Martins FR, Sampaio EVSB (2008) Levantamento quantitativo das plantas lenhosas em trechos de vegetação de caatinga em Pernambuco. *Revista Caatinga* 21:192–205

- Romano PA, Garcia EAC (1999) Policies for water-resources planning and management of the São Francisco River. In: Biswas AK, Cordeiro NV, Braga BPF, Tortajada C (eds) Management of Latin American River Basins: Amazon, Plata, and São Francisco. United Nations University Press, Tokyo, Japan, pp 245–272
- Salcedo IH, Menezes RSC (2009) Agroecosystem functioning and management in semi-arid Northeastern Brazil. In: Tiessen H, Stewart JWB (eds) Applying ecological knowledge to landuse decisions, Inter-American Institute for Global Change Research - IICA-IAI-759 Scope, Paris, France, pp 73–81
- Sampaio EVSB (1995) Overview of the Brazilian Caatinga. In: Bullock SH, Mooney HA, Medina E (eds) Seasonally dry tropical forests. Cambridge University Press, Cambridge, UK, pp 35–63
- Santos JC, Almeida-Cortez J (2009) Origins and maintenance of tropical biodiversity. In: Del Claro K, Oliveira PS, Rico-Gray V (eds) Tropical biology and conservation management, Volume V, EOLSS Publishers Co. Ltd., Oxford, UK, pp 214–226
- Santos JC, Leal IR, Almeida-Cortez JS, Fernandes GW, Tabarelli M (2011) Caatinga: the scientific negligence experienced by a dry tropical forest. *Tropical Conservation Science* 4:276–286. <https://doi.org/10.1177/194008291100400306>
- Santos MG, Oliveira MT, Figueiredo KV, Falcao HM, Arruda EC, Almeida-Cortez J, Sampaio EVSB, Ometto JPHB, Menezes RSC, Oliveira AFM, Pompelli MF, Antonino ACD (2014) Caatinga, the Brazilian dry tropical forest: can it tolerate climate changes? *Theoretical and Experimental Plant Physiology* 26:83–99. <https://doi.org/10.1007/s40626-014-0008-0>
- Schulz C, Koch R, Cierjacks A, Kleinschmit B (2017) Land change and loss of landscape diversity at the Caatinga domain – Analysis of pattern-process relationships with MODIS land cover products (2001-2012). *Journal of Arid Environments* 136:54–74. <https://doi.org/10.1016/j.jaridenv.2016.10.004>
- Selge F, Hagel H, Gunkel G, Doluschitz R (2015) Annual rainfall variability and economic dependency of smallholder agriculture in the semi-arid Northeast Brazil. *Revista Brasileira de Ciências Ambientais* 36:155–167. <https://doi.org/10.5327/Z2176-947820151009>
- Siegmund-Schultze M (ed) (2017) Guidance Manual—A compilation of actor-relevant content extracted from scientific results of the INNOVATE project. Universitätsverlag der TU Berlin, Berlin, Germany
- Silva FKG, de Faria Lopes S, Lopez LCS, de Melo JIM, Trovão DMDBM (2014) Patterns of species richness and conservation in the Caatinga along elevational gradients in a semiarid ecosystem. *Journal of Arid Environments* 110:47–52. <https://doi.org/10.1016/j.jaridenv.2014.05.011>
- Siqueira Filho JA, Conceição AA, Rapini A, Coelho AOP, Zuntini AR, Coutinho AJ, ... & Souza VC (2012) Flora das caatingas do rio São Francisco. In: Siqueira Filho JA (eds) Flora das Caatingas do rio São Francisco. Andrea Jakobsson Estúdio, Rio de Janeiro, Brasil, pp 447–542. Retrieved from https://www.researchgate.net/publication/299657454_Trepadeiras_do_Bioma_Caatinga. Accessed Oct 2018
- Tiessen H, Feller C, Sampaio EVSB, Garin P (1998) Carbon sequestration and turnover in semiarid savannas and dry forest. *Climatic Change* 40:105–117. <https://doi.org/10.1023/A:1005342932178>

- Tiessen H, Salcedo IH, Sampaio EVSB (1992) Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. *Agriculture, Ecosystems & Environment* 38:139–151. [https://doi.org/10.1016/0167-8809\(92\)90139-3](https://doi.org/10.1016/0167-8809(92)90139-3)
- Torres FSDM, Santos Pfaltzgraff PAD (2014) Geodiversidade do estado de Pernambuco, Programa Geologia do Brasil. Levantamento da Geodiversidade. CPRM, Recife Brazil. Retrieved from <http://rigeo.cprm.gov.br/jspui/handle/doc/16771>. Accessed Jan 2016
- UFCG - DCA–Universidade Federal de Campina Grande. Departamento de Ciências Atmosféricas - Dados Climatológicos do Estado de Pernambuco (2018). Retrieved from <http://www.dca.ufcg.edu.br/clima/dadospe.htm>. Accessed Jul 2018
- Velloso AL, Sampaio EVSB, Pareyn FGC (eds) (2002) Ecorregiões propostas para o bioma Caatinga. Recife, Brazil. Associação Plantas do Nordeste, Instituto de Conservação Ambiental - The Nature Conservancy do Brasil



CHAPTER 2

Grazing reduces Plant Species Diversity of Caatinga Dry Forests in North-eastern Brazil

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Abstract

Questions: In many arid and semi-arid regions of the world, livestock husbandry is the main land use and grazing is one of the main challenges for biodiversity conservation. This also applies to the Caatinga, a unique seasonally dry tropical forest in north-eastern Brazil. It is considered one of the most threatened ecosystems of

Brazil. To protect semi-arid regions from biodiversity loss, degradation, and desertification, sustainable management practices are urgently needed. However, the effect of different grazing intensities on plant diversity is not yet fully understood. In this study, we examined the effect of different grazing intensities on plant species composition, alpha and beta diversity.

Location: Vicinity of the Itaparica Reservoir, north-eastern Brazil.

Methods: We assessed the effects of different grazing intensities (high, intermediate, no/low) on species composition, alpha and beta diversity of the tree and shrub, and the herb layer in a Caatinga area. Plant diversity of the tree and shrub layer was assessed on 45 study plots (each 20 m × 20 m), while the diversity of herbs was studied on a subset of 36 plots (four subplots, each 2 m × 2 m).

Results: In total, we recorded 140 plant taxa including morphospecies. Grazing at high intensities significantly reduced almost all measures of alpha and beta diversity (tree and shrub layer) compared to areas with no or low grazing. In contrast, species composition was not significantly related to grazing but instead to altitude, which serves as an indicator of reduced anthropogenic impact such as slash-and-burn agriculture or tree harvesting.

Conclusion: Overall, the study results show that the current livestock management has negative effects on plant diversity in Caatinga ecosystems. These results have been incorporated into guidelines provided to regional stakeholders including recommendations for adapted land management practices which protect and foster the biodiversity of dry forests while sustaining local livelihoods.

Keywords: semi-arid, seasonally dry tropical forest, land use, goats, livestock husbandry, land management, Caatinga, Brazil, biodiversity, grazing, intermediate disturbance hypothesis

Introduction

Seasonally dry tropical forests (SDTF) occur in tropical regions with several months of drought (Mooney et al. 1995). They can be found in relatively disjunct scattered patches in South America, Africa, Asia, and Oceania (Espírito-Santo et al. 2006; Pennington et al. 2006). Despite representing about 42% of tropical forests world-

wide (Espírito-Santo et al. 2006), SDTF received much less scientific attention and conservation efforts than other tropical forests (Leal et al. 2005; Espírito-Santo et al. 2009; Miles et al. 2006). The two largest continuous areas of SDTF are both located in South America (Caatinga: north-eastern Brazil; Gran Chaco: eastern Bolivia, western Paraguay, and northern Argentina) and comprise more than 50% of the total tropical dry forests worldwide (Miles et al. 2006). With approximately 850,000 km² (Schulz et al. 2017), the larger of these two areas is the Caatinga. It covers about 10% of the Brazilian territory (IBGE 2004).

Overgrazing by livestock is often blamed for land degradation in arid and semi-arid areas although the impacts of grazing on the vegetation are manifold and often difficult to predict (Anderson & Hoffman 2007). Livestock may have an impact on plant species and species diversity in many ways, negative or positive (Sebata 2013). They can reduce the fitness of plant species directly by the repeated browsing and grazing of plant parts, including seedlings, saplings, and fruits (Cierjacks & Hensen 2004; Sebata 2013). In contrast, some species may benefit from persistent grazing pressure and show enhanced growth (Sebata 2013). Some livestock species, such as cattle, may facilitate the regeneration of plants by creating safe sites for germination and seedling establishment (Cierjacks et al. 2008). Further, livestock may alter plant species composition and vegetation structure by selective grazing, especially of plant species lacking protective mechanisms. Consequently, many species of SDTF exhibit spines and thorns (Santana & Souto 2006) or are known to be unpalatable for livestock, especially when green (Pfister & Malechek 1986; Ydoyaga-Santana et al. 2011). Indirect effects of grazing on vegetation include soil compaction through trampling (Piñeiro et al. 2010), nutrient enrichment by livestock excrements (Haynes & Williams 1993), and increased soil erosion due to the consumption of plants or leaf litter (Pfister & Malechek 1986), all of which may modify species composition.

Several theoretical models on the effect of grazing on plants exist. Milchunas et al. (1988), for example, proposed in their 'generalised model of the effects of grazing on plant community structure and diversity' that high grazing intensity will decrease plant diversity in semi-arid environments with long grazing history. The effect of grazing on plant diversity within SDTF was also analysed by a number of empirical studies (e.g., Blackmore & Vitousek 2000; Gillespie et al. 2000; Kraaij & Milton 2006; Noretto et al. 2006). Yet, Albuquerque et al. (2008) have argued that the role

of livestock has not yet been comprehensively investigated and that degradation may instead be a consequence of shifting cultivation and timber harvest (Kauffman et al. 1993; Alves Junior et al. 2013), which is then often followed by livestock husbandry. Hence, more studies are needed to obtain a detailed understanding of the interplay between different land-use practices (including varying grazing intensities) and biodiversity. Those findings are expected to contribute to an adapted land management that optimises productivity, conserves biodiversity, important ecosystem functions and services, and safeguards the livelihoods of the local population (Cierjacks & Hensen 2004; Bailey & Brown 2011; Espírito-Santo et al. 2009; Santos et al. 2014).

There is no definite list of Caatinga plant species (Araújo Filho & Crispim 2002). About one-third of the 596 woody species recorded here are endemic to the Caatinga (Araújo Filho & Crispim 2002). The number of herbaceous species is difficult to assess but is probably higher compared to woody species (Reis et al. 2006; Queiroz et al. 2015). With a population density of about 32 inhabitants per square kilometre (MMA 2011), the Caatinga area is one of the most densely populated semi-arid regions of the world (Salcedo & Menezes 2009). Due to low annual rainfall and restricted water access, livestock husbandry is the main land-use type in the region (Tiessen et al. 1998; Bakke et al. 2009) with approximately 10.4 million goats and 7.2 million sheep (88% and 39% respectively of all livestock in Brazil; Drumond et al. 2004). The vegetation of the Caatinga forests also supplies goods such as food, timber, charcoal, and medicinal plants (Drumond et al. 2004; Lucena et al. 2007) with firewood still being the main energy source within rural Caatinga areas (Santos et al. 2014). Today, 30–52% of the native Caatinga vegetation has been altered by human manipulations, such as slash-and-burn agriculture, livestock husbandry, and constructions (settlements, roads; Tiessen et al. 1992; Leal et al. 2005), which in many areas led to degradation with subsequent desertification (Menezes et al. 2012) and biodiversity loss (Leal et al. 2005). Thus, the Caatinga is considered one of the most threatened ecosystems within Brazil (Espírito-Santo et al. 2009). At present, only about 1% of the Caatinga area is strictly protected ('Unidades de Proteção Integral'; Leal et al. 2005). Yet, recent studies reported an increase in forest cover during the last decades (Aide et al. 2013; Schulz et al. 2017), indicating a slow recovery of the Caatinga vegetation (Cabral et al. 2013; Santos et al. 2013).

The aim of this study was to assess the effect of different grazing intensities on the alpha (within plots) and beta (across plots) diversity of woody and herbaceous plant species within the Caatinga dry forest vegetation. In addition to grazing intensity, plant diversity is expected to show a positive correlation with altitude due to an expected lower anthropogenic impact along with a lower water availability at higher elevations (Silva et al. 2014). Also, the distances to the nearest farm, city, and permanent stream are expected to show a positive correlation with plant diversity due to a lower anthropogenic impact at greater distances (Revermann et al. 2016). Our hypotheses were that: (1) grazing negatively affects the diversity of woody and herbaceous plants, and (2) plant diversity is positively related to altitude above sea level, and distance to the nearest farm, city, and permanent stream as proxies of reduced long-term human presence.

Materials and methods

Study area

The study was carried out in the municipalities of Itacuruba and Floresta in the vicinity of the Itaparica Reservoir (São Francisco River), federal state of Pernambuco, north-eastern Brazil. With a length of 2914 km, the São Francisco River is the major river of eastern South America. The reservoir dam was completed in 1988. A subsequent flooding led to the destruction of agricultural areas and two entire cities. About 10,400 households were resettled (Hagel et al. 2014). Today, the resettlers mainly either live in dry forest areas (Caatinga), often with poor soils and limited access to water, or in agrovilas within irrigated agricultural areas (Cierjacks et al. 2016).

The mean annual temperature of the area is 23–27°C with a high potential evapotranspiration (1500–2000 mm per year; Sampaio 1995). The average annual precipitation within the study area (Itacuruba) over the last 25 years was 391 mm (minimum 88 mm; maximum 748 mm; Sousa et al. 2013), with most of the rainfall occurring between November and April. However, the precipitation rate appears to be highly variable across the study area (own observations). Severe droughts occur every 40–50 years (Sampaio 1995). Part of our field campaign took place during the most recent drought, which started in 2010 and lasted three years.

The typical Caatinga seasonally dry forest within the study area comprises a sparse to dense tree layer with predominantly small trees and shrubs (mean height 2 m), scattered emergent trees (tree height > 4 m), cacti, and bromeliads. Trees and shrubs are typically deciduous with small, frequently pinnate leaves and often exhibit thorns and spines (Prado 2003). An herbaceous layer occurs only after rainfall events (Araújo et al. 2005). During the first part of the field campaign, which coincided with a severe drought, herbs were only found along river margins and were heavily grazed by livestock, which made analyses of different grazing intensities impossible. Only after the first rain at the end of 2013, a partially dense herb layer appeared.

The area is characterised by plains with hills (300–500 m a.s.l.) and few higher mountains (900–1000 m a.s.l.; Sampaio 1995). The study plots were located between 307 and 397 m a.s.l. with a slightly rising terrain. Due to the relatively small variation in altitude, we do not expect pronounced climatic changes along the altitudinal gradient, such as increasing precipitation and decreasing temperature. Rather, in this study, we expect altitude to be an indicator of accessibility to water (groundwater and surface water), with areas at lower altitude showing a better water availability due to runoff and a closer proximity to permanent streams. In addition, lower areas are considered to be associated with a higher probability of historical and recent human activities due to a better access to water (Silva et al. 2014). Planosols and Luvisols interspersed with Regosols and Leptosols are the most common soils found in Itacuruba and Floresta (following the FAO classification system; Embrapa 2001a,b; Torres & Santos Pfaltzgraff 2014). The soils are usually shallow, sandy, rocky (Schulz et al. 2016), and poor in nutrients (Cierjacks et al. 2016). The mean pH-value has been reported as 6.8 (Cierjacks et al. 2016).

Land use

In the study area, water availability is clearly the limiting factor. Accordingly, livestock farming, mainly of small ruminants, is the main agricultural sector (Sampaio 1995; own observations). The cultivation of crops is only practicable in small areas, either located in the vicinity of permanent streams or facilitated by the use of wells or irrigation facilities (see Cierjacks et al. 2016), which are only affordable for a small

part of the local population (personal communication with local farmers December 2012).

Densities of animals kept only on pasture should not exceed the carrying capacity of the Caatinga, which is known to be 0.07–0.1 livestock units ha⁻¹ (Tiessen et al. 1998). Yet, reported livestock densities were as high as 2.3 units ha⁻¹ (Schulz et al. 2016). A common practice among farmers, especially during droughts, is to allow their livestock to roam freely in unfenced Caatinga areas to enlarge the pasture area (own observations). As this makes it difficult to use stocking rates to estimate grazing intensities, we used the weight of animal faeces per m² as an indicator of true animal loads and grazing intensities (see Schulz et al. 2016). Besides supplementary forage produced on farms with access to water, farmers also feed cattle and lambs with pods of the exotic tree species *Prosopis juliflora* (algaroba), and, especially during droughts, with shredded shoots of the endemic bromeliad *Encholirium spectabile* (macambira) and the cactus *Cereus jamacaru* (mandacaru; Alves et al. 2009; Nunes et al. 2015; own observations). Such practices may also result in shifts of species composition and changes in biodiversity patterns, but there are as yet no studies on this issue. Moreover, land clearing for slash-and-burn agriculture and tree harvesting, especially during recent decades, may play a role in biodiversity dynamics.

Study design and data collection

We established 45 study plots (20 m × 20 m) in the municipalities of Itacuruba (city: 8°43'39.4"S, 38°41'05.2"W; 30 plots) and Floresta (city: 8°36'08.9"S, 38°34'15.4"W; 15 plots). A restricted randomisation approach was applied to cover the wide gradients of grazing intensity and water availability (see Schulz et al. 2016). Based on a first visual assessment, study plots were selected and classified into three grazing classes: (a) plots located on farmland (high grazing pressure), (b) plots located in unused Caatinga but with clear signs of livestock presence such as livestock tracks and faeces (intermediate grazing pressure), and (c) areas without clear signs of grazing or areas under preservation status (no/low grazing pressure). Moreover, all plots were classified into three water availability classes: (a) permanent water, located at the lakeshore within 5 m horizontal distance of the high water level, (b) temporary water, located along temporary water sources, and (c) no water, lo-

cated on sites without any signs of surface water in the vicinity (see Figure 2.1 for plot examples; Appendix 2.1 for vegetation plot data).

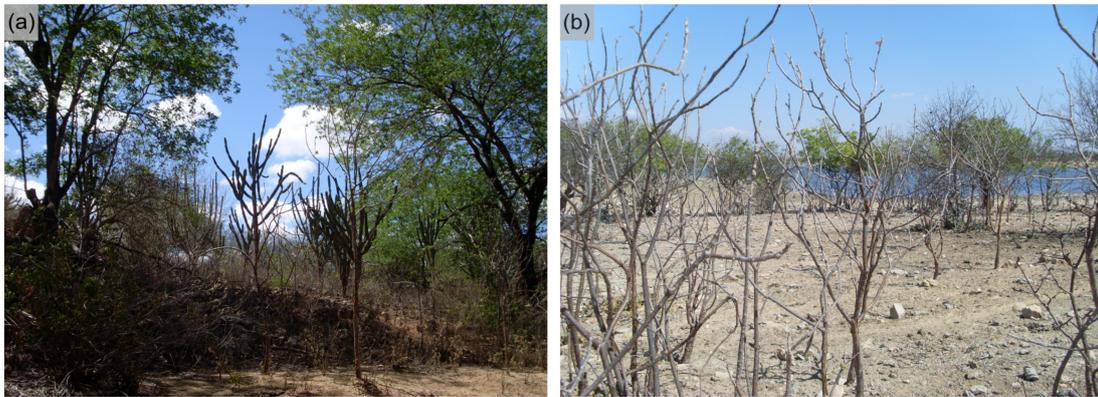


Figure 2.1 Caatinga dry forest vegetation: (a) area with low grazing impact in the vicinity of a temporary stream; plant species include *Cereus jamacaru* and *Jatropha mollissima*; (b) intensively grazed area in the vicinity of the Itaparica Reservoir with *Jatropha mollissima* being the dominant species. A livestock track can be seen in the foreground (photos: Jens von dem Bussche 2012).

We established at least four plots per factor combination to allow for a balanced study design and a relatively even plot distribution across the study area. The minimum distance between a plot and a road was 200 m, the minimum distance between two plots was 300 m, often covering a distance of some kilometres. The position and altitude of each plot were determined using a handheld GPS (Garmin eTrex 30, Garmin, Neuhausen am Rheinfall, Switzerland). Final grazing intensity was determined for all plots based on the dry weight of livestock faeces collected on six subplots (each 2 m × 2 m) per plot. The grazing intensity was subsequently classified as: (a) no/low grazing pressure (weight of livestock faeces < 5 g m⁻²), (b) intermediate grazing pressure (5–20 g m⁻²), and (c) high grazing pressure (> 20 g m⁻²; see Schulz et al. 2016 for further details). Following the reclassification, only one plot with low grazing intensity was located directly at the São Francisco River edge (Figure 2.2). Various types of livestock (goats, sheep, cows, horses, donkey) graze the Caatinga with goats clearly being the main livestock (Schulz et al. 2016). However, the faeces of all livestock types were analysed together to reflect the grazing regime. We also recorded the number of woody plants with clear signs of grazing per plot (20 m × 20 m) and found a positive correlation with mean faeces weight (GLM, $p = 0.005$) supporting the approach of using faeces weight to quantify

grazing intensity. As a proxy for anthropogenic effects, we measured the distance between each plot and the nearest city, farm, and permanent stream using satellite images provided by Google Earth (version 7.1.2.2041).

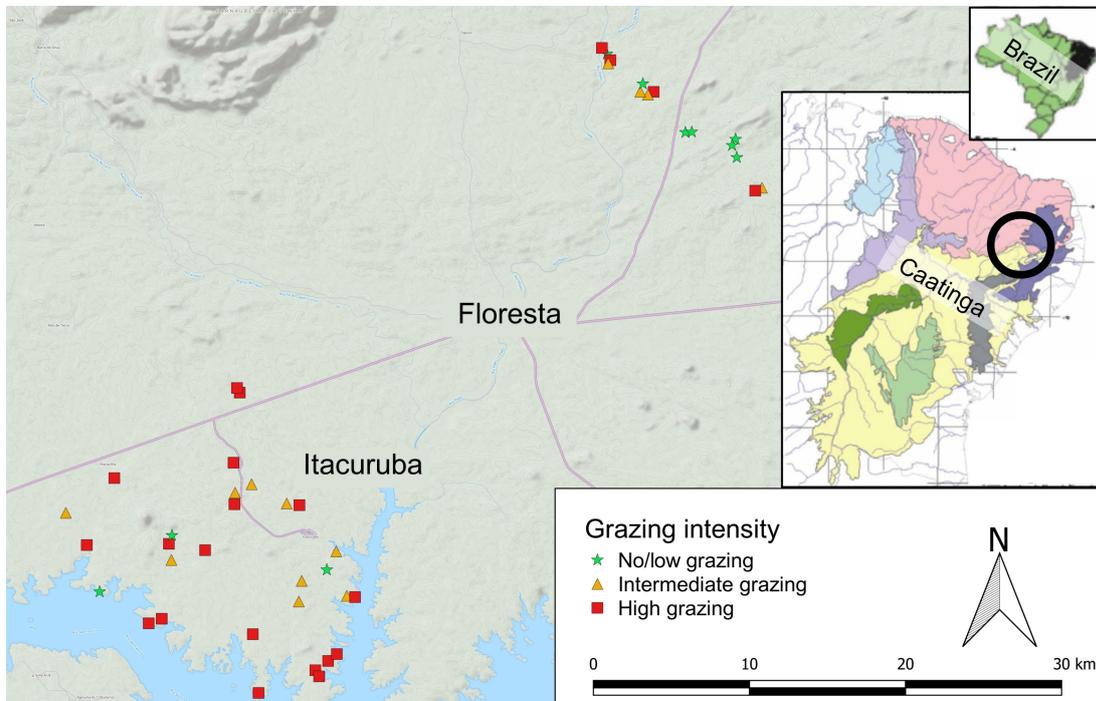


Figure 2.2 Plot distribution across the study area (municipalities of Itacuruba and Floresta). Different symbols indicate different grazing classes. Maps © www.thunderforest.com, Data © www.osm.org/copyright; QGIS Development Team (<http://www.qgis.org>). Maps of Brazil and Caatinga were adapted after Velloso et al. (2002). Different colours in the Caatinga map refer to different ecoregions: Complexo de Campo Maior (light blue), Complexo Ibiapaba – Araripe (purple), Depressão Sertaneja Setentrional (pink), Planalto da Borborema (dark purple), Depressão Sertaneja Meridional (yellow), Dunas do São Francisco (dark green), Complexo da Chapada Diamantina (light green), and Raso da Catarina (dark grey).

The diversity of trees, shrubs, cacti, bromeliads, epiphytes, and vines (hereafter referred to as tree and shrub layer) was assessed on each plot (20 m × 20 m), counting all individuals and the number of bromeliad rosettes. Additionally, we recorded the cover of woody species, litter, and sand, gravel, stones and rock per plot. The diversity of herbs (hereafter referred to as herb layer) was assessed on four subplots (each 2 m × 2 m) per plot ($n = 144$ subplots) with the cover of each species estimated using the Braun-Blanquet seven-class cover-abundance scale with r: very scattered; +: sparse and cover $\leq 1\%$; 1: abundant and low cover or sparse and high cover; 2: very abundant or covering 10–25%; 3: covering 25–50%,

number of individuals irrelevant; 4: covering 50–75%, number of individuals irrelevant; 5: covering 75–100%, number of individuals irrelevant (Braun-Blanquet 1964). Plant species were identified in cooperation with the herbarium Dardano de Andrade of the Agronomic Institute of Pernambuco, Recife. Taxon nomenclature for plants follows Flora do Brasil 2020 (<http://floradobrasil.jbrj.gov.br/>, accessed September 2016). The assessment of the tree and shrub layer was carried out in 2012–2013 during the drought, while the herb layer was assessed in 2014 after the first heavy rainfall. Due to time constraints and the loss of one plot owing to land-use change (conversion from pasture to cleared and then reforested area), the vegetation of the herb layer was assessed on 36 of the 45 plots.

Three 100 cm³ soil samples (topsoil, 0–5 cm) were taken per plot. Additionally, two soil profiles per plot were dug and soil samples (each 100 cm³) were taken every 10 cm from the soil surface down to bedrock (maximum depth = 60 cm). Soil organic carbon content and nitrogen were determined for all soil samples. Soil texture was determined following DIN/ISO11277 for the upper 10 cm of the soil (see Schulz et al. 2016 for further details).

Statistical analyses

All statistical analyses were performed using R version 3.2.3 (R core team 2015). Based on species abundances obtained from the vegetation relevés (individual/rosette numbers for the tree and shrub layer; cover data for the herb layer), we calculated relative abundances (equation 1) and the alpha diversity indices species richness (S), Shannon index (H'), Simpson index (D , equation 2), and Pielou's evenness (J').

$$\frac{n_i}{n} * 100\% \quad (1) \quad D = 1 - \sum_{i=1}^S \frac{n_i(n_i-1)}{n(n-1)} \quad (2)$$

where n_i = number/cover of individuals belonging to species i

n = total number/cover of individuals

S = species richness

The Shannon and Simpson indices were calculated using the package *vegan* (Oksanen et al. 2016). Cover classes from vegetation relevés (herb layer) were

transformed to mean cover percentage following Frey & Lössch (2010): r = 0.1%; + = 0.5%; 1 = 2.5%; 2 = 15%; 3 = 37.5%; 4 = 62.5%; 5 = 87.5%.

The Bray-Curtis dissimilarity index was used for the assessment of beta diversity, calculated using the package *vegan* (Oksanen et al. 2016). All dissimilarity values were arcsin transformed to achieve normal distribution.

All continuous variables were checked in terms of homogeneity, normality, and outliers (Zuur et al. 2010), and a nested data structure (Zuur et al. 2009). The data were analysed using generalised linear models (GLMs) with Gaussian (Shannon index, Simpson index, Pielou's evenness of the tree and shrub layer) or quasi-Poisson distribution (species richness of the tree and shrub layer, all diversity indices of the herb layer) due to overdispersion (Zuur et al. 2010). The data of each vegetation layer were analysed separately given the different abundance measures. In addition, separate models were fitted for each diversity index (species richness, Shannon and Simpson indices, Pielou's evenness) as response variable. First, the effect of each environmental parameter on plant diversity was tested: grazing intensity based on faeces weight, water availability classes, clay content, sand content, content of the skeleton fraction, C/N ratio, cover of sand, gravel, stones and rock at soil surface, cover of litter, cover of woody species (herbs only), distance to the nearest farmhouse, city and permanent stream, and altitude. In order to determine the main drivers of plant diversity, all parameters which showed a significant effect on plant diversity were incorporated in a statistical model (full model) for each diversity index. Yet, the distances to the nearest farmhouse, city, and permanent stream were highly significantly positively correlated with altitude (farmhouse: $R^2 = 0.556$, $p < 0.001$; city: $R^2 = 0.397$, $p < 0.001$; permanent stream: $R^2 = 0.771$, $p < 0.001$). As we did not expect further insights by including the distance variables in the model and due to a significantly worse performance of them compared to altitude (using the command 'drop1()' during model selection process; Zuur et al. 2009), we excluded them from the full models (Zuur et al. 2010). The full models included grazing intensity, altitude, content of the skeleton fraction, C/N ratio, water availability class, and cover of woody vegetation (herb layer only) as explanatory variables. Following Crawley (2007), stepwise backwards model selection was used to find the minimum adequate model.

Species composition and underlying environmental variables were visualised by non-metric multidimensional scaling (NMDS) using the function *metaMDS* (R pack-

age *vegan*; Oksanen et al. 2016). NMDS is particularly useful for community ecology as it is characterised by a high robustness (Leyer & Wesche 2007). For the ordination, we used the Bray-Curtis dissimilarity matrix (Faith et al. 1987). The stress value was used as quality measure (Leyer & Wesche 2007) with a stress value < 0.15 being considered reasonable for meaningful model interpretation. A Monte-Carlo randomisation test (1000 free permutations; Manly 1997) was used to evaluate the impact of each explanatory variable ($p < 0.05$) on species composition. The environmental variables altitude, cover of woody species, cover of litter, content of the skeleton fraction, C/N ratio, clay content, and sand content were fitted onto the ordination to depict their correlation with species composition.

Results

Biodiversity in Caatinga dry forest

We recorded 140 plant taxa including 25 morphospecies. Of these, 55% were identified to species level, 23% to genus level, 4% to family level, and 18% remained unidentified (see Appendix 2.2 for the species list). Trees and shrubs accounted for 54 species (including three hemi-parasitic shrub species), cacti for seven species, herbs for 38 species (including three herbaceous terrestrial bromeliads and one herbaceous epiphyte bromeliad species), and vines for seven species. For 39 species, the growth form remained unclear. The most abundant species (individual numbers) in the tree and shrub layer (excluding bromeliads) were *Sida galheirensis* (subshrub; relative abundance: 27%), *Aspidosperma pyrifolium* (tree; 24%), *Tacinga inamoena* (cactus; 10%), *Cenostigma pyramidale* (tree; 9%), and *Poincianella microphylla* (tree; 5%). Bromeliads were found on 14 of 45 plots with an average cover of 7% (referring to all plots) or 24% (referring only to plots with bromeliads; based on a mean diameter of 80 cm per bromeliad rosette). The most abundant herb taxa were *Aristida* cf. *adscensionis* (average cover: 52%), *Heliotropium* cf. *ternatum* (13%), *Staelia aurea* (9%), and *Portulaca elatior* (7%).

Table 2.1 Diversity indices (species richness, Shannon index, Simpson index, Pielou's evenness; means \pm standard error) at different grazing intensities (high, intermediate, no/low) within Caatinga vegetation. Different lowercase letters indicate significant differences between grazing classes in GLMs. Tree and shrub layer refers to all trees, shrubs, cacti, bromeliads, vines, and epiphytes (sampling unit 20 m \times 20 m). Herb layer refers to all herbaceous species (sampling unit four subplots per study plot, each 2 m \times 2 m).

| | Mean \pm SE | Min | Max | Grazing intensity | | |
|-----------------------------|-----------------|------|------|---------------------|----------------------|---------------------|
| | | | | High | Intermediate | No/low |
| Total species richness | 20.7 \pm 1.8 | 8 | 52 | 18.1 \pm 2.2 (a) | 22.1 \pm 3.7 (a) | 27.3 \pm 6.2 (a) |
| <i>Tree and shrub layer</i> | | | | | | |
| Species richness | 12.8 \pm 0.8 | 5 | 29 | 11.1 \pm 0.9 (a) | 13.6 \pm 1.4 (ab) | 15.8 \pm 2 (b) |
| Shannon index | 1.48 \pm 0.06 | 0.75 | 2.39 | 1.36 \pm 0.06 (a) | 1.51 \pm 0.1 (ab) | 1.75 \pm 0.13 (b) |
| Simpson index | 0.67 \pm 0.02 | 0.31 | 0.87 | 0.63 \pm 0.02 (a) | 0.68 \pm 0.04 (ab) | 0.74 \pm 0.03 (b) |
| Pielou's evenness | 0.60 \pm 0.02 | 0.3 | 0.82 | 0.58 \pm 0.02 (a) | 0.59 \pm 0.03 (a) | 0.65 \pm 0.04 (a) |
| <i>Herb layer</i> | | | | | | |
| Species richness | 8.4 \pm 1.3 | 1 | 29 | 6.9 \pm 1.4 (a) | 9.7 \pm 2.7 (a) | 10.8 \pm 3.5 (b) |
| Shannon index | 0.77 \pm 0.1 | 0 | 1.98 | 0.67 \pm 0.14 (a) | 0.8 \pm 0.18 (a) | 1.02 \pm 0.2 (a) |
| Simpson index | 0.39 \pm 0.05 | 0 | 0.38 | 0.35 \pm 0.07 (a) | 0.38 \pm 0.08 (a) | 0.51 \pm 0.08 (a) |
| Pielou's evenness | 0.40 \pm 0.05 | 0 | 1 | 0.35 \pm 0.07 (a) | 0.39 \pm 0.08 (a) | 0.56 \pm 0.1 (a) |

Diversity indices related to grazing and other factors

The total species richness is clearly higher in plots with no/low grazing intensity compared to the other grazing classes (Table 2.1), albeit not significantly. Yet, statistical analyses (GLMs) revealed a negative effect of grazing on plant species diversity of the tree and shrub layer. Species richness, Shannon and Simpson indices were significantly higher on plots with no/low grazing intensity compared to heavily grazed plots (Table 2.1). Plots with intermediate grazing pressure showed an intermediate plant diversity. For Pielou's evenness, a similar trend was found although the effect of grazing was not significant. The number of herbaceous species was also significantly higher in plots with no/low grazing compared to plots with intermediate or high grazing intensity, but the remaining diversity indices for the herb layer were not significantly affected by grazing (Table 2.1). Thirty-five of the woody species and 24 of the herbs occurred only on grazed plots (intermediate and/or high grazing intensity).

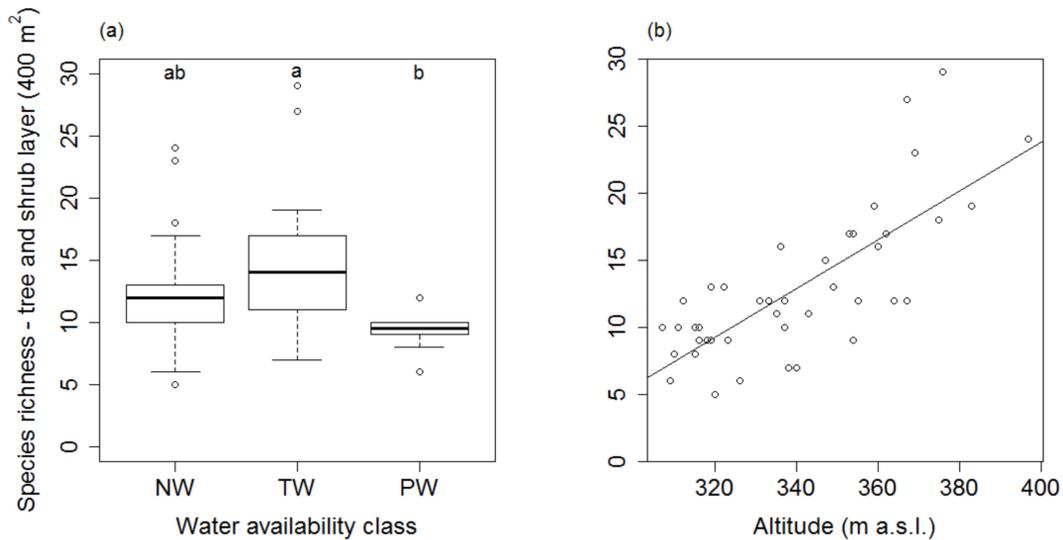


Figure 2.3 Species richness of the tree and shrub layer (including cacti, bromeliads, epiphytes, and vines; sampling unit 20 m × 20 m; 45 study plots) of Caatinga forest plots (a) related to water availability classes (GLM, $p = 0.005$). Lowercase letters refer to significant differences in GLM. NW—no water, PW—permanent water, TW—temporary water; (b) along the altitudinal gradient (GLM, $p < 0.001$).

The species richness, Shannon and Simpson indices of the tree and shrub layer were significantly affected by water availability classes. Plots located in the vicinity of permanent streams showed significantly lower species numbers compared to the other plots (Figure 2.3a). The soil parameter C/N ratio significantly positively affected the woody species richness, while the content of the skeleton fraction significantly negatively affected the species richness and Shannon index of the tree and shrub layer (Appendix 2.3). However, during the model selection process both performed worse compared to altitude. The C/N ratio was positively correlated with altitude ($R^2 = 0.113$, $p = 0.026$). Altitude proved to be the most important parameter in the statistical analyses with significant positive effects on the species richness and Shannon index of the woody and herbaceous layer (Figure 2.3b). Some of the rarer species were found exclusively on study plots at higher elevation (> 360 m a.s.l.; data not shown).

Species composition

Species composition of the tree and shrub layer and herb layer were most influenced by altitude (Figure 2.4). The cover of litter was also significantly correlated

with species composition of the woody species. In contrast, grazing was not significant and grouping of plots according to grazing intensity classes was rather weak.

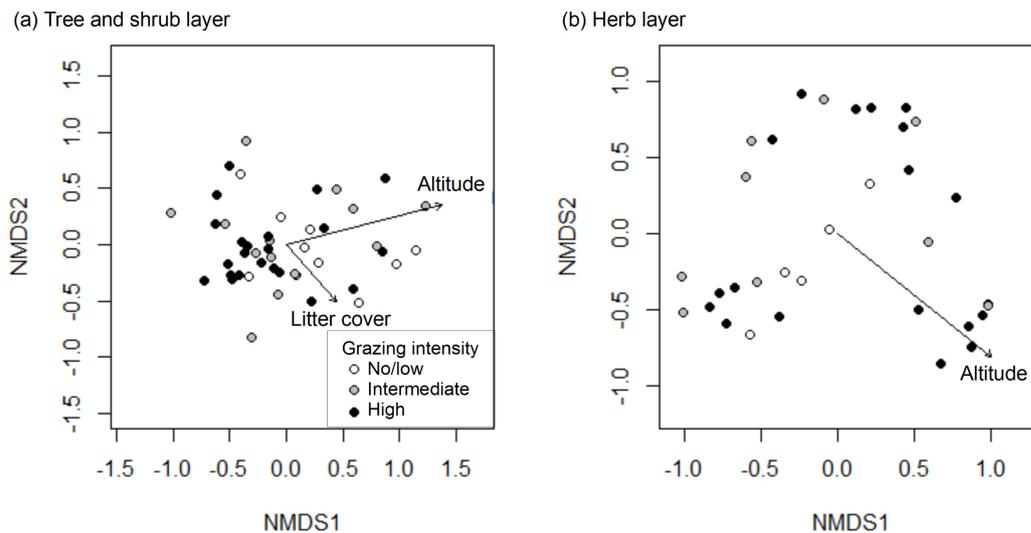


Figure 2.4 Correlation of environmental parameters (altitude in m a.s.l. and cover of litter in %) with species composition of (a) the tree and shrub layer, and (b) the herb layer of Caatinga dry forests according to NMDS (stress value 0.11, p of environmental parameters < 0.05)

Beta diversity of vegetation layers

Beta diversity (Bray-Curtis dissimilarity index) was significantly affected by grazing intensity. For the tree and shrub layer, plots with the highest grazing intensity showed the lowest beta diversity (Figure 2.5). In contrast, the beta diversity of the herbaceous species was lowest at intermediate grazing intensity (Appendix 2.4). The water availability classes showed no effect on beta diversity. However, altitude was again clearly the most important parameter (Appendix 2.5). These findings were confirmed by boosted regression tree models (data not shown).

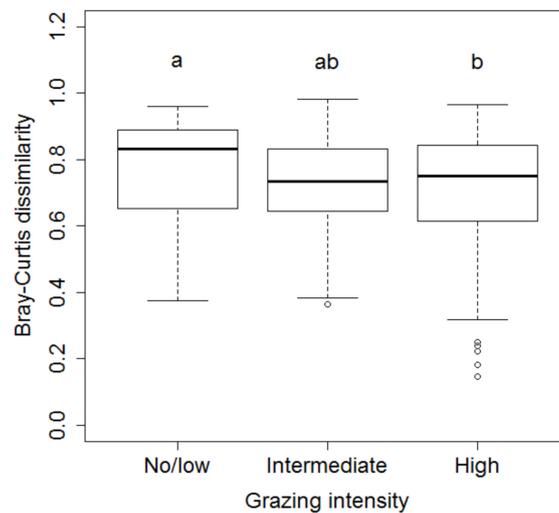


Figure 2.5 Beta diversity for the tree and shrub layer at three grazing intensities (no/low, intermediate, high). Lowercase letters indicate significant differences in GLM.

Discussion

In this study, we analysed how the diversity of the tree and shrub layer and herb layer of Caatinga forests, a highly threatened ecosystem type in north-eastern Brazil, was related to grazing by livestock (mainly goats). The study results showed negative impacts of the present grazing intensities on plant species diversity. This underlines the susceptibility of the studied ecosystem to damages and degradation, also reported by Maracajá et al. (2003) and Schulz et al. (2016, 2018).

Impact of grazing on plant diversity

Grazing intensities differed from no/low to high grazing pressure, with the latter clearly exceeding the carrying capacity of the Caatinga in many places (Schulz et al. 2016). In contrast to the widely accepted intermediate disturbance hypothesis (Huston 2014), which predicts the highest diversity at intermediate disturbance, all diversity parameters declined at intermediate or high grazing intensity compared to no/low grazing. These findings are consistent with the assumptions of the ‘dynamic equilibrium model’ proposed by Huston (2014). Besides disturbance, it also takes the productivity of a system into account. It states that in low productivity systems

the diversity declines with increasing disturbance. Further, analyses of the beta diversity showed, that plots with high grazing intensity were relatively similar to each other, while plots with no/low grazing intensity showed a higher dissimilarity. This is in line with the 'generalised model of the effects of grazing on plant community structure and diversity' proposed by Milchunas et al. (1988). They state that in semi-arid environments with long grazing history, the diversity declines with increasing grazing intensity. The study results also confirm the negative effects of grazing on biodiversity reported in other Caatinga studies (see Appendix 2.6 & Appendix 2.7) and in other semi-arid regions of the world (e.g., China: Säumel et al. 2011; Mongolia: Wan et al. 2015). However, a number of field studies in southern Africa did not find such a clear negative effect of grazing on species diversity (e.g., Hanke et al. 2014). Rutherford et al. (2012) even found a significant increase in species diversity under heavy grazing in a low productivity system with long grazing history.

Possible reasons for negative effects of livestock on plant diversity are manifold. Direct effects include the reduction in species numbers as entire plants or vital parts of certain species are consumed (Araújo Filho & Crispim 2002). During the rainy season, herbaceous species can make up more than 80% of the diet of ruminants; for species that are not adapted to biomass loss this can be devastating (Oliveira et al. 2016). Furthermore, as many Caatinga plant species exhibit protective mechanisms (spines and thorns, unpleasant taste, toxic compounds, hirsute leaves; Pfister & Malechek 1986; Figueiredo et al. 2012; Araújo-Filho 2013; Sebata 2013; Oliveira et al. 2016), palatable and unprotected species may decline in abundance due to selective grazing (Wan et al. 2015; Oliveira et al. 2016). In addition, goats are known to browse on twigs, leaves, or on the bark of trees and cacti (Araujo et al. 2010). However, in our study area, trees and cacti with damaged trunks were only observed occasionally (own observation), and thus the overall direct impact of browsing on these plant types is expected to be low. Livestock may also affect plant diversity by grazing of seedlings. In this study, seedlings were only occasionally found (including protected areas). Hence, we cannot assess if grazing influenced the number of seedlings or if the germination rate was low for other reasons, e.g., the prolonged drought. Indirect impacts of grazing may also occur, such as changes in plant diversity patterns caused by the consumption of fruits (Pfister & Malechek 1986), which may either decrease the regeneration success of some species or facilitate dispersal of adapted species. The pods of the exotic tree species *Prosopis*

juliflora (algaroba), for example, are fed to livestock and its seedlings were the most common ones found germinating in faeces samples (unpublished), which implies endozoochorous dispersal and potential spread of this exotic species. Nutrient enrichment by livestock excrement (Haynes & Williams 1993) and increased soil erosion due to the consumption of leaf litter (Pfister & Malechek 1986) may also indirectly modify species composition.

Impact of further environmental factors on plant biodiversity

In arid and semi-arid regions, the effect of rainfall and livestock on the vegetation cannot be easily disentangled. Studies on the Karoo shrubland in South Africa (Kraaij & Milton 2006; Anderson & Hoffman 2007) presented very mixed results with the overall conclusion that both grazing and rainfall affect the vegetation. In our study, the herbaceous vegetation was clearly triggered by rainfall events as a more or less dense vegetation layer occurred directly after the first heavy rainfall. Also, for the woody species an effect of the drought was apparent. Especially stems of *Sida galheirensis*, *Croton* spp., and partly *Cenostigma pyramidale* appeared to have died during the last drought (own observations, personal communication with local farmers 2012–2014). This effect, however, was less pronounced in the vicinity of permanent streams, where the number of dead trees was clearly lower compared to the other plots (data not shown). Further, species richness was lowest in the permanent water class suggesting that this class was rather a measure for grazing intensity (Adler et al. 2005).

The soil characteristics C/N ratio and content of the skeleton fraction showed significant effects on plant diversity. Yet, in the model selection process they showed less statistical power compared to the parameter altitude, which performed better and was ranked higher than grazing intensity, soil parameters, and water availability class in the statistical models. At higher elevations, we found a significantly higher plant diversity, with a higher number of rare species. However, as the study plots were located within a minor range of 307–397 m a.s.l. it seems probable that differences in plant diversity in our study are not caused by lower temperatures and higher precipitation at higher elevation. Instead, we assume that altitude performed best as it comprises several environmental parameters (Pavón et al. 2000). It was significantly correlated to grazing impact (Schulz et al. 2016), water availability (e.g,

distance to the nearest permanent stream; Schulz et al. 2016), soil characteristics (e.g., C/N ratio), and anthropogenic influences (Silva et al. 2014; Revermann et al. 2016; although these studies rely on different environmental conditions and sampling designs and may therefore be hardly comparable). Accordingly, distances to the nearest farmhouse, city, and permanent stream were consistently positively related to altitude. Grazing of livestock is more common at low elevations, which is likely also true for other activities, such as harvest of livestock fodder (e.g., bromeliads and cacti), and timber and fuel wood extraction. As a consequence, we found a higher species richness and Shannon index but lower evenness in protected areas. Similarly, Maracajá et al. (2003) found a lower species richness and Shannon index in an area used for livestock rearing compared to a protected area.

Finally, differences in species diversity might be attributed to the historic land use. Albuquerque et al. (2008) found no conclusive evidence that the degradation of the Caatinga is caused by overgrazing. Instead, they suggest that degradation of many areas was probably caused by shifting cultivation and wood harvest. For our study area, no reliable information concerning historic land clearing is available. Still, it can be assumed that the present livestock husbandry was preceded by intense timber harvest or slash-and-burn agriculture as remnants of former settlements, cleared areas, and cut trees were observed in almost all parts of the study area. This hypothesis is supported by the fact that, in degraded areas, exceptionally large individuals of *Aspidosperma pyriforme* were occasionally found as relicts of a former plant community that included larger trees. In most other areas currently subjected to high grazing pressure, small individuals (often < 100 cm in height; data not shown) of *A. pyriforme* are the norm. Consequently, species loss along the grazing gradient may also be caused by a combination of forest clearing and grazing over a longer period of time.

Implications for management

In vast areas of the Caatinga dry forest, livestock husbandry is the main land-use option for local farmers. In our study, moderate and high grazing intensity proved to have negative effects on plant diversity parameters. Further studies found negative effects on soil organic carbon stocks (Schulz et al. 2016) and anuran diversity (unpublished). Thus, to ensure a sustainable fodder production while safeguarding

other important ecosystem functions and biodiversity, we recommend a rotational grazing system including a reduction in free-roaming livestock and in animal loads. Additional livestock fodder, which can be used during dry seasons, should be produced using fodder plants with high nutritional value grown in irrigated areas (Cierjacks et al. 2016) or wetlands. It may be preserved and stored as hay or silage. To foster land-use change, these changes in land-use practice need to be accompanied by subsidies (Santos et al. 2014) and by measures to raise the environmental awareness of local people, especially farmers (Liniger et al. 2017).

The recovery of degraded Caatinga is expected to take a long time (more than 40 years; Cabral et al. 2013). To facilitate the recovery of species-poor and degraded areas, species-rich Caatinga areas must be efficiently protected as source habitats and stepping-stone habitats (preferably areas with wetland ecosystems or rocky outcrops) without pronounced land-use impact within a systematic conservation system (Siegmund-Schultze 2017).

Apart from direct human influences, the main threat to South American tropical dry forests, including the Caatinga, is climate change. This is expected to cause an increase in temperature and a decrease in precipitation (Miles et al. 2006; IPCC 2014) possibly leading to desertification. Accordingly, Oyama & Nobre (2003) predict a change from the present savanna-like Caatinga vegetation to a semi-desert if the environmental degradation proceeds. However, the loss of forest cover and plant diversity may in turn enhance climate change due to the emission of sequestered carbon and a lower carbon sequestration potential (Adeel et al. 2005; Oyama & Nobre 2003). Hence, effective protection and management options for existing forests in semi-arid areas are needed to counteract these processes. Recent studies suggest an increase in Caatinga forest cover during the last decades (Aide et al. 2013; Schulz et al. 2017) but the underlying processes (changes in grazing management or reduction of slash-and-burn agriculture) have not been studied so far.

Overall, the findings of our study argue for more sustainable land-use options to counteract biodiversity loss in grazed Caatinga forest systems and at the same time help to strengthen the resilience of livelihoods under climate change. Our study results have been incorporated into guidelines provided to regional stakeholders that include recommendations for adapted land management practices that better protect and foster biodiversity of dry forests in north-eastern Brazil while sustaining local livelihoods (Siegmund-Schultze 2017).

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Conflict of Interest

The authors declare that they have no conflict of interest.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1 Vegetation plot data. Plant species, their growth form and frequency in a caatinga area in northeastern Brazil.

Appendix S2 Plant species, their growth form and frequency in a caatinga area in northeastern Brazil.

Appendix S3 p values of generalised linear models (GLMs) with diversity indices as response variables.

Appendix S4 Beta diversity for the herb layer at three grazing intensities (no/low, intermediate, high).

Appendix S5 p values of generalised linear models (GLMs) with Bray–Curtis dissimilarity index as response variables.

Appendix S6 Plant diversity of caatinga systems in the tree and shrub layer with inclusion parameters and site description.

Appendix S7 Plant diversity of caatinga systems in the herb layer with site description.

References

- Adeel Z, Safriel U, Niemeijer D, White R, de Kalbermatten G, Glantz M, Yapi-Gnaore V (2005) Ecosystems and human well-being: Desertification synthesis. A report of the Millennium Ecosystem Assessment, World Resources Institute, Washington, USA
- Adler PB, Milchunas DG, Sala OE, Burke IC, Lauenroth WK (2005) Plant traits and ecosystem grazing effects: comparison of US sagebrush steppe and Patagonian steppe. *Ecological Applications* 15:774–792. <https://doi.org/10.1890/04-0231>
- Aide TM, Clark ML, Grau HR, López-Carr D, Levy MA, Redo D, Bonilla-Moheno M, Riner G, Andrade-Núñez MJ, Muñiz M (2013) Deforestation and reforestation of Latin America and the Caribbean (2001–2010). *Biotropica* 45:262–271. <https://doi.org/10.1111/j.1744-7429.2012.00908.x>
- Albuquerque SGD, Soares JGG, Guimarães Filho C (2008) Effect of grazing by steers and a long drought on a caatinga ligneous stratum in semi-arid northeast, Brazil. *Revista Caatinga* 21:17–28
- Alves JJA, Araújo MA, Nascimento SS (2009) Degradação da Caatinga: Uma investigação ecogeográfica. *Revista Caatinga* 22:126–135
- Alves Junior FT, Ferreira RLC, Marangon LC, Silva JAA, Gutiérrez-Céspedes HG (2013) Structure evaluation of the Caatinga vegetation for sustainable forest management in the municipality of Floresta, Pernambuco, Brazil. In: Gunkel G, Silva JAA, Sobral MC (eds) Sustainable management of water and land in semiarid areas. Editora Universitária UFPE, Recife, Brazil, pp 186–202
- Anderson PML, Hoffman MT (2007) The impacts of sustained heavy grazing on plant diversity and composition in lowland and upland habitats across the Kamiesberg mountain range in the Succulent Karoo, South Africa. *Journal of Arid Environments* 70:686–700. <https://doi.org/10.1016/j.jaridenv.2006.05.017>
- Araujo KD, Dantas RT, de Andrade AP, Parente HN, Érellens ÉS (2010) Uso de espécies da Caatinga na alimentação de rebanhos município de São João do Cariri – PB. *Raega-O Espaço Geográfico em Análise* 20:157–171. <https://doi.org/10.5380/raega.V20i0.20619>
- Araújo Filho JA, Crispim SMA (2002) Associated grazing of cattle, sheep and goats at the semi-arid region of northeast Brazil. Paper presented at the First Virtual Global Conference on Organic Beef Cattle Production, Sept 2nd–Oct 15th 2002. University of Contestado, Concordia, Brazil

- Araújo EL, Silva KA, Ferraz EMN, Sampaio EVSB, Silva SI (2005) Diversidade de herbáceas em microhabitats rochoso, plano e ciliar em uma área de caatinga, Caruaru, PE, Brasil. *Acta Botanica Brasilica* 19:285–294
- Araújo-Filho JA (2013) Tecnologias de manejo pastoril da Caatinga. In: Araújo-Filho JA (ed) Manejo pastoril sustentável da caatinga. Projeto Dom Helder Camara, Recife, Brazil, pp 119–144
- Bailey DW, Brown JR (2011) Rotational grazing systems and livestock grazing behavior in shrub-dominated semi-arid and arid rangelands. *Rangeland Ecology and Management* 64:1–9. <https://doi.org/10.2111/REM-D-09-00184.1>
- Bakke IA, Bakke OA, Salcedo IH, Andrade AD (2009) In situ fodder production of *Mimosa tenuiflora* under pruning in native caatinga tropical dry forest in Brazil. *Tropical Grasslands* 43:178–187
- Blackmore M, Vitousek PM (2000) Cattle grazing, forest loss, and fuel loading in a dry forest ecosystem at Pu'u Wa'aWa'a Ranch, Hawai'i. *Biotropica* 32:625–632
- Braun-Blanquet J (1964) *Pflanzensoziologie. Grundzüge der Vegetationskunde* (3rd ed). Springer, Berlin, Germany
- Cabral GAL, Sampaio EVSB, Almeida-Cortez J (2013) Estrutura espacial e biomassa da parte aérea em diferentes estádios sucessionais de Caatinga, Santa Terezinha-PB. *Revista Brasileira de Geografia Física* 6:566–574
- Cierjacks A, Hensen I (2004) Variation of stand structure and regeneration of Mediterranean holm oak along a grazing intensity gradient. *Plant Ecology* 173:215–223. <https://doi.org/10.1023/B:VEGE.0000029322.75004.ad>
- Cierjacks A, Pommeranz M, Schulz K, Almeida-Cortez JS (2016) Is crop yield related to weed species diversity and biomass in coconut and banana fields of northeastern Brazil? *Agriculture, Ecosystems & Environment* 220:175–183. <https://doi.org/10.1016/j.agee.2016.01.006>
- Cierjacks A, Rühr NK, Wesche K, Hensen I (2008) Effects of altitude and livestock on the regeneration of two tree line forming species in Ecuador. *Plant Ecology* 194: 207–221. <https://doi.org/10.1007/s11258-007-9285-x>
- Crawley MJ (2007). *The R book* (1st ed). John Wiley & Sons, Chichester, UK
- Drumond MA, Kiill LHP, Lima PCF, Oliveira MC, Oliveira VR, Albuquerque SG, Nascimento CES, Cavalcanti J (2004) Estratégias para o uso sustentável da biodiversidade da caatinga. In: Silva JMC, Tabarelli M, Fonseca MT, Lins LV (eds) *Biodiversidade da caatinga: áreas e ações prioritárias para a conservação*, Brasília, Brazil: Ministério do Meio Ambiente, Universidade Federal de Pernambuco, Recife, Brazil, pp 329–340
- Embrapa–Empresa Brasileira de Pesquisa Agropecuária Ministério da Agricultura, Pecuária e Abastecimento (2001a) Mapa Exploratório-Reconhecimento de solos do município de Floresta, PE. Retrieved from <http://www.uep.cnps.embrapa.br/solos/pe/floresta.pdf>. Accessed Oct 2013
- Embrapa–Empresa Brasileira de Pesquisa Agropecuária Ministério da Agricultura, Pecuária e Abastecimento (2001b) Mapa Exploratório-Reconhecimento de solos do município de Itacuruba, PE. Retrieved from <http://www.uep.cnps.embrapa.br/solos/pe/itacuruba.pdf>. Accessed Oct 2013
- Espírito-Santo MM, Fagundes M, Nunes YRF, Fernandes GW, Sánchez-Azofeifa GA, Quesada M (2006) Bases para a conservação e uso sustentável das florestas

- estacionais decíduas brasileiras: a necessidade de estudos multidisciplinares. *Unimontes Científica* 8:13–22
- Espírito-Santo MM, Sevilha AC, Anaya FC, Barbosa R, Fernandes GW, Sanchez-Azofeifa GA, Scariot A, Noronha SE, Sampaio CA (2009) Sustainability of tropical dry forests: two case studies in southeastern and central Brazil. *Forest Ecology and Management* 258:922–930. <https://doi.org/10.1016/j.foreco.2009.01.022>
- Faith DP, Minchin PR, Belbin L (1987) Compositional dissimilarity as a robust measure of ecological distance. *Vegetatio* 69:57–68. <https://doi.org/10.1007/BF00038687>
- Figueiredo JM, Araújo JM, Pereira ON, Bakke IA, Bakke OA (2012) Revegetation of degraded Caatinga sites. *Journal of Tropical Forest Science* 24:332–343
- Frey W, Lösch R (2010) *Geobotanik: Pflanze und Vegetation in Raum und Zeit* (3rd ed). Spektrum Akademischer Verlag, Heidelberg, Germany
- Gillespie TW, Grijalva A, Farris CN (2000) Diversity, composition, and structure of tropical dry forests in Central America. *Plant Ecology* 147:37–47. <https://doi.org/10.1023/A:1009848525399>
- Google Earth (2013) Version 7.1.2.2041. Retrieved from <http://www.google.com/earth>. Accessed Oct 2013
- Hagel H, Hoffmann C, Doluschitz R (2014) Mathematical programming models to increase land and water use efficiency in semi-arid NE-Brazil. *International Journal on Food System Dynamics* 5:173–181. <https://doi.org/10.18461/ijfsd.v5i4.542>
- Hanke W, Böhner J, Dreber N, Jürgens N, Schmiedel U, Wesuls D, Dengler J (2014) The impact of livestock grazing on plant diversity: an analysis across dryland ecosystems and scales in southern Africa. *Ecological Applications* 24:1188–1203. <https://doi.org/10.1890/13-0377.1>
- Haynes RJ, Williams PH (1993) Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy* 49:119–199. [https://doi.org/10.1016/S0065-2113\(08\)60794-4](https://doi.org/10.1016/S0065-2113(08)60794-4)
- Huston AM (2014) Disturbance, productivity, and species diversity: empiricism vs. logic in ecological theory. *Ecology* 95:2382–2396. <https://doi.org/10.1890/13-1397.1>
- IBGE–Instituto Brasileiro de Geografia e Estatística (2004). Mapa de Biomas e de Vegetação. Retrieved from <http://www.ibge.gov.br/home/presidencia/noticias/21052004biomashtml.shtm>. Accessed Jan 2014
- IPCC–Intergovernmental Panel on Climate Change, Magrin GO, Marengo JA, Boulanger J-P, Buckeridge MS, Castellanos E, Poveda G, Scarano FR, Vicuña S (2014) Central and South America. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds), *Climate Change 2014: Impacts, adaptation, and vulnerability. Part B: Regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 1499–1566
- Kauffman JB, Sanford RL, Cummings DL, Salcedo IH, Sampaio EVSB (1993) Biomass and nutrient dynamics associated with slash fires in neotropical dry forests. *Ecology* 74:140–151. <https://doi.org/10.2307/1939509>
- Kraaij T, Milton SJ (2006) Vegetation changes (1995–2004) in semi-arid Karoo shrubland, South Africa: effects of rainfall, wild herbivores and change in land use.

- Journal of Arid Environments 64:174–192. <https://doi.org/10.1016/j.jaridenv.2005.04.009>
- Leal IR, Silva JMC, Tabarelli M, Lacher TE (2005) Changing the course of biodiversity conservation in the Caatinga of northeastern Brazil. *Conservation Biology* 19:701–706. <https://doi.org/10.1111/j.1523-1739.2005.00703.x>
- Leyer I, Wesche K (2007) *Multivariate Statistik in der Ökologie: Eine Einführung*. Springer, Berlin, Germany
- Liniger HP, Mekdaschi Studer R, Moll P, Zander U (2017) Making sense of research for sustainable land management. Centre for Development and Environment (CDE). University of Bern, Switzerland and Helmholtz Centre for Environmental Research GmbH – UFZ, Leipzig, Germany
- Lucena RFP, Albuquerque UP, Monteiro JM, Almeida CFCBR, Florentino ATN, Ferraz JSF (2007) Useful plants of the semi-arid northeastern region of Brazil—a look at their conservation and sustainable use. *Environmental Monitoring Assessment* 125: 281–290. <https://doi.org/10.1007/s10661-006-9521-1>
- Manly BFJ (1997) *Randomization, bootstrap and Monte Carlo methods in biology*. Chapman & Hall, London, UK
- Maracajá PB, Batista CHF, Sousa AD, Vasconcelos WD (2003) Levantamento florístico e fitosociológico do estrato arbustivo-arbóreo de dois ambientes na vila Santa Catarina, Serra do Mel, RN. *Revista de Biologia e Ciências da Terra* 3:1–13
- Menezes RSC, Sampaio EVSB, Giongo V, Pérez-Marin AM (2012) Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. *Brazilian Journal of Biology* 72:643–653
- Milchunas DG, Sala OE, Lauenroth WK (1988) A generalized model of effects of grazing by large herbivores on grassland community structure. *American Naturalist* 132:87–106
- Miles L, Newton AC, DeFries RS, Ravilious C, May I, Blyth S, Kapos V, Gordon JE (2006) A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* 33:491–505. <https://doi.org/10.1111/j.1365-2699.2005.01424.x>
- MMA–Ministério do Meio Ambiente (2011) *Subsídios para a elaboração do plano de ação para a prevenção e controle do desmatamento na Caatinga*. Ministério do Meio Ambiente, Brasília, Brazil
- Mooney HA, Bullock SH, Medina E (1995) Introduction. In: Bullock SH, Mooney HA, Medina E (eds) *Seasonally dry tropical forests*. Cambridge University Press, New York, USA, pp 1–8
- Nosetto MD, Jobbágy EG, Paruelo JM (2006) Carbon sequestration in semi-arid rangelands: comparison of *Pinus ponderosa* plantations and grazing exclusion in NW Patagonia. *Journal of Arid Environments* 67:142–156. <https://doi.org/10.1016/j.jaridenv.2005.12.008>
- Nunes AT, Lucena RFP, Santos MVF, Albuquerque UP (2015) Local knowledge about fodder plants in the semi-arid region of Northeastern Brazil. *Journal of Ethnobiology and Ethnomedicine* 11:1–12. <https://doi.org/10.1186/1746-4269-11-12>
- Oksanen J, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, Simpson GL, Solymos P, Stevens H, Wagner H (2016). *Vegan: Community ecology package*. Version 2.3-5. Retrieved from <https://CRAN.R-project.org/package=vegan>. Accessed Oct 2016

- Oliveira OF, Santos MVF, Cunha MV, Dubeux jr JCB, Muir JP, de Mello ACL, Lira MA, Barros GFNP (2016) Botanical composition of Caatinga rangeland and diets selected by grazing sheep. *Tropical Grasslands* 4:71–81. [https://doi.org/10.17138/tgft\(4\)71-81](https://doi.org/10.17138/tgft(4)71-81)
- Oyama MD, Nobre CA (2003) A new climate-vegetation equilibrium state for tropical South America. *Geophysical research letters* 30:2199. <https://doi.org/10.1029/2003GL018600>
- Pavón NP, Hernández-Trejo H, Rico-Gray V (2000) Distribution of plant life forms along an altitudinal gradient in the semi-arid valley of Zapotitlán, Mexico. *Journal of Vegetation Science* 11:39–42. <https://doi.org/10.2307/3236773>
- Pennington RT, Lewis GP, Ratter JA (2006) An overview of the plant diversity, biogeography and conservation of neotropical savannas and seasonally dry forests. In: Pennington RT, Lewis GP, Ratter JA (eds) *Neotropical savannas and seasonally dry forests: Plant diversity, biogeography and conservation*. CRC Press, Boca Raton, USA, pp 1–29
- Pfister JA, Malechek JC (1986) Dietary selection by goats and sheep in a deciduous woodland of northeastern Brazil. *Journal of Range Management* 39:24–28. <https://doi.org/10.2307/3899680>
- Piñeiro G, Paruelo J, Oesterheld M, Jobbágy EG (2010) Pathways of grazing effects on soil organic carbon and nitrogen. *Rangeland Ecology & Management* 63:109–119. <https://doi.org/10.2111/08-255.1>
- Prado DE (2003) As caatingas da América do Sul. In: Leal IR, Tabarelli M, Cardoso da Silva JM (eds) *Ecologia e conservação da caatinga*. Universidade Federal de Pernambuco, Recife, Brazil, pp 3–74
- Queiroz RT, Moro MF, Loiola MIB (2015) Evaluating the relative importance of woody versus non-woody plants for alpha-diversity in a semiarid ecosystem in Brazil. *Plant Ecology and Evolution* 148:361–376. <https://doi.org/10.5091/plecevo.2015.1071>
- R Core Team (2015) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from <http://www.R-project.org>. Accessed Jan 2016
- Reis AMS, Araújo EL, Ferraz EMN, Moura AN (2006) Inter-annual variations in the floristic and population structure of an herbaceous community of "caatinga" vegetation in Pernambuco, Brazil. *Brazilian Journal of Botany* 29:497–508. <https://doi.org/10.1590/S0100-84042006000300017>
- Revermann R, Wallenfang J, Oldeland J, Finckh M (2016) Species richness and evenness respond to diverging land-use patterns—a cross-border study of dry tropical woodlands in southern Africa. *African Journal of Ecology* 55:152–161. <https://doi.org/10.1111/aje.12333>
- Rutherford MC, Powrie LW, Husted LB (2012) Plant diversity consequences of a herbivore-driven biome switch from grassland to Nama-Karoo shrub steppe in South Africa. *Applied Vegetation Science* 15:14–25. <https://doi.org/10.1111/j.1654-109X.2011.01160.x>
- Salcedo IH, Menezes RSC (2009) Agroecosystem functioning and management in semi-arid Northeastern Brazil. In: Tiessen H, Stewart JWB (eds) *Applying ecological knowledge to landuse decisions*. Inter-American Institute for Global Change Research – IICA-IAI-Scope, Paris, France, pp 73–81

- Sampaio EVSB (1995) Overview of the Brazilian Caatinga. In: Bullock SH, Mooney HA, Medina E (eds) Seasonally dry tropical forests. Cambridge University Press, Cambridge, UK, pp 35–63
- Santana JAS, Souto JS (2006) Diversidade e estrutura fitossociológica da Caatinga na estação ecológica do Seridó-RN. *Revista de Biologia e Ciências da Terra* 6:232–242
- Santos MG, Oliveira MT, Figueiredo KV, Falcão HM, Arruda EC, Almeida-Cortez J, Sampaio EVSB, Ometto JPHB, Menezes RSC, Oliveira AFM, Pompelli MF, Antonino ACD (2014) Caatinga, the Brazilian dry tropical forest: can it tolerate climate changes? *Theoretical and Experimental Plant Physiology*, 26:83–99. <https://doi.org/10.1007/s40626-014-0008-0>
- Santos JMFF, Santos DM, Lopes CGR, Silva KA, Sampaio EVSB, Araújo EL (2013) Natural regeneration of the herbaceous community in a semiarid region in Northeastern Brazil. *Environmental Monitoring and Assessment* 185:8287–8302. <https://doi.org/10.1007/s10661-013-3173-8>
- Säumel I, Ziche D, Yu R, Kowarik I, Overdieck D (2011) Grazing as driver for *Populus euphratica* woodland degradation in the semi-arid Aibi Hu Region, northwestern China. *Journal of Arid Environments* 75:265–269. <https://doi.org/10.1016/j.jaridenv.2010.10.013>
- Schulz K, Guschal M, Kowarik I, Almeida-Cortez JS, Sampaio EVSB, Cierjacks A (2018) Grazing, forest density, and carbon storage: towards a more sustainable land use in Caatinga dry forests of Brazil. *Regional Environmental Change*, 18:1969–1981. <https://doi.org/10.1007/s10113-018-1303-0>
- Schulz C, Koch R, Cierjacks A, Kleinschmit B (2017) Land change and loss of landscape diversity at the Caatinga domain – Analysis of pattern-process relationships with MODIS land cover products (2001-2012). *Journal of Arid Environments* 136:54–74. <https://doi.org/10.1016/j.jaridenv.2016.10.004>
- Schulz K, Voigt K, Beusch C, Almeida-Cortez JS, Kowarik I, Walz A, Cierjacks A (2016) Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil. *Forest Ecology and Management* 367:62–70. <https://doi.org/10.1016/j.foreco.2016.02.011>
- Sebata A (2013) Woody plant-herbivore interactions in semi-arid savanna ecosystems. In: Barros B, Fernandes MEB (eds) *Herbivory*. IntechOpen, pp 1–16. <https://doi.org/10.5772/48400>
- Siegmund-Schultze M (ed) (2017) *Guidance Manual – A compilation of actor-relevant content extracted from scientific results of the INNOVATE project*. Universitätsverlag der TU Berlin, Berlin, Germany
- Silva FKG, de Faria Lopes S, Lopez LCS, de Melo JIM, Trovão DMDBM (2014) Patterns of species richness and conservation in the Caatinga along elevational gradients in a semiarid ecosystem. *Journal of Arid Environments* 110:47–52. <https://doi.org/10.1016/j.jaridenv.2014.05.011>
- Sousa SCD, Oliveira VPVD, Silva JMFD, Melo RAD, Azevedo R (2013) The use of lands from small watershed of riacho Itacuruba PE. In: Gunkel G, Silva JAA, Sobral MC (eds) *Sustainable management of water and land in semiarid areas*. Editora Universitária, UFPE, Recife, Brazil, pp 129–143

- Tiessen H, Feller C, Sampaio EVSB, Garin P (1998) Carbon sequestration and turnover in semiarid savannas and dry forest. *Climatic Change* 40:105–117. <https://doi.org/10.1023/A:1005342932178>
- Tiessen H, Salcedo IH, Sampaio EVSB (1992) Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. *Agriculture, Ecosystems & Environment* 38:139–151. [https://doi.org/10.1016/0167-8809\(92\)90139-3](https://doi.org/10.1016/0167-8809(92)90139-3)
- Torres FSDM, Santos Pfaltzgraff PAD (2014) Geodiversidade do estado de Pernambuco, Programa Geologia do Brasil. Levantamento da Geodiversidade. CPRM, Recife, Brazil. Retrieved from <http://rigeo.cprm.gov.br/jspui/handle/doc/16771>. Accessed Jan 2016
- Wan H, Bai Y, Hooper DU, Schönbach P, Gierus M, Schiborra A, Taube F (2015) Selective grazing and seasonal precipitation play key roles in shaping plant community structure of semi-arid grasslands. *Landscape Ecology* 30:1767–1782. <https://doi.org/10.1007/s10980-015-0252-y>
- Ydoyaga-Santana DF, Lira MA, Santos MVFD, Ferreira MA, Silva MJA, Marques KA, Mello ACL, Santos DC (2011) Caracterização da caatinga e da dieta de novilhos fistulados, na época chuvosa, no semiárido de Pernambuco. *Revista Brasileira de Zootecnia* 40:69–78. <http://dx.doi.org/10.1590/S1516-35982011000100010>
- Zuur AF, Ieno EN, Elphick CS (2010) A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution* 1:3–14. <https://doi.org/10.1111/j.2041-210X.2009.00001.x>
- Zuur AF, Ieno EN, Walker NJ, Saveliev AA, Smith GM (2009) *Mixed effects models and extensions in ecology with R* (1st ed). Springer, New York, USA

Appendix

Supplementary Material

Appendix 2.1 Vegetation plot data (.csv format). Plant species, their growth form and frequency in a Caatinga area in north-eastern Brazil.

(data not shown; see online version of the article: <https://doi.org/10.1111/avsc.12434>)

Appendix 2.2 Plant species, their growth form and frequency in a Caatinga area in north-eastern Brazil. *Not included in statistical analyses. Nomenclature follows Flora do Brasil 2020 (June 2018, retrieved from <http://floradobrasil.jbrj.gov.br/>) except for *Cenostigma pyramidale* (September 2018, retrieved from <http://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:77158099-1>).

| Family | Species | Growth form | Frequency of occurrence (% of all plots) |
|--------------------------------------|---|---------------------------------------|--|
| Amaranthaceae | <i>Alternanthera tenella</i> Colla | herb | 19 |
| | <i>Amaranthus</i> cf. <i>viridis</i> L. | herb | 14 |
| | <i>Dysphania ambrosioides</i> (L.) Mosyakin & Clemants | herb | 6 |
| | <i>Froelichia humboldtiana</i> (Roem. & Schult.) Seub. | herb | 11 |
| | <i>Gomphrena demissa</i> Mart. | herb | 33 |
| | <i>Gomphrena vaga</i> Mart. | herb/shrub | 9 |
| | Anacardiaceae | <i>Myracrodruon urundeuva</i> Allemão | tree |
| <i>Schinopsis brasiliensis</i> Engl. | | tree | 11 |
| <i>Spondias tuberosa</i> Arruda | | tree | 9 |
| Apocynaceae | <i>Allamanda</i> sp. | - | 2 |
| | <i>Aspidosperma pyrifolium</i> Mart. | tree | 98 |
| Asteraceae | <i>Bidens pilosa</i> L. | herb | 17 |
| | <i>Centratherum</i> sp. | herb | 17 |
| | <i>Eclipta prostrata</i> (L.) L. | herb | 3 |
| | <i>Lagascea mollis</i> Cav. | herb | 33 |
| | <i>Tridax procumbens</i> L. | herb | 19 |
| Bignoniaceae | <i>Tabebuia aurea</i> (Silva Manso) Benth. & Hook. f. ex S. Moore | tree | 2 |
| Boraginaceae | <i>Cordia globosa</i> (Jacq.) Kunth. | shrub | 7 |
| | <i>Cordia leucocephala</i> Moric. | shrub | 2 |
| | <i>Cordia</i> sp. | shrub | 2 |
| | <i>Heliotropium procumbens</i> Mill. | herb | 22 |
| | <i>Heliotropium</i> cf. <i>ternatum</i> Vahl. | herb | 36 |
| Bromeliaceae | <i>Bromelia laciniosa</i> Mart. ex Schult. & Schult. f. | herb | 13 |
| | <i>Encholirium spectabile</i> Mart. ex Schult. & Schult. f. | herb | 13 |
| | <i>Neoglaziovia variegata</i> Mez. | herb | 18 |
| | <i>Tillandsia</i> sp. | herb (epiphyte) | 2 |

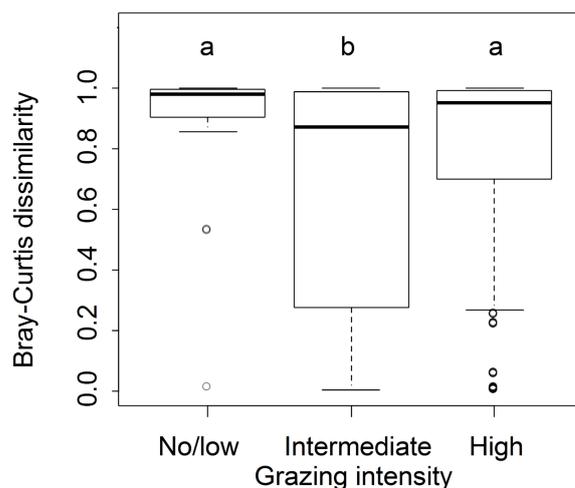
| Family | Species | Growth form | Frequency of occurrence (% of all plots) | |
|--|--|-------------------------------|--|----|
| Burseraceae | <i>Commiphora leptophloeos</i> (Mart.) J.B. Gillett | tree | 13 | |
| Cactaceae | <i>Cereus jamacaru</i> DC. | cactus | 22 | |
| | <i>Melocactus bahiensis</i> (Britton & Rose) Luetzelb. | cactus | _* | |
| | <i>Melocactus zehntneri</i> (Britton & Rose) Luetzelb. | cactus | 33 | |
| | <i>Pilosocereus gounellei</i> (Weber) Byl. et Rowl. | cactus | 62 | |
| | <i>Pilosocereus piauhyensis</i> (Gürke) Byl. et Rowl. | cactus | 2 | |
| | <i>Tacinga inamoena</i> (K.Schum.) N.P. Taylor & Stuppy | cactus | 93 | |
| | <i>Tacinga palmadora</i> (Britton & Rose) N.P. Taylor & Stuppy | cactus | 36 | |
| Capparaceae | <i>Cynophalla</i> aff. <i>hastata</i> (Jacq.) J. Presl | shrub | 7 | |
| Celastraceae | <i>Maytenus rigida</i> Mart. | tree | 13 | |
| Cleomaceae | <i>Cleome</i> sp. | - | 6 | |
| Convolvulaceae | <i>Evolvulus glomeratus</i> Nees & C. Mart. | herb | 6 | |
| | <i>Evolvulus</i> sp. 1 | - | 2 | |
| | <i>Evolvulus</i> sp. 2 | - | 3 | |
| | <i>Ipomoea asarifolia</i> (Desr.) Roem. & Schult. | herb | 2* | |
| | <i>Ipomoea subincana</i> (Choisy) Meisn. | vine | 11 | |
| | <i>Ipomoea</i> sp. 1 | - | 3 | |
| | <i>Ipomoea</i> sp. 2 | - | 17 | |
| | <i>Jacquemontia</i> sp. 1 | vine | 7 | |
| | <i>Jacquemontia</i> sp. 2 | - | 22 | |
| | Euphorbiaceae | <i>Chamaesyce</i> sp. | - | 33 |
| | | <i>Cnidoscolus urens</i> (L.) | herb | 11 |
| <i>Cnidoscolus</i> aff. <i>vitifolius</i> (Mill.) Pohl | | tree | 4 | |
| <i>Cnidoscolus quercifolius</i> Pohl | | tree | 82 | |
| <i>Croton</i> aff. <i>blanchetianus</i> Baill. | | shrub | 2 | |
| <i>Croton cordiifolius</i> Baill. | | shrub | 16 | |
| <i>Croton heliotropiifolius</i> Kunth. | | shrub | 20 | |
| <i>Croton hirtus</i> L' Hér. | | shrub | 28* | |
| <i>Croton</i> sp. 1 | | shrub | 27 | |
| <i>Croton</i> sp. 2 | | shrub | 11 | |
| <i>Croton</i> sp. 3 | | shrub | 4 | |
| <i>Croton</i> sp. 4 | | shrub | 9 | |
| <i>Ditaxis malpighiacea</i> (Ule) Pax & K. Hoffm. | | shrub | 4 | |
| <i>Jatropha mollissima</i> (Pohl) Baill. | | tree | 89 | |
| <i>Jatropha ribifolia</i> (Pohl) Baill. | | tree | 13 | |
| <i>Manihot</i> sp. | | tree | 4 | |
| <i>Sapium glandulosum</i> (L.) Morong | tree | 2 | | |
| Fabaceae | Aff. <i>Amburana cearensis</i> (Fr. Allem.) A.C. Smith | tree | 2 | |

| Family | Species | Growth form | Frequency of occurrence (% of all plots) |
|----------------|---|-------------|--|
| | <i>Anadenanthera colubrina</i> var. <i>cebil</i> (Griseb.) Altschul | tree | 18 |
| | <i>Bauhinia</i> sp. | shrub/tree | 9 |
| | <i>Chloroleucon dumosum</i> (Benth.) G.P.Lewis | tree | 2 |
| | <i>Cenostigma pyramidale</i> (Tul.) Gagnon & G.P.Lewis | tree | 89 |
| | Aff. <i>Libidibia ferrea</i> (Mart. ex Tul.) L.P. Queiroz | tree | 7 |
| | <i>Macroptilium martii</i> (Benth.) Maréchal & Baudet | herb (vine) | .* |
| | <i>Mimosa tenuiflora</i> (Willd.) Poir | tree | 13 |
| | <i>Mimosa ophthalmocentra</i> Mart. ex Benth. | tree | 4 |
| | <i>Mimosa</i> sp. | tree | 9 |
| | <i>Piptadenia stipulacea</i> (Benth.) Ducke | tree | 2 |
| | <i>Pithecellobium diversifolium</i> Benth. | tree | 2 |
| | <i>Pithecellobium</i> sp. | tree | 4 |
| | <i>Poincianella microphylla</i> (Mart. ex G. Don) L.P. Queiroz | tree | 24 |
| | <i>Prosopis juliflora</i> (Sw.) DC. | tree | 22 |
| | <i>Senegalia tenuifolia</i> (L.) Britton & Rose | tree | 4 |
| | <i>Zornia brasiliensis</i> Vogel | herb | 8 |
| Lamiaceae | <i>Ocimum</i> sp. | - | 11 |
| Loranthaceae | Loranthaceae sp. 1 | - | 2 |
| | Loranthaceae sp. 2 | - | 2 |
| Malvaceae | <i>Herissantia tiubae</i> (K. Schum.) Brizicky | herb | 6 |
| | <i>Herissantia</i> sp. | - | 14 |
| | <i>Melochia tomentosa</i> L. | shrub | 42 |
| | <i>Sida galheirensis</i> Ulbr. | subshrub | 71 |
| | <i>Waltheria rotundifolia</i> Schrank | subshrub | 4 |
| | Malvaceae sp. | - | 31 |
| Nyctaginaceae | <i>Guapira pernambucensis</i> (Casar.) Lundell | tree | 11 |
| Phytolaccaceae | <i>Microtea paniculata</i> Moq. | herb | 11 |
| Poaceae | <i>Aristida</i> cf. <i>adscensionis</i> | herb | 86 |
| | <i>Cenchrus echinatus</i> L. | herb | 14 |
| | <i>Cenchrus</i> sp. | herb | 6 |
| | <i>Dactyloctenium</i> cf. <i>aegyptium</i> (L.) Willd. | herb | 3 |
| | Aff. <i>Enteropogon mollis</i> | herb | 8 |
| | <i>Eragrostis tenella</i> (L.) P.Beauv. ex Roem. & Schult. | herb | 3 |
| | <i>Tragus berteronianus</i> Schult. | herb | 25 |
| | Poaceae sp. | herb | 8 |
| Portulacaceae | <i>Portulaca elatior</i> Mart. ex Rohrb. | herb | 44 |
| | <i>Portulaca oleracea</i> L. | herb | 11 |
| Polygalaceae | <i>Polygala</i> sp. | - | 3 |
| Rhamnaceae | <i>Ziziphus joazeiro</i> Mart. | tree | 2 |
| Rubiaceae | <i>Diodella teres</i> (Walter) Small | herb | 19 |

| Family | Species | Growth form | Frequency of occurrence (% of all plots) |
|-------------------|---|----------------------|--|
| | <i>Staelia aurea</i> K. Schum. | herb | 53 |
| Sapindaceae | <i>Serjania comata</i> Radlk. | vine | 9 |
| Sapotaceae | <i>Sideroxylon obtusifolium</i> (Roem. & Schult.) T.D.Penn. | tree | 18 |
| Schrophulariaceae | <i>Angelonia</i> sp. | - | 6 |
| | Schrophulariaceae sp. | - | 8 |
| Selaginellaceae | <i>Selaginella</i> aff. <i>convoluta</i> (Arn.) Spring | herb | 7* |
| Solanaceae | <i>Physalis</i> sp. | - | 3 |
| Turneraceae | <i>Turnera pumilea</i> L. | herb | 44 |
| | <i>Turnera</i> sp. | - | 3 |
| | <i>Piriqueta</i> sp. | - | 31 |
| | Turneraceae sp. | shrub | 2 |
| Verbenaceae | <i>Lippia grata</i> Schauer | shrub/subshrub | 7 |
| Viscaceae | <i>Phoradendron</i> aff. <i>piauianum</i> Tul. | hemi-parasitic shrub | 2 |
| | <i>Phoradendron</i> sp. | hemi-parasitic shrub | 2 |
| Vitaceae | <i>Cissus</i> sp. | vine | 2 |
| Xanthorrhoeaceae | <i>Aloe</i> sp. | herb | 2 |
| | Morphospecies 1 | - | 2 |
| | Morphospecies 2 | shrub | 9 |
| | Morphospecies 3 | - | 4 |
| | Morphospecies 4 | - | 2 |
| | Morphospecies 5 | - | 2 |
| | Morphospecies 6 | - | 4 |
| | Morphospecies 7 | - | 2 |
| | Morphospecies 8 | - | 7 |
| | Morphospecies 9 | - | 2 |
| | Morphospecies 10 | - | 2 |
| | Morphospecies 11 | - | 2 |
| | Morphospecies 12 | - | 2 |
| | Morphospecies 13 | - | 2 |
| | Morphospecies 14 | - | 2 |
| | Morphospecies 15 | vine | 20 |
| | Morphospecies 16 | vine | 4 |
| | Morphospecies 17 | vine | 9 |
| | Morphospecies 18 | hemi-parasitic shrub | 11 |
| | Morphospecies 19 | - | 6 |
| | Morphospecies 20 | - | 3 |
| | Morphospecies 21 | - | 6 |
| | Morphospecies 22 | - | 6 |
| | Morphospecies 23 | - | 11 |
| | Morphospecies 24 | - | 3 |
| | Morphospecies 25 | herb | 14 |

Appendix 2.3 p values of generalised linear models (GLMs) with diversity indices as response variables. For each diversity index (species richness, Shannon index, Simpson index, Pielou's evenness) and vegetation layer, a separate GLM was fitted. Numbers in bold-parameter remains in minimal adequate model.

| | Grazing intensity | C/N ratio | Skeleton fraction | Water availability class | Altitude |
|-----------------------------|-------------------|-----------|-------------------|--------------------------|-------------------|
| <i>Tree and shrub layer</i> | | | | | |
| Species richness | 0.0201 | 0.0208 | 0.0027 | 0.005 | < 0.001 |
| Shannon index | 0.0153 | ns | 0.0353 | 0.0142 | < 0.001 |
| Simpson index | 0.0349 | ns | ns | 0.0136 | < 0.001 |
| Pielou's evenness | ns | ns | ns | ns | ns |
| <i>Herb layer</i> | | | | | |
| Species richness | ns | ns | ns | ns | < 0.001 |
| Shannon index | ns | ns | ns | ns | 0.0068 |
| Simpson index | ns | ns | ns | ns | ns |
| Pielou's evenness | ns | ns | ns | ns | ns |



Appendix 2.4 Beta diversity for the herb layer at three grazing intensities (no/low, intermediate, high). Lowercase letters indicate significant difference in GLM (p model = 0.05).

Appendix 2.5 p values of generalised linear models (GLMs) with Bray-Curtis-dissimilarity index as response variable. For each vegetation layer and explanatory variable, a separate GLM was fitted.

| | Grazing intensity | Water availability class | Altitude |
|--|-------------------|--------------------------|----------|
| <i>Bray-Curtis dissimilarity index</i> | | | |
| Tree and shrub layer | 0.0221 | ns | < 0.001 |
| Herb layer | 0.0341 | ns | < 0.001 |

Appendix 2.6 Plant diversity of caatinga systems in the tree and shrub layer with inclusion parameters and site description. Studies in the municipalities of Itacuruba and Floresta, and other Caatinga areas are shown. PBH—perimeter at breast height; DBH—diameter at breast height; DGL—diameter at ground level; PGL—perimeter at ground level. *200 m² or point-centred quarter method

| Study region, distance to present study area (authors) | Plot size (m × m) | Species richness per class (mean) | Shannon index (mean) | Inclusion parameters (diameters—cm; total height—m) | Site description |
|--|-------------------|---|---|---|---|
| Itacuruba and Floresta (this study) | 20 × 20 | no/low grazing: 15.78 intermediate grazing: 13.64 high grazing: 11.14 | 1.48 (total) low grazing: 1.62 intermediate grazing: 1.51 high grazing: 1.43 | trees, shrubs, bromeliads, cacti, vines, epiphytes; all sizes | no/low, intermediate, and high grazing intensity |
| Itacuruba and Floresta (this study) | 20 × 20 | no/low grazing: 14.44 intermediate grazing: 12 high grazing: 10.23 | 1.45 (total) low grazing: 1.75 intermediate grazing: 1.45 high grazing: 1.33 | trees, shrubs, cacti; all sizes | no/low, intermediate, and high grazing intensity |
| Floresta, 70 km (north)east (Ferraz et al. 2013) | 20 × 20 | 3–11 (no classes) | 2.105 | PBH ≥ 6 (≅ ≈ DBH ≥ 2) | no wood extraction for at least 50 years, sporadically grazed by goats |
| Serra Negra do Norte, 250 km north-east (Santana & Souto 2006) | 20 × 10 | - | 2.35 | DGL ≥ 3 & total height ≥ 1 | ecological station, protected for at least 20 years |
| Serra do Mel, 400 km north-east (Maracajá et al. 2003) | 20 × 10 | protected: 14 livestock: 7 | protected: 1.29 livestock: 0.79 | PGL ≥ 10 | protected, livestock rearing |
| Floresta and Betânia, 35–100 km north-east (Rodal et al. 2008) | 10 × 10 | - | - | DGL ≥ 3 & total height ≥ 1 (without bromeliads and vines) | private natural heritage reserve (RPPN): at least 20 years without use |
| Floresta/Betânia, 40 km north-east (Cavalcanti et al. 2009) | 10 × 10 | 2001: 27 2006: 28 | 2001: 1.84 2006: 1.85 | DGL ≥ 3 & total height ≥ 1 | private natural heritage reserve (RPPN): clear cut, since 1991 without use; two years (2001 and 2006) |
| São Joao do Cariri, 250 km north-east (Andrade et al. 2005) | 20 × 10 | - | protected: 1.51 degraded: 1.43 | PGL ≥ 10 | experimental station: protected (no wood extraction), degraded area (agricultural area without use for 30 years), both with livestock rearing |
| Cariri, 250–280 km north-east (Silva et al. 2014) | * | 400 m: 38 500 m: 41 600 m: 60 | - | - | altitude gradient: 400, 500, 600 m a.s.l., livestock (goats, cattle), and logging in accessible areas |

Ferraz JSF, Ferreira RLC, Silva JAA (2013) Analysis and uses of shrubs and trees by the Indians in an area of Caatinga in the municipality of Floresta, Itaparica region of Pernambuco, Brazil. In: Gunkel G, Silva JAA, Sobral MC (eds) Sustainable management of water and land in semiarid areas. Editora Universitária UFPE, Recife, Brazil, pp 165–185

Santana JAS, Souto JS (2006) Diversidade e estrutura fitossociológica da Caatinga na estação ecológica do Seridó-RN. *Revista de Biologia e Ciências da Terra* 6:232–242

Maracajá PB, Batista CHF, Sousa AD, Vasconcelos WD (2003) Levantamento florístico e fitossociológico do estrato arbustivo-arbóreo de dois ambientes na vila Santa Catarina, Serra do Mel, RN. *Revista de Biologia e Ciências da Terra* 3:1–13

Rodal MJN, Martins FR, Sampaio EVSB (2008) Levantamento quantitativo das plantas lenhosas em trechos de vegetação de caatinga em Pernambuco. *Revista Caatinga* 21:192–205

Cavalcanti ADC, Rodal MJN, Sampaio EVSB, Costa KCC (2009) Mudanças florísticas e estruturais, após cinco anos, em uma comunidade de Caatinga no estado de Pernambuco, Brasil. *Acta Botanica Brasilica* 23:1210–1212

Andrade LD, Pereira IM, Leite UT, Barbosa MRV (2005) Análise da cobertura de duas fitofisionomias de caatinga, com diferentes históricos de uso, no município de São João do Cariri, Estado da Paraíba. *Cerne* 11:253–262

Silva FKG, de Faria Lopes S, Lopez LCS, de Melo JIM, Trovão DMDBM (2014) Patterns of species richness and conservation in the Caatinga along elevational gradients in a semiarid ecosystem. *Journal of Arid Environments* 110:47–52. <https://doi.org/10.1016/j.jaridenv.2014.05.011>

Appendix 2.7 Plant diversity of caatinga systems in the herb layer with site description. Studies in the municipalities of Itacuruba and Floresta, and other Caatinga areas are shown. P. evenness–Pielou's evenness.

| Study area, distance to present study area (authors) | Plot size (m × m), sampling method | Species richness (mean) | Shannon index (mean) | P. evenness (mean) | Site description |
|--|------------------------------------|---|---|--------------------------|--|
| Itacuruba and Floresta (this study) | 2 × 2, cover classes | no/low grazing: 10.83 intermediate grazing: 9.73 high grazing: 6.95 | 0.77 (total) no/low grazing: 1.02 intermediate grazing: 0.8 high grazing: 0.67 | 0.4 | no/low, intermediate, and high grazing intensity |
| Caraúbas, 320 km north(east) (Benevides et al. 2007) | 1 × 1, individuals counted | protected: 27 anthropogenic: 32 | protected: 2.41 anthropogenic: 2.46 | - | Semi-protected, anthropogenically modified; both used as pasture |
| Petrolândia, 70 km south-east (Silva et al. 2009) | 1 × 1, individuals counted | sedimentary: 78 crystalline: 69 | - | - | crystalline shield, sedimentary basin; last 20 years without agricultural use or livestock rearing |
| Experimental research station IPA, Caruaru, 270 km east: (Araújo et al. 2005) | 1 × 1, individuals counted | rocky: 32 flat: 42 river margin: 39 | rocky: 2.09 flat: 2.08 river margin: 2.52 | - | rocky, flat, river margin |
| (Reis et al. 2006) | 1 × 1, individuals counted | 2002: 55 2003: 59 | 2002: 2.66 2003: 3.01 | 2002: 0.71 2003: 0.77 | protected area; two years: 2002 (high precipitation) 2003 (low precipitation) |
| (Santos et al. 2013) | 1 × 1, individuals counted | 2008: 84 2009: 80 | 2008: 1.91 2009: 1.94 | - | anthropogenic area: cactus plantation regenerating for 15 years; two years: 2008, 2009 |

Benevides DS, Maracaja PB, Sizenando Filho FA, de Moura Guerra AMN, Pereira TFC (2007) Estudo da flora herbácea da Caatinga no Município de Caraúbas no Estado do Rio Grande do Norte. *Revista Verde de Agroecologia e Desenvolvimento Sustentável* 2:33–44

Silva KA, Araújo EL, Ferraz EMN (2009) Estudo florístico do componente herbáceo e relação com solos em áreas de caatinga do embasamento cristalino e bacia sedimentar, Petrolândia, PE, Brasil. *Acta Botanica Brasilica* 23:100–110

Araújo EL, Silva KA, Ferraz EMN, Sampaio EVSB, Silva SI (2005) Diversidade de herbáceas em microhabitats rochoso, plano e ciliar em uma área de caatinga, Caruaru, PE, Brasil. *Acta Botanica Brasilica* 19:285–294

Reis AMS, Araújo EL, Ferraz EMN, Moura AN (2006) Inter-annual variations in the floristic and population structure of an herbaceous community of "caatinga" vegetation in Pernambuco, Brazil. *Brazilian Journal of Botany* 29:497–508. <http://dx.doi.org/10.1590/S0100-84042006000300017>

Santos JMFF, Santos DM, Lopes CGR, Silva KA, Sampaio EVSB, Araújo EL (2013) Natural regeneration of the herbaceous community in a semiarid region in Northeastern Brazil. *Environmental Monitoring and Assessment* 185:8287–8302. <https://doi.org/10.1007/s10661-013-3173-8>



CHAPTER 3

Is Crop Yield related to Weed Species Diversity and Biomass in Coconut and Banana Fields of Northeastern Brazil?

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Abstract

The ability to accommodate crop production for an ever-growing human population and achieve conservation of rapidly declining biodiversity remains a challenging task worldwide. In agroecosystems, weed diversity and biomass are frequently assumed to be negatively related to crop yield and biomass. However, positive effects of weed species (pollinator and parasitoid attraction) and different resource acquisition strategies may reduce the competitive character of weeds—a potential that can be exploited within land-sharing approaches (i.e., biodiversity conservation and agricul-

ture on the same site). This study aimed at analysing the relationships of weed diversity and biomass to crop yield and biomass in coconut and banana fields within an irrigation farming scheme established in former Caatinga seasonal dry forest ecosystems around the Itaparica Reservoir, Pernambuco, Brazil. Within each of 21 selected crop fields, we collected weed diversity and biomass data in the fields' centre and edge along with general information on crop yield and the use of fertilisers and other agrochemical inputs. We found no evidence for a negative relationship of crop yield or biomass and weed diversity. On the contrary, crop yield and weed alpha diversity were significantly positively correlated (Shannon and Simpson indices, evenness). In contrast, weed biomass showed a significant negative correlation to crop yield. The use of organic fertiliser had a significant positive effect on crop yield, whereas no impact of herbicides or insecticides was detected. In addition, the field edge provided habitat for more weed species than the field centre. Overall, our data show that in perennial tropical crop fields high yield is not opposed to high weed diversity. Moreover, the data suggest that organic farming in the area will likely not lead to yield losses. Nevertheless, the related weed assemblages inhabited only a few typical species of the native dry forest vegetation which makes their contribution to biodiversity conservation at the landscape scale debatable.

Keywords: fertiliser, field edge, herbicide, insecticide, land sharing, organic farming

Introduction

More than 30% of the ice-free area of the earth is currently directly used for agriculture (Hurt et al. 2011). At the same time, the world is facing an accelerated extinction rate of species and a dramatic loss of biodiversity in all biomes (Millennium Ecosystem Assessment 2005). As land must be used to provide food for earth's continuously growing population, the success of biodiversity conservation is tightly linked to our ability to integrate conservation efforts into human-driven landscapes (Fahrig et al. 2011).

Two main strategies known as land sparing and land sharing have been proposed to protect biodiversity (Phalan et al. 2011). Land sparing refers to the practice of intensifying agriculture on productive soils to gain areas for efficient

species conservation in other places, whereas land sharing aims at integrating conservation and crop production on the same site (also described as wildlife-friendly farming; Green et al. 2005). Up to now, neither of these strategies seems appropriate to achieve all conservation goals and for all land-use systems (Grau et al. 2013). In particular, land sharing seems to be the more appropriate option in agroforestry and in livestock systems, whereas land sparing has been shown to be efficient in cash crop production schemes such as oil seeds, wheat, and sugar cane (Clough et al. 2011; Grau et al. 2013). In both options, agrarian habitats will play a pivotal role in biodiversity conservation due to their wide distribution and huge area they cover.

Crop yield and weed biomass have commonly been assumed to be negatively related (Zimdahl 2007). There may also be a negative correlation between crop yield and weed diversity (Clough et al. 2011; Syswerda & Robertson 2014). However, weed–crop competition is expected to be less pronounced when the species are characterised by high functional diversity in terms of resource acquisition traits (Smith et al. 2009). In fact, there is growing empirical evidence that diverse crop and weed communities may show no (Epperlein et al. 2014) or even a positive relationship of crop and weed biomass (Smith et al. 2009). Accordingly, weed diversity and crop yield may be unrelated (Pollnac et al. 2009) or positively related (Hooper et al. 2005). Moreover, the combination of functionally different crop species such as cocoa and banana has been shown to lead to higher yield overall and per crop plant (Deheuvels et al. 2012).

Such positive weed–crop relationships can be expected to rely on beneficial plant–plant interactions (see Wardle et al. 1998) which may derive, for example, from functional complementarity in terms of root and canopy architecture of the plants involved (Brooker et al. 2015). Complementarity enables resource sharing, mitigation of severe environmental effects, or the supply of resources from one species to the other (Nakamura 2008). Consequently, positive plant–plant interactions and the resulting biodiversity impacts are often more obvious under cases of resource limitation (Mulder et al. 2001; Brooker et al. 2008; Nakamura 2008). The beneficial interaction among species may be direct, as in the case of the community's exploitation of limited resources (e.g., phosphorous; see Karanika et al. 2007; Oelmann et al. 2011), or indirect through a more diverse and abundant community of soil organisms (Zak et al. 2003; Chung et al. 2007; Hol et al. 2013), pol-

linators (Bennett & Isaacs 2014), or herbivore predators (Gosme et al. 2012; Puech et al. 2014).

However, agroecosystems do not necessarily yield more biomass when only a few species are present (Coulis et al. 2014). Positive biodiversity effects have more often been reported in species-rich communities such as grasslands (Bullock et al. 2001; Karanika et al. 2007; Tilman et al. 2012), prairies (Bonin & Tracy 2012), or artificial moss communities (Mulder et al. 2001). In such ecosystems, complementarity of species seems to play a more pronounced role for positive biodiversity effects (complementarity effect) rather than selection effects, i.e., the beneficial impact of individual species with particular traits occurring randomly in species-rich communities (Cardinale et al. 2007; Fargione et al. 2014). In biodiversity experiments, also the duration of plant–plant interactions increased the probability of positive biodiversity effects (Cardinale et al. 2007; Fargione et al. 2014). Whether such findings also apply to crop production systems is still discussed (Schöb et al. 2015).

In tropical latitudes, natural ecosystems, including tropical dry forests (Bianchi & Haig 2013), are continuously being transformed to pastures and agricultural land (Pan et al. 2011), leading to severe losses of biodiversity. The Caatinga of northeastern Brazil is the largest seasonal dry forest region in South America. Approximately 50% of the area supporting native vegetation in the past has been either completely converted or heavily modified by land-use (Menezes et al. 2012). Overuse together with the presumed impact of regional climate change is accelerating desertification (Oyama & Nobre 2003), although recent surveys indicate a slight increase in forest cover during the last decade (e.g., Menezes et al. 2012). Different agroecosystems such as coconut (*Cocos nucifera* L.) and banana (*Musa × paradisiaca* L.) fields cover about 10% of the area (Menezes et al. 2012) and may contribute to biodiversity conservation. However, only a few studies have addressed the link between biodiversity and crop yield in such ecosystems (Aguiar et al. 2013). We hypothesise that complementarity of weeds and crops in terms of belowground and light resources is particularly pronounced in perennial crop fields due to the different plant functional types involved and to the long interaction time, which increases the probability of positive biodiversity effects.

This study aims at determining the relationship between the biomass and diversity of weeds and the yield and biomass of coconut and banana crops in irrigated areas within former Caatinga dry forest areas around the Itaparica Reservoir,

Pernambuco, Brazil. Coconut and banana are the most frequently grown crops in the area (Silva et al. 2007). In particular, we analysed the following questions: (1) Are crop yield and crop plant biomass correlated with weed diversity and biomass, and if so, positively or negatively? (2) Which environmental and management variables influence crop yield, weed diversity, and biomass of crop plants and weeds? (3) Are there differences between the crop–weed relationships of coconut and banana fields? Based on these data, we draw conclusions on a diversity-optimised crop production in tropical dry forest ecosystems.

Materials and methods

Study area

The study was carried out in the São Francisco river catchment in Pernambuco, Brazil. The area is located in the semi-arid northeastern part of Brazil and predominantly covered by Caatinga seasonal dry forests with linear remnants of riparian forests along water courses. The Caatinga covers about 750,000 km² of northeastern Brazil (Lima Araújo et al. 2007); it harbours a very diverse and distinctive set of plant species with a high endemism rate (Giulietti et al. 2002). The climate of the study area is characterised by 403–448 mm of annual precipitation with a pronounced rainy season between January and May and a mean temperature of 26°C (Silva et al. 2007).

We selected twelve coconut and nine banana fields within the irrigation schemes of Icó-Mandantes and Apolônio Sales in the municipality of Petrolândia adjacent to the northern shore of the São Francisco River. This river section was transformed into the Itaparica Reservoir following construction of a dam in 1988. The related flooding of fertile soils along the São Francisco River required the resettlement of about 40,000 people. Many of them received new land within the irrigation schemes established in the Caatinga dry forests. Coconut and banana represented 25.0% and 7.7% of the cropped area in the studied irrigation schemes and were the most common crop species along with fruit trees (e.g., guava, mango), onion and melon (Silva et al. 2007). Crop fields are monocultures; intercropping is exclusively carried out during the first three years after coconut planting with peanut, beans or manioc. Fertilisation is most commonly performed organically with goat

manure or with a mixture of chemical fertilisers (containing nitrogen, phosphorus and potassium at different proportions) and goat manure (Table 3.1). In the area, different irrigation techniques are present: drip, spray, and micro-spray—the latter applying water to tree-shaped crops with a high precision which makes the irrigation system less water-consuming and reduces the risk of salinisation. Irrigation is conducted continuously the whole year round.

Table 3.1 The use of fertilisers, insecticides, and herbicides, as well irrigation technique and grazing on the studied banana and coconut fields.

| Crop species | Field no. | Fertiliser | Insecticide | Herbicide | Irrigation technique | Grazing |
|--------------|-----------|--------------------|-------------|-----------|----------------------|---------|
| Banana | 1 | Organic | Yes | No | Spray | No |
| | 2 | Organic + chemical | No | Yes | Micro-spray | No |
| | 3 | No | No | No | No | No |
| | 4 | Organic + chemical | Yes | Yes | Micro-spray | No |
| | 5 | Organic + chemical | No | Yes | Spray | No |
| | 6 | Organic + chemical | No | Yes | Micro-spray | No |
| | 7 | Organic + chemical | Yes | Yes | Micro-spray | No |
| | 8 | No | No | No | No | No |
| | 9 | Organic + chemical | No | Yes | Micro-spray | No |
| Coconut | 10 | Organic | Yes | No | Spray | No |
| | 11 | Organic + chemical | Yes | Yes | Micro-spray | No |
| | 12 | Organic + chemical | Yes | No | Spray | Yes |
| | 13 | No | No | No | Spray | No |
| | 14 | Organic | No | No | Spray | No |
| | 15 | Organic + chemical | Yes | Yes | Micro-spray | No |
| | 16 | Organic + chemical | Yes | Yes | Drip | No |
| | 17 | Organic | No | No | Spray | Yes |
| | 18 | Organic + chemical | Yes | Yes | Spray | No |
| | 19 | Organic + chemical | Yes | Yes | Spray | No |
| | 20 | Organic + chemical | Yes | Yes | Drip | No |
| | 21 | Chemical | Yes | Yes | Spray | Yes |

Study design and data collection

Within each of the 21 crop fields selected, we established two square 25-m² plots for vegetation analysis—one in the centre of the field and one at its edge (see Batáry et al. 2012). The exact position was determined using a handheld GPS (Garmin) in the

plot centre. In each of the resulting 42 plots, we carried out a vegetation relevé according to the method of Braun-Blanquet (1964). Plant identification was done in cooperation with the herbarium of Instituto Agronômico de Pernambuco (IPA) based on Castro (2011), Moreira & Bragança (2011), Amorim & Alves (2012), and Maia-Silva et al. (2012). Plant taxonomy follows Jardim Botânico do Rio de Janeiro (2015). We collected three soil samples (0–5 cm in depth) along the plot's diagonal and harvested aboveground vegetation < 1 m in height from two square 0.25-m² subplots in two opposite corners for weed biomass assessment. Biomass samples of weeds were dried at 60°C and weighed. Leaf area index (LAI) of the crop plant layer was measured at 1 m above ground level at the sites where soil cores were collected and averaged using a LAI-2200 device (Licor). Crop density was calculated using the distances between planting rows and between crop plants within rows. Biomass of crop plants was estimated using allometric equations provided by Kumar & Nair (2011) for banana and by Schroth et al. (2002) for coconut. For this, we measured circumference at breast height of all crop plants present in each plot. For coconut, the mean height of the palms was estimated and a mean number of 20 leaves was assumed. Aboveground biomass of coconut trees was calculated as $DM = -35.7 + 1.73 (0.000206 BA H + 1.4 L)$ (DM: aboveground dry matter in kg; BA: basal area in cm²; H: height in cm; L: leave number). Banana plant biomass was calculated as $DM = 0.03 D^{2.13}$ (DM: aboveground dry matter in kg; D: diameter at breast height in cm). Mean crop plant biomass was extrapolated to t ha⁻¹ for each field based on crop density values. All data were collected during the rainy season from March to April 2014.

Soil samples were dried at 60°C and weighed. After sieving through a 2-mm mesh, 10 g of the fraction < 2 mm was shaken for 1 hour in 25 ml deionised water. We determined pH at 22.2°C using a pH electrode (VWR Symphony SP90M5). To assess possible effects of soil salinisation, we determined the electrical conductivity of the sample with the same device. Carbon (C) and nitrogen (N) contents as well as C/N ratio of a milled subsample (swing mill produced by Siebtechnik) were analysed in a CN-analyser (elementar vario EL cube). Possible correction measurements for inorganic C in carbonate minerals (see Cierjacks et al. 2010) were not performed due to the missing gas production after treating subsamples with HCl.

Assessment of crop yield and agricultural management

Data on crop yield, the use of fertilisers (none, organic, chemical, both), herbicides (yes, no), and insecticides (yes, no) were determined through interviews with the leaseholders of the fields (Table 3.1). Where possible, yield data were cross-checked with official rural extension and sales documents. Management parameters refer to the most frequently applied practices within the last three years. Accordingly, yield data represent means of the past years and are related to the entire fields without differentiation into centre and edge.

For comparison between crop species, we transformed fruit quantities given by the leaseholders into mass by assuming a mean coconut weight of 1.7 kg and a mean banana weight of 0.2 kg (own measurements).

Data analyses and statistics

Cover classes from vegetation relevés were transformed to mean cover percentage following Frey & Lössch (2010) as follows: r = 0.1%; + = 0.5%; 1 = 2.5%; 2 = 15%; 3 = 37.5%; 4 = 62.5%; 5 = 87.5%. These data were used for analyses of species composition and diversity indices. All statistical tests were conducted with R, version 3.1.1 (R Development Core Team 2014).

Species composition and underlying environmental predictors were visualised by non-metric multidimensional scaling (NMDS), using the functions *metaMDS* and *vector fitting* in the R packages *vegan* (Oksanen et al. 2008) and *mass* (Venables & Ripley 2002). NMDS is an iterative method that places samples (here plots) in a k-dimensional space based on the ranked distances among them. Compared to other ordination techniques, NMDS is characterised by high robustness, which makes it particularly suitable for community ecology (Leyer & Wesche 2007). For the ordination, we used the Bray-Curtis dissimilarity matrix which shows a good rank order relation to ordering sites along gradients (Faith et al. 1987). The stress value of the ordination was calculated as quality measure (Leyer & Wesche 2007). A stress value < 0.15 is considered sufficient for enabling meaningful model interpretation. To find the best solution with two configurations characterised by minimum stress, the function uses Procrustes rotations and optimises the solution iteratively. We used a maximum of 20 random starts and selected a five-dimensional model which showed the lowest stress value. To illustrate the correlation of management and

environmental variables with the species composition, environmental data was fitted onto the ordination. The significance of each variable was evaluated with a Monte-Carlo randomisation test (1000 free permutations of the data) which compared the R^2 values of the present dataset to those of the randomised dataset (Manly 1997). Only explanatory variables with a p value < 0.05 were included.

Alpha diversity was assessed using different indices such as species richness, the Shannon and Simpson indices, as well as evenness (E-evenness calculated as: $\exp(H)/S$ with H being the Shannon entropy and S the species richness), all of which were calculated in the package *BiodiversityR* (Kindt & Coe 2005).

The entire set of metric variables was analysed in terms of homogeneity (Fligner test), normality (Shapiro–Wilk test) or outliers (Zuur et al. 2009). Values for Simpson index and evenness were arcsine-transformed prior to analyses to normalise data as these indices are scaled as proportion data. We chose generalised linear mixed models (GLMMs) to determine which variables influence crop yield, biodiversity, and biomass as our dataset is nested with two plots (field edge and central plot) per field, which causes spatial autocorrelation (Zuur et al. 2009). GLMMs are an extension of generalised linear models, which allow for the analysis of datasets characterised by heterogeneity and spatial correlation. To avoid various levels of the sample units when used as fixed effects, these models can integrate the sampling units and their nested structure as random effects (Zuur et al. 2009). In this study, environmental and management variables were included as fixed effects, whereas *field* and *plot* were random effects with *plot position* nested within field. Crop yield, richness, and crop biomass were modelled in the R package *lme4* based on Poisson distribution (Bates 2010) due to strong deviation from normality and skewed distribution. Model parameters were estimated using Laplace approximation. All other diversity indices and biomass values were modelled in the *nlme* package (Pinheiro & Bates 1995) where model parameters rely on restricted maximum likelihood (REML) estimation. To keep the complexity of the models low, we did not consider interactions among the predictor variables. Models were compared and selected using the Akaike information criterion (AIC; Zuur et al. 2009).

In a first step, we carried out modelling for yield–diversity and yield–biomass relationships including crop species as factor, which significantly influences crop yield. In a second step, crop yield, biomass, and weed diversity indices were modelled based on all recorded management and environmental variables.

Results

Yield–weed relationships

Overall, we found 77 weed species within the study plots, 12 of which could not be identified at genus level but were included into the analyses as morphospecies (Appendix 3.1). Legume species with potential for N fixation accounted for 15.6% of the total weed richness. The weed species composition of the study plots was clearly differentiated between both crop species (Figure 3.1). In addition, species composition was related to differences in soil pH and crop biomass. However, pH was only slightly higher in banana fields compared to coconut fields (Table 3.2). In accordance to the correlation with crop biomass, also LAI influenced the weed species assemblage. The use of insecticides was the only management parameter that proved to be related to weed species composition. In contrast, there was no clear pattern concerning the difference in species composition in central and edge plots.

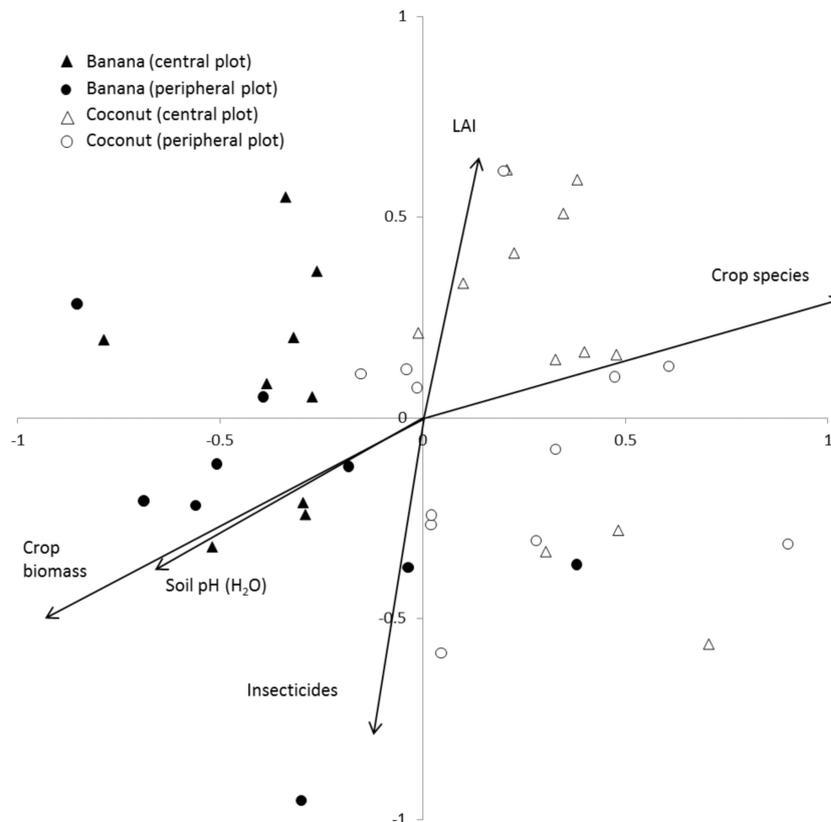


Figure 3.1 Impact of management and environmental parameters on species composition of banana and coconut fields in semi-arid northeastern Brazil according to NMDS (stress value 0.11, p value of environmental parameters < 0.05).

Mean crop yield per ha and year in coconut fields was more than twice as high as yield in banana fields (Table 3.2). Soil conditions were similar between the two crop species but with slightly higher pH and lower electrical conductivity in banana fields (Table 3.2). Generalised linear mixed models revealed significant positive correlations between most weed alpha diversity indices (Shannon index, Simpson index, evenness) and crop yield—even when considering the significant differences in yield between the crop species within the models (Figure 3.2). Accordingly, richness showed a positive effect within the model although without reaching the level of significance. Crop biomass was significantly positively related to yield in both crop species, whereas weed biomass and crop yield showed significant negative relationships (Figure 3.3). In addition, yield depended significantly on crop species.

Table 3.2 Means (with standard error in parentheses) of crop yield and biomass, weed biomass and biodiversity indices, and soil conditions in centre and edge plots of banana ($n = 9$) and coconut ($n = 12$) fields in semi-arid northeastern Brazil.

| | Banana | | Coconut | |
|--|---------------|---------------|---------------|---------------|
| | Centre | Edge | Centre | Edge |
| Mean crop yield (t ha ⁻¹ year ⁻¹) | 31.0 (9.3) | | 64.7 (8.6) | |
| Mean crop plant biomass (t ha ⁻¹) | 60.8 (13.0) | | 25.6 (3.6) | |
| Weed biomass (g m ⁻²) | 78.0 (26.4) | 102.0 (17.3) | 82.0 (12.4) | 92.6 (15.2) |
| Leaf area index of crop plant layer | 2.3 (0.4) | 1.9 (0.2) | 2.5 (0.1) | 2.2 (0.1) |
| <i>Weed diversity</i> | | | | |
| Richness | 8.3 (1.0) | 12.8 (1.1) | 11.8 (1.3) | 14.3 (1.0) |
| Shannon index | 1.60 (0.19) | 1.94 (0.25) | 1.86 (0.16) | 2.15 (0.15) |
| Simpson index | 0.70 (0.07) | 0.74 (0.08) | 0.77 (0.05) | 0.82 (0.05) |
| Evenness | 0.68 (0.07) | 0.63 (0.09) | 0.63 (0.06) | 0.66 (0.06) |
| <i>Soil</i> | | | | |
| N content (%) | 0.065 (0.010) | 0.090 (0.017) | 0.064 (0.003) | 0.063 (0.004) |
| C content (%) | 0.53 (0.12) | 0.84 (0.19) | 0.54 (0.05) | 0.52 (0.06) |
| C/N ratio | 7.7 (0.4) | 8.9 (0.5) | 8.3 (0.4) | 8.1 (0.4) |
| Electrical conductivity (μS cm ⁻¹) | 87.4 (20.7) | 132.3 (24.3) | 90.9 (12.9) | 288.3 (187.9) |
| pH (H ₂ O) | 6.8 (0.2) | 7.2 (0.2) | 6.7 (0.1) | 6.7 (0.1) |

Drivers of crop yield, weed diversity, and biomass in perennial crop fields

Coconut fields had a significantly higher crop yield than banana fields with a significantly positive effect of organic and mixed (organic and chemical) fertilisation (Figure 3.4). Only in one case chemical fertiliser was applied exclusively (Table 3.1). Therefore, the separated effect of chemical fertiliser could not be assessed. Inclusion of biodiversity indices as explanatory variables into the model led to slightly improved AIC values in terms of the Shannon (AIC = 467.3) and Simpson indices (AIC = 467.5; Appendix 3.2). There was no evidence that herbicide or insecticide use increases crop yield.

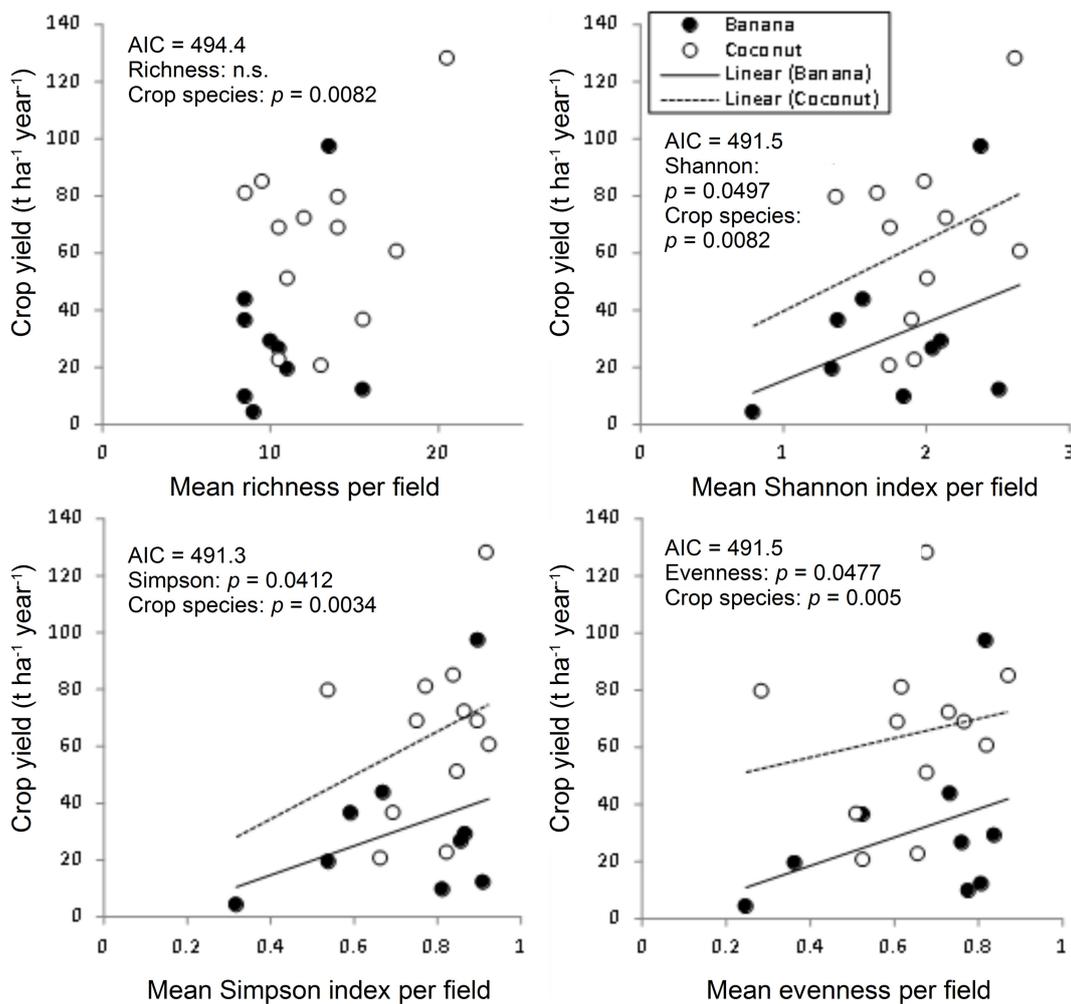


Figure 3.2 Yield–weed diversity relationships in banana and coconut fields in northeastern Brazil. Model documentation refers to generalised linear mixed models for crop yield based on biodiversity index and crop species ($\text{glmer}(\text{Yield} \sim \text{Biodiversity} + \text{Crop} + (1|\text{Field}))$, family = “poisson”, $n = 21$). Lines indicate linear regression of the respective variables to show the slope of significant correlations.

Species richness was significantly higher in the field's edge compared to the centre (AIC = 231.5, $p = 0.0016$; Appendix 3.2). Other alpha diversity measures showed less clear responses (Appendix 3.2). In accordance with richness, the Shannon index was slightly but not significantly higher in field edge compared to central plots, whereas the Simpson index and evenness correlated negatively with weed biomass (AIC = 26.8, $p = 0.0057$; AIC = 16.8, $p < 0.0001$ respectively).

The model on weed biomass indicated a significant decrease with LAI (AIC = 373.6, $p < 0.0001$). In contrast, crop biomass was significantly different between crop species (AIC = 183.3, $p < 0.0004$; see both models in Appendix 3.2).

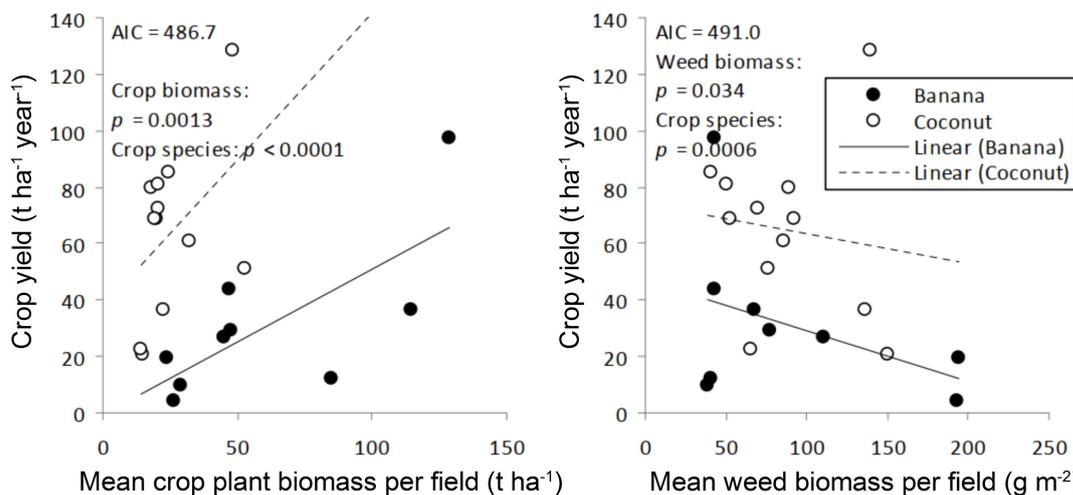


Figure 3.3 Yield–biomass relationships in banana and coconut fields. Model documentation refers to generalised linear mixed models for crop yield based on biomass data and crop species ($\text{glmer}(\text{Yield} \sim \text{Biomass} + \text{Crop} + (1|\text{Field}), \text{family} = \text{"poisson"}), n = 21$). Lines indicate linear regression of the respective variables to show the slope of significant correlations.

Discussion

Yield–weed relationships

This study provides further evidence that weed diversity is not necessarily always related to crop yield in perennial production systems (as also shown for oil palm fields by Samedani et al. 2014 and for cherry fields by Serrine et al. 2008). On the contrary, our data imply positive and mostly significant relationships between crop yield and weed diversity indices. Consequently, the complementarity of the related crop and weed species appears to be more relevant in the studied system than

competition among both plant types. Complementarity is expected to be more frequent in ecosystems composed by functionally different plants which rely on separate resource pools in soil (Smith et al. 2009). This may be the case in our study system with herb-layer weeds and upper-layer perennial crops such as banana and coconut representing pronouncedly different trait combinations. In addition, limited nutrients as present in the poor sandy soils of the study area may lead to direct positive interactions among plant species, which are less likely in rich soils where a few plant species become dominant in terms of biomass production and outcompete others (Brooker et al. 2008). Apart from direct plant–plant interactions, the associated faunal diversity may be relevant (e.g., Clough et al. 2007; Serrine et al. 2008; Gosme et al. 2012) but our data do not allow for the detection of possible indirect biodiversity effects, and further studies on this aspect will be necessary.

In accordance with Clough et al. (2011), who found that tree species diversity in Indonesian cocoa fields did not affect crop yield, our data show that high yield and high weed diversity may be combined in agroecosystems to achieve sufficient crop production and biodiversity conservation at the same sites. In contrast, herb species richness and cocoa yield in Indonesia were significantly and negatively related. As

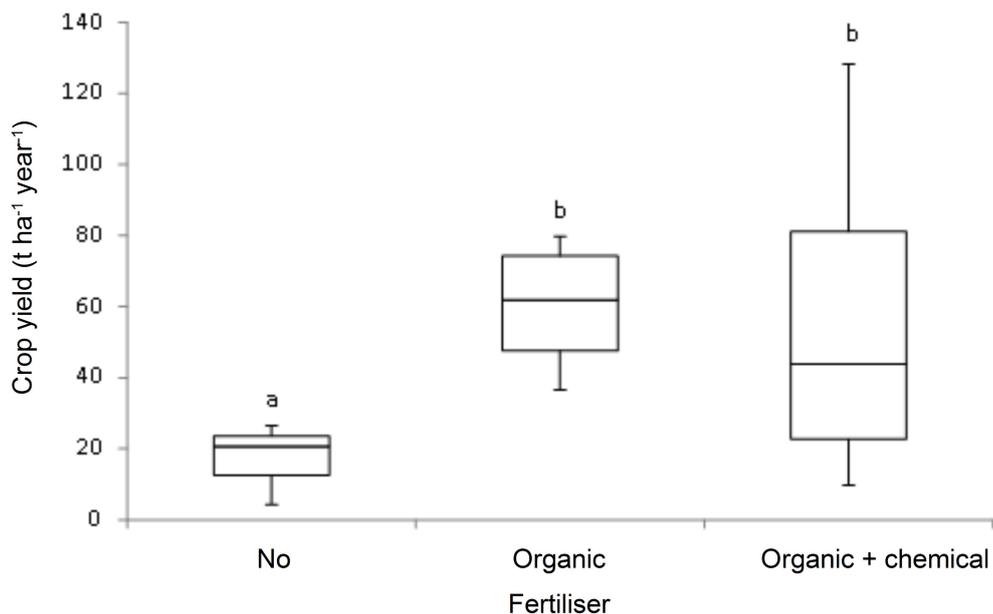


Figure 3.4 Impact of fertiliser types on crop yield in banana and coconut fields. Boxplots show median and quartiles. Different letters indicate significant differences ($p < 0.05$) among fertiliser types in generalised linear mixed model (glmer (Yield ~ Crop + Fertiliser + (1|Field), family = “poisson”), AIC = 468.1, crop species: $p = 0.0046$, $n = 21$).

cocoa is a shade-demanding tree, the low species richness in highly productive cocoa fields points to low light availability at the herb layer in this particular production scheme with high LAI values > 5 (Zuidema et al. 2005), which may explain why the results of Clough et al. (2011) differ from ours.

In contrast to diversity, weed biomass had a negative impact on crop yield (Figure 3.3). This result shows that a herb layer composed of only a few species may be detrimental to perennial crop production and may require the use of herbicides, albeit the positive effects of a species-rich herb layer on crop yield (which may particularly apply to the legume species of the weed flora). The diverging effects of diversity and biomass of weeds on crop yield may be one reason for the often opposing positions in science on the impact of weeds (Zimdahl 2007; Smith et al. 2009; but see Pollnac et al. 2009).

Drivers of crop yield, weed diversity, and biomass in perennial crop fields

Crop yield was positively related to fertiliser use, and no differences were found among different fertiliser types (Figure 3.4). In particular, goat manure as organic fertiliser proved to have a positive impact on crop yield that seemed equivalent to a mixture of organic and chemical nutrient sources. In contrast, herbicides and insecticides did not show a positive effect on crop yield. This is in line with other studies on perennial crops in which the eradication of the herb layer led to similar or even significantly lower yields compared to fields with natural herb layer or cover crops (Solomou & Sfougaris 2011; Samedani et al. 2014). However, the negative effect of weed biomass on crop yield in our study may point to the necessity to use herbicides when a few species become dominant in terms of biomass production.

Still, these findings provide evidence that organic farming may be an option in the study region if organic fertiliser supply (mostly goat manure) remains assured. Although further studies with larger sample sizes are needed to confirm our results that yields were not affected by fertiliser type, the cost reduction through lower consumption of agrochemicals could be an incentive to farmers to switch their production system to organic farming (as shown for cherry fields by Sirrine et al. 2008). The market for organically grown products is currently small in Brazil and there is little support from regional networks and institutions for a transformation towards organic

farming (Oelofse et al. 2011). However, should this situation change in the future, these organically grown crops could prove to be even more financially valuable.

Our study indicates factors that are associated with high weed diversity in banana and coconut fields of northeastern Brazil. As in other agroecosystems, weed diversity was higher along the edges of the field than in the centre (e.g., Romero et al. 2008; Batáry et al. 2012; Poggio et al. 2013). This adds support for the idea that species-rich field edges have a critical role in biodiversity (see Marshall & Moonen 2002; Nicholls & Altieri 2013), including in perennial crops. However, the biodiversity of agroecosystems is clearly different to that of the surrounding Caatinga vegetation. In particular, woody species typical of the original vegetation are scarce both in the fields' edge and in the centre, while at the same time permanent water supply by irrigation enables a species-rich weed flora (as has also been reported by Aguiar et al. 2013). Thus, the irrigation farming system, which is novel to the study area, maintains a particular species pool at the landscape scale but fails to be a refugium for specialised Caatinga species. This is in line with results from Europe where agrodiversity has been shown to contribute little to the conservation of uncommon or endangered species (Kleijn et al. 2006). However, agroecosystems may play a role for biodiversity conservation in the study area when they are accompanied by an efficient network of protected areas for the original flora. In addition, the positive relation between crop yield and species richness implies that biodiversity provides important services to agricultural production schemes (Gaba et al. 2015).

Coconut fields harbour a similar species richness as banana fields but the species composition was clearly different in coconut and banana fields (Figure 3.1; Appendix 3.1). At the landscape scale, biodiversity may therefore be enhanced by crop diversification with different weed species communities accompanying each crop species (e.g., Poggio et al. 2013; Colbach et al. 2014).

There was no evidence that herbicides had any impact on alpha diversity or species composition in contrast to other studies (Colbach et al. 2014) but species assemblage was affected by insecticides (Figure 3.1). As many species are insect-pollinated, insecticides seem to efficiently inhibit regeneration of certain species, which may have produced the observed shift in species occurrence and abundance.

Conclusion

Overall, this study on highly productive perennial agroecosystems in northeastern Brazil sheds light on possible drivers of weed diversity in such systems. Consequently, our results contribute to improved assessment of the potential of banana and coconut farms for biodiversity conservation and as part of land-sharing approaches in the study area. The positive relation of crop yield with weed diversity shows that there is the potential for enhanced use of complementary plant–plant interactions in agriculture along with related ecosystem services (Gaba et al. 2015). This may particularly apply to areas with poor soils where functionally different species exploit and cycle diverging nutrient sources.

There was no evidence that the use of costly agrochemicals is related to higher crop yield in our particular production system. Therefore, the reduction or entire substitution of chemical fertilisers, herbicides, and insecticides should be explored with regard to possible changes in productivity.

To enhance biodiversity conservation in the area, a differentiated approach seems appropriate. The use of a wide range of crops within these agroecosystems may increase species numbers in agricultural systems at the landscape scale as weed species composition proved to be clearly different between crop species. Due to the relevance of field edges as source habitats, these edges should be explicitly established irrespective of crop species. In addition, a system of protected areas featuring the original vegetation should be installed and maintained to protect the native species and to provide seed sources for species-rich agroecosystems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.agee.2016.01.006>.

References

- Aguiar MI, Silva Fialho J, Araújo F, Campanha M, Oliveira TS (2013) Does biomass production depend on plant community diversity? *Agroforestry Systems* 87:699–711. <https://doi.org/10.1007/s10457-012-9590-9>
- Amorim BS, Alves M (2012) Malvaceae of a semi-arid region from Pernambuco, Brazil. ECCo, The Field Museum, Chicago, USA
- Batáry P, Holzschuh A, Orci KM, Samu F, Tschamntke T (2012) Responses of plant, insect and spider biodiversity to local and landscape scale management intensity in cereal crops and grasslands. *Agriculture, Ecosystems & Environment* 146:130–136. <https://doi.org/10.1016/j.agee.2011.10.018>
- Bates DM (2010) lme4: Mixed-effects modeling with R. R Development Core Team, Vienna, Austria
- Bennett AB, Isaacs R (2014) Landscape composition influences pollinators and pollination services in perennial biofuel plantings. *Agriculture, Ecosystems & Environment* 193:1–8. <https://doi.org/10.1016/j.agee.2014.04.016>
- Bianchi CA, Haig SM (2013) Deforestation trends of tropical dry forests in Central Brazil. *Biotropica* 45:395–400. <https://doi.org/10.1111/btp.12010>
- Bonin CL, Tracy BF (2012) Diversity influences forage yield and stability in perennial prairie plant mixtures. *Agriculture, Ecosystems & Environment* 162:1–7. <https://doi.org/10.1016/j.agee.2012.08.005>
- Braun-Blanquet J (1964) *Pflanzensoziologie: Grundzüge der Vegetationskunde* (2nd ed). Springer, Vienna, Austria.
- Brooker RW, Bennett AE, Cong WF, Daniell TJ, George TS, Hallett PD, Hawes C, Iannetta PPM, Jones HG, Karley AJ, Li L, McKenzie BM, Pakeman RJ, Paterson E, Schöb C, Shen J, Squire G, Watson CA, Zhang C, Zhang F, Zhan J, White PJ (2015) Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist* 206:107–117. <http://dx.doi.org/10.1111/nph.13132>
- Brooker RW, Maestre FT, Callaway RM, Lortie CL, Cavieres LA, Kunstler G, Liancourt P, Tielbörger K, Travis JMJ, Anthelme F, Armas C, Coll L, Corcket E, Delzon S, Forey E, Kikvidze Z, Olofsson J, Pugnaire F, Quiroz CL, Saccone P, Schifffers K, Seifan M,

- Touzard B, Michalet R (2008) Facilitation in plant communities: the past, the present, and the future. *Journal of Ecology* 96:18–34. <https://doi.org/10.1111/j.1365-2745.2007.01295.x>
- Bullock JM, Pywell RF, Burke MJW, Walker KJ (2001) Restoration of biodiversity enhances agricultural production. *Ecology Letters* 4:185–189. <https://doi.org/10.1046/j.1461-0248.2001.00215.x>
- Cardinale BJ, Wright JP, Cadotte MW, Carroll IT, Hector A, Srivastava DS, Loreau M, Weis JJ (2007) Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proceedings of the National Academy of Sciences* 104:18123–18128. <https://doi.org/10.1073/pnas.0709069104>
- Castro AS (2011) Flores da Caatinga - Caatinga flowers. Edição Bilingue, Instituto Nacional do Semiárido, Campina Grande, Brazil
- Chung H, Zak DR, Reich PB, Ellsworth DS (2007) Plant species richness, elevated CO₂, and atmospheric nitrogen deposition alter soil microbial community composition and function. *Global Change Biology* 13:980–989. <https://doi.org/10.1111/j.1365-2486.2007.01313.x>
- Cierjacks A, Kleinschmit B, Babinsky M, Kleinschroth F, Markert A, Menzel M, Ziechmann U, Schiller T, Graf M, Lang F (2010) Carbon stocks of soil and vegetation on Danubian floodplains. *Journal of Plant Nutrition and Soil Science* 173:644–653. <https://doi.org/10.1002/jpln.200900209>
- Clough Y, Barkmann J, Juhbandt J, Kessler M, Wanger TC, Anshary A, Buchori D, Cicuzza D, Darrasi K, Putra DD, Erasmi S, Pitopang R, Schmidt C, Schulze CH, Seidel D, Steffan-Dewenter I, Stenchly K, Vidal S, Weist M, Wielgoss AW, Tschardtke T (2011) Combining high biodiversity with high yields in tropical agroforests. *Proceedings of the National Academy of Sciences* 108:8311–8316. <https://doi.org/10.1073/pnas.1016799108>
- Clough Y, Holzschuh A, Gabriel D, Purtauf T, Kleijn D, Kruess A, Steffan-Dewenter I, Tschardtke T (2007) Alpha and beta diversity of arthropods and plants in organically and conventionally managed wheat fields. *Journal of Applied Ecology* 44:804–812. <https://doi.org/10.1111/j.1365-2664.2007.01294.x>
- Colbach N, Granger S, Guyot SHM, Mézière D (2014) A trait-based approach to explain weed species response to agricultural practices in a simulation study with a cropping system model. *Agriculture, Ecosystems & Environment* 183:197–204. <https://doi.org/10.1016/j.agee.2013.11.013>
- Coulis M, Bernard L, Gérard F, Hinsinger P, Plassard C, Villeneuve M, Blanchart E (2014) Endogenic earthworms modify soil phosphorus, plant growth and interactions in a legume–cereal intercrop. *Plant and Soil* 379:149–160. <https://doi.org/10.1007/s11104-014-2046-4>
- Deheuvels O, Avelino J, Somarriba E, Malezieux E (2012) Vegetation structure and productivity in cocoa-based agroforestry systems in Talamanca, Costa Rica. *Agriculture, Ecosystems & Environment* 149:181–188. <https://doi.org/10.1016/j.agee.2011.03.003>
- Epperlein LRF, Prestele JW, Albrecht H, Kollmann J (2014) Reintroduction of a rare arable weed: Competition effects on weed fitness and crop yield. *Agriculture, Ecosystems & Environment* 188:57–62. <https://doi.org/10.1016/j.agee.2014.02.011>

- Fahrig L, Baudry J, Brotons L, Burel FG, Crist TO, Fuller RJ, Sirami C, Siriwarden GM, Martin J-L (2011) Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecology Letters* 14:101–112. <https://doi.org/10.1111/j.1461-0248.2010.01559.x>
- Faith DP, Minchin PR, Belbin L (1987) Compositional dissimilarity as a robust measure of ecological distance. *Vegetatio* 69:57–68. <https://doi.org/10.1007/BF00038687>
- Fargione J, Tilman D, Dybzinski R, Hille J, Lambers R, Clark C, Harpole WS, Knops JMH, Reich PB, Loreau M (2014) From selection to complementarity: shifts in the causes of biodiversity–productivity relationships in a long-term biodiversity experiment. *Proceedings of the Royal Society B Biological Science* 274:871–876. <https://doi.org/10.1098/rspb.2006.0351>
- Frey W, Lösch R (2010) *Geobotanik: Pflanze und Vegetation in Raum und Zeit* (3rd ed). Spektrum Akademischer Verlag, Heidelberg, Germany
- Gaba S, Lescourret F, Boudsocq S, Enjalbert J, Hinsinger P, Journet EP, Marie-Laure Navas M-L, Wery J, Louarn G, Malézieux E, Pelzer E, Prudent M, Ozier-Lafontaine H (2015) Multiple cropping systems as drivers for providing multiple ecosystem services: from concepts to design. *Agronomy for Sustainable Development* 35:607–623. <https://doi.org/10.1007/s13593-014-0272-z>
- Giulietti AM, Harley RM, Queiros LP, Barbosa MRV, Bocage Neta AL, Figueiredo MA (2002) Plantas endêmicas da Caatinga. In: Sampaio EVSB, Giulietti AM, Virgínio J, Gamarra-Rojas CFL (eds) *Vegetação e flora das Caatingas*. APNE / CNIP, Recife, Brazil, pp 103–115
- Gosme M, de Villemandy M, Bazot M, Jeuffroy M-H (2012) Local and neighbourhood effects of organic and conventional wheat management on aphids, weeds, and foliar diseases. *Agriculture, Ecosystems & Environment* 161:121–129. <https://doi.org/10.1016/j.agee.2012.07.009>
- Grau R, Kuemmerle T, Macchi L (2013) Beyond ‘land sparing versus land sharing’: environmental heterogeneity, globalization and the balance between agricultural production and nature conservation. *Current Opinion in Environmental Sustainability* 5:477–483. <https://doi.org/10.1016/j.cosust.2013.06.001>
- Green RE, Cornell SJ, Scharlemann JPW, Balmford A (2005) Farming and the fate of wild nature. *Science* 307:550–555. <https://doi.org/10.1126/science.1106049>
- Hol WHG, de Boer W, ten Hooven F, van der Putten WH (2013) Competition increases sensitivity of wheat (*Triticum aestivum*) to biotic plant-soil feedback. *PLoS ONE* 8:e66085. <https://doi.org/10.1371/journal.pone.0066085>
- Hooper DU, Chapin FS, Ewel JJ, Hector A, Inchausti P, Lavorel S, Lawton JH, Lodge DM, Loreau M, Naeem S, Schmid B, Setälä H, Symstad AJ, Vandermeer J, Wardle DA (2005) Effects of biodiversity on ecosystem functioning: A consensus of current knowledge. *Ecological Monographs* 75:3–35. <https://doi.org/10.1890/04-0922>
- Hurt GC, Chini LP, Frolking S, Betts RA, Feddema J, Fischer G, Fisk JP, Hibbard K, Houghton RA, Janetos A, Jones CD, Kindermann G, Kinoshita T, Klein Goldewijk K, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, van Vuuren DP, Wang YP (2011) Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change* 109:117–161. <https://doi.org/10.1007/s10584-011-0153-2>

- Jardim Botânico do Rio de Janeiro (2015) Lista de Espécies da Flora do Brasil. Jardim Botânico do Rio de Janeiro, Brazil. Retrieved from <http://floradobrasil.jbrj.gov.br/>. Accessed Sep 2015
- Karanika ED, Alifragis DA, Mamolos AP, Veresoglou DS (2007) Differentiation between responses of primary productivity and phosphorus exploitation to species richness. *Plant and Soil* 297:69–81. <https://doi.org/10.1007/s11104-007-9320-7>
- Kindt R, Coe R (2005) Tree diversity analysis. A manual and software for common statistical methods for ecological and biodiversity studies. ICRAF, Nairobi, Kenya
- Kleijn D, Baquero RA, Clough Y, Díaz M, de Esteban J, Fernández F, Gabriel D, Herzog F, Holzschuh A, Jöhl R, Knop E, Kruess A, Marshall EJP, Steffan-Dewenter I, Tscharrnke T, Verhulst J, West TM, Yela JL (2006) Mixed biodiversity benefits of agri-environment schemes in five European countries. *Ecology Letters* 9:243–254. <https://doi.org/10.1111/j.1461-0248.2005.00869.x>
- Kumar BM, Nair PR (2011) Carbon sequestration potential of agroforestry systems. opportunities and challenges. *Advances in Agroforestry*, vol. 8. Springer, New York, USA
- Leyer I, Wesche K (2007) *Multivariate Statistik in der Ökologie: Eine Einführung*. Springer, New York, USA
- Lima Araújo E, Castro CC, Albuquerque UP (2007) Dynamics of Brazilian Caatinga – A review concerning the plants, environment and people. *Functional Ecosystems and Communities* 1:15–28
- Maia-Silva C, Silva CI, Hrcir M, Queiroz RT, Imperatriz-Fonseca VL (2012) *Guia de plantas visitadas por abelhas na Caatinga (1st ed)*. Fundação Brasil Cidadão Fortaleza, Brazil
- Manly BFJ (1997) *Randomization, bootstrap and Monte Carlo methods in biology*. Chapman & Hall, London, UK
- Marshall EJP, Moonen AC (2002) Field margins in northern Europe: their functions and interactions with agriculture. *Agriculture, Ecosystems and Environment* 89:5–21. [https://doi.org/10.1016/S0167-8809\(01\)00315-2](https://doi.org/10.1016/S0167-8809(01)00315-2)
- Menezes RSC, Sampaio EVSB, Giongo V, Pérez-Marin AM (2012) Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. *Brazilian Journal of Biology* 72:643–653. <https://doi.org/10.1590/S1519-69842012000400004>
- Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, USA, pp 1–155
- Moreira HJC, Bragança HBN (2011) *Manual de identificação de plantas infestantes: Cultivos de verão*. FMC, Campinas, Brazil
- Mulder CPH, Uliassi DD, Doak DF (2001) Physical stress and diversity-productivity relationships: The role of positive interactions. *Proceedings of the National Academy of Sciences* 98:6704–6708. <https://doi.org/10.1073/pnas.111055298>
- Nakamura N (2008) Species richness and aggregation effects on the productivity of ruderal plant communities under drought perturbation. *Bioscience Horizons* 1:128–135. <https://doi.org/10.1093/biohorizons/hzn017>
- Nicholls CI, Altieri MA (2013) Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. *Agronomy of Sustainable Development* 33:257–274. <https://doi.org/10.1007/s13593-012-0092-y>

- Oelmann Y, Richter AK, Roscher C, Rosenkranz S, Temperton VM, Weisser WW, Wilcke W (2011) Does plant diversity influence phosphorus cycling in experimental grasslands? *Geoderma* 167-168:178–187. <https://doi.org/10.1016/j.geoderma.2011.09.012>
- Oelofse M, Høgh-Jensen H, Abreu LS, Almeida GF, El-Araby A, Hui QY, Sultan T, Neergaard A (2011) Organic farm conventionalisation and farmer practices in China, Brazil and Egypt. *Agronomy for Sustainable Development* 31:689–698. <https://doi.org/10.1007/s13593-011-0043-z>
- Oksanen J, Kindt R, Legendre P, O'Hara B, Simpson GL, Solymos P, Stevens MHH, Wagner H (2009) *Vegan: community ecology package*. R package version 1.15–4
- Oyama MD, Nobre CA (2003) A new climate-vegetation equilibrium state for tropical South America. *Geophysical Research Letters* 30:2199. <https://doi.org/10.1029/2003GL018600>
- Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. *Science* 333:988–993. <https://doi.org/10.1126/science.1201609>
- Phalan B, Onial M, Balmford A, Green RE (2011) Reconciling food production and biodiversity conservation: Land sharing and land sparing compared. *Science* 333:1289–1291. <https://doi.org/10.1126/science.1208742>
- Pinheiro JC, Bates DM (1995) *Mixed-Effects Models in S and S-PLUS*. Springer, New York, USA
- Poggio SL, Chaneton EJ, Ghersa CM (2013) The arable plant diversity of intensively managed farmland: Effects of field position and crop type at local and landscape scales. *Agriculture, Ecosystems & Environment* 166:55–64. <https://doi.org/10.1016/j.agee.2012.01.013>
- Pollnac FW, Maxwell D, Menalled FD (2009) Weed community characteristics and crop performance: a neighbourhood approach. *Weed Research* 49:242–250. <https://doi.org/10.1111/j.1365-3180.2009.00688.x>
- Puech C, Baudry J, Joannon A, Poggi S, Aviron S (2014) Organic vs. conventional farming dichotomy: Does it make sense for natural enemies? *Agriculture, Ecosystems & Environment* 194:48–57. <https://doi.org/10.1016/j.agee.2014.05.002>
- R Development Core Team (2014) *R: A Language and Environment for Statistical Computing*, Version 3.1.1. Foundation for Statistical Computing, Vienna, Austria, Retrieved from <http://www.R-project.org>. Accessed Dec 2014
- Romero A, Chamorro L, Sans FX (2008) Weed diversity in crop edges and inner fields of organic and conventional dryland winter cereal crops in NE Spain. *Agriculture, Ecosystems & Environment* 124:97–104. <https://doi.org/10.1016/j.agee.2007.08.002>
- Samedani B, Juraimi AS, Abdullah SAS, Rafii MY, Rahim AA, Anwar MP (2014) Effect of cover crops on weed community and oil palm yield. *International Journal of Agriculture & Biology* 16:23–31
- Schöb C, Kerle S, Karley AJ, Morcillo L, Pakeman RJ, Newton AC, Brooker RW (2015) Intraspecific genetic diversity and composition modify species-level diversity–productivity relationships. *New Phytologist*. 205:720–730. <https://doi.org/10.1111/nph.13043>

- Schroth G, D'Angelo SA, Teixeira WG, Haagd D, Lieberei R (2002) Conversion of secondary forest into agroforestry and monoculture plantations in Amazonia: consequences for biomass, litter and soil carbon stocks after 7 years. *Forest Ecology and Management* 163:131–150. [https://doi.org/10.1016/S0378-1127\(01\)00537-0](https://doi.org/10.1016/S0378-1127(01)00537-0)
- Silva MM, Candeias AL, Silva VOF, Carvalho RCO (2007) Family agriculture in Brazilian semi-arid. In: Gunkel G, Sobral MC (eds) *Reservoir and River Basin Management. Exchange of Experiences from Germany, Portugal and Brazil*. Technische Universität Berlin, Berlin, Germany, pp 227–238
- Sirrine JR, Letourneau DK, Shennan C, Sirrine D, Fouch R, Jackson L, Mages A (2008) Impacts of groundcover management systems on yield, leaf nutrients, weeds, and arthropods of tart cherry in Michigan, USA. *Agriculture, Ecosystems & Environment* 125:239–245. <https://doi.org/10.1016/j.agee.2008.01.005>
- Smith RG, Atwood LW, Warren ND (2014) Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. *PLoS ONE* 9:e97351. <https://doi.org/10.1371/journal.pone.0097351>
- Smith RG, Mortensen DA, Ryan MR (2009) A new hypothesis for the functional role of diversity in mediating resource pools and weed–crop competition in agroecosystems. *Weed Research* 50:37–48. <https://doi.org/10.1111/j.1365-3180.2009.00745.x>
- Solomou A, Sfougaris A (2011) Comparing conventional and organic olive groves in central Greece: plant and bird diversity and abundance. *Renewable Agriculture and Food Systems* 26:297–316. <https://doi.org/10.1017/S1742170511000111>
- Syswerda SP, Robertson GP (2014) Ecosystem services along a management gradient in Michigan (USA) cropping systems. *Agriculture, Ecosystems & Environment* 189:28–35. <https://doi.org/10.1016/j.agee.2014.03.006>
- Tilman D, Reich PB, Isbell F (2012) Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. *Proceedings of the National Academy of Sciences* 109:10394–10397. <https://doi.org/10.1073/pnas.1208240109>
- Venables WN, Ripley BD (2002) *Modern Applied Statistics with S*. (4th ed). Springer, New York, USA
- Wardle DA, Nilsson M-C, Gallet C, Zackrisson O (1998) An ecosystem-level perspective of allelopathy. *Biological Reviews* 73:305–319. <https://doi.org/10.1111/j.1469-185X.1998.tb00033.x>
- Zak DR, Holmes WE, White DC, Peacock AD, Tilman D (2003) Plant diversity, soil microbial communities and ecosystem function: Are there links? *Ecology* 84:2042–2050. <https://doi.org/10.1890/02-0433>
- Zimdahl RL (2007) *Fundamentals of weed science*. Academic Press, Elsevier, London, UK
- Zuidema PA, Leffelaar PA, Gerritsma W, Mommer L, Anten NP (2005) A physiological production model for cocoa (*Theobroma cacao*): model presentation, validation and application. *Agricultural Systems* 84:195–225. <https://doi.org/10.1016/j.agry.2004.06.015>
- Zuur A, Ieno EN, Walker N, Saveliev AA, Smith GM (2009) *Mixed effects models and extensions in ecology with R*. Springer, New York, USA

Appendix

Supplementary Material

Appendix 3.1 Weed species and their frequency in banana and coconut fields in northeastern Brazil.

| Plant family | Species | Frequency of occurrence (% of all plots) | |
|----------------|--|---|---------|
| | | Banana | Coconut |
| Amaranthaceae | <i>Amaranthus viridis</i> L. | 39 | 17 |
| Asteraceae | <i>Acanthospermum hispidum</i> DC. | 6 | 13 |
| | <i>Ageratum conyzoides</i> L. | 0 | 4 |
| | <i>Bidens pilosa</i> L. | 6 | 25 |
| | <i>Chromolaena odorata</i> (L.) R.M.King & H. Rob. | 0 | 4 |
| | <i>Conyza bonariensis</i> (L.) Cronq. | 0 | 33 |
| | <i>Eclipta prostrata</i> (L.) L. | 6 | 0 |
| | <i>Emilia sonchifolia</i> (L.) DC. ex Wight | 11 | 42 |
| | <i>Pluchea sagittalis</i> (Lam.) Cabrera | 0 | 4 |
| | <i>Porophyllum ruderale</i> (Jacq.) Cass. | 0 | 13 |
| | <i>Tridax procumbens</i> L. | 22 | 42 |
| | <i>Vernonia cinerea</i> (L.) Less. | 0 | 4 |
| Commelinaceae | <i>Commelina benghalensis</i> L. | 67 | 75 |
| | <i>Tripogandra diuretica</i> (Mart.) Handlos | 0 | 8 |
| Convolvulaceae | <i>Evolvulus frankenioides</i> Moric. | 39 | 33 |
| | <i>Ipomoea asarifolia</i> (Desr.) Roem. & Schult. | 28 | 17 |
| | <i>Merremia aegyptia</i> (L.) Urb. | 0 | 4 |
| Cucurbitaceae | <i>Citrullus lanatus</i> (Thunb.) Matsum. & Nakai | 6 | 0 |
| | <i>Momordica charantia</i> L. | 0 | 4 |
| Cyperaceae | <i>Cyperus compressus</i> L. | 6 | 21 |
| | <i>Cyperus distans</i> L. | 6 | 4 |
| | <i>Cyperus entrerianus</i> Boeck. | 6 | 4 |
| | <i>Cyperus laetus</i> J.Presl & C.Presl | 6 | 8 |
| Euphorbiaceae | <i>Croton</i> cf. <i>blanchetianus</i> Baill. | 0 | 8 |
| | <i>Croton heliotropiifolius</i> Kunth | 0 | 4 |
| | <i>Croton lobatus</i> L. | 6 | 4 |
| | <i>Euphorbia geniculata</i> Ortega | 28 | 21 |
| | <i>Euphorbia hirta</i> L. | 67 | 63 |
| | <i>Jatropha gossypifolia</i> L. | 6 | 13 |
| Fabaceae | <i>Aeschynomene biflora</i> (Mill.) Fawc. & Rendle | 0 | 25 |
| | <i>Chamaecrista pascuorum</i> (Benth.) H.S.Irwin & Barneby | 6 | 0 |
| | <i>Crotalaria pallida</i> Aiton | 0 | 13 |

| Plant family | Species | Frequency of occurrence (% of all plots) | |
|----------------|--|---|---------|
| | | Banana | Coconut |
| | <i>Crotalaria pilosa</i> Mill. | 0 | 8 |
| | <i>Desmodium incanum</i> (Sw.) DC. | 6 | 25 |
| | <i>Indigofera hirsuta</i> L. | 6 | 8 |
| | <i>Mimosa</i> sp. | 0 | 4 |
| | <i>Senna occidentalis</i> (L.) Link | 0 | 13 |
| | Fabaceae sp. 1 | 6 | 0 |
| | Fabaceae sp. 2 | 6 | 0 |
| | Fabaceae sp. 3 | 6 | 0 |
| | Fabaceae sp. 4 | 0 | 13 |
| Loganiaceae | <i>Spigelia anthelmia</i> L. | 0 | 4 |
| Malvaceae | <i>Herissantia crispa</i> (L.) Brizicky | 39 | 46 |
| | <i>Pavonia cancellata</i> (L.) Cav. | 0 | 8 |
| | <i>Pavonia</i> cf. <i>glazioviana</i> Gürke | 0 | 4 |
| | <i>Pavonia humifusa</i> A.St.-Hil. | 0 | 8 |
| | <i>Piriqueta guianensis</i> subsp. <i>elongata</i> (Urb.) Arbo | 6 | 0 |
| | <i>Pseudomalachra tuberculifera</i> H.Monteiro | 6 | 0 |
| | <i>Sida cordifolia</i> L. | 11 | 21 |
| | <i>Sida galheirensis</i> Ulbr. | 11 | 17 |
| | <i>Sida rhombifolia</i> L. | 0 | 8 |
| | <i>Sidastrum micranthum</i> (A.St.-Hil.) Fryxell | 0 | 4 |
| | <i>Waltheria rotundifolia</i> Schrank | 11 | 8 |
| Molluginaceae | <i>Mollugo verticillata</i> L. | 28 | 21 |
| Nyctaginaceae | <i>Boerhavia diffusa</i> L. | 22 | 13 |
| Phyllanthaceae | <i>Phyllanthus niruri</i> L. | 39 | 67 |
| Plantaginaceae | <i>Scoparia dulcis</i> L. | 11 | 21 |
| | <i>Stemodia maritima</i> L. | 6 | 13 |
| Poaceae | <i>Cenchrus ciliaris</i> L. | 17 | 0 |
| | <i>Cenchrus echinatus</i> L. | 67 | 54 |
| | <i>Dactyloctenium aegyptium</i> (L.) Willd. | 67 | 38 |
| | <i>Digitaria bicornis</i> (Lam.) Roem. & Schult. | 78 | 75 |
| | <i>Eragrostis</i> cf. <i>amabilis</i> (L.) Wight & Arn. | 44 | 63 |
| | <i>Eragrostis ciliaris</i> (L.) R.Br. | 6 | 0 |
| | <i>Melinis repens</i> (Willd.) Zizka | 11 | 17 |
| Portulacaceae | <i>Portulaca</i> sp. | 0 | 8 |
| | <i>Portulaca oleracea</i> L. | 33 | 0 |
| Rubiaceae | <i>Richardia grandiflora</i> (Cham. & Schltld.) Steud. | 28 | 25 |
| Turneraceae | <i>Turnera subulata</i> Sm. | 0 | 13 |

| Plant family | Species | Frequency of occurrence (% of all plots) | |
|--------------|-----------------|---|---------|
| | | Banana | Coconut |
| - | Morphospecies 1 | 6 | 0 |
| - | Morphospecies 2 | 6 | 13 |
| - | Morphospecies 3 | 0 | 4 |
| - | Morphospecies 4 | 0 | 8 |
| - | Morphospecies 5 | 0 | 8 |
| - | Morphospecies 6 | 6 | 0 |
| - | Morphospecies 7 | 11 | 17 |
| - | Morphospecies 8 | 6 | 0 |

Appendix 3.2 Model documentation.

GLMM for yield

```
> model1<-glmer(Yield~Richness+Crop species+(1|Field),
family="poisson")
> summary(model1)
Generalized linear mixed model fit by maximum likelihood
(Laplace
Approximation) [glmerMod]
Family: poisson ( log )
Formula: Yield ~ Richness + Crop species + (1 | Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 494.4 | 498.6 | -243.2 | 486.4 | 17 |

Scaled residuals:

| Min | 1Q | Median | 3Q | Max |
|-----------|-----------|----------|----------|----------|
| -0.052062 | -0.006178 | 0.002193 | 0.003892 | 0.009457 |

Random effects:

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.4634 | 0.6807 |

Number of obs: 21, groups: Field, 21

Fixed effects:

| | Estimate | Std. Error | z value | Pr(> z) |
|--------------|----------|------------|---------|-------------|
| (Intercept) | 9.55958 | 0.57704 | 16.567 | < 2e-16 *** |
| Richness | 0.04141 | 0.05026 | 0.824 | 0.40998 |
| Crop species | 0.85994 | 0.32516 | 2.645 | 0.00818 ** |

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

| | (Intr) Richness |
|--------------|-----------------|
| Richness | -0.919 |
| Crop species | 0.079 -0.384 |

```
> model2<-glmer(Yield~Shannon+Crop species+(1|Field),
family="poisson")
> summary(model2)
Generalized linear mixed model fit by maximum likelihood
(Laplace
Approximation) [glmerMod]
Family: poisson ( log )
Formula: Yield ~ Shannon + Crop species + (1 | Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 491.5 | 495.7 | -241.8 | 483.5 | 17 |

Scaled residuals:

| Min | 1Q | Median | 3Q | Max |
|-----------|-----------|----------|----------|----------|
| -0.039107 | -0.004890 | 0.001177 | 0.003435 | 0.009727 |

Random effects:

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.4042 | 0.6358 |

Number of obs: 21, groups: Field, 21

Fixed effects:

| | Estimate | Std. Error | z value | Pr(> z) |
|--------------|----------|------------|---------|-------------|
| (Intercept) | 8.9028 | 0.5963 | 14.929 | < 2e-16 *** |
| Shannon | 0.6175 | 0.3146 | 1.963 | 0.04968 * |
| Crop species | 0.8183 | 0.2899 | 2.823 | 0.00476 ** |

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

| | (Intr) Shannon |
|--------------|----------------|
| Shannon | -0.935 |
| Crop species | -0.022 -0.254 |

```
> model3<-glmer(Yield~Arcsin Simpson+Crop
species+(1|Field), family="poisson")
> summary(model3)
Generalized linear mixed model fit by maximum likelihood
(Laplace
Approximation) [glmerMod]
Family: poisson ( log )
Formula: Yield ~ Arcsin Simpson + Crop species + (1 | Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 491.3 | 495.5 | -241.6 | 483.3 | 17 |

Scaled residuals:

| Min | 1Q | Median | 3Q | Max |
|-----------|-----------|----------|----------|----------|
| -0.037831 | -0.003003 | 0.000265 | 0.003653 | 0.010061 |

Random effects:

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.3992 | 0.6318 |

Number of obs: 21, groups: Field, 21

Fixed effects:

| | Estimate | Std. Error | z value | Pr(> z) |
|----------------|----------|------------|---------|-------------|
| (Intercept) | 8.9319 | 0.5626 | 15.877 | < 2e-16 *** |
| Arcsin Simpson | 1.2720 | 0.6231 | 2.041 | 0.04122 * |
| Crop species | 0.8365 | 0.2854 | 2.931 | 0.00338 ** |

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

| | (Intr) Arcsin Simpson |
|----------------|-----------------------|
| Arcsin Simpson | -0.927 |
| Crop species | -0.075 -0.217 |

```
> model4<-glmer(Yield~Arcsin Evenness+Crop
species+(1|Field), family="poisson")
```

```
> summary(model4)
```

```
Generalized linear mixed model fit by maximum likelihood
(Laplace
```

```
Approximation) [glmerMod]
```

```
Family: poisson ( log )
```

```
Formula: Yield ~ Arcsin Evenness + Crop species + (1 | Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 491.5 | 495.7 | -241.7 | 483.5 | 17 |

```
Scaled residuals:
```

| Min | 1Q | Median | 3Q | Max |
|-----------|-----------|----------|----------|----------|
| -0.038390 | -0.003066 | 0.000315 | 0.005215 | 0.009797 |

```
Random effects:
```

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.4031 | 0.6349 |

```
Field (Intercept) 0.4031 0.6349
```

```
Number of obs: 21, groups: Field, 21
```

```
Fixed effects:
```

| | Estimate | Std. Error | z value | Pr(> z) |
|-----------------|----------|------------|---------|--------------|
| (Intercept) | 8.9842 | 0.5534 | 16.234 | < 2e-16 *** |
| Arcsin Evenness | 1.5540 | 0.7848 | 1.980 | 0.047685 * |
| Crop species | 0.9742 | 0.2800 | 3.479 | 0.000504 *** |

```
---
```

```
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Correlation of Fixed Effects:
```

| | (Intr) Arcsin Evenness |
|-----------------|------------------------|
| Arcsin Evenness | -0.924 |
| Crop species | -0.308 0.020 |

```
> model5<-glmer(Yield~Crop biomass+Crop species+(1|
Field), family="poisson")
```

```
> summary(model5)
```

```
Generalized linear mixed model fit by maximum likelihood
(Laplace
```

```
Approximation) [glmerMod]
```

```
Family: poisson ( log )
```

```
Formula: Yield ~ Crop biomass + Crop species + (1 | Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 486.7 | 490.9 | -239.4 | 478.7 | 17 |

```
Scaled residuals:
```

| Min | 1Q | Median | 3Q | Max |
|-----------|-----------|----------|----------|----------|
| -0.053187 | -0.007331 | 0.003256 | 0.004628 | 0.013391 |

```
Random effects:
```

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.321 | 0.5666 |

```
Field (Intercept) 0.321 0.5666
```

```
Number of obs: 21, groups: Field, 21
```

```
Fixed effects:
```

| | Estimate | Std. Error | z value | Pr(> z) |
|--------------|----------|------------|---------|--------------|
| (Intercept) | 9.060613 | 0.347585 | 26.067 | < 2e-16 *** |
| Crop biomass | 0.015405 | 0.004801 | 3.208 | 0.00134 ** |
| Crop species | 1.504106 | 0.301480 | 4.989 | 6.07e-07 *** |

```
---
```

```
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Correlation of Fixed Effects:
```

| | (Intr) Crop biomass |
|--------------|---------------------|
| Crop biomass | -0.839 |
| Crop species | -0.810 0.560 |

```
> model6<-glmer(Yield~Weed biomass+Crop species+(1|
Field), family="poisson")
```

```
> summary(model6)
```

```
Generalized linear mixed model fit by maximum likelihood
(Laplace
```

```
Approximation) [glmerMod]
```

```
Family: poisson ( log )
```

```
Formula: Yield ~ Weed biomass + Crop species + (1 | Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 491.0 | 495.2 | -241.5 | 483.0 | 17 |

```
Scaled residuals:
```

| Min | 1Q | Median | 3Q | Max |
|-----------|-----------|----------|----------|----------|
| -0.039041 | -0.002067 | 0.001019 | 0.004869 | 0.009770 |

```
Random effects:
```

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.3942 | 0.6279 |

```
Field (Intercept) 0.3942 0.6279
```

```
Number of obs: 21, groups: Field, 21
```

```
Fixed effects:
```

| | Estimate | Std. Error | z value | Pr(> z) |
|--------------|----------|------------|---------|--------------|
| (Intercept) | 10.54918 | 0.33449 | 31.538 | < 2e-16 *** |
| Weed biomass | -0.01228 | 0.00580 | -2.117 | 0.034226 * |
| Crop species | 0.94654 | 0.27699 | 3.417 | 0.000633 *** |

```
---
```

```
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Correlation of Fixed Effects:
```

| | (Intr) Weed biomass |
|--------------|---------------------|
| Weed biomass | -0.780 |
| Crop species | -0.495 0.028 |

```
> model7<-glmer(Yield~Fertilizer+Crop species+(1|Field),
family="poisson")
> summary(model7)
Generalized linear mixed model fit by maximum likelihood
(Laplace)
Approximation [glmerMod]
Family: poisson ( log )
Formula: Yield ~ Fertilizer + Crop species + (1 | Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 468.1 | 473.1 | -229.0 | 458.1 | 15 |

Scaled residuals:

| Min | 1Q | Median | 3Q | Max |
|-----------|-----------|----------|----------|----------|
| -0.035468 | -0.006254 | 0.001292 | 0.002938 | 0.015738 |

Random effects:

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.375 | 0.6123 |

Number of obs: 20, groups: Field, 20

Fixed effects:

| | Estimate | Std. Error | z value | Pr(> z) |
|--------------------|----------|------------|---------|-------------|
| (Intercept) | 9.2251 | 0.3660 | 25.202 | < 2e-16 *** |
| Fertilizer organic | 1.1274 | 0.4825 | 2.337 | 0.01945 * |
| Fertilizer mixed | 0.9694 | 0.3966 | 2.445 | 0.01450 * |
| Crop species | 0.8052 | 0.2841 | 2.835 | 0.00459 ** |

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

| | (Intr) Fertilizer organic | Fertilizer mixed | Crop species |
|--------------------|---------------------------|------------------|--------------|
| Fertilizer organic | -0.644 | | |
| Fertilizer mixed | -0.823 | 0.689 | |
| Crop species | -0.259 | -0.245 | -0.147 |

```
> model8<-glmer(Yield~Fertilizer+Crop
species+Shannon+(1|Field), family="poisson")
> summary(model8)
Generalized linear mixed model fit by maximum likelihood
(Laplace)
Approximation [glmerMod]
Family: poisson ( log )
Formula: Yield ~ Fertilizer + Crop species + Shannon + (1 |
Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 467.3 | 473.3 | -227.7 | 455.3 | 14 |

Scaled residuals:

| Min | 1Q | Median | 3Q | Max |
|-------------|------------|------------|-----------|-----------|
| -0.03144435 | -0.0061200 | -0.0001304 | 0.0042542 | 0.0119263 |

Random effects:

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.3264 | 0.5714 |

Number of obs: 20, groups: Field, 20

Fixed effects:

| | Estimate | Std. Error | z value | Pr(> z) |
|--------------------|----------|------------|---------|-------------|
| (Intercept) | 8.3913 | 0.5921 | 14.171 | < 2e-16 *** |
| Fertilizer organic | 1.0548 | 0.4521 | 2.333 | 0.01966 * |
| Fertilizer mixed | 0.7224 | 0.3968 | 1.820 | 0.06869 . |
| Crop species | 0.7098 | 0.2708 | 2.622 | 0.00875 ** |
| Shannon | 0.5681 | 0.3296 | 1.724 | 0.08473 . |

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

| | (Intr) Fertilizer organic | Fertilizer mixed | Crop species | Shannon |
|--------------------|---------------------------|------------------|--------------|---------|
| Fertilizer organic | -0.294 | | | |
| Fertilizer mixed | -0.148 | 0.674 | | |
| Crop species | 0.021 | -0.220 | -0.060 | |
| Shannon | -0.817 | -0.093 | -0.361 | -0.204 |

```
> model9<-glmer(Yield~Fertilizer+Crop species+Arcsin
Simpson+(1|Field), family="poisson")
> summary(model9)
Generalized linear mixed model fit by maximum likelihood
(Laplace)
Approximation [glmerMod]
Family: poisson ( log )
Formula: Yield ~ Fertilizer + Crop species + Arcsin Simpson +
(1 | Field)
```

| AIC | BIC | logLik | deviance | df.resid |
|-------|-------|--------|----------|----------|
| 467.5 | 473.5 | -227.8 | 455.5 | 14 |

Scaled residuals:

| Min | 1Q | Median | 3Q | Max |
|-----------|-----------|----------|----------|----------|
| -0.032396 | -0.004806 | 0.000448 | 0.004442 | 0.010768 |

Random effects:

| Groups | Name | Variance | Std.Dev. |
|--------|-------------|----------|----------|
| Field | (Intercept) | 0.3298 | 0.5743 |

Number of obs: 20, groups: Field, 20

Fixed effects:

| | Estimate | Std. Error | z value | Pr(> z) |
|--------------------|----------|------------|---------|-------------|
| (Intercept) | 8.5128 | 0.5505 | 15.462 | < 2e-16 *** |
| Fertilizer organic | 1.0293 | 0.4563 | 2.256 | 0.02409 * |
| Fertilizer mixed | 0.7158 | 0.4022 | 1.780 | 0.07514 . |
| Crop species | 0.7306 | 0.2702 | 2.704 | 0.00685 ** |
| Arcsin Simpson | 1.0660 | 0.6440 | 1.655 | 0.09788 . |

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

| | (Intr) Fertilizer organic | Fertilizer mixed | Crop species | Arcsin Simpson |
|--------------------|---------------------------|------------------|--------------|----------------|
| Fertilizer organic | -0.297 | | | |
| Fertilizer mixed | -0.177 | 0.682 | | |
| Crop species | -0.029 | -0.218 | -0.070 | |
| Arcsin Simpson | -0.782 | -0.130 | -0.381 | -0.167 |

GLMM for biodiversity and biomass

```
> model10<-glmer(Richness~Edge-center+(1|Field),
family="poisson")
> summary(model10)
Generalized linear mixed model fit by maximum likelihood
(Laplace
Approximation) [glmerMod]
Family: poisson ( log )
Formula: Richness ~ Edge-center + (1 | Field)

      AIC      BIC    logLik deviance df.resid
 231.5   236.7  -112.8   225.5     39

Scaled residuals:
   Min     1Q  Median     3Q      Max
-2.01295 -0.53515  0.05642  0.39773  2.36949

Random effects:
 Groups Name      Variance Std.Dev.
Field (Intercept) 0.02763  0.1662
Number of obs: 42, groups: Field, 21

Fixed effects:
      Estimate Std. Error z value Pr(>|z|)
(Intercept) 2.31683   0.07759  29.86 < 2e-16 ***
Edge      0.28421   0.08993   3.16  0.00158 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
      (Intr)
Edge -0.661
```

```
> model11<-lme(Shannon~Edge-center,random=~1|Field/
Edge-center)
> summary(model11)
Linear mixed-effects model fit by REML
Data: NULL
      AIC      BIC    logLik
 86.84161  95.28601 -38.42081

Random effects:
Formula: ~1 | Field
      (Intercept)
StdDev: 0.2887866

Formula: ~1 | Edge-center %in% Field
      (Intercept) Residual
StdDev: 0.4897108 0.1734923

Fixed effects: Shannon ~ Edge-center
      Value Std.Error DF  t-value p-value
(Intercept) 1.7524286 0.1297092 20 13.510443 0.0000
Edge      0.3061429 0.1603319 20  1.909432 0.0707
Correlation:
      (Intr)
Edge -0.618

Standardized Within-Group Residuals:
      Min      Q1      Med      Q3      Max
-0.70976937 -0.19846790  0.05576828  0.21610973
0.51419317

Number of Observations: 42
Number of Groups:
      Field Edge-center %in% Field
      21          42
```

```
> model12<-lme(Arcsin Simpson~Weed
biomass,random=~1|Field/Edge-center)
> summary(model12)
Linear mixed-effects model fit by REML
Data: NULL
      AIC      BIC    logLik
 26.81983  35.26423 -8.409915

Random effects:
Formula: ~1 | Field
      (Intercept)
StdDev: 0.09331884

Formula: ~1 | Edge-center %in% Field
      (Intercept) Residual
StdDev: 0.2234729 0.07026592

Fixed effects: Arcsin Simpson ~ Weed biomass
      Value Std.Error DF  t-value p-value
(Intercept) 1.1078784 0.07663649 20 14.456277 0.0000
Weed biomass -0.0045121 0.00145682 20 -3.097206
0.0057
Correlation:
      (Intr)
Weed biomass -0.841

Standardized Within-Group Residuals:
      Min      Q1      Med      Q3      Max
-0.72591980 -0.20870658  0.04567165  0.21898079
0.42810498

Number of Observations: 42
Number of Groups:
      Field Edge-center %in% Field
      21          42
```

```

> model13<-lme(Arcsin Evenness~Weed
biomass,random=~1|Field/Edge-center)
> summary(model13)
Linear mixed-effects model fit by REML
Data: NULL
      AIC   BIC logLik
16.83415 25.27854 -3.417073

Random effects:
Formula: ~1 | Field
(Intercept)
StdDev: 0.08786642

Formula: ~1 | Edge-center %in% Field
(Intercept) Residual
StdDev: 0.1949752 0.0630128

Fixed effects: Arcsin Evenness ~ Weed biomass
      Value Std.Error DF  t-value p-value
(Intercept) 0.9814796 0.06801874 20 14.429547 0e+00
Weed biomass -0.0056023 0.00129075 20 -4.340312 3e-04
Correlation:
(Intr)
Weed biomass -0.839

Standardized Within-Group Residuals:
      Min      Q1      Med      Q3      Max
-0.67520168 -0.16636789 0.01616481 0.20420023
0.56439125

Number of Observations: 42
Number of Groups:
      Field Edge-center %in% Field
      21      42

```

```

> model14<-lme(Weed biomass~LAI,random=~1|Field)
> summary(model14)
Linear mixed-effects model fit by REML
Data: NULL
      AIC   BIC logLik
373.5597 380.3152 -182.7798

Random effects:
Formula: ~1 | Field
(Intercept) Residual
StdDev: 17.126 16.1117

Fixed effects: Weed biomass ~ LAI
      Value Std.Error DF  t-value p-value
(Intercept) 92.81454 12.092184 20 7.675581 0e+00
LAI -21.96111 5.075352 20 -4.327012 3e-04
Correlation:
(Intr)
LAI -0.929

Standardized Within-Group Residuals:
      Min      Q1      Med      Q3      Max
-1.9106976 -0.5683453 -0.0345045 0.5117976 1.6905431

Number of Observations: 42
Number of Groups: 21

```

```

> model1<-glmer(Biomass crop~Crop species+(1|Field),
family="poisson")
> summary(model1)
Generalized linear mixed model fit by maximum likelihood
(Laplace
Approximation) [glmerMod]
Family: poisson ( log )
Formula: Biomass crop ~ Crop species + (1 | Field)

      AIC   BIC logLik deviance df.resid
183.3 186.4 -88.6 177.3 18

Scaled residuals:
      Min      1Q  Median      3Q      Max
-0.56131 -0.22215 -0.08458 0.21416 0.46996

Random effects:
Groups Name Variance Std.Dev.
Field (Intercept) 0.225 0.4743
Number of obs: 21, groups: Field, 21

Fixed effects:
      Estimate Std. Error z value Pr(>|z|)
(Intercept) 3.9477 0.1656 23.834 < 2e-16 ***
Crop species -0.7873 0.2230 -3.531 0.000415 ***
---
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
(Intr)
Crop species -0.741

```

Appendix 3.3 Plots_Cierjacks et al.kml
(data not shown; see online version of the article:
<https://doi.org/10.1016/j.agee.2016.01.006>)



CHAPTER 4

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

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 (Hurtt 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 & 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 & 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 & 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 openings that may affect the subsequent vegetation structure.

Although numerous studies have analysed the impact of grazing on carbon stock dynamics (e.g., Nosoetto et al. 2006), it is crucial to assess different grazing intensities to disentangle the underlying mechanisms and to guide appropriate land-use decisions (Bailey & Brown 2011; Cierjacks & 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 (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 north-east and the south-east. 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 & 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 pyrifolium* Mart. (pereiro) were the most abundant tree species in our study area. In total, we found 61 woody species of which at least nine are known to be unpalatable for livestock (see Appendix 4.1 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 nearest farmhouse 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 & 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 & 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 × 20 m²) 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 plot overall) to obtain a balanced study design and a more or less even plot distribution across the study area (see Appendix 4.2 for plot distribution across the study area and Appendix 4.3 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 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 & Silva (2005). For all individuals with a diameter at ground level (DGL) $> 3 \text{ cm}$, we measured the circumference at ground level (Sampaio & Silva 2005). When branch-

ing occurred, all branches were measured individually even if the DGL of the particular branch was < 3 cm (Sampaio & 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 & 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 & 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 & Silva (2005; see Appendix 4.4 for equations). For bromeliads, the mean weight per rosette was calculated, which proved to be an easy and precise method (see Appendix 4.4). 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 & Harmon 1995; Peichl & 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 & Silva (2005) stated that, for individuals with DGL > 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 be-

cause 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 $15.74 \pm 1.92 \text{ Mg ha}^{-1}$. Trees and shrubs (including emergent trees) contributed 89% to the total carbon stocks (Table 4.1). 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 (Appendix 4.5). *P. pyramidalis*, *P. microphylla*, and *A. pyriformium* were the most abundant tree species. They contributed 60% to the total carbon stocks (Table 4.1) and represented 75% of the individual trees and shrubs (only individuals with DGL > 3 cm) in the study area (see also Appendix 4.5).

Table 4.1 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 shrub 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>P.</i> <i>pyramidalis</i> , <i>P. microphylla</i> , and <i>Aspidosperma</i> <i>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.</i> <i>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 |
| Tree/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 |

Aboveground carbon stocks related to grazing

Carbon stocks of herbaceous plant species after the first sufficient rainfall were significantly negatively affected by grazing intensity (Figure 4.1). In contrast, we found no evidence of grazing impacts on carbon stocks overall or on any other plant type studied. Also, mean carbon stock per tree/shrub individual was not significantly related to grazing intensity (see Table 4.1).

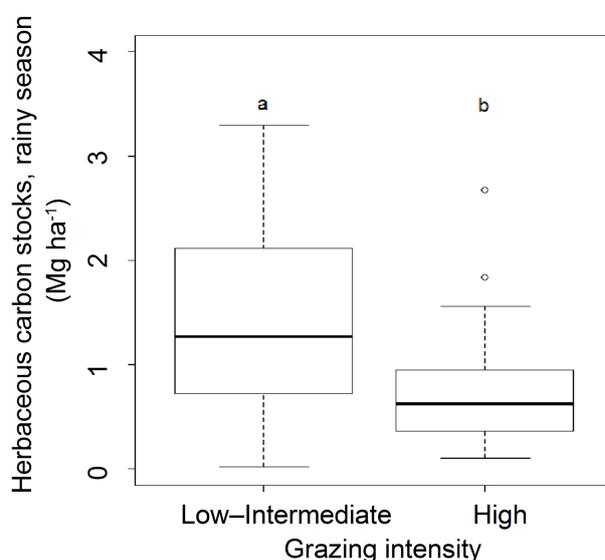


Figure 4.1 Carbon stocks of the herbaceous layer of Caatinga forest during the rainy season at different grazing intensities. Different lowercase letters indicate significant differences (GLM, p grazing = 0.0285).

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 Appendix 4.5).

The total density of the most abundant tree species was not affected by grazing intensity (Appendix 4.5). They also showed a large number of individuals in the

smallest diameter classes, which indicates sufficient recruitment in the *Poincianella* species and *A. pyriformis* irrespective of grazing (Figure 4.2; Appendix 4.5). Accordingly, we found no significant differences in the number of individuals in the smallest diameter classes (> 0–3 cm and > 3–10 cm; Appendix 4.5) 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 *A. pyriformis* (Appendix 4.5).

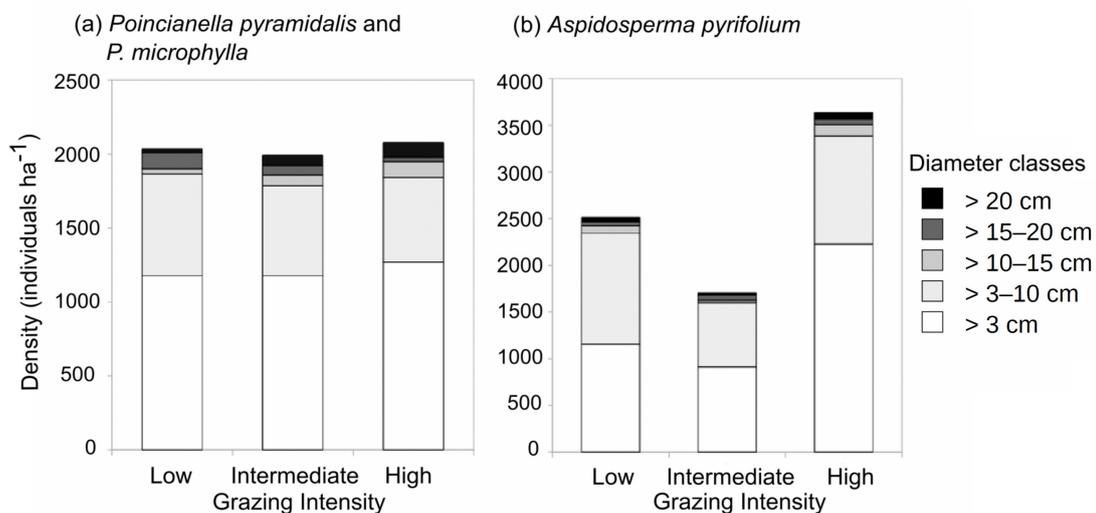


Figure 4.2 Population structure (diameter classes) of the most important tree species (a) *Poincianella pyramidalis* and *P. microphylla*, and (b) *Aspidosperma pyriformis* at different grazing intensities. The diameter class '> 20 cm' includes trees with a diameter at ground level up to 76 cm.

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 (Figure 4.3). 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, DGL > 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.

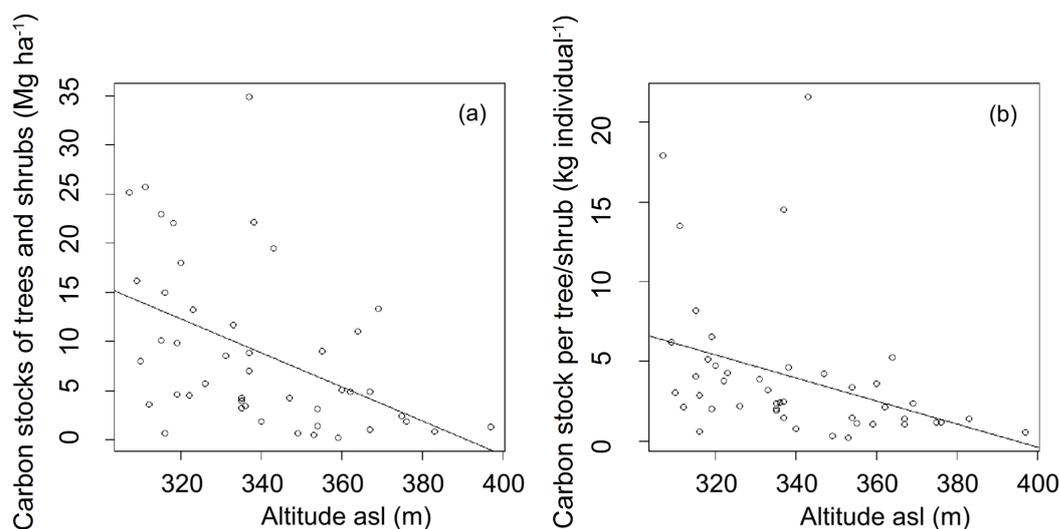


Figure 4.3 (a) Carbon stocks of trees and shrubs (without emergent trees; GLM, p altitude = 0.0014). (b) Carbon stocks per tree/shrub individual (without emergent trees; GLM, p altitude = 0.0151) in Caatinga vegetation at different altitudes.

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 > 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 Appendix 4.6), 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 & Costa 2011; Tiessen et al. 1998), but comparable or even higher than in other areas (e.g., Rodal et al. 2008; Santana & Souto 2006; see Appendix 4.6). 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 (Appendix 4.6). 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 (Appendix 4.6).

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 & Maleček 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 & Maleček 1986), and most of the foliage is consumed during the dry season as litter (Araújo Filho et al. 1998; Araújo Filho 2013; Pfister & Maleček 1986) with no direct effect on trees. Goats also feed on the bark of trees or cacti (Araújo 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 graz-

ing intensities were often located at low elevations and often in the vicinity of the lake—areas that are expected to have easily accessible ground water. A higher nutrient input (manure) may additionally enhance plant growth.

Fruits and flowers are also important food sources (Pfister & Malecek 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 & Malecek 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 & 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; Figure 4.2), a lower number of emergent trees, and a higher number of trees with DGL > 3 cm (without emergent trees; Appendix 4.5). 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, farm-

ers, and residents supports this view. Still, this assumption is substantiated by the fact that in degraded areas scattered exceptionally large individuals of *A. pyrifolium* 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. pyrifolium* is low due to their low palatability. *A. pyrifolium* is generally not a forage species, e.g., causing abortions in goats (Souza Lima & 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 above-ground 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 (Figure 4.3). 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 (Silva et al. 2014; Revermann et al. 2016), and soil characteristics (Navar et al. 2014; Scheffer & Schachtschabel 2010). We assume a higher water availability at lower elevations caused by a reduced distance to ground water (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. Addition-

ally, 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 (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 pyrifolium*). 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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Electronic supplementary material

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References

- Aide TM, Clark ML, Grau HR, López-Carr D, Levy MA, Redo D, Bonilla-Moheno M, Riner G, Andrade-Núñez MJ, Muñiz M (2012) Deforestation and reforestation of Latin America and the Caribbean (2001–2010) *Biotropica* 45:262–271. <https://doi.org/10.1111/j.1744-7429.2012.00908.x>
- Albuquerque UPD, Andrade LDHC, Silva ACOD (2005) Use of plant resources in a seasonal dry forest (Northeastern Brazil). *Acta Botanica Brasilica* 19:27–38
- Albuquerque SGD, Soares JGG, Guimarães Filho C (2008) Effect of grazing by steers and a long drought on a caatinga ligneous stratum in semi-arid northeast, Brazil. *Revista Caatinga* 21:17–28
- Allen VG, Batello C, Berretta EJ, Hodgson J, Kothmann M, Li X, McIvor J, Milne J, Morris C, Peeters A, Sanderson M (2011) An international terminology for grazing lands and grazing animals. *Grass and Forage Science* 66:2–28. <https://doi.org/10.1111/j.1365-2494.2010.00780.x>
- Althoff TD, Menezes RSC, de Carvalho AL, de Siqueira Pinto A, Santiago GACF, Ometto JPHB, von Randow C, Sampaio EVSB (2016) Climate change impacts on the sustainability of the firewood harvest and vegetation and soil carbon stocks in a tropical dry forest in Santa Teresinha Municipality, Northeast Brazil. *Forest Ecology and Management* 360:367–375. <https://doi.org/10.1016/j.foreco.2015.10.001>
- Alves JJA, de Araújo MA, do Nascimento SS (2009) Degradação da Caatinga: uma investigação ecogeográfica. *Revista Caatinga* 22:126–135
- Amorim IL, Sampaio EVSB, de Lima Araújo E (2005) Flora e estrutura da vegetação arbustivo-arbórea de uma área de caatinga do Seridó, RN, Brasil. *Acta Botanica Brasilica* 19:615–623
- Araújo-Filho JA (2013) Tecnologias de manejo pastoril da Caatinga. In: Araújo-Filho JA (ed) *Manejo pastoril sustentável da caatinga*. Projeto Dom Helder Camara, Recife, Brazil, pp 119–144
- Araújo Filho JAD, Leite ER, Silva ND (1998) Contribution of woody species to the diet composition of goat and sheep in Caatinga vegetation. *Pasture Tropicalis* 20:41–45
- Araujo KD, Dantas RT, de Andrade AP, Parente HN, Éllens ÉS (2010) Uso de espécies da Caatinga na alimentação de rebanhos município de São João do Cariri – PB. *Raega-O Espaço Geográfico em Análise* 20:157–171. <https://doi.org/10.5380/raega.v20i0.20619>
- Bailey DW, Brown JR (2011) Rotational grazing systems and livestock grazing behavior in shrub-dominated semi-arid and arid rangelands. *Rangeland Ecology & Management* 64:1–9. <https://doi.org/10.2111/REM-D-09-00184.1>

- Bergmeier E, Petermann J, Schröder E (2010) Geobotanical survey of wood-pasture habitats in Europe: diversity, threats and conservation. *Biodiversity and Conservation* 19. <https://doi.org/10.1007/s10531-010-9872-3>
- Braga BPF, Gondim Filho JGC, Sugai MRVB, Costa SV, Rodrigues V (2012) Impacts of Sobradinho Dam, Brazil. In: Tortajada C, Altinbilek D, Biswas AK (eds) *Impacts of large dams. A global assessment*, Springer Berlin, Berlin, Germany, pp 153–170
- Cierjacks A, Hensen I (2004) Variation of stand structure and regeneration of Mediterranean holm oak along a grazing intensity gradient. *Plant Ecology* 173:215–223. <https://doi.org/10.1023/B:VEGE.0000029322.75004.ad>
- Cierjacks A, Rühr NK, Wesche K, Hensen I (2008) Effects of altitude and livestock on the regeneration of two tree line forming *Polylepis* species in Ecuador. *Plant Ecology* 194:207–221. <https://doi.org/10.1007/s11258-007-9285-x>
- Cierjacks A, Kleinschmit B, Babinsky M, Kleinschroth F, Markert A, Menzel M, Ziechmann U, Schiller T, Graf M, Lang F (2010) Carbon stocks of soil and vegetation on Danubian floodplains. *Journal of Plant Nutrition and Soil Science* 173:644–653. <https://doi.org/10.1002/jpln.200900209>
- Cierjacks A, Pommeranz M, Schulz K, Almeida-Cortez JS (2016) Is crop yield related to weed species diversity and biomass in coconut and banana fields of northeastern Brazil? *Agriculture, Ecosystems & Environment* 220:175–183. <https://doi.org/10.1016/j.agee.2016.01.006>
- Crawley MJ (2007) *The R book* (1st ed). John Wiley & Sons, Chichester, UK
- da Silva FKG, de Faria Lopes S, Lopez LCS, de Melo JIM, Trovão DMDBM (2014) Patterns of species richness and conservation in the Caatinga along elevational gradients in a semiarid ecosystem. *Journal of Arid Environments* 110:47–52. <https://doi.org/10.1016/j.jaridenv.2014.05.011>
- Embrapa–Empresa Brasileira de Pesquisa Agropecuária Ministério da Agricultura, Pecuária e Abastecimento (2001a) Mapa Exploratório-Reconhecimento de solos do município de Floresta, PE. Retrieved from <http://www.uep.cnps.embrapa.br/solos/pe/floresta.pdf>. Accessed Oct 2013
- Embrapa–Empresa Brasileira de Pesquisa Agropecuária Ministério da Agricultura, Pecuária e Abastecimento (2001b) Mapa Exploratório-Reconhecimento de solos do município de Itacuruba, PE. Retrieved from <http://www.uep.cnps.embrapa.br/solos/pe/itacuruba.pdf>. Accessed Oct 2013
- FAO–Food and Agriculture Organization of the United Nations (2001) *Lecture notes on the major soils of the world*. Driessen P, Deckers J, Spaargaren O, Nachtergaele F (eds). Retrieved from <http://www.fao.org/3/a-y1899e.pdf>. Accessed Sep 2016
- Fleming GM, Wunderle Jr JM, Ewert DN (2016) Diet preferences of goats in a subtropical dry forest and implications for habitat management. *Tropical Ecology* 57:279–297
- Freitas ADS, Sampaio EVSB, Silva BLR, Almeida Cortez JS, Menezes RSC (2012) How much nitrogen is fixed by biological symbiosis in tropical dry forests? 2. Herbs. *Nutrient Cycling in Agroecosystems* 94:181–192. <https://doi.org/10.1007/s10705-012-9545-6>
- González-Pech PG, Jesús Torres-Acosta JF, Sandoval-Castro CA, Tun-Garrido J (2015) Feeding behavior of sheep and goats in a deciduous tropical forest during the dry

- season: The same menu consumed differently. *Small Ruminant Research* 133:128–134. <https://doi.org/10.1016/j.smallrumres.2015.08.020>
- Google Earth (2013) Version 7.1.2.2041. Retrieved from <http://www.google.com/earth>. Accessed Oct 2013
- Hagel H, Hoffmann C, Doluschitz R (2014) Mathematical programming models to increase land and water use efficiency in semi-arid NE-Brazil. *International Journal on Food System Dynamics* 5:173–181. <https://doi.org/10.18461/ijfsd.v5i4.542>
- Hurtt GC, Chini LP, Frolking S, Betts RA, Feddema J, Fischer G, Fisk JP, Hibbard K, Houghton RA, Janetos A, Jones CD, Kindermann G, Kinoshita T, Klein Goldewijk K, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, van Vuuren DP, Wang YP (2011) Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic Change* 109:117–161. <https://doi.org/10.1007/s10584-011-0153-2>
- Ibáñez J, Martínez J, Schnabel S (2007) Desertification due to overgrazing in a dynamic commercial livestock–grass–soil system. *Ecological Modelling* 205:277–288. <https://doi.org/10.1016/j.ecolmodel.2007.02.024>
- Junior FTA, Ferreira RLC, Marangon LC, Silva JAA, Gutiérrez-Céspedes HG (2013) Structure evaluation of the Caatinga vegetation for sustainable forest management in the municipality of Floresta, Pernambuco, Brazil. In: Gunkel G, Silva JAA, Sobral MC (eds) *Sustainable management of water and land in semiarid areas*, Editora Universitária UFPE, Recife, Brazil, pp 186–202
- Kauffman JB, Sanford RL, Cummings DL, Salcedo IH, Sampaio EVSB (1993) Biomass and nutrient dynamics associated with slash fires in neotropical dry forests. *Ecology* 74:140–151. <https://doi.org/10.2307/1939509>
- Kengen S, Pareyn F, Barcellos NDE, Campello FCB (2000) Forest management in a semi-arid region in Brazil: a case study of the state of Rio Grande do Norte. In: Dore MHI, Guevara R (eds) *Sustainable Forest Management and Global Climate Change: Selected Case Studies from the Americas*, Edward Elgar Pub, Cheltenham, UK, pp 261–269
- Köhl M, Lasco R, Cifuentes M, Jonsson Ö, Korhonen KT, Mundhenk P, Navar JJ, Stinson G (2015) Changes in forest production, biomass and carbon: Results from the 2015 UN FAO Global Forest Resource Assessment. *Forest Ecology and Management* 352:21–34. <https://doi.org/10.1016/j.foreco.2015.05.036>
- Krankina ON, Harmon ME (1995) Dynamics of the dead wood carbon pool in northwestern Russian boreal forests. In: Apps MJ, Price D, Wisniewski J (eds) *Boreal forests and global change*, Springer, Dordrecht, Netherlands, pp 227–238. https://doi.org/10.1007/978-94-017-0942-2_24
- Kyriazopoulos AP, Sklavou P, Nastis AS, Papanastasis VP (2009) Interactions between grazing behaviour and plant community structure in shrubland and their consequences on desertification. In: Papachristou TG, Parissi ZM, Ben Salem H, Morand-Fehr P (eds) *Nutritional and foraging ecology of sheep and goats, Zaragoza: CIHEAM / FAO / NAGREF (Options Méditerranéennes: Série A. Séminaires Méditerranéens; n. 85)*, pp 91–97

- Leal IR, da Silva JMC, Tabarelli M, Lacher TE (2005) Changing the course of biodiversity conservation in the Caatinga of northeastern Brazil. *Conservation Biology* 19:701–706. <https://doi.org/10.1111/j.1523-1739.2005.00703.x>
- Liniger HP, Mekdaschi Studer R, Moll P, Zander U (2017) Making sense of research for sustainable land management. Centre for Development and Environment (CDE), University of Bern, Switzerland and Helmholtz Centre for Environmental Research GmbH – UFZ, Leipzig, Germany
- Lucena RF, Albuquerque UP, Monteiro JM, Almeida CFCBR, Florentino AT, Ferraz JSF (2007) Useful plants of the semi-arid northeastern region of Brazil – a look at their conservation and sustainable use. *Environmental Monitoring and Assessment* 125: 281–290. <https://doi.org/10.1007/s10661-006-9521-1>
- Manzano MG, Návar J (2000) Processes of desertification by goats overgrazing in the Tamaulipan thornscrub (matorral) in north-eastern Mexico. *Journal of Arid Environments* 44:1–17. <https://doi.org/10.1006/jare.1999.0577>
- Marengo JA, Chou SC, Torres RR, Giarolla A, Alves LM, Lyra A (2014) Climate change in Central and South America: Recent trends, future projections, and impacts on regional agriculture. CCAFS Working Paper no. 73. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. Available online at: www.ccafs.cgiar.org
- Marinho FP, Mazzochini GG, Manhães AP, Weisser WW, Ganade G (2016) Effects of past and present land use on vegetation cover and regeneration in a tropical dry-land forest. *Journal of Arid Environments* 132:26–33. <https://doi.org/10.1016/j.jaridenv.2016.04.006>
- Menezes RSC, Sampaio EVSB, Giongo V, Pérez-Marin AM (2012) Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. *Brazilian Journal of Biology* 72:643–653. <https://doi.org/10.1590/S1519-69842012000400004>
- MMA–Ministério do Meio Ambiente (2010) Monitoramento do desmatamento nos biomas brasileiros por satélite – Monitoramento do bioma Caatinga entre 2002 e 2008. Ministério do Meio Ambiente & Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis. Brasília, Brazil. Retrieved from http://www.mma.gov.br/estruturas/sbf_chm_rbbio/_arquivos/relatrio_tcnico_caatinga_72.pdf. Accessed Sep 2016
- MMA–Ministério do Meio Ambiente (2011) Subsídios para a elaboração do plano de ação para a prevenção e controle do desmatamento na Caatinga. Ministério do Meio Ambiente, Brasília, Brazil. Retrieved from http://www.mma.gov.br/estruturas/203/_arquivos/diagnostico_do_desmatamento_na_caatinga_203_2_203_1.pdf. Accessed Sep 2015
- Navar J, Rodriguez-Flores F, Dominguez-Calleros PA, Perez-Verdin G (2014) Diversity-productivity relationship in the northeastern Tamaulipan thornscrub forest of Mexico. *International Journal of Ecology*. <https://doi.org/10.1155/2014/196073>
- Nosetto MD, Jobbágy EG, Paruelo JM (2006) Carbon sequestration in semi-arid rangelands: comparison of *Pinus ponderosa* plantations and grazing exclusion in NW Patagonia. *Journal of Arid Environments* 67:142–156. <https://doi.org/10.1016/j.jaridenv.2005.12.008>
- Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S,

- Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the world's forests. *Science* 333:988–993. <https://doi.org/10.1126/science.1201609>
- Peichl M, Arain MA (2006) Above- and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. *Agricultural and Forest Meteorology* 140:51–63. <https://doi.org/10.1016/j.agrformet.2006.08.004>
- Pfister JA, Malechek JC (1986) Dietary selection by goats and sheep in a deciduous woodland of northeastern Brazil. *Journal of Range Management* 39:24–28. <https://doi.org/10.2307/3899680>
- Prentice IC, Farquhar GD, Fasham MJR, Goulden ML, Heimann M, Jaramillo VJ, Kheshgi HS, LeQuéré C, Scholes RJ, Wallace DWR (2001) The carbon cycle and atmospheric carbon dioxide. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) *Climate change 2001: the scientific basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp 185–237
- R Core Team (2015) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from <http://www.R-project.org>. Accessed Jan 2016
- Revermann R, Wallenfang J, Oldeland J, Finckh M (2016) Species richness and evenness respond to diverging land-use patterns—a cross-border study of dry tropical woodlands in southern Africa. *African Journal of Ecology*. 55:152–161. <https://doi.org/10.1111/aje.12333>
- Rodal MJN, Martins FR, Sampaio EVSB (2008) Levantamento quantitativo das plantas lenhosas em trechos de vegetação de caatinga em Pernambuco. *Revista Caatinga* 21:192–205
- Romano PA, Garcia, EAC (1999) Policies for water-resources planning and management of the São Francisco River. In: Biswas AK, Cordeiro NV, Braga BPF, Tortajada C (eds) *Management of Latin American River Basins: Amazon, Plata, and São Francisco*. United Nations University Press, Tokyo, Japan, pp 245–272
- Salcedo IH, Menezes RSC (2009) Agroecosystem functioning and management in semi-arid Northeastern Brazil. In: Tiessen H, Stewart JWB (eds) *Applying ecological knowledge to landuse decisions. Inter-American Institute for Global Change Research - IICA-IAI-Scope*, Paris, France, pp 73–81
- Sampaio EVSB (1995) Overview of the Brazilian Caatinga. In: Bullock SH, Mooney HA, Medina E (eds) *Seasonally dry tropical forests*. Cambridge University Press, Cambridge, UK, pp 35–63
- Sampaio EVSB (2010) Características e potencialidades. In: Gariglio MA, Sampaio EVSB, Cestaro LA, Kageyama P (eds) *Uso sustentável e conservação dos recursos florestais da caatinga*. Ministério do Meio Ambiente, Brasília, Brazil, pp 29–48
- Sampaio EVSB, Costa TL (2011) Estoques e fluxos de carbono no semi-árido nordestino: estimativas preliminares. *Revista Brasileira de Geografia Física* 6:1275–1291
- Sampaio EVSB, Silva GC (2005) Biomass equations for Brazilian semiarid caatinga plants. *Acta Botanica Brasilica* 19:935–943. <https://doi.org/10.1590/S0102-33062005000400028>
- Sampaio EVSB, Gasson P, Baracat A, Cutler D, Pareyn F, Lima KC (2010) Tree biomass estimation in regenerating areas of tropical dry vegetation in northeast

- Brazil. Forest ecology and management 259:1135–1140. <https://doi.org/10.1016/j.foreco.2009.12.028>
- Santana JAS, Souto JS (2006) Diversidade e estrutura fitossociológica da Caatinga na Estação Ecológica do Seridó-RN. *Revista de Biologia e Ciências da Terra* 6: 232–242
- Scheffer F, Schachtschabel P (2010) *Lehrbuch der Bodenkunde* (16th ed). Spektrum Akademischer Verlag, Heidelberg, Germany
- Schneider S, Siegmund-Schultze M, Holanda Júnior EV, Alves FSF, Valle Zárate A (2012) Is a geographical certification a promising production and commercialization strategy for smallholder sheep farming in Ceará, Brazil? *Journal of Agriculture, Food Systems, and Community Development* 2:107–127. <https://doi.org/10.5304/jafscd.2012.022.013>
- Schulz K, Voigt K, Beusch C, Almeida-Cortez JS, Kowarik I, Walz A, Cierjacks A (2016) Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil. *Forest Ecology and Management* 367:62–70. <https://doi.org/10.1016/j.foreco.2016.02.011>
- Schulz C, Koch R, Cierjacks A, Kleinschmit B (2017) Land change and loss of landscape diversity at the Caatinga phytogeographical domain – Analysis of pattern-process relationships with MODIS land cover products (2001–2012). *Journal of Arid Environments* 136:54–74. <https://doi.org/10.1016/j.jaridenv.2016.10.004>
- Sousa SCD, Oliveira VPVD, Silva JMFD, Melo RAD, Azevedo R (2013) The use of lands from small watershed of riacho Itacuruba-PE. In: Gunkel G, Silva JAA, Sobral MC (eds) *Sustainable management of water and land in semiarid areas*. Editora Universitária UFPE, Recife, Brazil, pp 129–143
- Souza Lima MCJ, Soto-Blanco B (2010) Poisoning in goats by *Aspidosperma pyrifolium* Mart.: Biological and cytotoxic effects. *Toxicon* 55:320–324. <https://doi.org/10.1016/j.toxicon.2009.08.004>
- Steffens M, Kölbl A, Totsche KU, Kögel-Knabner I (2008) Grazing effects on soil chemical and physical properties in a semiarid steppe of Inner Mongolia (PR China). *Geoderma* 143:63–72. <https://doi.org/10.1016/j.geoderma.2007.09.004>
- Tavares FM, Schulz K, Pereira RCA, Cierjacks A, Almeida-Cortez JS (2016) Floristic survey of the Caatinga in areas with different grazing intensities, Pernambuco, northeast Brazil. *Journal of Environmental Analysis and Progress* 01:43–51
- Tiessen H, Feller C, Sampaio EVSB, Garin P (1998) Carbon sequestration and turnover in semiarid savannas and dry forest. *Climatic Change* 40:105–117. <https://doi.org/10.1023/A:1005342932178>
- Torres FSDM, Santos Pfaltzgraff PAD (2014) Geodiversidade do estado de Pernambuco, Programa Geologia do Brasil. Levantamento da Geodiversidade. CPRM, Recife, Brazil. Retrieved from <http://rigeo.cprm.gov.br/jspui/handle/doc/16771>. Accessed Jan 2016
- Winter TC (2001) The concept of hydrologic landscapes. *Journal of the American Water Resources Association* 37:335–349. <https://doi.org/10.1111/j.1752-1688.2001.tb00973.x>
- Zuur AF, Ieno EN, Walke, N.J, Saveliev AA, Smith GM (2009) *Mixed effects models and extensions in ecology with R* (1st ed). Springer, New York, USA

Zuur AF, Ieno EN, Elphick CS (2010) A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution* 1:3–14. <https://doi.org/10.1111/j.2041-210X.2009.00001.x>

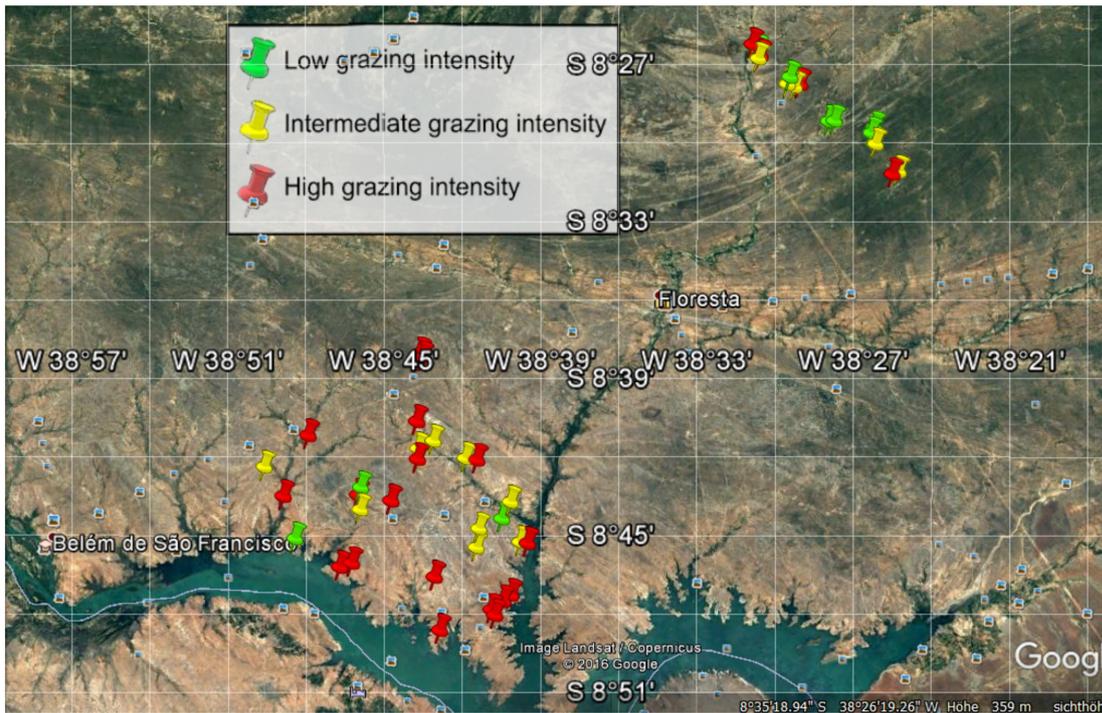
Appendix

Supplementary Material

Appendix 4.1 Woody plant species in a Caatinga area in north-eastern Brazil. Nomenclature follows Flora do Brasil 2020 (<http://floradobrasil.jbrj.gov.br/>).

| Family | Species | Growth form |
|---------------|---|-------------|
| Amaranthaceae | <i>Gomphrena vaga</i> Mart. | herb/shrub |
| Anacardiaceae | <i>Myracrodruon urundeuva</i> Allemão | tree |
| | <i>Schinopsis brasiliensis</i> Engl. | tree |
| | <i>Spondias tuberosa</i> Arruda | tree |
| Apocynaceae | <i>Allamanda</i> sp. | - |
| | <i>Aspidosperma pyriforme</i> Mart. | tree |
| Bignoniaceae | <i>Tabebuia aurea</i> (Silva Manso) Benth. & Hook. f. ex S. Moore | tree |
| Boraginaceae | <i>Cordia globosa</i> (Jacq.) Kunth. | shrub |
| | <i>Cordia leucocephala</i> Moric. | shrub |
| | <i>Cordia</i> sp. | shrub |
| Burseraceae | <i>Commiphora leptophloeos</i> (Mart.) J.B. Gillett | tree |
| Cactaceae | <i>Cereus jamacaru</i> DC. | cactus |
| | <i>Melocactus bahiensis</i> (Britton & Rose) Luetzelb. | cactus |
| | <i>Melocactus zehntneri</i> (Britton & Rose) Luetzelb. | cactus |
| | <i>Pilosocereus gounellei</i> (Weber) Byl. et Rowl. | cactus |
| | <i>Pilosocereus piauhyensis</i> (Guerke) Byl. et Rowl. | cactus |
| | <i>Tacinga inamoena</i> (K.Schum.) N.P. Taylor & Stuppy | cactus |
| | <i>Tacinga palmadora</i> (Britton & Rose) N.P. Taylor & Stuppy | cactus |
| Capparaceae | <i>Cynophalla</i> aff. <i>hastata</i> (Jacq.) J. Presl | shrub |
| Celastraceae | <i>Maytenus rigida</i> Mart. | tree |
| Euphorbiaceae | <i>Cnidoscolus</i> aff. <i>vitifolius</i> (Mill.) Pohl | tree |
| | <i>Cnidoscolus quercifolius</i> Pohl | tree |
| | <i>Croton</i> aff. <i>blanchetianus</i> Baill. | shrub |
| | <i>Croton cordiifolius</i> Baill. | shrub |
| | <i>Croton heliotropiifolius</i> Kunth. | shrub |
| | <i>Croton hirtus</i> L' Hér. | shrub |
| | <i>Croton</i> sp. 1 | shrub |
| | <i>Croton</i> sp. 2 | shrub |
| | <i>Croton</i> sp. 3 | shrub |
| | <i>Croton</i> sp. 4 | shrub |
| | <i>Ditaxis malpighiacea</i> (Ule) Pax & K. Hoffm. | shrub |
| | <i>Jatropha mollissima</i> (Pohl) Baill. | tree |

| Family | Species | Growth form |
|---------------|---|----------------------|
| | <i>Jatropha ribifolia</i> (Pohl) Baill. | tree |
| | <i>Manihot</i> sp. | tree |
| | <i>Sapium glandulosum</i> (L.) Morong | tree |
| Leguminosae | Aff. <i>Amburana cearensis</i> (Fr. Allem.) A.C. Smith | tree |
| | <i>Anadenanthera colubrina</i> var. <i>cebil</i> (Griseb.) Altschul | tree |
| | <i>Bauhinia</i> sp. | shrub/tree |
| | <i>Chloroleucon dumosum</i> (Benth.) G.P.Lewis | tree |
| | Aff. <i>Libidibia ferrea</i> (Mart. ex Tul.) L.P. Queiroz | tree |
| | <i>Mimosa tenuiflora</i> (Willd.) Poir | tree |
| | <i>Mimosa ophthalmocentra</i> Mart. ex Benth. | tree |
| | <i>Mimosa</i> sp. | tree |
| | <i>Piptadenia stipulacea</i> (Benth.) Ducke | tree |
| | <i>Pithecellobium diversifolium</i> Benth. | tree |
| | <i>Pithecellobium</i> sp. | tree |
| | <i>Poincianella microphylla</i> (Mart. ex G. Don) L.P. Queiroz | tree |
| | <i>Poincianella pyramidalis</i> (Tul.) L.P. Queiroz | tree |
| | <i>Prosopis juliflora</i> (Sw.) DC. | tree |
| | <i>Senegalia tenuifolia</i> (L.) Britton & Rose | tree |
| Malvaceae | <i>Melochia tomentosa</i> L. | shrub |
| | <i>Sida galheirensis</i> Ulbr. | subshrub |
| | <i>Waltheria rotundifolia</i> Schrank | subshrub |
| | Malvaceae sp. | - |
| Nyctaginaceae | <i>Guapira pernambucensis</i> (Casar.) Lundell | tree |
| Rhamnaceae | <i>Ziziphus joazeiro</i> Mart. | tree |
| Sapotaceae | <i>Sideroxylon obtusifolium</i> (Roem. & Schult.) T.D.Penn. | tree |
| Turneraceae | Turneraceae sp. | shrub |
| Verbenaceae | <i>Lippia grata</i> Schauer | shrub/subshrub |
| | Morphospecies 1 | shrub |
| | Morphospecies 2 | hemi-parasitic shrub |



Appendix 4.2 Location of study plots in the municipalities of Itacuruba and Floresta. Different grazing intensity classes were based on a first visual assessment.



Appendix 4.3 Caatinga vegetation: (a) preserved area with low grazing impact; dominant species include *Encholirium spectabile* (foreground); (b) intensively grazed area (fenced area) with remaining *Aspidosperma pyriforme* (foreground), *Poincianella pyramidalis*, and *Pilosocereus gounellei* (background). Photos: Jens von dem Bussche 2012.

Appendix 4.4 Allometric equations to estimate oven-dry aboveground plant biomass (kg) of Brazilian semi-arid Caatinga species found on the study plots. DGL—diameter at ground level (cm); DBH—diameter at breast height (cm). Measured DGLs were converted to DBH following Sampaio & Silva (2005). *Mean weight per rosette (kg). SE— standard error.

| Species | Habit of plants | Equations | R ² | Source |
|--|------------------|------------------------------|----------------|--|
| <i>Anadenanthera colubrina</i> var. <i>cebil</i> | arboreal | 0.4138*DBH ^{1.7718} | 0.64 | Sampaio et al. (2010) – equation <i>Mimosa tenuiflora</i> |
| <i>Aspidosperma pyrifolium</i> | arboreal | 0.0081*DGL ^{2.4698} | 0.506 | 30 specimens measured, harvested, dried, weighed |
| <i>Bauhinia</i> sp. | shrubby–arboreal | 0.0644*DGL ^{2.1999} | 0.8467 | Sampaio & Silva (2005) – equation small species |
| <i>Cnidoscolus quercifolius</i> | arboreal | 0.0689*DGL ^{2.0557} | 0.7668 | Sampaio & Silva (2005) – equation <i>Jatropha mollissima</i> |
| <i>Cnidoscolus</i> aff. <i>vitifolius</i> | arboreal | 0.0689*DGL ^{2.0557} | 0.7668 | Sampaio & Silva (2005) – equation <i>J. mollissima</i> |
| <i>Croton</i> sp. | shrubby | 0.4171*DBH ^{1.5601} | 0.62 | Sampaio et al. (2010) |
| <i>Guapira pernambucensis</i> | arboreal | 0.0644*DGL ^{2.1999} | 0.8467 | Sampaio & Silva (2005) – equation small species |
| <i>Ipomoea subincana</i> | shrubby | 0.0644*DGL ^{2.1999} | 0.8467 | Sampaio & Silva (2005) – equation small species |
| <i>Jatropha mollissima</i> | arboreal | 0.0689*DGL ^{2.0557} | 0.7668 | Sampaio & Silva (2005) |
| <i>Lippia grata</i> | shrubby | 0.4171*DBH ^{1.5601} | 0.62 | Sampaio et al. (2010) – equation <i>Croton sonderianus</i> |
| Malvaceae | shrubby | 0.4171*DBH ^{1.5601} | 0.62 | Sampaio et al. (2010) – equation <i>Croton sonderianus</i> |
| <i>Manihot</i> sp. | arboreal | 0.0689*DGL ^{2.0557} | 0.7668 | Sampaio and Silva (2005) – equation <i>J. mollissima</i> |
| <i>Maytenus rigida</i> | arboreal | 0.1142*DGL ^{2.2543} | 0.9605 | Sampaio & Silva (2005) |
| <i>Mimosa tenuiflora</i> | arboreal | 0.4138*DBH ^{1.7718} | 0.64 | Sampaio et al. (2010) |
| <i>Myracrodruon urundeuva</i> | arboreal | 0.0596*DGL ^{2.4878} | 0.9739 | Sampaio & Silva (2005) |
| <i>Pithecelobium</i> sp. | arboreal | 0.0871*DGL ^{2.3366} | 0.9505 | Sampaio & Silva (2005) – equation large species |
| <i>Poincianella microphylla</i> | arboreal | 0.3129*DBH ^{1.8838} | 0.68 | Sampaio et al. (2010) – equation <i>P. pyramidalis</i> |
| <i>Poincianella pyramidalis</i> | arboreal | 0.3129*DBH ^{1.8838} | 0.68 | Sampaio et al. (2010) |
| <i>Prosopis juliflora</i> | arboreal | 0.0871*DGL ^{2.3366} | 0.9505 | Sampaio & Silva (2005) – equation large species |
| <i>Sideroxylon obtusifolium</i> | arboreal | 0.0871*DGL ^{2.3366} | 0.9505 | Sampaio & Silva (2005) – equation large species |
| Morphospecies 1–5 | shrubby | 0.0644*DGL ^{2.1999} | 0.8467 | Sampaio & Silva (2005) – equation small species |
| Morphospecies 6 | arboreal | 0.0871*DGL ^{2.3366} | 0.9505 | Sampaio & Silva (2005) – equation large species |
| <i>Cereus jamacaru</i> | cacti | 0.0268*DGL ^{2.3440} | 0.9658 | Sampaio & Silva (2005) |
| <i>Melocactus zehntneri</i> | cacti | 4E-10*DGL ^{7.232} | 0.9943 | 3 specimens measured, harvested, dried, weighed |

| Species | Habit of plants | Equations | R ² | Source |
|---------------------------------|-----------------|-------------------------------|----------------|--|
| <i>Pilosocereus gounellei</i> | cacti | 0.0268*DGL ^{2.3440} | 0.9658 | Sampaio & Silva (2005) – equation <i>Cereus jamacaru</i> |
| <i>Pilosocereus piauhyensis</i> | cacti | 0.0268*DGL ^{2.3440} | 0.9658 | Sampaio & Silva (2005) – equation <i>C. jamacaru</i> |
| <i>Tacinga inamoena</i> | cacti | 0.0001*DGL ^{2.1274} | 0.8105 | 20 specimens measured, harvested, dried, weighed |
| <i>Tacinga palmadora</i> | cacti | 8.3931*DGL ^{-2.2663} | 0.9724 | 3 specimens measured, harvested, dried, weighed |
| <i>Bromelia laciniosa</i> | bromeliad | 0.1018* | 0.0307 (SE) | 15 rosettes harvested, dried, weighed |
| <i>Encholirium spectabile</i> | bromeliad | 0.389* | 0.0589 (SE) | 15 rosettes harvested, dried, weighed |
| <i>Neoglaziovia variegata</i> | bromeliad | 0.0786* | 0.0079 (SE) | 15 rosettes harvested, dried, weighed |

Appendix 4.5 Plant densities (individuals ha⁻¹) of Caatinga vegetation (means \pm standard error; SE) at different grazing intensities (high, intermediate, low). Different lowercase letters indicate significant differences between grazing classes in generalised linear models. The overall forest density includes saplings and emergent trees.

| | Mean \pm SE | Min | Max | Grazing intensity | | | No. plots with this plant type |
|---|---------------------|------|--------|-----------------------|--------------------------|--------------------------|--------------------------------------|
| | | | | High | Intermediate | Low | |
| Overall forest density (trees, shrubs, cacti together) [individuals ha ⁻¹] | 10,305 \pm 867 | 3425 | 38,850 | 8961 \pm 810 (a) | 10,898 \pm 2210 (a) | 12,667 \pm 1367 (a) | 45 |
| Emergent trees, DGL > 3 cm; height > 4 m [individuals ha ⁻¹] | 191 \pm 34 | 0 | 900 | 132 \pm 29 (a) | 200 \pm 72 (ab) | 322 \pm 95 (b) | 29 |
| Trees and shrubs, DGL > 3 cm; height < 4m [individuals ha ⁻¹] | 2438 \pm 221 | 200 | 7900 | 2532 \pm 272 (a) | 1829 \pm 266 (b) | 3155 \pm 698 (ab) | 45 |
| Trees and shrubs, DGL > 3–10 cm; without <i>P. pyrami-</i> <i>dalis</i> , <i>P. microphylla</i> , <i>A. pyrifolium</i> [individuals ha ⁻¹] | 531 \pm 117 | 0 | 4400 | 327 \pm 81 (a) | 378 \pm 123 (a) | 1266 \pm 439 (b) | 34 |
| <i>P. pyramidalis</i> and <i>P.</i> <i>microphylla</i> , total [individuals ha ⁻¹] | 2031 \pm 306 | 0 | 7600 | 2068 \pm 482 (a) | 1971 \pm 510 (a) | 2033 \pm 567 (a) | 43 |
| <i>P. pyramidalis</i> and <i>P.</i> <i>microphylla</i> , DGL > 0–3 cm [individuals ha ⁻¹] | 1222 \pm 237 | 0 | 6200 | 1268 \pm 380 (a) | 1179 \pm 352 (a) | 1178 \pm 499 (a) | 39 |
| <i>P. pyramidalis</i> and <i>P.</i> <i>microphylla</i> , DGL > 3–10 cm [individuals ha ⁻¹] | 607 \pm 81 | 0 | 2300 | 572 \pm 119 (a) | 607 \pm 154 (a) | 689 \pm 139 (a) | 39 |
| <i>A. pyrifolium</i> , total [individuals ha ⁻¹] | 2809 \pm 502 | 0 | 14,200 | 3632 \pm 875 (a) | 1707 \pm 524 (a) | 2511 \pm 815 (a) | 43 |
| <i>A. pyrifolium</i> , DGL > 0–3 cm [individuals ha ⁻¹] | 1604 \pm 389 | 0 | 11,600 | 2227 \pm 684 (a) | 914 \pm 456 (a) | 1156 \pm 523 (a) | 36 |
| <i>A. pyrifolium</i> , DGL > 3–10 cm [individuals ha ⁻¹] | 1009 \pm 155 | 0 | 5100 | 1159 \pm 214 (a) | 685 \pm 134 (a) | 1144 \pm 509 (a) | 41 |
| Cacti [individuals ha ⁻¹] | 1207 \pm 212 | 0 | 7075 | 1175 \pm 338 (a) | 1423 \pm 374 (a) | 947 \pm 288 (a) | 44 |
| Bromeliads [rosettes ha ⁻¹] | 1488 \pm 468 | 0 | 13,050 | 1013 \pm 632 (a) | 1639 \pm 780 (a) | 2414 \pm 1204 (a) | 13 |

Appendix 4.6 (a) Aboveground carbon stocks (AGCS) of major ecosystems and (b) AGCS of Caatinga systems with physiognomic parameters of the study area located in the municipalities Itacuruba and Floresta and other studies carried out in different Caatinga areas. AGCS—estimates of aboveground carbon stocks (Mg ha^{-1}); AGCS_h—aboveground carbon stocks of herbaceous plant species during the rainy season in 2013 and 2014 (Mg ha^{-1}); IC—inclusion criteria for trees and shrubs; FD—forest density (individuals ha^{-1}); meanTH—mean tree height (m); maxTH—maximum tree height (m); DGL—diameter at ground level; DBH—diameter at breast height (≈ 1.3 m).

| (a) Major ecosystems | AGCS | AGCS _h | | | | |
|---|--------|-------------------|--|--|--|--|
| Boreal forests (Prentice et al. 2001) | 64 | - | | | | |
| Temperate forests (Prentice et al. 2001) | 57 | - | | | | |
| Tropical forests (Prentice et al. 2001) | 120 | - | | | | |
| Caatinga, general (Tiessen et al. 1998) | 15–150 | 2.5–7.5 | | | | |
| Pasture, native/planted (Sampaio & Costa 2011) | 5/0 | - | | | | |

| (b) Caatinga studies | AGCS _h | AGCS | FD | meanTH | maxTH | IC |
|--|-------------------|------------------------------------|---------------|-----------|------------|---|
| Study area; distance to study area (authors) | | | | | | |
| Itacuruba and Floresta (this study) | 0–3.29 | 0.87–72.16 (mean ≈ 16) | 2676 | 2 | 12 | DGL > 3 cm |
| Serra Negra do Norte; 250 km north-east (Amorim et al. 2005) | - | 12.5 | 3250 | 3.4 | 9.5 | DGL > 3 cm |
| Serra Talhada; 130 km north (Kauffman et al. 1993) | - | ≈ 37 | - | - | - | - |
| Santa Teresinha; 200 km north-east (Freitas et al. 2012) | 0.9–3.2 | - | - | - | - | - |
| Floresta and Betânia; 35–100 km north-east (Rodal et al. 2008) | - | - | 1076– 2172 | 3.35–5.50 | 7.02–13.24 | DGL ≥ 3 cm and total height ≥ 1 m |
| Serra Negra do Norte; 250 km north-east (Santana & Souto 2006) | - | - | 4080 | 2.45 | | DGL ≥ 3 cm and total height ≥ 1 m |



CHAPTER 5

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 $16.86 \pm 1.28 \text{ Mg ha}^{-1} \text{ C}$ with approximately one-quarter found in the upper 5 cm of the soil profile ($4.14 \pm 0.43 \text{ Mg ha}^{-1} \text{ C}$) and the remainder ($12.57 \pm 0.97 \text{ Mg ha}^{-1} \text{ C}$) 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.

Keywords: carbon cycle, degradation, desertification, livestock, semi-arid, soil

Introduction

The accelerated increase in atmospheric CO₂ 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 CO₂ emissions with the removal of CO₂ from the atmosphere (IPCC 2013). Terrestrial ecosystems may work as efficient carbon sinks, which can significantly reduce atmospheric CO₂ 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 SOC¹ 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 & Kwon 2000).

Land-use change can cause a pronounced reduction in SOC stocks (Boddey et al. 2012; Post & Kwon 2000; Schimel et al. 2001), albeit increases in SOC have also been reported (e.g., Boddey et al. 2012; Guo & Gifford 2002). Carbon dioxide emissions through altered land use were estimated at 2–4 Pg y⁻¹ C during the 1990s (Schimel et al. 2001). Consequently, scientific interest in the potential of different land-use options, including grazing regimes (e.g., Follett & 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 & Návar 2000) and in some cases may reduce species diversity (Reeder & 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 & Jackson 2000)—and water availability, which can be lowered through herbivore trampling by compaction of

¹ SOC—soil organic carbon

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 km² (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 & 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 &

Hensen 2004; Cierjacks et al. 2008) and knowledge of the mechanisms by which grazing affects SOC remains limited (Follett & 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 altitude² 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.

Materials and methods

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 & 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

² altitude above sea level

shrubby). The main plant families of Caatinga forests are Fabaceae, Euphorbiaceae, and Cactaceae (Tavares et al. unpublished; Sampaio 1995; Figure 5.1).

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 high temperature, high potential evapotranspiration, and erratic precipitation results in low plant-available moisture for 7–11 months per year (Sampaio 1995). Droughts are common and severe droughts that last several years occur every 40–50 years (Sampaio 1995).

Most of the Caatinga area is rather flat with smooth elevations between 300 and 500 m and scattered higher mountains and plateaus (900–1000 m; Sampaio 1995). The geology of the study area is characterised by a Proterozoic crystalline basement (Sampaio 1995). Most of the soils are shallow, clayey, and rocky. The most



Figure 5.1 Caatinga dry forest vegetation with the typical tree species catingueira (*Poincianella pyramidalis* (Tul.) L. P. Queiroz) and pereiro (*Aspidosperma pyrifolium* Mart.) in the foreground. A livestock track can be seen in the centre.

common soils found in Itacuruba and Floresta are Planosols and Luvisols interspersed with Regosols and Leptosols (following the FAO classification system; Embrapa 2001a,b; Torres & Santos Pfaltzgraff 2014). This diversity results in a complex mosaic of soils with extremely different characteristics, depths, and water availabilities (Sampaio 1995).

Land use

Irrigation farming is only feasible in some areas where access to water is available (see Cierjacks et al. 2016). Consequently, livestock farming of small ruminants and cattle is the most common land-use type in the study area (Sampaio 1995). Many farmers of the study region stated that the animals, mainly goats, are kept in fenced areas with a rotating pasture system. The animal loads reported were as high as 2.3 livestock units ha⁻¹ (Table 5.1; personal assessment) and hence 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 on pasture. In some parts of the Caatinga, the native ungulate gray brocket (*Mazama gouazoubira*) and the collared peccary (*Pecari tajacu*) occur (Oliveira et al. 2003). In our study area, however, there was no evidence of their presence. Faeces of mocó (*Kerodon rupestris*), a rodent endemic to eastern Brazil, were found occasionally but their grazing impact appeared to be very low.

Some areas are known to have been cleared to establish cropping fields or trees have been harvested for using their timber or for the production of charcoal.

Table 5.1 Reported livestock numbers and mean faeces weights of five farms located in the municipality of Itacuruba [personal assessment (2012–2013)]. Conversion into lu³ following LDS NRW (2005), in which 1 small ruminant = 0.1 lu and 1 cow = 1 lu. Average carrying capacity of Caatinga vegetation is 0.1 lu ha⁻¹ (Tiessen et al. 1998).

| Farm | Number of goats | Number of cattle | Number of sheep | Area [ha] | lu ha ⁻¹ | Mean faeces weight [g m ⁻²] | Mean faeces weight [g m ⁻²] per 0.1 lu ha ⁻¹ |
|------|-----------------|------------------|-----------------|-----------|---------------------|---|---|
| 1 | 5 | 0 | 76 | 23 | 0.4 | 28 | 8 |
| 2 | 20 | 0 | 54 | 14 | 0.5 | 12 | 2 |
| 3 | 250 | 5 | 80 | 150 | 0.3 | 45.5 | 18 |
| 4 | 800 | 160 | 500 | 171 | 1.7 | 61 | 4 |
| 5 | 2 | 26 | 80 | 15 | 2.3 | 241 | 11 |

³ lu—livestock unit

On farms where a clear grazing management is practised, exclusively cattle and lambs are fed with forage grass, seeds of the exotic tree species algaroba (*Prosopis juliflora* (Sw.) DC.), or during droughts with shoots of bromeliads and cacti. Other farmers allow their livestock to roam freely in unfenced areas. Particularly during periods of drought, animals may be set free to enlarge the pasture area. Therefore, the real animal loads and grazing intensities in the majority of the study area could not be inferred from the farmers' information, a challenge that is further aggravated by the unknown roaming behaviour of grazing animals.

Study design and data collection

We randomly established 45 study plots of 20 × 20 m² within the municipalities of Itacuruba and Floresta. We used two stratification criteria to cover wide gradients of grazing intensity and water availability. (1) Plots were stratified into three different grazing intensity classes based on visual assessment: heavy grazing pressure (plots located on pastures), intermediate grazing pressure (plots located in unused Caatinga forest), and preserved Caatinga (areas without clear signs of grazing). (2) The study area was further stratified into three different water availability classes (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). In this context, water availability was also considered a proxy for ground water availability, as there was no other information on ground water available. Within each combination of stratification criteria, we selected five plots to obtain a balanced study design and a more or less even plot distribution across the study area. All plots were at least 300 m from each other and at least 200 m from roads. Soil analyses were not conducted on 3 of the 45 plots due to damaged sample material. The position and altitude of each plot was determined using a handheld GPS (Garmin eTrex 30). Water availability was reassessed by measuring the distance between a plot and the nearest permanent water body using satellite images provided by Google Earth (2013).

Grazing intensity can be quantified using different methods, such as livestock faeces counts (Cierjacks & Hensen 2004), weighing of faeces, assessing trampling of paths (Cierjacks et al. 2008), or radio telemetry (Coates & Penning 2000); in some cases, proxies such as the distance to water body (Säumel et al. 2011) may

also be used. In this study, we assessed grazing intensity by the dry weight of faeces, which is particularly suited for dry regions without pronounced activity of dung beetles where slow faeces decomposition is characteristic (see Cierjacks & Hensen 2004). On each plot, six permanent subplots (each $2 \times 2 \text{ m}^2$) were established. On each subplot all faeces (goat/sheep, cow, donkey/horse) were collected, dried, and weighed. Faeces collection was conducted twice, at the beginning of the study in 2012 and a second time on the same plots about 7 months later in 2013. The correlation of faeces amounts from the first and the second collection was highly significant ($r^2 = 0.87$) which shows that the droppings are a reproducible indicator of long-term animal presence in a given area and that the subplots were distributed appropriately. Goat faeces were the most frequently collected faeces type. Due to the similar values at both collection times, we used the mean dry weight of both to reclassify the plots according to their grazing intensity. Cierjacks & Hensen (2004) reported a significant correlation between animal loads and the amount of animal faeces. We classified the plots as follows: (1) $> 20 \text{ g m}^{-2}$ = high grazing intensity. This class limit is based on the mean faeces weight data. Only one of the plots located on pastures showed a mean faeces weight less than 20 g m^{-2} . As this plot is located in the middle of a distinct group of boulders this value was not considered for classification as the faeces weights on other parts of the farm are expected to be higher. (2) $5\text{--}20 \text{ g m}^{-2}$ = intermediate grazing intensity. (3) $< 5 \text{ g m}^{-2}$ = low grazing intensity. The boundary value for low grazing intensity was set based on the mean faeces weight of plots located on preserved Caatinga without any sign of surface water. Here, except for one plot, the mean faeces weights were $< 5 \text{ g m}^{-2}$. The faeces weights of all species were analysed together due to the heterogeneity of droppings, which led to frequent zero counts in different animal groups and made a species-related analysis impossible.

Three 100 cm^3 soil samples of the upper soil profile (0–5 cm) were taken along the western edge of each plot. Additionally, two soil profiles per plot were dug in the north-western and north-eastern corners of each plot, where we sampled 100 cm^3 every 10 cm down to the bedrock with a maximum depth of 60 cm.

On each plot, plant diversity was assessed by carrying out vegetation relevés according to the methodology of Braun-Blanquet (1964). Plant identification was carried out in cooperation with the herbarium Dardano de Andrade of the Agronomic Institute of Pernambuco, Recife. The aboveground biomass was assessed sep-

arately for perennial and herbaceous plants. On one 10 × 10 m² subplot per plot, the circumference at ground level was measured of all individuals with diameter at ground level > 3 cm. Biomass was estimated using allometric equations provided by Sampaio & Silva (2005) and Sampaio et al. (2010). New equations were established for pereiro (*Aspidosperma pyriforme* Mart.) and several cacti and bromeliad species (Schulz et al. unpublished). The biomass of herbaceous species was assessed on three 2 × 2 m² subplots. All herbaceous individuals on the subplot were harvested, dried, and weighed.

Soil organic carbon stock analyses

Soil analyses were carried out in the laboratory at Technische Universität Berlin. All soil samples were dried at 60°C to a constant weight (at least 24 h). After cooling in a desiccator for 30 min, each sample was weighed (value used of calculation of raw bulk density ρ_{Core} according to the approach of Throop et al. 2012; Table 5.2) and then hand-sieved through a 2 mm screen. Coarse aggregates, which were not stones, were ground to pass through the sieve. The separated fine soil was weighed again, and the coarse material (skeletal fraction) was discarded (Throop et al. 2012). The weight of fine soil was used to calculate hybrid bulk density (ρ_{Hybrid} in the sense of Throop et al. 2012): $\rho_{\text{Hybrid}} [\text{g}/\text{cm}^3] = \text{dry weight of fine soil} [\text{g}] / \text{core volume} [\text{cm}^3]$. Hybrid bulk densities were the base for SOC stock calculations, as the coarse material does not contain organic material.

To ensure that the samples did not contain inorganic carbon, we used hydrochloric acid and tested for gas development from carbonate. From each sample, about 3 g were ground finely in an oscillating mill. SOC concentrations were determined by dry combustion (Vario EL III 125 Elementar Analyser, Elementar, Hanau, Germany) of two replicates per sample. The average elemental SOC content of the replicates was used to calculate SOC stocks by multiplying by bulk density of the respective horizon and horizon depth (10 cm): $\text{SOC stock} [\text{g}/\text{cm}^2] = \text{bulk density } \rho_{\text{Hybrid}} [\text{g}/\text{cm}^3] \times \text{SOC content} [\text{g kg}^{-1}] \times \text{depth} [\text{cm}]$. C stocks were calculated separately for the total soil profile, the upper 5 cm, and greater soil depths (5–maximum 60 cm). Bulk densities of the 0–10 cm soil depth were used for the calculation of the carbon stocks within the upper 5 cm of the soil profile. SN⁴ stocks

⁴ SN—soil nitrogen

were calculated analogously. Soil texture was determined following DIN/ISO11277 for the upper 10 cm of soil.

Statistical analyses

Statistical analyses were performed using R version 2.15.1 (R Core Team 2012). The entire set of continuous variables was checked in terms of homogeneity, normality, or outliers (Zuur et al. 2010). Data on SOC, clay content, altitude, biomass, and species richness were log-transformed to obtain normal distribution. The data were analysed using linear models (LMs) to determine which variables influence the overall SOC and the SOC of the upper 5 cm and the greater soil depths. For each of the three soil compartments, separate models were fitted. To analyse the importance of each predictor variable (grazing intensity, clay content, altitude, Shannon index, species richness, aboveground biomass) backwards stepwise model selection was used to find the minimum adequate model (Crawley 2007). Tukey's HSD test was conducted during the post-hoc analyses to identify significant differences among the three grazing classes.

Results

SOC stocks in Caatinga dry forests

Most of the plots ($n = 28$) were characterised as sandy soils with different contents of loam. The soils of the remaining 14 plots were classified as loamy. The mean bulk density $\rho_{\text{Hybrid}} \pm$ standard error of all soil samples was $0.96 \pm 0.02 \text{ g cm}^{-3}$, $\rho_{\text{Core}} \pm$ standard error was at 1.21 ± 0.02 (see Table 5.2). The soil depth ranged between 20 and 60 cm to bedrock and was not related to topographic position.

The carbon content of all analysed soil samples originated exclusively from organic carbon, as none of the soil samples showed a reaction to hydrochloric acid, which would indicate the presence of carbonate. Most soil samples were characterised by a very low content of SOC, with only a few soil samples having carbon contents higher than 5 mg g^{-1} (Table 5.2). SOC levels were highest in the upper 5 cm of the soil profile and decreased at greater soil depths. The mean soil C stock of all plots was $16.86 \pm 1.28 \text{ Mg ha}^{-1} \text{ C}$. Mean C stocks of the upper 5 cm and greater soil depths were 4.14 ± 0.43 and $12.57 \pm 0.97 \text{ Mg ha}^{-1} \text{ C}$ respectively, which

indicates that approximately one-quarter of the C was located in the upper 5 cm of the soil profile.

Table 5.2 Soil and environmental variables at three grazing intensities in the Caatinga. Values are means \pm SE (standard error). Different lowercase letters indicate significant differences between grazing classes (LMs, TukeyHSD posthoc tests $p < 0.05$).

| | No/light grazing | Intermediate grazing | High grazing |
|---|------------------------|------------------------|------------------------|
| SOC stocks 0–5 cm [Mg ha ⁻¹] | 7.02 \pm 1.71 (a) | 3.68 \pm 0.27 (ab) | 3.39 \pm 0.32 (b) |
| SOC stocks 5–60 cm [Mg ha ⁻¹] | 15.82 \pm 2.81 (a) | 11.90 \pm 1.57 (a) | 11.82 \pm 1.18 (a) |
| SN stocks 0–5 cm [Mg ha ⁻¹] | 0.64 \pm 0.14 (a) | 0.31 \pm 0.02 (ab) | 0.29 \pm 0.04 (b) |
| SN stocks 5–60 cm [Mg ha ⁻¹] | 1.52 \pm 0.13 (a) | 1.14 \pm 0.12 (a) | 1.24 \pm 0.11 (a) |
| SOC content 0–5 cm [mg g ⁻¹] | 16.66 \pm 3.64 (a) | 7.37 \pm 0.63 (b) | 7.16 \pm 0.61 (b) |
| SOC content 5–60 cm [mg g ⁻¹] | 5.4 \pm 0.96 (a) | 3.18 \pm 0.46 (a) | 4.12 \pm 0.46 (a) |
| SN content 0–5 cm [mg g ⁻¹] | 1.29 \pm 0.33 (a) | 0.64 \pm 0.04 (b) | 0.68 \pm 0.07 (b) |
| SN content 5–60 cm [mg g ⁻¹] | 0.51 \pm 0.07 (a) | 0.31 \pm 0.03 (b) | 0.36 \pm 0.03 (b) |
| Raw bulk density ρ_{Core} (10 cm) [g cm ⁻³] | 1.09 \pm 0.04 (a) | 1.22 \pm 0.04 (a) | 1.25 \pm 0.04 (a) |
| Raw bulk density ρ_{Core} (10–60 cm) [g cm ⁻³] | 1.09 \pm 0.05 (a) | 1.2 \pm 0.03 (ab) | 1.27 \pm 0.03 (b) |
| Hybrid bulk density ρ_{Hybrid} (10 cm) [g cm ⁻³] | 0.88 \pm 0.05 (a) | 1.01 \pm 0.04 (a) | 0.95 \pm 0.03 (a) |
| Hybrid bulk density ρ_{Hybrid} (10–60 cm) [g cm ⁻³] | 0.88 \pm 0.06 (a) | 0.97 \pm 0.04 (a) | 0.99 \pm 0.03 (a) |
| Skeletal fraction [mg g ⁻¹] | 187.79 \pm 22.83 (a) | 199.75 \pm 18.71 (a) | 251.27 \pm 19.06 (a) |
| Clay content [mg g ⁻¹] | 142.22 \pm 39.86 (a) | 117.33 \pm 24.92 (a) | 116.89 \pm 20.08 (a) |
| Silt content [mg g ⁻¹] | 228.69 \pm 8.84 (a) | 188.06 \pm 8.21 (b) | 203.18 \pm 9.17 (ab) |
| Sand content [mg g ⁻¹] | 629.06 \pm 45.04 (a) | 694.6 \pm 29.15 (a) | 679.99 \pm 23.19 (a) |
| Altitude [m] | 352.22 \pm 6.81 (a) | 340.93 \pm 5.38 (ab) | 333.77 \pm 4.73 (b) |
| Distance to nearest permanent water body [km] | 16.09 \pm 3.47 (a) | 9.34 \pm 2.35 (b) | 6.00 \pm 1.53 (b) |
| Total number of plots | 9 | 14 | 22 |

Impact of grazing and other factors influencing SOC stocks

Overall SOC stocks were significantly positively related to altitude and clay content (Figure 5.2, Table 5.3). Plots with intermediate or high grazing intensities showed lower overall SOC stocks compared to plots with low grazing intensity. However, this effect was not significant.

Plots where intermediate or high intensity grazing took place had significantly lower SOC stocks in the upper 5 cm (ca. 3.5 Mg ha⁻¹) than plots with no or little grazing (Figure 5.3). However, in contrast to the overall SOC stocks, here, altitude and clay content were not significant (Table 5.3).

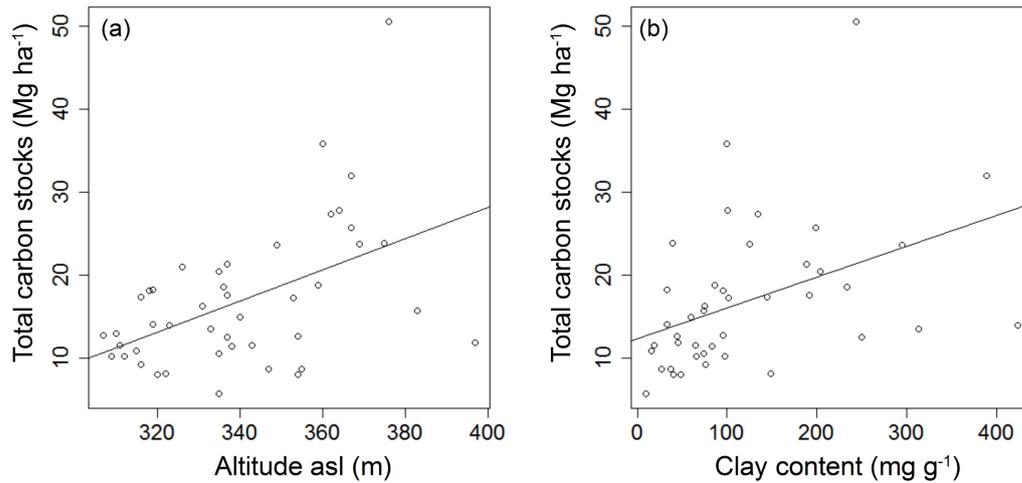


Figure 5.2 Overall soil organic carbon stocks in Caatinga soils at different (a) altitudes ($p = 0.0029$) and (b) clay contents ($p = 0.0001$).

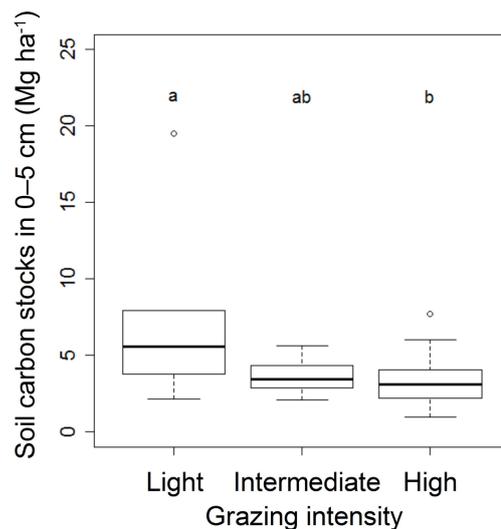


Figure 5.3 Soil organic carbon stock in the upper 5 cm of Caatinga soils at different grazing intensities. Different lowercase letters indicate significant differences (Tukey's HSD test).

Similarly to the overall SOC, grazing did not significantly affect the SOC stocks at greater soil depths (> 5 cm), although the data did indicate a negative effect. Again, altitude and clay content were significantly positively correlated with the SOC stocks of greater soil depths (see Table 5.3 for model parameters).

The distance to the nearest permanent water body was not included in the models because there was a strong positive correlation between distance and altitude (multiple R -squared = 0.6343, adjusted R -squared = 0.6251, $p < 0.0001$) and the model with distance to water showed lower predictive power. There was also a correlation between grazing intensity and altitude. The heavily grazed plots were at significantly lower elevations compared to lightly grazed plots (Table 5.2). Neither the depth to bedrock, species richness, Shannon index, nor aboveground biomass showed a significant effect on the SOC stocks in any of the statistical models.

Table 5.3 Model parameters of the multiple linear models for different soil depths.

| | p altitude | p clay content | p grazing | Multiple R -squared | Adjusted R -squared | p model |
|---------|--------------|------------------|-------------|-----------------------|-----------------------|-----------|
| 0–5 cm | - | - | 0.0082 | 0.2183 | 0.1782 | 0.0082 |
| 5–60 cm | 0.0097 | < 0.0001 | - | 0.5168 | 0.492 | < 0.0001 |
| 0–60 cm | 0.0029 | 0.0001 | - | 0.4599 | 0.4322 | < 0.0001 |

Livestock faeces

Analysing the effect of actual grazing intensities in the field without experimental manipulation (e.g., exclosures) is a new approach. Based on our data (for an extract of the dataset see Table 5.1), we calculated a daily excretion of faeces for one small ruminant to be approximately 290 g (calculated as *mean faeces weight of the second measurement/number of days between measurements*). This is in accordance with Kallah & Adamu (1988) who found that Red Sokoto goats excrete about 240 g per day. However, we found a pronounced variability in mean faeces weight per 0.1 lu ha⁻¹ which might be explained by the heterogeneous distribution of excreting animals which show spatial preferences e.g., around water bodies.

We also calculated that the mean persistence of the faeces of small ruminants in the Caatinga during a period of drought is approximately 1.5 years (calculated as *mean faeces weight of small ruminants in the first measurement/mean yearly increase in small ruminant faeces*). However, those calculations refer to a period of

drought in the study area. Numbers are likely to differ during years of average precipitation.

Discussion

SOC stocks in Caatinga dry forests

SOC stocks within our study area were generally very low (about 17 Mg ha⁻¹). Other studies carried out in the Caatinga revealed clearly higher SOC stocks, e.g., Tiessen et al. (1998) with 20 Mg ha⁻¹ C or Kauffman et al. (1993) with 26.2 Mg ha⁻¹ C for 0–10 cm soil depth. Barros et al. (2015) calculated carbon stocks for different management systems (from native vegetation to permanent agriculture) for a soil depth of 0–40 cm ranging from 35.13 to 46.46 Mg ha⁻¹ based on bulk density values ranging from 1.3 to 1.9 g cm⁻³. Lower SOC stock in our study are a consequence of using ρ_{Hybrid} rather than ρ_{Core} for calculation. In addition, such findings may be caused by low clay content (see Wiesemeier et al. 2015). In our study area, sandy soils are prevailing, which are generally characterised by low C contents (e.g., Hassink 1994). Compared to Barros et al. (2015), bulk density ρ_{Hybrid} in our study resulted in considerably lower but more realistic carbon stocks (Throops et al. 2012), particularly in greater soil depths. Besides the low clay content on our study plots, another reason for the lower carbon contents may be the prolonged drought in the study area, which led to reduced net primary production and hence less C available for SOC formation (e.g., Buringh 1984).

Despite their very low SOC stocks compared to other ecosystems [e.g., Prentice et al. (2001) give estimates for tropical forests: 122 Mg ha⁻¹ C; temperate forests: 147 Mg ha⁻¹ C; boreal forests: 274 Mg ha⁻¹ C], Caatinga soils still play an important role as carbon sinks due to their large spatial extent. Caatinga soils, which cover an area of approximately 700,000 km² store about 1.4 Pg C.

Impact of grazing and other factors influencing SOC stocks

In keeping with our first hypothesis, grazing at intermediate or heavy levels significantly reduced the SOC stocks in the upper 5 cm of the soil profile, by ca. 3.5 Mg ha⁻¹. Similar results have already been detected for other arid and semi-

arid ecosystems (e.g., Kotzé et al. 2013; Wang et al. 2014; Wiesmeier et al. 2015). However, those studies have not yet been carried out for the Caatinga.

In the open Caatinga (including preserved areas), we found a mean of 21 g m⁻² of faeces, which is equivalent to about 0.26 livestock units ha⁻¹ (compare Table 5.1). In particular, goats invade into remote sites and preserved areas. We only found one plot without any animal faeces. Sampaio (1995) reports a carrying capacity of max. 0.1 livestock units ha⁻¹. Accordingly, nearly all of our plots—not only those located on pastures—can be considered overgrazed.

If we consider the whole Caatinga at about 700,000 km², of which about 60% is used for grazing (Sampaio 1995), and if we assume a carbon loss of 7.6 Mg ha⁻¹ C through land-use change from no to heavy grazing intensity (calculated as the difference between SOC stocks of the upper 5 cm and the greater soil depths (> 5 cm) of lightly grazed plots and the SOC stocks of the upper 5 cm and the greater soil depths (> 5 cm) of heavily grazed plots), we can estimate that about 0.319 Pg SOC has already been lost due to overgrazing. Consequently, our study provides evidence that in forests of semi-arid and arid regions, unsustainable livestock farming is a relevant driver of land degradation, which is accompanied by a severe constraint of ecosystem functions such as carbon sequestration.

The inclusion of further parameters (clay content and altitude) significantly improved model prediction (multiple *R*-squared grazing only = 0.0795; multiple *R*-squared other parameters = 0.5196). Altitude proved to be among the main factors influencing SOC stock in greater soil depths (> 5 cm) and soil overall. With increasing elevation, the SOC stocks increased. This may be attributed to a more balanced water regime, lower temperature, and higher precipitation at higher altitudes. As a consequence of higher primary productivity, SOC stocks increase. Moreover, plots located near the lake were also at a lower altitude. In general, livestock congregate around water bodies (Säumel et al. 2011; von Wehrden et al. 2012). In our study area, no areas adjacent to the lake showed low grazing intensity. Milchunas & Lauenroth (1993) quantified the effects of grazing on vegetation and soils over a global range of ecosystems and found that on dry sites water, rather than herbivory, explains most of the variation in productivity.

The effect of clay content on SOC stocks was significant for the overall soil profile and the greater soil depths (> 5 cm). SOC is significantly positively correlated to clay amount. This result is consistent with a study by Menezes et al. (2012) who

also found a close relation between overall organic carbon and clay content in Caatinga soils. The effect can be explained by the agglomeration of organic material in clay particles (Burke et al. 1989).

In contrast, neither plant diversity nor aboveground biomass showed any effect on soil carbon stocks. Species diversity (richness) and SOC stocks showed a trend towards positive correlation but this was not significant. It has been suggested that a multifunctional response of different species to aridity and lengthy dry seasons may lead to enhanced primary productivity in species-rich communities compared to poorer ones (Yachi & Loreau 1999) and furthermore that enhanced primary productivity may be related to increased amounts of C available for SOC formation (Oesterheld et al. 1999; Piñeiro et al. 2010). In our study area, the most abundant tree species was catingueira (*Poincianella pyramidalis* (Tul.) L. P. Queiroz), a legume species not capable of fixing nitrogen (e.g., Freitas et al. 2010). Species which are known to nodulate (e.g., *Mimosa hostilis* Benth.; Freitas et al. 2010) occurred occasionally in our study region (Schulz et al. unpublished). Hence, we expected that a higher species richness would also imply a higher number of N-fixing species. Based on this, we assumed a significant relationship between species diversity and SOC, but we found no evidence for such causal relationships.

Aboveground biomass was highest at low altitude (Schulz et al. unpublished), possibly due to a greater water availability and facilitated by an increased fertility of the nutrient-poor Caatinga soil due to the faeces and urine of the animals (Haynes & Williams 1993). Herbivores consume biomass, which reduces the amount of C available for SOC formation in soil, thus enhancing ecosystem C release to the atmosphere (Oesterheld et al. 1999; Piñeiro et al. 2010) and possibly leading to lower SOC stocks.

In this study, we investigated the effect of total aboveground biomass, which showed no significant effect on the SOC stocks. The aboveground biomass in this region mainly consists of woody parts and thus contributes rather little to the formation of SOC in contrast to litter, which is very important for SOC formation (e.g., Reeder & Schuman 2002; Stavi et al. 2008). In our study region, leaf litter is present for only a short period of the year after the rainy season. The mean litter cover on our study plots was low at $17.1 \pm 1.9\%$ (unpublished data). This may explain the lack of a positive effect of aboveground biomass on SOC.

The historic and present land use in the Caatinga reflects a shift in cultivation and livestock farming. Both typically require cutting and burning (slash-and-burn systems) of Caatinga vegetation, which in the long run can be expected to reduce C stocks (Kauffman et al. 1993). Fraga & Salcedo (2004) examined soil C and N stocks under Caatinga and adjacent agricultural or pasture areas. Carbon stocks of cultivated areas were approximately half of the levels of native Caatinga. Furthermore, soil erosion during strong rain events is an important process which has to be considered when studying decreases in soil C concentrations of the Caatinga ecosystem (Fraga & Salcedo 2004). In our study, we frequently observed degraded soils, most of them also stony (Table 5.2), possibly due to erosion processes. Fraga & Salcedo (2004) reported that during a period of 35 years after native Caatinga was deforested to establish pastures or cropping fields, erosion led to a 43% loss of SOC. Avoiding soil erosion, degradation, and loss of C after the removal of native vegetation for preparation of pastures, crop fields, or harvesting timber may therefore be an important conservation practice to protect the Caatinga ecosystem from detrimental grazing effects (Menezes et al. 2012).

Conclusion

Overall this study provides evidence that grazing has a detrimental impact on SOC stocks in Caatinga forest ecosystems of north-eastern Brazil. We conclude that changes in land use, in particular the reduction of grazing pressure, would have a pronounced impact on C storage and sequestration in Caatinga dry forests, which are pivotal for ecosystem resilience and soil fertility. To maintain and increase SOC stocks, livestock farming with lower stocking rates of ungulates seems indispensable. This could be achieved by reducing the number of livestock, by enlarging pasture areas, or by supplying extra feed. Our results highlight the need for a local grazing management plan including the implementation of a legally compulsory rotation system, which allows areas to recover from grazing impacts. This would ultimately contribute to the conservation of the unique dry forest systems of Caatinga. The findings of our study and of others on socio-economical aspects of livestock husbandry in the study area should therefore be discussed with stakeholders and decision makers. Based on guidelines the stakeholders agree on, land-use strategies

can be improved, by reducing and monitoring livestock numbers, for maintaining and enhancing ecosystem functions of Caatinga dry forests.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.foreco.2016.02.011>. These data include Google maps of the most important areas described in this article.

References

- Araújo Filho JC, Gunkel G, Sobral MCM, Kaupenjohann M, Lopes HL (2013) Soil attributes functionality and water eutrophication in the surrounding area of Itaparica Reservoir, Brazil. *Revista Brasileira de Engenharia Agrícola e Ambiental* 17: 1005–1013
- Barros JDS, Chaves LHG, Pereira WE (2015) Carbon and nitrogen stocks under different management systems in the Paraíba “Sertão”. *African Journal of Agricultural Research* 10:130–136. <https://doi.org/10.5897/AJAR2014.8706>

- Boddey RM, Alves BJR, Urquiaga S, Jantalia CP, Martin-Neto L, Madari BE, Milori DMBP, Machado PLOA (2012) Estoques de carbono nos solos do Brasil - Quantidade e mecanismos de acúmulo e preservação. In: Lima MA, Boddey RM, Bruno JRA, Alves BJR, Machado PLOA, Urquiaga S (eds) Estoques de carbono e emissões de gases de efeito estufa na agropecuária brasileira. Embrapa, Brasília, Barzil, pp 32–82
- Braun-Blanquet J (1964) Pflanzensoziologie. Grundzüge der Vegetationskunde (3rd ed). Springer, Vienna, Austria
- Buringh P (1984) Organic carbon in soils of the world. In: Woodwell GM (ed) The role of terrestrial vegetation in the global carbon cycle: measurement by remote sensing. John Wiley & Sons Ltd, pp 91–109
- Burke IC, Yonker CM, Parton WJ, Cole CV, Schimel DS, Flach K (1989) Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. *Soil Science Society of America Journal* 53:800–805. <https://doi.org/10.2136/sssaj1989.03615995005300030029x>
- Cardinale BJ, Wright JP, Cadotte MW, Carroll IT, Hector A, Srivastava DS, Weis JJ (2007) Impacts of plant diversity on biomass production increase through time because of species complementarity. *Proceedings of the National Academy of Sciences* 104:18123–18128. <https://doi.org/10.1073/pnas.0709069104>
- Cierjacks A, Hensen I (2004) Variation of stand structure and regeneration of Mediterranean holm oak along a grazing intensity gradient. *Plant Ecology* 173:215–223. <https://doi.org/10.1023/B:VEGE.0000029322.75004.ad>
- Cierjacks A, Rühr NK, Wesche K, Hensen I (2008) Effects of altitude and livestock on the regeneration of two tree line forming species in Ecuador. *Plant Ecology* 194:207–221. <https://doi.org/10.1007/s11258-007-9285-x>
- Cierjacks A, Pommeranz M, Schulz K, Almeida-Cortez JS (2016) Is crop yield related to weed species diversity and biomass in coconut and banana fields of northeastern Brazil? *Agriculture, Ecosystems & Environment* 220:175–183. <https://doi.org/10.1016/j.agee.2016.01.006>
- Coates DB, Penning P (2000) Measuring animal performance. In: 't Mannetje L, Jones RM (eds) Field and laboratory methods for grassland and animal production research. CAB International, Cambridge, UK, pp 353–402
- Crawley MJ (2007) *The R book* (1st ed). John Wiley & Sons, Chichester, UK
- Derner JD, Boutton TW, Briske DD (2006) Grazing and ecosystem carbon storage in the North American Great Plains. *Plant and Soil* 280:77–90. <https://doi.org/10.1007/s11104-005-2554-3>
- Embrapa–Empresa Brasileira de Pesquisa Agropecuária Ministério da Agricultura, Pecuária e Abastecimento (2001a) Mapa Exploratório-Reconhecimento de solos do município de Floresta, PE. Retrieved from <http://www.uep.cnps.embrapa.br/solos/pe/floresta.pdf>. Accessed Oct 2013
- Embrapa–Empresa Brasileira de Pesquisa Agropecuária Ministério da Agricultura, Pecuária e Abastecimento (2001b) Mapa Exploratório-Reconhecimento de solos do município de Itacuruba, PE. Retrieved from <http://www.uep.cnps.embrapa.br/solos/pe/itacuruba.pdf>. Accessed Oct 2013

- Follett RF, Reed DA (2010) Soil carbon sequestration in grazing lands: societal benefits and policy implications. *Rangeland Ecology & Management* 63:4–15. <https://doi.org/10.2111/08-225.1>
- Fraga VS, Salcedo IH (2004) Declines of organic nutrient pools in tropical semi-arid soils under subsistence farming. *Soil Science Society of America Journal* 68:215–224. <https://doi.org/10.2136/sssaj2004.2150>
- Freitas ADS, Sampaio EVSB, Santos CERS, Fernandes AR (2010) Biological nitrogen fixation in tree legumes of the Brazilian semi-arid caatinga. *Journal of Arid Environments* 74:344–349. <https://doi.org/10.1007/s10705-012-9545-6>
- Giongo V, Galvão SRS, Mendes AMS, Gava CAT, Cunha TJF (2011) Soil organic carbon in the Brazilian semi-arid tropics. *Dynamic Soil, Dynamic Plant* 5:12–20.
- Google Earth (2013) Version 7.1.2.2041. Retrieved from <http://www.google.com/earth>. Accessed Oct 2013
- Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: a meta analysis. *Global Change Biology* 8:345–360. <https://doi.org/10.1046/j.1354-1013.2002.00486.x>
- Hart RH (2001) Plant biodiversity on shortgrass steppe after 55 years of zero, light, moderate, or heavy cattle grazing. *Plant Ecology* 155:111–118. <https://doi.org/10.1023/A:1013273400543>
- Hassink J (1994) Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. *Soil Biology and Biochemistry* 26:1221–1231. [https://doi.org/10.1016/0038-0717\(94\)90147-3](https://doi.org/10.1016/0038-0717(94)90147-3)
- Hassink J (1997) The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil* 191:77–87. <https://doi.org/10.1023/A:1004213929699>
- Haynes RJ, Williams PH (1993) Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy* 49:119–199. [https://doi.org/10.1016/S0065-2113\(08\)60794-4](https://doi.org/10.1016/S0065-2113(08)60794-4)
- IPCC–Intergovernmental Panel on Climate Change (2013). Summary for Policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, USA
- Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10:423–436. [https://doi.org/10.1890/1051-0761\(2000\)010\[0423:TVDOSO\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2)
- Kallah MS, Adamu AM (1988) The importance of animal faeces as fertiliser. In: Gefu JO, Adu IF, Lefadeju EA, Kallah MS, Awogbade MO (eds) *Pastoralism in Nigeria: Past, Present and Future*. Proceedings of the National Conference on Pastoralism in Nigeria held at NAPRI Shika-Zaria, 26–29 June 1988, pp 118–126
- Kauffman JB, Sanford RL, Cummings DL, Salcedo IH, Sampaio EVSB (1993) Biomass and nutrient dynamics associated with slash fires in neotropical dry forests. *Ecology* 74:140–151. <https://doi.org/10.2307/1939509>

- Kirschbaum MUF (2000) Will changes in soil organic carbon act as a positive or negative feedback on global warming? *Biogeochemistry* 48:21–51. <https://doi.org/10.1023/A:1006238902976>
- Kotzé E, Sandhage-Hofmann A, Meinel J A, du Preez CC, Amelung W (2013) Rangeland management impacts on the properties of clayey soils along grazing gradients in the semi-arid grassland biome of South Africa. *Journal of Arid Environments* 97:220–229. <https://doi.org/10.1016/j.jaridenv.2013.07.004>
- Lal R (2004) Carbon sequestration in dryland ecosystems. *Environmental management* 33:528–544. <https://doi.org/10.1007/s00267-003-9110-9>
- LDS NRW–Landesamt für Datenverarbeitung und Statistik Nordrhein-Westfalen (2005) Agrarstrukturerhebung 2003 - Gemeinde- und Kreisstatistik der landwirtschaftlichen Betriebe – Betriebsgrößen, Bodennutzung und Viehhaltung; sozialökonomische Betriebstypen und betriebswirtschaftliche Ausrichtung; Arbeitskräfte – Korrigierte Fassung. LDS NRW, Germany
- Maia SMF, Xavier FAS, Oliveira TS, Mendonça ES, Araújo Filho JA (2007) Organic carbon pools in a Luvisol under agroforestry and conventional farming systems in the semi-arid region of Ceará, Brazil. *Agroforestry Systems* 71:127–138
- Manzano MG, Návar J (2000) Processes of desertification by goats overgrazing in the Tamaulipan thornscrub (matorral) in north-eastern Mexico. *Journal of Arid Environments* 44:1–17. <https://doi.org/10.1006/jare.1999.0577>
- Mayes M, Marin-Spiotta E, Szymanski L, Erdoğan MA, Ozdoğan M, Clayton M (2014) Soil type mediates effects of land use on soil carbon and nitrogen in the Konya Basin, Turkey. *Geoderma* 232:517–527. <https://doi.org/10.1016/j.geoderma.2014.06.002>
- Menezes RSC, Sampaio EVSB, Giongo V, Pérez-Marin AM (2012) Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. *Brazilian Journal of Biology* 72:643–653. <https://doi.org/10.1590/S1519-69842012000400004>
- Milchunas DG, Lauenroth WK (1993) Quantitative effects of grazing on vegetation and soils over a global range of environments. *Ecological Monographs* 63:327–366. <https://doi.org/10.2307/2937150>
- Miles L, Newton AC, DeFries RS, Ravillious C, May I, Blyth S, Gordon JE (2006) A global overview of the conservation status of tropical dry forests. *Journal of Biogeography* 33:491–505. <https://doi.org/10.1111/j.1365-2699.2005.01424.x>
- MMA–Ministério do Meio Ambiente (2011) Subsídios para a elaboração do plano de ação para a prevenção e controle do desmatamento na Caatinga. Ministério do Meio Ambiente, Brasília, Brazil. Retrieved from http://www.mma.gov.br/estruturas/203/_arquivos/diagnostico_do_desmatamento_na_caatinga_203_2_203_1.pdf. Accessed Sep 2015
- Oosterheld M, Loreti J, Semmartin M, Paruelo J (1999) Grazing, fire, and climate effects on primary productivity of grasslands and savannas. In: Walker LR (ed) *Ecosystems of disturbed ground*. Elsevier, Amsterdam, Netherlands, pp 287–306
- Oliveira JA, Gonçalves PR, Bonvicino CR (2003) Mamíferos da Caatinga. In: Leal IR, Tabarelli M, da Silva JMC (eds) *Ecologia e Conservação da Caatinga*, Universitária da UFPE, Recife, Brazil, pp 275–302

- Piñeiro G, Paruelo J, Oesterheld M, Jobbágy EG (2010) Pathways of grazing effects on soil organic carbon and nitrogen. *Rangeland Ecology & Management* 63:109–119. <https://doi.org/10.2111/08-255.1>
- Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology* 6:317–327. <https://doi.org/10.1046/j.1365-2486.2000.00308.x>
- Prentice IC, Farquhar GD, Fasham MJR, Goulden ML, Heimann M, Jaramillo VJ, Kheshgi HS, LeQuéré C, Scholes RJ, Wallace DWR (2001) The Carbon Cycle and Atmospheric Carbon Dioxide. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) *Climate Change 2001: the Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp 185–237
- R Core Team (2012) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from <http://www.R-project.org/>. Accessed Jan 2016
- Reeder JD, Schuman GE (2002) Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. *Environmental Pollution* 116:457–463. [https://doi.org/10.1016/S0269-7491\(01\)00223-8](https://doi.org/10.1016/S0269-7491(01)00223-8)
- Resh SC, Binkley D, Parrota JA (2002) Greater soil carbon sequestration under nitrogen-fixing trees compared with Eucalyptus species. *Ecosystems* 5:217–253. <https://doi.org/10.1007/s10021-001-0067-3>
- Rieger I, Lang F, Kowarik I, Cierjacks A (2014) The interplay of sedimentation and carbon accretion in riparian forests. *Geomorphology* 214:157–167. <https://doi.org/10.1016/j.geomorph.2014.01.023>
- Romano PA, Garcia EAC (1999) Policies for water-resources planning and management of the São Francisco River. In: Biswas AK, Cordeiro NV, Braga BPF, Tortajada C (eds) *Management of Latin American River Basins: Amazon, Plata, and São Francisco*. United Nations University Press, Tokyo, Japan, pp 245–272
- Salcedo IH, Menezes RSC (2009) Agroecosystem functioning and management in semi-arid Northeastern Brazil. In: Tiessen H, Stewart JWB (eds) *Applying ecological knowledge to landuse decisions. Inter-American Institute for Global Change Research - IICA-IAI-Scope*, Paris, France, pp 73-81
- Sampaio EVSB (1995) Overview of the Brazilian Caatinga. In: Bullock SH, Mooney HA, Medina E (eds) *Seasonally dry tropical forests*. Cambridge University Press, Cambridge, UK, pp 35–63
- Sampaio EVSB (2010) Características e potencialidades. In: Gariglio MA, Sampaio EVSB, Cestaro LA, Kageyama P (eds) *Uso sustentável e conservação dos recursos florestais da caatinga*. Ministério do Meio Ambiente, Brasília, Brazil, pp 29–48
- Sampaio EVSB, Silva GC (2005) Biomass equations for Brazilian semiarid caatinga plants. *Acta Botanica Brasilica* 19:935–943. <https://doi.org/10.1590/S0102-33062005000400028>
- Santos JC, Leal IR, Almeida-Cortez JS, Fernandes GW, Tabarelli M (2011) Caatinga: the scientific negligence experienced by a dry tropical forest. *Tropical Conservation Science* 4:276–286

- Säumel I, Ziche D, Yu R, Kowarik I, Overdieck D (2011) Grazing as driver for *Populus euphratica* woodland degradation in the semi-arid Aibi Hu Region, northwestern China. *Journal of Arid Environments* 75:265–269. <https://doi.org/10.1016/j.jaridenv.2010.10.013>
- Schils R, Kuikman P, Liski J, Van Oijen M, Smith P, Webb J, Alm J, Somogyi Z, Van den Akker J, Billett M, Emmett B, Evans C, Lindner M, Palosuo T, Bellamy P, Alm J, Jandl R, Hiederer R (2008) Review of existing information on the interrelations between soil and climate change. (ClimSoil). Final report
- Schimel DS, House JI, Hibbard KA, Bousquet P, Ciais P, Peylin P, Braswell BH, Apps MJ, Baker D, Bondeau A, Canadell J, Churkina G, Cramer W, Denning AS, Field CB, Friedlingstein P, Goodale C, Heimann M, Houghton RA, Melillo JM, Moore III B, Murdiyarso D, Noble I, Pacala SW, Prentice IC, Raupach MR, Rayner PJ, Scholes RJ, Steffen WL, Wirth C (2001) Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature* 414:169–172. <https://doi.org/10.1038/35102500>
- Sousa SCD, Oliveira VPVD, Silva JMFD, Melo RAD Azevedo R (2013) The use of lands from small watershed of riacho Itacuruba-PE. In: Gunkel G, Silva JAA, Sobral MC (eds) *Sustainable Management of Water and Land in Semiarid Areas*. Editora Universitária UFPE, Recife, Brazil, pp 129–143
- Stavi I, Ungar ED, Lavee H, Sarah P (2008) Grazing-induced spatial variability of soil bulk density and content of moisture, organic carbon and calcium carbonate in a semi-arid rangeland. *Catena* 75:288–296. <https://doi.org/10.1016/j.catena.2008.07.007>
- Stern M, Quesada M, Stoner KE (2002) Changes in composition and structure of a tropical dry forest following intermittent cattle grazing. *Revista de Biología Tropical* 50: 1021–1034.
- Throop HL, Archer SR, Monger HC, Waltman S (2012) When bulk density methods matter: Implications for estimating soil organic carbon pools in rocky soils. *Journal of Arid Environments* 77: 66–71. <https://doi.org/10.1016/j.jaridenv.2011.08.020>
- Tiessen H, Feller C, Sampaio EVSB, Garin P (1998) Carbon sequestration and turnover in semiarid savannas and dry forest. *Climatic Change* 40:105–117. <https://doi.org/10.1023/A:1005342932178>
- Tilman D, Reich PD, Isbell F (2012) Biodiversity impacts ecosystem productivity as much as resources, disturbance, or herbivory. *Proceedings of the National Academy of Sciences* 109:10394–10397. <https://doi.org/10.1073/pnas.1208240109>
- Torres FSDM, Santos Pfaltzgraff PAD (2014) Geodiversidade do estado de Pernambuco, Programa Geologia do Brasil. Levantamento da Geodiversidade. CPRM, Recife, Brazil. Retrieved from <http://rigeo.cprm.gov.br/jspui/handle/doc/16771>. Accessed Jan 2016
- Von Wehrden H, Hanspach J, Kaczensky P, Fische, J, Wesche K (2012) Global assessment of the non-equilibrium concept in rangelands. *Ecological Applications* 22: 393–399. <https://doi.org/10.1890/11-0802.1>
- Wang D, Wu GL, Zhu YJ, Shi ZH (2014) Grazing exclusion effects on above-and below-ground C and N pools of typical grassland on the Loess Plateau (China). *Catena* 123:113–120. <https://doi.org/10.1016/j.catena.2014.07.018>

- Wiesmeier M, Munro S, Barthold F, Steffens M, Schad P, Kögel-Knabner I (2015) Carbon storage capacity of semi-arid grassland soils and sequestration potentials in Northern China. *Global Change Biology* 21:3836–3845. <https://doi.org/10.1111/gcb.12957>
- Wu H, Wiesmeier M, Yu Q, Steffens M, Han X, Kögel-Knabner I (2012) Labile organic C and N mineralization of soil aggregate size classes in semiarid grasslands as affected by grazing management. *Biology and Fertility of Soils* 48:305–313. <https://doi.org/10.1007/s00374-011-0627-4>
- Yachi S, Loreau M (1999) Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. *Proceedings of the National Academy of Sciences* 96:1463–1468. <https://doi.org/10.1073/pnas.96.4.1463>
- Zuur AF, Ieno EN, Elphick CS (2010) A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution* 1:3–14. <https://doi.org/10.1111/j.2041-210X.2009.00001.x>



CHAPTER 6

Synthesis

The following chapter will summarise and discuss the key findings of the thesis with respect to the overall aims. It will follow the main objectives of the thesis. These are:

- (1) Analysing the Caatinga plant diversity and species assemblage along a gradient of land-use intensity (preserved Caatinga, intermediate grazing intensity, high grazing intensity, irrigation farming).
- (2) Quantifying organic carbon stocks (above- and belowground) in areas with different land-use intensities.
- (3) Exploring the role of further environmental parameters such as proxies for anthropogenic influences, soil properties, and altitude.

Plant diversity, species assemblage, and land use

Several studies investigated the plant diversity of Caatinga dry forests. However, for the first time, plant diversity is related to actual land-use intensities (preserved Caatinga, varying grazing intensities, irrigation farming). While other studies investigated exclosures or succession areas to determine the effect of grazing on the vegetation, using livestock faeces for the determination of actual grazing intensities is a new approach for the Caatinga region. Moreover, this study presents the first assessment of weed species diversity within an area of irrigation farming (formerly Caatinga dry forest). Further, the present work is the most comprehensive study regarding considered plant types. While other surveys either investigated woody plants (with a certain minimal diameter size) or herbaceous species, the present study takes into account all vascular plant species found on the study plots:

trees, shrubs, subshrubs, cacti, bromeliads, vines, and herbs of all sizes including weed species found in areas of irrigation farming.

Plot sizes and methods for the assessment of plant diversity differed according to the different plant types and land use. The tree and shrub layer (including cacti, bromeliads, and vines) of Caatinga dry forest areas was assessed on 20 m × 20 m plots ($n = 45$ plots). Here, all individuals were counted due to the overall low forest densities and the difficulty of estimating cover values of trees and shrubs. These numbers were also used to determine overall forest densities. The herb layer of Caatinga dry forest areas was assessed after the first rainfall in 2014 on four 2 m × 2 m subplots per plot (in total 16 m²), due to time constraints on 36 of the 45 study plots only. In contrast to the spatially highly heterogeneous Caatinga dry forests, the vegetation in the agrarian areas was relatively homogeneous and smaller study plots were sufficient for the assessment of weed diversity. It was assessed on two 5 m × 5 m plots per crop field, with one located in the centre of a field and a second one at the field edge. Both plots per crop field were regarded as

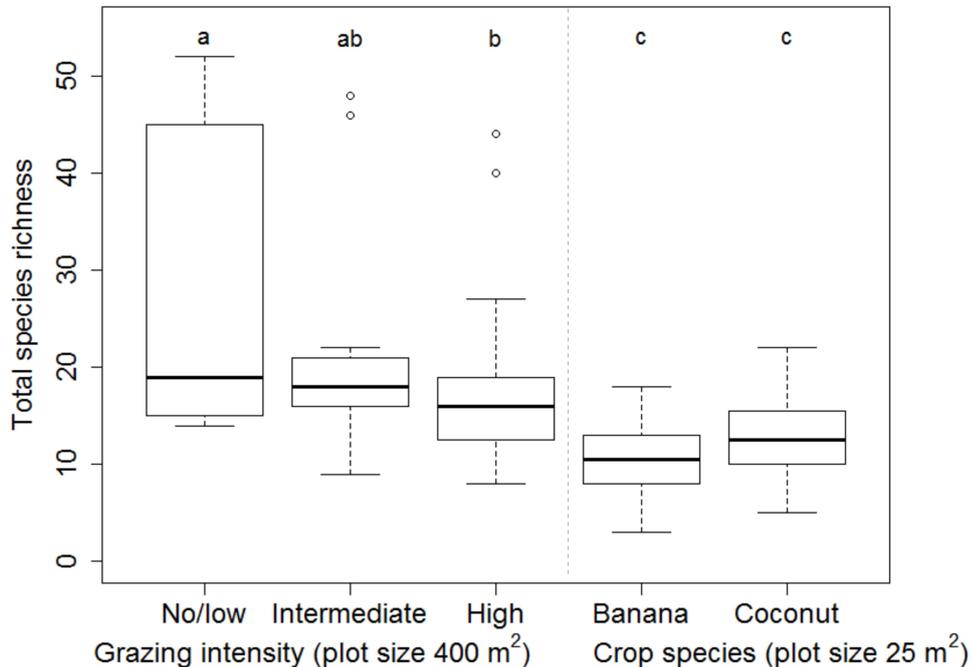


Figure 6.1 Plant species richness of all species found in Caatinga forests at different grazing intensities (no/low, intermediate, high) and agrarian areas with different crop species (banana, coconut). Lowercase letters indicate significant differences in GLMs. The species richness of herbs (Caatinga) was assessed on smaller subplots (16 m² per plot).

independent. The method of Braun-Blanquet (cover-abundance scale; 1964) was used for the assessment of weed species in the agrarian areas and herbaceous plant species in the Caatinga dry forests.

In total, 209 plant species were found of which 34 could not be identified at species level, 10 could not be identified at genus level, and 33 could not be identified at family level. Plant species include trees, shrubs, subshrubs, cacti, bromeliads, herbs, vines, hemiparasites, and epiphytes (Appendix 6.1). 140 and 77 plant taxa were found on the Caatinga dry forest and agrarian plots respectively. Comparing the full set of plant species, areas with the lowest grazing impact clearly showed the highest number of plant species (mean = 27), while agrarian areas showed generally lower species numbers (mean = 12; Figure 6.1). The most striking difference in species composition was the absence of tree species in the agrarian areas. While trees were the largest portion of plant species in the Caatinga, no trees, cacti, or bromeliads were found in the crop fields (Appendix 6.1). This finding is most likely explained by the complete removal of the native Caatinga vegetation before the establishment of crop fields. Yet, 22 subshrub and shrub species were found within the crop fields, indicating the recovery of native Caatinga vegetation. Twenty of these 22 woody species were native species with four of them being endemic to the Caatinga. However, only 13 plant species were found in the agrarian areas as well as the Caatinga plots, with only nine of them being native to the Caatinga. The species numbers in grazed Caatinga dry forest areas were clearly lower compared to the agrarian areas when tree species were excluded (Appendix 6.2; Appendix 6.3), which is probably attributed to the low number of herbaceous species found during this study. Although the sampling of herbaceous species was carried out after the first heavy rainfall, the persisting drought accompanied by high grazing pressure probably led to an overall low number of herbaceous species (Chapter 2). A high number of recently dead trees and shrubs (own observations; oral information by farmers) confirm the negative effect of the prolonged drought on the native vegetation. Overall, the data indicate a lack of Caatinga plant species within the studied Caatinga dry forest areas and reinforce the assumption that many of the investigated places were degraded. Three endemic Caatinga plant species were found exclusively in plots of the agrarian field edges (Appendix 6.1), emphasising the importance of field margins for biodiversity conservation. Favourable growing conditions, a lack of grazing pressure, and a robustness against

pesticides (Chapter 3) probably facilitate the presence of these species in the agrarian areas.

Organic carbon stocks and land management

The importance of organic carbon (OC) storage and stocks for the climate has long been acknowledged (e.g., Canadell & Raupach 2008). It is also well known that OC stocks as well as the potential to store carbon is threatened due to a vegetation loss caused by anthropogenic impacts (e.g., Menezes et al. 2012). Yet, there is a lack of scientific research which assesses OC stocks and elaborates on the effect of actual land-use intensities (preserved areas, livestock husbandry with varying grazing intensities, irrigation farming) on OC stocks in the tropics. The present work aims at filling this gap and presents the first comprehensive study on OC stocks (above- and belowground) for the Caatinga region with its main focus on the effect of different land-use intensities. Previous Caatinga studies on carbon stocks regarded either woody species of a certain size, herbaceous species, or soil. In contrast, the present work present a comprehensive overview including woody plants with a diameter at ground level > 3 cm as well as herbaceous plants (Chapter 4), soil organic carbon stocks (Chapter 5), and extends the assessment of carbon stocks to agrarian areas (Chapter 3). Moreover, in the present study, the weight of livestock faeces is used to determine the effect of actual grazing intensities on OC stocks compared less precise methods used in other studies (livestock numbers, exclosures, or reserves).

Aboveground carbon stocks

The plot sizes for the assessment of aboveground carbon stocks (AGCS) differed according to the different plant types and ecosystems (Caatinga: tree and shrub layer including cacti and bromeliads, herbs; agrarian areas: crop plants, weeds). In the relatively heterogeneous Caatinga dry forest areas, the assessment of the tree and shrub layer was carried out on 10 m × 10 m plots, while in the homogeneous crop fields with only one crop species, a smaller plot size of 5 m × 5 m seemed sufficient for the assessment of crop biomass. On each plot, the circumference and height of plants were measured at ground level (Caatinga dry forests, only plants with diameter at ground level > 3 cm) or at breast height (crop fields, all crop plants).

Then, allometric equations were used to estimate the aboveground biomass of each plant. The plots sizes also differed for the assessment of herbaceous biomass. In the Caatinga dry forests, two subplots (each 2 m × 2 m) were used while in the densely vegetated crop fields, two smaller subplots per plot (0.5 m × 0.5 m) were considered. Here, all herbaceous plants or weed species (< 1 m in height) were harvested, dried, and weighed to determine biomass values. In all cases, biomass values were multiplied by 0.5 to gain carbon stock values.

The overall AGCS were highest in the banana fields (30.83 Mg ha⁻¹; Appendix 6.4), which is probably attributed to the high number of pseudostems per individual. In the Caatinga dry forests, the highest overall carbon stocks were found in areas with high grazing intensity (18.35 Mg ha⁻¹; Figure 6.2; Appendix 6.4), despite lower forest densities (Chapter 4). This might be explained by a higher number of large trees in the fenced pasture areas, which are protected in order to provide shade for the livestock. Herbaceous carbon stocks were clearly highest in the Caatinga dry forests with no/low and intermediate grazing intensity (mean = 1.42 Mg ha⁻¹; rainy

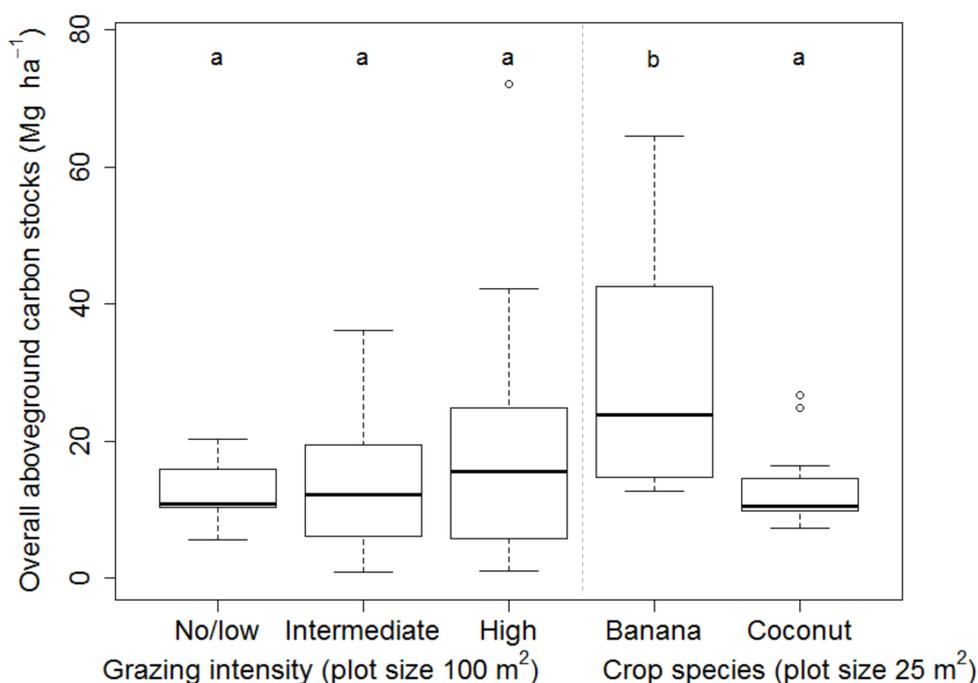


Figure 6.2 Overall aboveground carbon stocks of Caatinga vegetation at different grazing intensities (no/low, intermediate, high) and in agrarian areas with different crop species (banana, coconut). Lowercase letters indicate significant differences in GLMs. Aboveground carbon stocks of herbs (Caatinga) and weed species (crop fields) were assessed on smaller subplots (8 m² and 0.25 m² respectively).

season). In comparison, the AGCS of weed species (including subshrub and shrub species) in the agrarian areas were clearly lower (mean = 0.44 Mg ha⁻¹; banana and coconut together). This seems surprising, as about 22% of the 63 identified plant species within the agrarian plots were naturalised or cultivated plant species with favourable growing conditions (a year-round high water availability and no grazing pressure). Yet, the application of herbicides apparently suppresses a high weed biomass, despite a high weed species diversity (Chapter 3).

Soil organic carbon stocks

The assessment of soil organic carbon (SOC) stocks followed the same routine in the Caatinga dry forests and agrarian areas (Chapter 3 & 5). Per plot, three soil samples (100 cm³; 0–5 cm in depth) were taken and analysed.

Within both ecosystems, SOC stocks were severely affected by the current land use. In the Caatinga dry forests, SOC stocks in the upper 5 cm were significantly reduced by grazing (7.02 Mg ha⁻¹ vs. 3.39 Mg ha⁻¹; Figure 6.3; Appendix 6.5; Chapter 5). In the agrarian areas, SOC stocks were approximately as low as SOC stocks in the grazed Caatinga areas. The effect of land-use conversion from natural to agriculturally used ecosystems on SOC stocks has been investigated in several studies (Ogle et al. 2005; Zinn et al. 2005). Usually, tillage is found to have detrimental effects on SOC stocks in agrarian lands (Ogle et al. 2005; Maia et al. 2010; Giongo et al. 2018; Zinn et al. 2005). However, fields of perennial crops, such as coconut and banana, are normally not yearly ploughed. Thus, the lower SOC stocks in this study are presumably attributed to different processes. The year-round high temperature and water availability, which promote microbiological activity, probably lead to a higher rate of soil organic matter decomposition (Giardina & Ryan 2000) and thus lower SOC stocks. This assumption is also in line with Ogle et al. (2005) who found that in long-term cultivation the reduction of SOC was highest in tropical moist climates.

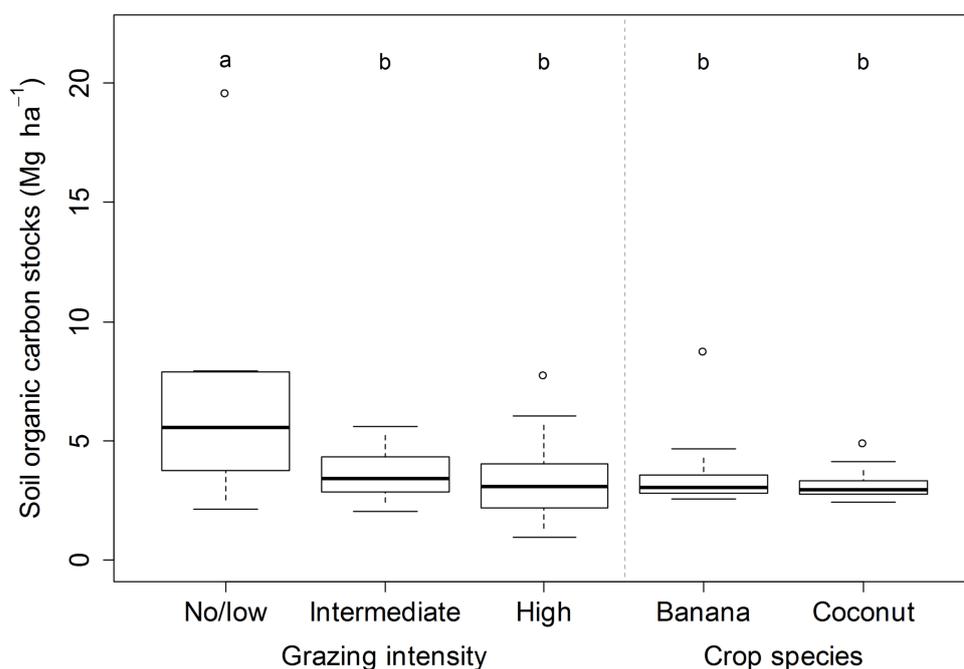


Figure 6.3 Soil organic carbon stocks of Caatinga soils at different grazing intensities (no/low, intermediate, high) and agrarian areas with different crop species (banana, coconut). Lowercase letters indicate significant differences in GLMs.

Impact of further parameters on vegetation and carbon stocks

The present study is focussing on the effect of different land-use options on the native Caatinga vegetation and SOC stocks. Nevertheless, to reveal underlying mechanisms, interactions, and dependencies, the role of further environmental parameters is explored. For each of the response variables (biodiversity indices, AGCS, forest density, population structure, and SOC), a set of environmental variables was analysed in addition to the explanatory variable 'grazing intensity'. These were: the distance to the nearest farmhouse, city, or permanent stream (for all response variables), altitude (for all response variables), biodiversity indices (for SOC), AGCS (for SOC), soil characteristics (for SOC and biodiversity), water availability class (for biodiversity), and the cover of sand, gravel, stones and rock, litter, and woody species (for biodiversity).

The distances to the next farmhouse, city, or permanent stream were analysed as means of anthropogenic impact (e.g., livestock density, slash-and-burn agriculture, timber and fuel wood extraction). In nearly all cases, an effect of these distance

measures on the response variable was found. However, the distance measures were also strongly positively correlated with altitude, but performed statistically worse. Therefore, the distance measures were excluded from all statistical analyses. Soil characteristics were found to have significant effects on the plant diversity (Chapter 2). However, again they were correlated to altitude and performed worse in the statistical analyses. Of all tested variables, altitude was by far the most important parameter with the highest predictive power in nearly all of the statistical analyses, also in comparison to grazing intensity. Yet, all study plots were within a minor range between 304 m and 397 m a.s.l. and thus, pronounced climatic changes along the altitudinal gradient cannot be expected. It is more likely that altitude showed such a strong effect, as it comprises various environmental parameters. For example, altitude can be regarded as an indicator for water availability. In this study, areas at low elevation are likely to have a higher water availability as they are either located near permanent water bodies or gain more water due to runoff. None of the plots was located at such high altitude that a higher precipitation is expected compared to lower areas. Moreover, the parameter altitude also serves as a proxy for anthropogenic impact. Areas at lower elevation are usually more accessible with a good access to water (e.g., rivers). This in turn increased and increases historic and present anthropogenic influences including a higher grazing pressure in lower areas (Revermann et al. 2016; Silva et al. 2014). Observed differences in Caatinga dry forest vegetation and carbon stocks might therefore also be attributed to the historic land use, such as intense timber harvest and slash-and-burn agriculture, often followed by overgrazing. This assumption is substantiated by the fact that in degraded areas, scattered exceptionally large individuals of *Aspidosperma pyriformium* were found, while the majority of these trees were characterised by small size. This suggests a former vegetation structure with higher plant densities and more large trees.

Outlook

The present study reveals significant negative effects of the current land use on plant diversity, species assemblage, and carbon stocks. Yet, the results suggest that further environmental parameters such as soil properties, water availability, or other anthropogenic influences (e.g., slash-and-burn agriculture, tree harvesting) play also

an important role. However, all these parameters are correlated in some way. In order to disentangle underlying processes, future studies should aim at including data on water availability (precipitation, availability of ground water, runoff). In order to assess the effect of the present land use on the vegetation it is important to take into account information regarding the historic land use (e.g., interviews with local residents) as the recovery of native vegetation takes a very long time in seasonally dry tropical forests. Moreover, the study region should be extended to different eco-regions of Caatinga dry forests or seasonally dry tropical forests in general to confirm study results or, instead, to reveal further underlying mechanisms. Although the Caatinga vegetation is adapted to the semi-arid climate, the vegetation within the study area was clearly affected by the last prolonged drought. For the assessment of drought damages, long-term studies are needed to monitor the vegetation under varying climatic conditions. In order to counteract climate change, it would be important to investigate whether or not the current land use contributes to the mortality of certain tree species and thus leads to a decline in ecosystem functions (e.g., carbon sequestration).

The findings of this study also reveal that the usage of agrochemicals did not increase the crop yield in coconut or banana fields. Thus, the reduction or entire substitution of agrochemicals (chemical fertilisers, herbicides, and insecticides) should be monitored with respect to possible changes in productivity and biodiversity.

Conclusions

This thesis presents a comprehensive study on plant diversity, forest density, population structure (regeneration), and carbon stocks (above- and belowground) for an area of Caatinga dry forests with different land-use intensities (preserved, grazed, converted to irrigated crop fields). It presents novel insights regarding the drivers of Caatinga vegetation and soil organic carbon stocks. Overall, this study provides evidence that the current land use is detrimental to the Caatinga vegetation and soil organic stocks. In contrast to the widely accepted intermediate disturbance hypothesis, the findings of this study show that grazing at intermediate and high intensities considerably reduced plant species diversity in Caatinga dry forests. In contrast, agrarian areas showed a high plant diversity, yet the species assemblage

showed only few similarities with the vegetation of neighbouring Caatinga dry forests. Although the overall aboveground carbon stocks in the Caatinga dry forests were not significantly reduced by grazing, the recruitment of Caatinga tree and shrub species (excluding the most common tree species) was negatively affected. In agrarian areas, no tree, cacti, or bromeliad species were found at all. However, agrarian use with year-round irrigation led to a notable gain in aboveground carbon stocks, albeit lower soil organic carbon stocks. In the Caatinga dry forests, soil organic carbon stocks were significantly reduced by grazing.

The main aim of stakeholder-based studies, such as the present work, is to derive sustainable land management recommendations based on the findings of the study. In cooperation with project partners from the overall research project INNOVATE and together with farmers and other stakeholders (e.g., NGOs), land-use recommendations were developed, discussed, and incorporated in a guidance manual. The most important recommendations are: Sustainable land management should aim at a rotational grazing system with reduced stockings numbers (max. 1 goat/sheep per hectare) and reduced free roaming livestock. Additionally, silage or hay as livestock fodder would support a higher vegetation cover. These measures should be accompanied by the efficient protection of species-rich Caatinga dry forest areas as source and stepping-stone habitats (preferably areas in wetland ecosystems, lake shores, or rocky outcrops) to allow for the recovery of species-poor and degraded areas. The conversion from Caatinga dry forests to agrarian land should aim at the sustainable production of perennial crops, including the cessation of agrochemical use in coconut and banana fields and the preference of organic fertiliser (goat manure). In addition, field margins should be preserved as they play a major role for agrarian biodiversity and provide habitats for pest predators, both with positive effects on crop yield (for more information see Siegmund-Schultze 2017).

References

- Braun-Blanquet J (1964) *Pflanzensoziologie. Grundzüge der Vegetationskunde* (3rd ed). Springer, Vienna, Austria
- Canadell JG, Raupach MR (2008) Managing forests for climate change mitigation. *Science* 320:1456–1457. <https://doi.org/10.1126/science.1155458>

- Giardina CP, Ryan MG (2000) Evidence that decomposition rates of organic carbon in mineral soil do not vary with temperature. *Nature* 404:858–861. <https://doi.org/10.1038/35009076>
- Giongo V, Salviano AM, Angelotti F, Taura T, Carvalho Leite LF, Ferreira Cunha TJ (2018) Low carbon technologies for agriculture in dryland: Brazilian Experience. In: Rao CS, Shanker AK, Shanker C (eds) *Climate Resilient Agriculture*. IntechOpen. <https://doi.org/10.5772/intechopen.72363>
- Maia SMF, Ogle SM, Cerri CC, Cerri CEP (2010) Changes in soil organic carbon storage under different agricultural management systems in the Southwest Amazon region of Brazil. *Soil and Tillage Research* 106:177–184. <https://doi.org/10.1016/j.still.2009.12.005>
- Menezes RSC, Sampaio EVSB, Giongo V, Pérez-Marin AM (2012) Biogeochemical cycling in terrestrial ecosystems of the Caatinga biome. *Brazilian Journal of Biology* 72:643–653. <https://doi.org/10.1590/S1519-69842012000400004>
- Ogle SM, Breidt FJ, Paustian K (2005) Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry* 72:87–121. <https://doi.org/10.1007/s10533-004-0360-2>
- Revermann R, Wallenfang J, Oldeland J, Finckh M (2016) Species richness and evenness respond to diverging land-use patterns—a cross-border study of dry tropical woodlands in southern Africa. *African Journal of Ecology* 55:152–161. <https://doi.org/10.1111/aje.12333>
- Siegmund-Schultze M (ed) (2017) *Guidance Manual – A compilation of actor-relevant content extracted from scientific results of the INNOVATE project*. Universitätsverlag der TU Berlin, Berlin, Germany
- Silva FKG, Faria Lopes S, Lopez LCS, Melo JIM, Trovão DMDBM (2014) Patterns of species richness and conservation in the Caatinga along elevational gradients in a semiarid ecosystem. *Journal of Arid Environments* 110:47–52. <https://doi.org/10.1016/j.jaridenv.2014.05.011>
- Zinn YL, Lal R, Resck DV (2005) Changes in soil organic carbon stocks under agriculture in Brazil. *Soil and Tillage Research* 84:28–40. <https://doi.org/10.1016/j.still.2004.08.007>

Appendix

Appendix 6.1 Plant species, their distribution, growth form, and origin. Nomenclature follows Flora do Brasil 2020 (<http://floradobrasil.jbrj.gov.br/>). [Common synonym]. (x) Not included in statistical analysis. *Endemic.

| Family | Species | Dry forests | Crop fields | Growth form | Origin | |
|---|---|--|-------------|----------------|-------------|---------|
| Amaranthaceae | <i>Alternanthera tenella</i> Colla | x | | herb | native | |
| | <i>Amaranthus</i> cf. <i>viridis</i> L. | x | x | herb | naturalised | |
| | <i>Dysphania ambrosioides</i> (L.) Mosyakin & Clemants | x | | herb | naturalised | |
| | <i>Froelichia humboldtiana</i> (Roem. & Schult.) Seub. | x | | herb | native | |
| | <i>Gomphrena demissa</i> Mart. | x | | herb | native* | |
| | <i>Gomphrena vaga</i> Mart. | x | | herb/shrub | native* | |
| Anacardiaceae | <i>Myracrodruon urundeuva</i> Allemão | x | | tree | native | |
| | <i>Schinopsis brasiliensis</i> Engl. | x | | tree | native | |
| | <i>Spondias tuberosa</i> Arruda | x | | tree | native* | |
| Apocynaceae | <i>Allamanda</i> sp. | x | | - | - | |
| | <i>Aspidosperma pyriforme</i> Mart. | x | | tree | native | |
| Asteraceae | <i>Acanthospermum hispidum</i> DC. | | x | herb | native | |
| | <i>Ageratum conyzoides</i> L. | | x | herb | native | |
| | <i>Bidens pilosa</i> L. | x | x | herb | naturalised | |
| | <i>Centratherum</i> sp. | x | | herb | - | |
| | <i>Chromolaena odorata</i> (L.) R.M.King & H. Rob. | | x | herb/subshrub | native | |
| | <i>Conyza bonariensis</i> (L.) Cronquist | | x | herb | native | |
| | <i>Cyanthillium cinereum</i> (L.) H.Rob. | | x | herb | native | |
| | <i>Eclipta prostrata</i> (L.) L. | x | x | herb | native | |
| | <i>Emilia sonchifolia</i> (L.) DC. ex Wight | | x | herb | native | |
| | <i>Lagascea mollis</i> Cav. | x | | herb | native | |
| | <i>Pluchea sagittalis</i> (Lam.) Cabrera | | x | herb/subshrub | native | |
| | <i>Porophyllum ruderale</i> (Jacq.) Cass. | | x | herb | native | |
| | <i>Tridax procumbens</i> L. | x | x | herb | native | |
| | <i>Tabebuia aurea</i> (Silva Manso) Benth. & Hook. f. ex S. Moore | x | | tree | native | |
| | Boraginaceae | <i>Cordia</i> sp. | x | | shrub | - |
| <i>Euploca humilis</i> (L.) Feuillet [<i>Heliotropium</i> cf. <i>ternatum</i> Vahl] | | x | | herb, subshrub | native | |
| <i>Euploca procumbens</i> (Mill.) Diane & Hilger [<i>Heliotropium procumbens</i> Mill.] | | x | | herb | native | |
| <i>Varronia globosa</i> Jacq. [<i>Cordia globosa</i> (Jacq.) Kunth] | | x | | shrub | native | |
| <i>Varronia leucocephala</i> (Moric.) J.S.Mill. [<i>Cordia leucocephala</i> Moric.] | | x | | shrub | native* | |
| Bromeliaceae | | <i>Bromelia laciniosa</i> Mart. ex Schult. & | x | | herb | native* |

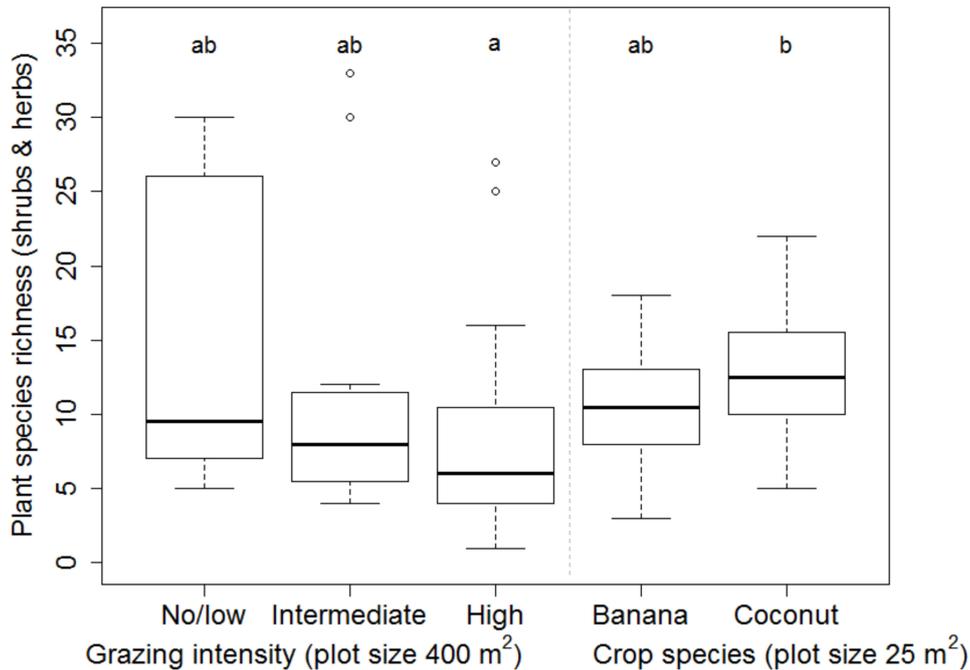
| Family | Species | Dry forests | Crop fields | Growth form | Origin |
|----------------|---|-------------|-------------|----------------------------|-------------|
| | Schult. f. | | | | |
| | <i>Encholirium spectabile</i> Mart. ex Schult. & Schult. f. | x | | herb | native* |
| | <i>Neoglaziovia variegata</i> (Arruda) Mez. | x | | herb | native* |
| | <i>Tillandsia</i> sp. | x | | herb (epiphyte) | - |
| Burseraceae | <i>Commiphora leptophloeos</i> (Mart.) J.B. Gillett | x | | tree | native |
| Cactaceae | <i>Cereus jamacaru</i> DC. | x | | tree (succulent) | native* |
| | <i>Melocactus bahiensis</i> (Britton & Rose) Luetzelb. | (x) | | herb/subshrub (succulent) | native* |
| | <i>Melocactus zehntneri</i> (Britton & Rose) Luetzelb. | x | | subshrub (succulent) | native* |
| | <i>Pilosocereus gounellei</i> (F.A.C.Weber) Byles & Rowley | x | | shrub (succulent) | native* |
| | <i>Pilosocereus piauhyensis</i> (Gürke) Byles & G.D.Rowley | x | | shrub (succulent) | native* |
| | <i>Tacinga inamoena</i> (K.Schum.) N.P. Taylor & Stuppy | x | | subshrub (succulent) | native* |
| | <i>Tacinga palmadora</i> (Britton & Rose) N.P. Taylor & Stuppy | x | | subshrub/shrub (succulent) | native* |
| Capparaceae | <i>Cynophalla</i> aff. <i>hastata</i> (Jacq.) J.Presl | x | | shrub | native |
| Celastraceae | <i>Monteverdia rigida</i> (Mart.) Biral [Maytenus rigida Mart.] | x | | shrub/tree | native* |
| Cleomaceae | <i>Cleome</i> sp. | x | | - | - |
| Commelinaceae | <i>Commelina benghalensis</i> L. | | x | herb | naturalised |
| | <i>Tripogandra diuretica</i> (Mart.) Handlos | | x | herb | native |
| Convolvulaceae | <i>Evolvulus frankenioides</i> Moric. | | x | herb | native |
| | <i>Evolvulus glomeratus</i> Nees & Mart. | x | | herb/subshrub | native |
| | <i>Evolvulus</i> sp. 1 | x | | - | - |
| | <i>Evolvulus</i> sp. 2 | x | | - | - |
| | <i>Ipomoea asarifolia</i> (Desr.) Roem. & Schult. | (x) | x | herb (vine) | native |
| | <i>Ipomoea subincana</i> (Choisy) Meisn. | x | | (vine) | native* |
| | <i>Ipomoea</i> sp. 1 | x | | - | - |
| | <i>Ipomoea</i> sp. 2 | x | | - | - |
| | <i>Jacquemontia</i> sp. 1 | x | | (vine) | - |
| | <i>Jacquemontia</i> sp. 2 | x | | - | - |
| | <i>Merremia aegyptia</i> (L.) Urb. | | x | (vine) | native |
| Cucurbitaceae | <i>Citrullus lanatus</i> (Thunb.) Matsum. & Nakai | | x | (vine) | cultivated |
| | <i>Momordica charantia</i> L. | | x | (vine) | naturalised |
| Cyperaceae | <i>Cyperus compressus</i> L. | | x | herb | native |
| | <i>Cyperus distans</i> L. | | x | herb | native |
| | <i>Cyperus entrerianus</i> Boeckeler | | x | herb | native |
| | <i>Cyperus rigens</i> C.Presl | | x | herb | native |

| Family | Species | Dry forests | Crop fields | Growth form | Origin | |
|---|--|--|-------------|-------------------------|-------------------------|--------|
| Euphorbiaceae | <i>Astraea lobata</i> (L.) Klotzsch | | x | herb | native | |
| | <i>Chamaesyce</i> sp. | x | | - | - | |
| | <i>Cnidoscolus urens</i> (L.) Arthur | x | | subshrub/shrub | native | |
| | <i>Cnidoscolus</i> aff. <i>vitifolius</i> (Mill.) Pohl | x | | shrub/tree | native | |
| | <i>Cnidoscolus quercifolius</i> Pohl | x | | shrub/tree | native* | |
| | <i>Croton</i> cf. <i>blanchetianus</i> Baill. | x | x | shrub | native* | |
| | <i>Croton cordiifolius</i> Baill. | x | | shrub | native* | |
| | <i>Croton heliotropiifolius</i> Kunth | x | x | shrub | native | |
| | <i>Croton hirtus</i> L' Hér. | (x) | | herb | native | |
| | <i>Croton</i> sp. 1 | x | | shrub | - | |
| | <i>Croton</i> sp. 2 | x | | shrub | - | |
| | <i>Croton</i> sp. 3 | x | | shrub | - | |
| | <i>Croton</i> sp. 4 | x | | shrub | - | |
| | <i>Ditaxis malpighiacea</i> (Ule) Pax & K. Hoffm. | x | | subshrub/shrub | native* | |
| | <i>Euphorbia heterophylla</i> L. | | x | herb | native | |
| | <i>Euphorbia hirta</i> L. | | x | herb | native | |
| | <i>Jatropha mollissima</i> (Pohl) Baill. | x | | shrub/tree | native | |
| | <i>Jatropha gossypifolia</i> L. | | x | herb/subshrub/ shrub | native | |
| | <i>Jatropha ribifolia</i> (Pohl) Baill. | x | | subshrub/shrub | native | |
| | <i>Manihot</i> sp. | x | | tree | - | |
| | <i>Sapium glandulosum</i> (L.) Morong | x | | shrub/tree | native | |
| | Fabaceae | <i>Aeschynomene brasiliana</i> (Poir.) DC. | | x | herb/subshrub/ shrub | native |
| | | Aff. <i>Amburana cearensis</i> (Allemão) A.C.Sm. | x | | tree | native |
| <i>Anadenanthera colubrina</i> var. <i>cebil</i> (Griseb.) Altschul | | x | | tree | native | |
| <i>Bauhinia</i> sp. | | x | | shrub/tree | - | |
| <i>Chamaecrista pascuorum</i> (Benth.) H.S.Irwin & Barneby | | | x | herb/subshrub | native* | |
| <i>Chloroleucon dumosum</i> (Benth.) G.P.Lewis | | x | | tree | native* | |
| <i>Crotalaria pallida</i> Aiton | | | x | subshrub | naturalised | |
| <i>Crotalaria pilosa</i> Mill. | | | x | herb/subshrub | native | |
| <i>Desmodium incanum</i> (Sw.) DC. | | | x | subshrub | naturalised | |
| <i>Cenostigma pyramidale</i> (Tul.) Gagnon & G.P.Lewis | | | | | | |
| [<i>Poincianella pyramidalis</i> (Tul.) L.P.Queiroz] | | x | | shrub/tree | native* | |
| <i>Indigofera hirsuta</i> L. | | | x | herb/subshrub | native | |
| Aff. <i>Libidibia ferrea</i> (Mart. ex Tul.) L.P.Queiroz | | x | | tree | native* | |
| <i>Macroptilium martii</i> (Benth.) Maréchal & Baudet | | (x) | | herb (vine) | native | |

| Family | Species | Dry forests | Crop fields | Growth form | Origin |
|----------------|--|-------------|-------------|-------------------------|-------------|
| | <i>Mimosa tenuiflora</i> (Willd.) Poir | x | | subshrub/ shrub/tree | native |
| | <i>Mimosa ophthalmocentra</i> Mart. ex Benth. | x | | shrub/tree | native* |
| | <i>Mimosa</i> sp. 1 | x | | tree | - |
| | <i>Mimosa</i> sp. 2 | | x | - | - |
| | <i>Piptadenia stipulacea</i> (Benth.) Ducke | x | | shrub | native* |
| | <i>Pithecellobium diversifolium</i> Benth. | x | | shrub/tree | native* |
| | <i>Pithecellobium</i> sp. | x | | tree | - |
| | <i>Poincianella microphylla</i> (Mart. ex G.Don) L.P.Queiroz | x | | shrub/tree | native* |
| | <i>Prosopis juliflora</i> (Sw.) DC. | x | | tree | cultivated |
| | <i>Senna occidentalis</i> (L.) Link | | x | shrub/subshrub | native |
| | <i>Senegalia tenuifolia</i> (L.) Britton & Rose | x | | shrub (vine) | native |
| | <i>Zornia brasiliensis</i> Vogel | x | | subshrub | native |
| | Fabaceae sp. 1 | | x | - | - |
| | Fabaceae sp. 2 | | x | - | - |
| | Fabaceae sp. 3 | | x | - | - |
| | Fabaceae sp. 4 | | x | - | - |
| Lamiaceae | <i>Ocimum</i> sp. | x | | - | - |
| Loganiaceae | <i>Spigelia anthelmia</i> L. | | x | herb | native |
| Loranthaceae | Loranthaceae sp. 1 | x | | - | - |
| | Loranthaceae sp. 2 | x | | - | - |
| Malvaceae | <i>Herissantia crispa</i> (L.) Brizicky | | x | herb/subshrub/ shrub | native |
| | <i>Herissantia tiubae</i> (K. Schum.) Brizicky | x | | - | - |
| | <i>Herissantia</i> sp. | x | | - | - |
| | <i>Melochia tomentosa</i> L. | x | | shrub | |
| | <i>Pavonia cancellata</i> (L.) Cav. | | x | herb | native |
| | <i>Pavonia</i> cf. <i>glazioviana</i> Gürke | | x | shrub | native* |
| | <i>Pavonia humifusa</i> A.St.-Hil. | | x | herb | native |
| | <i>Pseudomalachra tuberculifera</i> H.Monteiro | | x | herb | - |
| | <i>Sida cordifolia</i> L. | | x | herb/subshrub | native |
| | <i>Sida galheirensis</i> Ulbr. | x | x | subshrub | native* |
| | <i>Sida rhombifolia</i> L. | | x | herb | native |
| | <i>Sidastrum micranthum</i> (A.St.-Hil.) Fryxell | | x | shrub/subshrub | native |
| | <i>Waltheria rotundifolia</i> Schrank | x | x | subshrub | native |
| | Malvaceae sp. | x | | - | - |
| Molluginaceae | <i>Mollugo verticillata</i> L. | | x | herb | native |
| Nyctaginaceae | <i>Boerhavia diffusa</i> L. | | x | herb | naturalised |
| Nyctaginaceae | <i>Guapira pernambucensis</i> (Casar.) Lundell | x | | shrub | native* |
| Phyllanthaceae | <i>Phyllanthus niruri</i> L. | | x | herb/subshrub | native |

| Family | Species | Dry forests | Crop fields | Growth form | Origin |
|-------------------|---|---|-------------|------------------------|-----------------------|
| Phytolaccaceae | <i>Microtea paniculata</i> Moq. | x | | herb | native |
| Plantaginaceae | <i>Scoparia dulcis</i> L. | | x | herb/subshrub | native |
| | <i>Stemodia maritima</i> L. | | x | herb | native |
| Poaceae | <i>Aristida</i> cf. <i>adscensionis</i> | x | | herb | - |
| | <i>Cenchrus ciliaris</i> L. | | x | herb | naturalised |
| | <i>Cenchrus echinatus</i> L. | x | x | herb | native |
| | <i>Cenchrus</i> sp. | x | | - | - |
| | <i>Dactyloctenium</i> cf. <i>aegyptium</i> (L.) Willd. | x | x | herb | naturalised |
| | <i>Digitaria bicornis</i> (Lam.) Roem. & Schult. | | x | herb | naturalised |
| | Aff. <i>Enteropogon mollis</i> | x | | herb | native |
| | <i>Eragrostis ciliaris</i> (L.) R.Br. | | x | herb | naturalised |
| | <i>Eragrostis tenella</i> (L.) P.Beauv. ex Roem. & Schult. | x | x | herb | naturalised |
| | <i>Melinis repens</i> (Willd.) Zizka | | x | herb | naturalised |
| | <i>Tragus berteronianus</i> Schult. | x | | herb | native |
| Poaceae sp. | x | | herb | - | |
| Portulacaceae | <i>Portulaca elatior</i> Mart. | x | | herb | native |
| | <i>Portulaca oleracea</i> L. | x | x | herb | native |
| | <i>Portulaca</i> sp. | | x | - | - |
| Polygalaceae | <i>Polygala</i> sp. | x | | - | - |
| Rhamnaceae | <i>Ziziphus joazeiro</i> Mart. | x | | tree | native* |
| Rubiaceae | <i>Hexasepalum teres</i> (Walter) J.H. Kirkbr. [Diodella teres (Walter) Small] | x | | herb/subshrub | native |
| | <i>Staelia virgata</i> (Link ex Roem. & Schult.) K.Schum. [Staelia aurea K. Schum.] | x | | herb/subshrub | native |
| | <i>Richardia grandiflora</i> (Cham. & Schltld.) Steud. | | x | herb/subshrub | native |
| | Santalaceae | <i>Phoradendron quadrangulare</i> (Kunth) Griseb. [Phoradendron aff. <i>piauhyanum</i> Trel.] | x | | herb (hemi-parasitic) |
| | <i>Phoradendron</i> sp. | x | | shrub (hemi-parasitic) | - |
| Sapindaceae | <i>Serjania comata</i> Radlk. | x | | (vine) | native |
| Sapotaceae | <i>Sideroxylon obtusifolium</i> (Roem. & Schult.) T.D.Penn. | x | | shrub/tree | native |
| Schrophulariaceae | <i>Angelonia</i> sp. | x | | - | - |
| | Schrophulariaceae sp. | x | | - | - |
| Selaginellaceae | <i>Selaginella</i> aff. <i>convoluta</i> (Arn.) Spring | (x) | | <i>selaginella</i> | - |
| Solanaceae | <i>Physalis</i> sp. | x | | - | - |
| Turneraceae | <i>Piriqueta guianensis</i> subsp. <i>elongata</i> (Urb.) Arbo | | x | herb | native* |
| | <i>Turnera pumilea</i> L. | x | | herb | native |
| | <i>Turnera subulata</i> Sm. | | x | shrub | native |

| Family | Species | Dry forests | Crop fields | Growth form | Origin |
|------------------|-----------------------------|-------------|-------------|------------------------|--------|
| | <i>Turnera</i> sp. | x | | - | - |
| | <i>Piriqueta</i> sp. | x | | - | - |
| | Turneraceae sp. | x | | shrub | - |
| Verbenaceae | <i>Lippia grata</i> Schauer | x | | shrub/subshrub | native |
| Vitaceae | <i>Cissus</i> sp. | x | | (vine) | - |
| Xanthorrhoeaceae | <i>Aloe</i> sp. | x | | herb | - |
| | Morphospecies 1 | x | | - | - |
| | Morphospecies 2 | x | | shrub | - |
| | Morphospecies 3 | x | | - | - |
| | Morphospecies 4 | x | | - | - |
| | Morphospecies 5 | x | | - | - |
| | Morphospecies 6 | x | | - | - |
| | Morphospecies 7 | x | | - | - |
| | Morphospecies 8 | x | | - | - |
| | Morphospecies 9 | x | | - | - |
| | Morphospecies 10 | x | | - | - |
| | Morphospecies 11 | x | | - | - |
| | Morphospecies 12 | x | | - | - |
| | Morphospecies 13 | x | | - | - |
| | Morphospecies 14 | x | | - | - |
| | Morphospecies 15 | x | | (vine) | - |
| | Morphospecies 16 | x | | (vine) | - |
| | Morphospecies 17 | x | | (vine) | - |
| | Morphospecies 18 | x | | shrub (hemi-parasitic) | - |
| | Morphospecies 19 | x | | - | - |
| | Morphospecies 20 | x | | - | - |
| | Morphospecies 21 | x | | - | - |
| | Morphospecies 22 | x | | - | - |
| | Morphospecies 23 | x | | - | - |
| | Morphospecies 24 | x | | - | - |
| | Morphospecies 25 | x | | - | - |
| | Morphospecies 26 | | x | - | - |
| | Morphospecies 27 | | x | - | - |
| | Morphospecies 28 | | x | - | - |
| | Morphospecies 29 | | x | - | - |
| | Morphospecies 30 | | x | - | - |
| | Morphospecies 31 | | x | - | - |
| | Morphospecies 32 | | x | - | - |
| | Morphospecies 33 | | x | - | - |



Appendix 6.2 Plant species richness of shrubs, subshrubs, and herbs found in Caatinga forests at different grazing intensities (no/low, intermediate, high) and agrarian areas with different crop species (banana, coconut). Lowercase letters indicate significant differences in GLMs. The species richness of herbs (Caatinga) was assessed on smaller subplots (16 m² per plot).

Appendix 6.3 Species richness (means \pm standard error) of Caatinga dry forests at different grazing intensities (no/low, intermediate, high) and agrarian areas with different crop species (banana, coconut). Overall species richness includes trees, subshrubs, shrubs, herbs, vines, bromeliads, cacti, and epiphytes. Plot sizes: Caatinga, tree and shrub layer (including vines, bromeliads, cacti, and epiphytes)—400 m²; Caatinga, herb layer—four 4 m² subplots; crop fields, weed species—25 m². Different lowercase letters indicate significant differences in GLMs. *Zero values were not included in GLM.

| | Caatinga | | | Crop fields | |
|--|-------------------------|--------------------------|-------------------------|--------------------------|-------------------------|
| | No/low | Intermediate | High | Banana | Coconut |
| Overall species richness | 27.33 \pm 6.22 (a) | 22.09 \pm 3.69 (ab) | 18.16 \pm 2.15 (b) | 10.56 \pm 0.86 (c) | 13.04 \pm 0.9 (c) |
| Species richness of trees | 7.67 \pm 0.92 (a)* | 6.79 \pm 0.54 (a)* | 6.64 \pm 0.37 (a)* | 0* | 0* |
| Species richness of subshrubs, shrubs, and herbs | 14.5 \pm 3.98 (ab) | 12 \pm 2.87 (ab) | 8.84 \pm 1.61 (a) | 10.56 \pm 0.86 (ab) | 13.04 \pm 0.82 (b) |

Appendix 6.4 (a) Aboveground carbon stocks (means \pm standard error) of Caatinga dry forests at different grazing intensities (no/low, intermediate, high) and (b) agrarian areas with different crop species (banana, coconut). Carbon stocks of trees and shrub were calculated for individuals with a diameter at ground level > 3 cm. Carbon stocks of emergent trees (tree height > 4 m), smaller trees and shrubs, cacti, bromeliads, and herbs are presented separately. Different lowercase letters indicate significant differences in GLMs. In the Caatinga dry forests, aboveground carbon stocks of woody species (including bromeliads) were determined in 45 study plots, each 100 m² (no/low: $n = 9$; intermediate: $n = 14$; high: $n = 22$). Herbaceous biomass was sampled on 39 plots (with 2 subplots, each 4 m²). For analysing aboveground carbon stocks in agrarian areas, 9 banana and 12 coconut fields were investigated. Crop plants were measured on 25 m². Weed biomass was assessed on a 0.25 m² subplot per plot.

| | Mean | No/low | Intermediate | High |
|---|---------------------|----------------------------|----------------------------|----------------------------|
| <i>(a) Caatinga</i> | | | | |
| Overall carbon stocks [Mg ha ⁻¹] | 15.74 \pm 1.92 | 12.08 \pm 1.59 (a) | 13.97 \pm 2.48 (a) | 18.35 \pm 3.44 (a) |
| Emergent trees, height > 4 m [Mg ha ⁻¹] | 5.08 \pm 1.37 | 3.9 \pm 1.66 (a) | 3.55 \pm 1.58 (a) | 6.54 \pm 2.48 (a) |
| Trees and shrubs height < 4 m [Mg ha ⁻¹] | 8.89 \pm 1.23 | 6.53 \pm 1.23 (a) | 8.35 \pm 2.54 (a) | 10.19 \pm 1.81 (a) |
| Bromeliads [Mg ha ⁻¹] | 0.35 \pm 0.14 | 0.39 \pm 0.18 (a) | 0.45 \pm 0.37 (a) | 0.26 \pm 0.16 (a) |
| Cacti [Mg ha ⁻¹] | 0.44 \pm 0.21 | 0.19 \pm 0.09 (a) | 0.27 \pm 0.12 (a) | 0.65 \pm 0.41 (a) |
| Herbs, dry season [Mg ha ⁻¹] | 0.0025 \pm 0.0008 | 0.0041 \pm 0.0021 (a) | 0.0032 \pm 0.0018 (a) | 0.0014 \pm 0.0005 (a) |
| Herbs, rainy season [Mg ha ⁻¹] | 1.12 \pm 0.13 | 1.42 \pm 0.21 (b) | | 0.8 \pm 0.14 (a) |
| <i>(b) Crop fields</i> | | | | |
| | Mean | Banana | Coconut | |
| Overall carbon stocks [Mg ha ⁻¹] | 20.79 \pm 2.39 | 30.83 \pm 4.3 (a) | 13.26 \pm 1.23 (b) | |
| Crop plants [Mg ha ⁻¹] | 20.35 \pm 2.4 | 30.38 \pm 4.34 (a) | 12.82 \pm 1.22 (b) | |
| Weeds (herbs, subshrubs, shrubs) [Mg ha ⁻¹] | 0.44 \pm 0.04 | 0.45 \pm 0.08 (a) | 0.44 \pm 0.05 (a) | |

Appendix 6.5 Soil organic carbon stocks (means \pm standard error) in Caatinga dry forests with different grazing intensities (no/low, intermediate, high) and agrarian areas with different crop species (banana, coconut). Different lowercase letters indicate significant differences in GLMs.

| | Caatinga | | | Crop fields | |
|--|-------------------------|-------------------------|-------------------------|------------------------|------------------------|
| | No/low | Intermediate | High | Banana | Coconut |
| SOC stocks 0–5 cm [Mg ha ⁻¹] | 7.02 \pm 1.71 (a) | 3.68 \pm 0.27 (b) | 3.39 \pm 0.32 (b) | 3.8 \pm 0.61 (a) | 3.17 \pm 0.19 (a) |
| SOC stocks 5–60 cm [Mg ha ⁻¹] | 15.82 \pm 2.81 (a) | 11.90 \pm 1.57 (a) | 11.82 \pm 1.18 (a) | - | - |
| SOC content 0–5 cm [mg g ⁻¹] | 16.66 \pm 3.64 (a) | 7.37 \pm 0.63 (b) | 7.16 \pm 0.61 (b) | 6.86 \pm 1.14 (b) | 5.3 \pm 0.35 (b) |
| SOC content 5–60 cm [mg g ⁻¹] | 5.4 \pm 0.96 (a) | 3.18 \pm 0.46 (a) | 4.12 \pm 0.46 (a) | - | - |



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