GUILHERME DE CASTRO OLIVEIRA

MODELLING THE SEASONALLY DRY FORESTS IN THE SEMIARID REGION OF BRAZIL: CURRENT AND FUTURE DISTRIBUTION IN CMIP-5 SCENARIOS

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Solos e Nutrição de Plantas para obtenção do título de *Doctor Scientiae.*

Orientador: Márcio Rocha Francelino

Coorientadores: Elpídio Inácio Fernandes Filho
Carlos Ernesto G. R. Schaefer

VIÇOSA - MINAS GERAIS
2020

Ficha catalográfica elaborada pela Biblioteca Central da Universidade Federal de Viçosa - Campus Viçosa

T

Oliveira, Guilherme de Castro, 1986-

O48m Modelling the seasonally dry tropical forests in the
2020 Semiarid region of Brazil : current and future distribution in
CMIP-5 scenarios / Guilherme de Castro Oliveira. – Viçosa,
MG, 2020.
168 f. : il. (algumas color.) ; 29 cm.

Inclui apêndices.
Orientador: Márcio Rocha Francelino.
Tese (doutorado) - Universidade Federal de Viçosa.
Referências bibliográficas: f.95-117.

1. Mudanças climáticas. 2. Caatinga. 3. Florestas decíduas.
4. Mata Atlântica - Conservação - Legislação - Brasil.
I. Universidade Federal de Viçosa. Departamento de Solos.
Programa de Pós-Graduação em Solos e Nutrição de Plantas.
II. Título.

CDD 22. ed. 363.7

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APROVADA: 31 de Julho de 2020

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Márcio Rocha Francelino
(Orientador)

AGRADECIMENTOS

A realização deste trabalho só foi possível graças ao apoio de muitas pessoas, às quais tenho grande gratidão. Eu não teria chegado aqui sem vocês.

Agradeço ao meu orientador Márcio Francelino e aos coorientadores Carlos Schaefer e Elpídio Fernandes Filho pela oportunidade deste projeto e pela confiança no meu trabalho.

Aos companheiros que tiveram um papel fundamental nos trabalhos de campo e discussões posteriores: Daniel Arruda, Hugo Galvão, Guilherme Corrêa, Prímula Viana, Márcio Venicios, Priscila Mendes, Gabriel Palucci e João Reis. Também ao pessoal do Herbário de Montes Claros, sob supervisão da Prof. Rubia Fonseca, pela identificação das espécies. Agradeço!

Aos colegas do LABGEO, onde iniciei minha vida acadêmica e tanto aprendi ao longo desses anos, por todos os bons momentos compartilhados. Especialmente ao Gustavo Veloso pela ajuda com o processamento dos dados.

Aos estagiários Laís Muniz, Jefferson Fernandes, Marco Antônio Saraiva e Sabrina Paes Leme. Obrigado pela paciência e zelo na compilação de dados.

À Claudia (Terrantar) pela ajuda com questões que eu jamais conseguiria resolver e ao Henrique pela preparação das amostras de solo.

Agradeço à CAPES e ao CNPq pela concessão da minha bolsa de estudos. O presente trabalho foi realizado com apoio da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Código de Financiamento 001.

À Universidade Federal de Viçosa e aos funcionários do Departamento de Solos.

Ao DAAD pela bolsa de estudos na Alemanha. Ao professor Hermann Behling e a equipe do departamento de Palinologia da Universidade de Göttingen: Caio, Ricardo, Daniela, Sabrina, Anggi, Vincent, Jörg, Uta. Ao Jackson Rodrigues e ao João José Lelis no trabalho coleta de amostras palinológicas.

À banca examinadora, pelas sugestões e discussões que enriqueceram este trabalho.

Às pessoas que estiveram ao meu lado nos momentos mais difíceis desta trajetória. Meus pais, Cristina e Adriel e minha irmã Adna, que sempre me apoiaram incondicionalmente. Aos meus avós e tios que foram referências para mim. À Gabriela, pelo companheirismo, pela leveza, por todo amor. Muito obrigado!

ABSTRACT

OLIVEIRA, Guilherme de Castro, D.Sc., Universidade Federal de Viçosa, July, 2020. **Modelling the Seasonally Dry Forests in the semiarid region of Brazil: current and future distribution in CMIP-5 scenarios**. Advisor: Márcio Rocha Francelino. Co-advisors: Elpídio Inácio Fernandes Filho and Carlos Ernesto Gonçalves Reynaud Schaefer.

Climate models of the Intergovernmental Panel on Climate Change, 5th Assessment Report (IPCC AR-5) predict scenarios of increasing aridity in the semiarid region of Brazil throughout the 21st century. The expansion of the dry zone has a high potential for environmental and socio-economic impact in the region and may affect biodiversity, ecosystem services and agricultural systems severely. As a result, the impacts of environmental changes may lead to mass migration if they make these regions uninhabitable. To develop consistent conservation and adaptation strategies for impacts mitigation, it is necessary to employ multiple tools to estimate the potential effects of environmental changes in ecosystems. One of these tools is the environmental niche modelling, whereby the current distribution of species and plant formations is compared to the potential distribution in climate scenarios. However, for the semiarid region of Brazil, no studies have assessed these potential impacts in detail, to date. To enable this, it is necessary to deepen the knowledge of the environment-vegetation relationship in the Seasonally Dry Tropical Forests that occur in the region. In this context, the central objectives of this thesis were: a) to differentiate the main vegetations found in the semiarid region, stressing the distinction between the Arboreal Caatinga and the Atlantic Dry Forest in the southern semiarid ecotone and, b) to evaluate the climate change impacts on vegetation distribution in the RCP 4.5 and RCP 8.5 scenarios. It is concluded that climate change will lead to the expansion of the Caatinga biome, particularly southward (North of Minas) and to the west of Bahia. However, the General Circulation Models were conflicting, resulting in high uncertainty in the prediction models. This uncertainty was significantly reduced with the inclusion of soil attributes, which led to more consistent outputs. Soil attributes were also crucial to distinguish vegetations in the current climate at the regional and local scales. The physiognomic-based criteria to distinguish Atlantic Dry Forest and Arboreal Caatinga in the southern semiarid ecotone was inaccurate to represent the species pool. Conversely, climate and soil explained most of the variation in species composition. The lower dissimilarity among Arboreal Caatinga communities suggests that this vegetation was changed by abiotic homogenization. Niche models can improve the phytogeographic classification and provide more accurate assessments of the environmental changes impacts in the semiarid region.

Keywords: Climate change. Caatinga. Niche Modelling. Dry tropical forests.

RESUMO

OLIVEIRA, Guilherme de Castro, D.Sc., Universidade Federal de Viçosa, julho de 2020. **Modelagem das Florestas Sazonalmente Secas na região semiárida do Brasil: distribuição atual e nos cenários CMIP-5**. Orientador: Márcio Rocha Francelino. Coorientadores: Elpídio Inácio Fernandes Filho e Carlos Ernesto Gonçalves Reynaud Schaefer.

As projeções dos modelos climáticos nos cenários do quinto Relatório de Avaliação do Painel Intergovernamental sobre Mudanças Climáticas (IPPC AR-5) indicam aumento da aridez na região semiárida do Brasil ao longo do século XXI. A expansão da zona seca tem grande potencial de impacto ambiental e socioeconômico na região, podendo afetar a biodiversidade, os serviços ecossistêmicos e os sistemas agrícolas. Em consequência, os impactos da mudança ambiental podem levar a migrações em massa caso tornem essas regiões inabitáveis. Para desenvolver estratégias consistentes de conservação, adaptação e mitigação de impactos, é necessário o uso de múltiplas ferramentas que permitam estimar o efeito das mudanças ambientais nos ecossistemas. Uma destas ferramentas é a modelagem de nicho ambiental, através da qual a distribuição de espécies ou formações vegetais no presente é comparada com a distribuição potencial nos cenários climáticos. No entanto, para a região semiárida do Brasil, até o momento não há modelos que permitam avaliar esses impactos em detalhe. Para que isso seja possível, é preciso aprimorar o conhecimento da relação ambiente-vegetação nas Florestas Tropicais Sazonalmente Secas presentes na região. Neste contexto, os objetivos centrais desta tese foram: a) diferenciar as principais vegetações presentes na região semiárida, com ênfase na distinção entre a Caatinga Arbórea e a Floresta Decidual e, b) avaliar os impactos das mudanças climáticas na distribuição das vegetações nos cenários RCP 4.5 e RCP 8.5. Conclui-se que as mudanças climáticas levarão à expansão do bioma Caatinga, principalmente em direção ao sul (Norte de Minas) e oeste da Bahia. No entanto, os Modelos de Circulação Geral são contrastantes, o que resultou em maior incerteza nos modelos de predição. Essa incerteza foi significativamente reduzida com a inclusão de atributos do solo, os quais levaram à modelos mais consistentes. Os atributos do solo também foram essenciais para distinguir as vegetações no clima atual. A diferenciação fisionômica entre Caatinga Arbórea e Floresta Decidual foi imprecisa para representar a composição de espécies das comunidades, a qual foi explicada por clima e solo. Baixos valores de dissimilaridade foram verificados entre comunidades de Caatinga Arbórea, sugerindo que essa vegetação foi homogeneizada. O desenvolvimento de modelos de nicho podem contribuir para melhorar a classificação fitogeográfica e prover modelos mais precisos para avaliar os impactos das mudanças climáticas na região.

Palavras-chave: Mudanças climáticas. Caatinga. Modelagem de nicho. Florestas Tropicais secas.

SUMMARY

1 INTRODUCTION

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1 INTRODUCTION

The Brazilian SDTF in the framework of global climate changes

In 2015 the atmospheric CO_2 concentration stabilized above 400 ppm for the first time in at least 800,000 years (Lüthi *et al* 2008, Petit *et al* 1999). Record temperatures in the Antarctic summer were documented in February 2020[1]. Glaciers are melting at unprecedented speed in modern history (Turner *et al* 2017, Miller *et al* 2013, Pendleton *et al* 2019, Tedesco and Fettweis 2019, Zhang *et al* 2008). Clear signs are occurring all over the planet and society has increasingly been convinced, if not by science, by reality itself, that we are facing an abrupt climate change. In this picture, the status of a recently recognized biome - the Seasonally Dry Tropical Forests (SDTF) - is particularly worrying.

The Seasonally Dry Tropical Forests occur globally in the tropical range (Miles *et al* 2006). They are shrubby to arboreal forests, characterized by a strong rainfall seasonality and a well-defined dry season with intense droughts (Mooney *et al* 1995, Linares-Palomino *et al* 2011b, Pennington *et al* 2009), when most trees shed their leaves completely. It is estimated that the remaining SDTF area is on the order of 1,000,000 km², and more than half of this is located in South America (Miles *et al* 2006). Brazil has the largest continuous STDF unit in the continent, represented mainly by the Caatinga biome in the northeast region of the country (Silva *et al* 2018).

Independent studies have shown that climate change has intensified aridity in semiarid regions due to worsening droughts and rising temperatures (Huang *et al* 2016, 2012, Dai 2013, Ji *et al* 2014). In addition to the increased aridity, the geographical expansion of these arid zones is also expected. According to Feng and Fu (2013), by the end of the 21st century the semiarid regions will increase globally by about 10%. Particularly for Brazil, the climate models converge regarding the rise in both temperature and number of consecutive dry days, regardless of the CO_2 concentration scenario (Salazar *et al* 2007, Marengo *et al* 2017). As a consequence, such climate changes are expected to affect the biogeography of Brazil, with a reduction in humid tropical forests and expansion of dry and semi-desertic formations (Oyama and Nobre 2003, Salazar *et al* 2007, Cox *et al* 2004, Cook and Vizy 2008). Though it is still uncertain how resistant the dry vegetation will be to the new climatic conditions (Santos *et al* 2014, Allen *et*

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[1] https://www.bbc.com/news/world-51500692

al 2017). What seems assured is that protected areas will play a key role in this context (Acosta Salvatierra *et al* 2017, Oliveira *et al* 2012). However, this is worrying because less than 1% of Caatinga is covered by fully protected areas (Leal *et al* 2005).

Socio-environmental fragility places the semiarid region among the most critical in Brazil in the context of climate changes (Rito *et al* 2017a, Souza *et al* 2015, Menezes *et al* 2012, Acosta Salvatierra *et al* 2017, Althoff *et al* 2016, Santos *et al* 2014, Ribeiro *et al* 2015). As for the social dimension, the Brazilian semiarid is the most populated on the planet, with about 28 million inhabitants (Tabarelli *et al* 2018). The region is among those with the lowest human development index in Brazil (PNUD 2015). There is a high dependence on rainfall and ecosystem services for the sustenance of local populations (Albuquerque *et al* 2018). In turn, ecosystem services are influenced by climate and their provisioning is being affected by climate change (Althoff *et al* 2016, Menezes *et al* 2012, Mooney *et al* 2009, Rito *et al* 2017a), jeopardizing the livelihoods of populations, agricultural systems and biodiversity conservation. These impacts may lead to mass migration throughout the 21st century if agricultural systems become unsustainable (Barbieri *et al* 2010).

In the environmental perspective, the main threats in the semiarid region are the result of human activity, which are intensified by climate change (Melo 2018). They can be summarized in acute and chronic disturbances (Singh 1998, Albuquerque *et al* 2018b). Acute disturbances are intense and occur in a well-defined period, allowing vegetation to recover after the intervention. On the other hand, chronic disturbances occur constantly over a long period, hampering the ecosystem from returning to its original state (Singh 1998). Consequently, chronic disturbances deeply change ecosystems on the long term. However, they are less impactful at first sight and difficult to measure, as they occur diffusely without dramatically changing the vegetation cover.

In the semiarid region, chronic disturbances such as grazing and firewood collection for domestic use represent a silent threat (Melo 2018, Ribeiro *et al* 2015). For example, browsing on natural vegetation over centuries has led to profound impacts in some ecosystems (Schulz *et al* 2016, 2019), especially in areas that were slashed and burned before the introduction of livestock (Marinho *et al* 2016). As examples of acute disturbances, Caatinga forests were razed to supply the energy demand of the plaster industry and the construction of reservoirs (Sampaio *et al* 2018). Ultimately, the consequences of such disturbances are loss of diversity (Ribeiro *et al* 2019, Rito *et al* 2017c), soil erosion and desertification (Tomasella *et al* 2018, Souza *et al*

2015) and alteration of natural ecosystems by the dominance of invasive species (Andrade *et al* 2010, Gelbard and Belnap 2003).

Unlike the rainforests, which attracted the attention of naturalists and researchers for their exuberance, the dry forests were neglected and their diversity was late recognized (Prado 2000). Consequently, there is a strong contrast between these biomes regarding knowledge and conservation efforts (Pennington *et al* 2018). In the context of Brazil, rainforests have been extensively sampled and are the focus of many conservation and monitoring programs, with the global engagement of society. On the other hand, dry forests have undergone a constant and silent degradation process (Melo 2018), with little sampling effort over decades. Although they were one of the earliest forests occupied in Brazil, the SDTF were less affected by the expansion of the agricultural frontier than the Atlantic Forest, the Cerrado and, more recently, the Amazon Forest, in which deforestation has dramatically changed - and still changing (Escobar 2019) - the landscape. As a result of a long-term diffuse exploitation of natural resources, it is presently difficult to differentiate natural areas from anthropized ones in the Brazilian semiarid (Andrade-Lima 1981, Melo 2018).

The lack of specific legislation for biodiversity protection and management of Caatinga is an aggravating factor of such anthropogenic disturbances. Without sufficient protected areas (Velloso *et al* 2002, Acosta Salvatierra *et al* 2017, Leal *et al* 2005), the biome is now intensely fragmented (Antongiovanni *et al* 2018, Lôbo *et al* 2011) and natural vegetation remnants outside the few protected areas also degraded (Ribeiro *et al* 2015, 2019). In view of this picture, it is urgent to take measures to protect the SDTF in Brazil. Currently, a draft bill for Caatinga protection is in the House of Representatives (*Projeto de Lei* 4623/19). It foresees the implementation of protected areas, ecological-economic zoning and sustainable extractivism policy. This legislation may be a milestone in the conservation of this valuable biome. Simultaneously, the development of inclusive technologies is needed to meet energy demand (Nobre *et al* 2019) and prepare the agricultural systems of the semiarid region for a warmer future.

Origins of SDTF in Brazil - state of the art

The old concept that the floristic assembly of dry forests was a subset of the surrounding tropical forests (Rizzini 1976) contributed to less attention given to research in the SDTF in Brazil. However, after a remarkable sampling effort in the last decades, it is now widely recognized that the Caatinga is a hot-spot of endemism and rare taxa (Fernandes *et al* 2020, Giulietti *et al* 2004).

Recent surveys have shown that between 15-30% of Caatinga species are endemic (Queiroz *et al* 2018, Fernandes *et al* 2020, Giulietti *et al* 2002). Still, the Caatinga is probably the Brazilian biome with the least known floristic (Giulietti *et al* 2004). The urgency to extend the sampling effort is evidenced by the increase in the number of endemic species identified in a short period. Andrade-Lima (1982, in Prado, 2003) listed 3 endemic genera. Prado (2003) listed 12 genera and 183 endemic species. In the following year, Giulietti *et al* (2004) identified 18 genera and 318 species. In 2020, Fernandes *et al* (2020) reported 31 genera and 526 endemic species. The diversity of Caatinga is not restricted to the plants. High rates of endemism are also recorded for reptiles, birds, fishes, mammals and insects (Lima *et al* 2018, Carmignotto and Astúa 2018, Mesquita *et al* 2018). The fact is that the more we know about the Caatinga, the more we move away from the idea that it is a floristically poor biome, highlighting it as unique in the world (Silva *et al* 2003, Neves *et al* 2015).

Although SDTFs share similar ecological characteristics globally, each continent harbours distinct floristic groups, suggesting independent origins in America, Africa and Asia (Pennington *et al* 2018). Concerning the evolution of Neotropical Dry Forests in northeastern Brazil, many authors have sought to explain the origin of diversity and the high endemism rates (Oliveira-Filho *et al* 2006a, Linares-Palomino *et al* 2011a, Collevatti *et al* 2013b, Queiroz 2006). Hypotheses on different migratory routes were raised (Prado and Gibbs 1993, Pennington *et al* 2000a, Mayle 2004) and remained unconfirmed for decades.

Thanks to novel phylogenetic studies, it was clarified that most Caatinga endemic taxa are Mesoamerican lineages that established in the northeast region of Brazil from the Middle to Late Miocene (Queiroz *et al* 2018). Another relevant information from these studies is that the biogeographical history divides the Caatinga into two groups. The so-called Crystalline Caatinga, which occurs on crystalline basement surfaces (Moro *et al* 2016, Queiroz 2006), contains endemic lineages that differentiated earlier in the region by vicariance. In turn, species from sedimentary and karstic areas speciated *in situ* much more recently, over the last 1.5 Ma (Queiroz et al 2018). Lineages descending from Africa and other South American SDTF units are also present, but in a smaller number (Queiroz *et al* 2018).

The arrival of the earliest lineages coincides precisely with the Middle Miocene Climate Optimum (Langhian ~16 - 11.6 M.a., You *et al* 2009). The Middle Miocene was marked by important changes in the global climate. The first stage of this period, the Middle Miocene

Climate Optimum (MMCO), was characterized by warm conditions, comparable to late Oligocene. Although the global climate remained warmer than today throughout the Miocene (Pound *et al* 2012), an important climatic transition associated with the large expansion of the Antarctic ice sheet and global cooling occurred between ~ 15 and 13 Ma, the so-called Middle Miocene Climate Transition (MMCT). The main evidence for this transition is the increase of O δ18O shown in benthic foraminifera records (Lear *et al* 2010, Shevenell *et al* 2008, Holbourn *et al* 2005). In this cooler and drier period, some studies suggest that the sea level was 43m below the current one (Frigola *et al* 2018). With the emergence of the shallow northern continental shelf of South America, a direct land connection between northeastern Brazil and the Caribbean was likely formed.

The entangled evolution of Caatinga's phytogeographical classification

The phytogeographic classification of Caatinga is one of the oldest issues in the context of Brazilian biogeography and is still debated today. Over time, the classification systems varied between floristic and physiognomic criteria. It is remarkable the persistence in framing the Caatinga in the universal phytogeographic systems - which was sometimes controversial - abandoning regional terminologies. The following is a synthesis of this evolution, with information obtained from Veloso *et al* (1991), Joly *et al* (1999) and IBGE (2012). Dozens of systems were developed since the 19th century. In this brief review, only a few will be cited to expose the main changes that occurred since then. A background of the entangled evolution of phytogeographic systems regarding the dry forests of the semiarid region is needed to understand the objectives of this thesis.

The German naturalist Carl Friedrich Philipp von Martius published the first phytogeographic classification of Brazil in 1824, in the book Flora Brasiliensis, volume XXI. Martius referred to the dry forests of northeast Brazil as Hamadryads. One century later, Gonzaga de Campos (1926) proposed a physiognomic-structural classification. In this, the name 'Caatingas' appeared for the first time in a classification system. Alberto Sampaio (1940) took up the floristic concept and used the term '*Zona das Caatingas*'. Shortly after, Lindalvo Bezerra dos Santos (1942) and Aroldo de Azevedo (1950) used a purely physiognomic system, in which the Caatinga was included among the shrub and herbaceous formations. Andrade-Lima (1966) preserved the term 'Caatinga', and for the first time included structural units of these vegetations: arboreal (dense or open) and shrubby. This was the first map in which the delimitation of the Caatinga resembles that of the current official vegetation maps (IBGE 2004).

An important milestone in Brazilian phytogeography was the RADAMBRASIL project, carried out in the 1970s and 1980s. For the first time, vegetations were mapped on a large scale with support of radar imagery. The classification system used in the RADAMBRASIL project was inspired by the physiognomic-ecological concept of Ellemberg & Muller-Dombois (1967). The Brazilian vegetation was then classified into 12 phytoecological regions. The term 'Caatinga' was abandoned and replaced by 'Steppe' in an attempt to frame this vegetation in a universal classification system (Veloso *et al* 1991). The Steppe was subdivided into dense arboreal, open arboreal, park and gramineous. Finally, the classification system and the maps produced by the RADAMBRASIL project served as the basis for the official vegetation map of Brazil (IBGE 2004), in which another new designation was implemented: ‘Steppic Savannah’ (‘*Savana-Estépica*’), with the following physiognomic types: forests, woodlands, parks and grasslands.

Though officially adopted, the term *'Savana-Estépica*' is criticized by many authors and little used in international journals. It brings us to conceive this vegetation as something between a Savannah and a Steppe, or a mixture of both. The problem is that the term 'Savannah' originally refers to non-forested vegetation, adapted to periodic fires and oligotrophic soils (Staver *et al* 2017, Langan *et al* 2017), in which the grass stratum is as important as the arboreal one in terms of coverage. Moreover, soil water storage is crucial to the ecology of the Savannahs (Oliveira *et al* 2005), unlike Caatinga where roots explore a limited soil volume (Pinheiro *et al* 2013). If the last possibility was a floristic similarity, it is known that from a phylogenetic perspective Cerrado and Caatinga also have distinct evolutions (Pennington *et al* 2009). In turn, 'Steppe' is a type of open, non-forest vegetation, which occurs outside the tropical zone, where the temperature is usually below 0ºC in winter and can reach 40ºC in summer. Except for the aridity, the steppe occurs in a climate very different from the Caatinga, where the minimum annual temperature is rarely below 14ºC (Fick and Hijmans 2017). It is therefore clear that, for both international and local audience, the term '*Savana-Estépica'* does not portray the Caatinga precisely, as it is not a mixture or an intergrade of both vegetation.

Due to this imprecision, most published works have used the terms 'Caatinga' and 'Seasonally Dry Tropical Forest' (or simply 'Dry Forest') together (Santos *et al* 2012, Behling *et al* 2000, Cook and Vizy 2008, Pennington *et al* 2006, 2009). Thus, the representation of the regional uniqueness of this vegetation is kept while it fits in a modern and widely recognised concept of a global biome (Arruda *et al* 2018, Maksic *et al* 2019, Cook and Vizy 2008, Pennington *et al* 2018, Silva *et al* 2018). Evidence of this is that the search for the term

'Caatinga' in Nature journal results in 46 research articles (May 2020) while 'Steppic Savanna' - and similar terms - were not used in any studies.

In short, besides 'Caatinga', other designations have already been used: steppe, savannah, thicket, scrub, thorny woods and deciduous forest. In the midst of so many classification systems, it is worth noting that Martius made the first scientific description of the Brazilian dry forests more than two hundred years after the semiarid region settlement in the 17th century. Therefore, it is not known to what extent the earliest characterization of the Caatinga vegetation represents its original or secondary vegetation.

Current Challenges

Presently, the focus of many research groups is on revealing which factors explain the occurrence of the plant formations and the species distribution in the semiarid region (Silva and Souza 2018, Ribeiro *et al* 2015, Souza *et al* 2019a, Carrión *et al* 2017, Santos *et al* 2012, Neves *et al* 2015, Andrade-Lima 1981, Arruda *et al* 2020). In general, the authors still using classification systems with an underlying physiognomic bias, but the emergence of modern techniques of data analysis has allowed species composition, functional traits, phylogeny and environment to play a more important role (Santos *et al* 2012, Silva and Souza 2018, Neves *et al* 2015, Queiroz *et al* 2018, Särkinen *et al* 2011). Another relevant factor that has also been elucidated is the effect of chronic anthropogenic disturbances (Rito *et al* 2017a, Sfair *et al* 2018, Ribeiro *et al* 2015, Albuquerque *et al* 2018b, Ribeiro *et al* 2019, Zorger *et al* 2019). Independently, these works have contributed to a better understanding of the complex phytogeography of SDTF in Brazil.

Based on the novel research, we draw preliminary conclusions on phytogeography of semiarid. First, it is unequivocal that - disregarding the anthropic factor - niche control is preponderant in relation to neutral processes (Santos *et al* 2012, Neves *et al* 2015, Souza *et al* 2019a, Arruda *et al* 2020, 2015a, Pinho *et al* 2019). Secondly, different types of chronic anthropogenic disturbances cause deep and lasting impacts on vegetation. These changes are observed in functional composition (Sfair *et al* 2018, Ribeiro *et al* 2019, Zorger *et al* 2019), biomass (Souza *et al* 2019b), structure (Ribeiro *et al* 2015), regrowth (Marinho *et al* 2016) and species composition (Rito *et al* 2017c). In this sense, a general pattern that has been observed is that the effect of anthropogenic disturbance is enhanced as the climate becomes more arid (Pinho *et al* 2019, Rito *et al* 2017a, Sfair *et al* 2018).

A key issue in the phytogeography of the semiarid region is the distinction between the Arboreal Caatinga and Atlantic Dry Forest vegetations. Independent research has shown remarkable environmental, floristic and physiognomic similarity between these vegetations (Andrade-Lima 1981, Arruda *et al* 2015b; Santos *et al* 2012). Thus, it is disputable how consistent their discrimination is, especially by physiognomic-based criteria. This is an important issue for two main reasons. Firstly, the Arboreal Caatinga is not protected by the Atlantic Forest Law because it is associated with the Caatinga biome. Assuming that in fact there is a great floristic and environmental similarity with the presence of many species of the Atlantic Forest, it is reasonable that the so-called Arboreal Caatinga is also included. Secondly, there are consequences for modelling the distribution of these vegetations. If the physiognomic classification does not represent the environmental niche and the species composition precisely, one expects high noise in niche models because they mix very different vegetations or separate vegetations that are very similar.

Thesis objectives and framework

The number of studies published about Caatinga grew exponentially from the 1990s (Silva *et al* 2018). Therefore, the status of unknown vegetation was surpassed, but there are still many gaps in the knowledge of this complex domain of dry forests. Two key topics will be addressed in this thesis: a) the drivers that govern the distribution of the different types of vegetation in the semiarid region, with emphasis on the differentiation between Arboreal Caatinga and Atlantic Dry Forest and, b) how climate changes will potentially affect the distribution of these vegetations.

Specifically, the objective of this thesis was to answer the following questions: i) what environmental factors govern the vegetation distribution in the semiarid region; ii) how important is the soil to differentiate them; iii) do the Arboreal Caatinga and Atlantic Dry Forest formations represent distinct units in terms of environment and species composition and, iv) how will climate changes potentially affect the distribution of dry forests in the semiarid region?

To answer the aforementioned questions, this thesis was organized into four chapters. In Chapter I, we addressed the main plant formations of the Brazilian semiarid region, aiming to model their key environmental properties in terms of climate and soil. To do this, we use a database of soil profiles to characterize these vegetations with site-level data. A special focus was placed on the environmental similarity between the Atlantic Dry Forest and the Arboreal Caatinga, and the possible implications for the enforcement of the Atlantic Forest Law.

In Chapter II, we verified whether the environmental similarity between Arboreal Caatinga and Atlantic Dry Forest was also confirmed in the species composition and floristic similarity at the community level. We examined the influence of the environment on the organization of the communities and vegetation structure and the feasibility of the physiognomic criteria to distinct these vegetations. We analysed sampled fragments in the southern semiarid ecotone, north of the State of Minas Gerais, Jequitinhonha Valley and central-west Bahia.

Chapter III was dedicated to exposing the edaphic heterogeneity in the semiarid region and producing a spatial database of topsoil attributes. We used the RADAMBRASIL soil maps to spatialize 14 topsoil attributes. Based on these data, we proposed soil Units to represent the spatial distribution of key topsoil attributes in the region and its relationship with broad-scale vegetation distribution.

In Chapter IV, we proceeded to model the vegetation distribution in the semiarid region. We used different machine learning algorithms and three General Circulation Models to predict the vegetation distribution in current and both IPCC RCP 4.5 and 8.5 climatic scenarios for the end of the 21st century. To achieve this, we used a novel approach that included the soil attributes database produced in Chapter III.

Throughout this thesis, two terminologies were used for the Caatinga vegetations. In Chapters I and II, they were differentiated as Caatinga and Arboreal Caatinga. In this approach, we consider as 'Caatinga' the dense or open shrub formations and as 'Arboreal Caatinga' the forest formations. In Chapter IV, the classification followed the reports of the RADAMBRASIL project, updated by IBGE to the current vegetation classification system (IBGE 2012). In this, there is a more detailed separation of the physiognomic types. The Caatinga vegetations were divided in: Caatinga (*Savana-Estépica* and *Savana-Estépica parque*), Arboreal Caatinga (*Savana-Estépica arborizada*) and Caatinga Forest (*Savana-Estépica Florestada*). Therefore, the ‘Arboreal Caatinga’ in Chapters I and II correspond to the ‘Caatinga Forest’ in Chapter IV.

2 CHAPTER I

Climate and soils at the Brazilian semiarid and the forest-Caatinga problem: new insights and implications for conservation

Article published in Environmental Research Letters, Vol. 14, n.10., 2019

Abstract

This study aimed to test two hypotheses: i) on the Brazilian semiarid territory, the climate has greater weight as a driver of vegetation than the soil and; ii) the arboreal Caatinga is a vegetation whose environmental attributes are similar to the Dry Forest, in terms of soil and climate attributes. We analyzed attributes of the superficial horizon of 156 standardized profiles distributed throughout the Brazilian semiarid region. Bioclimatic variables were obtained from the WorldClim platform and extracted to profiles location. The main vegetation types in the region were considered: Caatinga, arboreal Caatinga, Dry Forest and Cerrado. Variable selection was performed with hierarchical correlation dendrogram and recursive feature elimination algorithm. Linear Discriminant Analysis and Random Forest algorithm were used for modelling the edaphic and climate niche and predict the vegetation with the selected variables. Climate and soil, individually, were able to separate the vegetation, but the climate was no better predictor than the soil. Therefore, we reject the first hypothesis. However, the better prediction was attained with the combined use of soil and climate attributes. The parsimonious Random Forest model had good performance, with Kappa 0.61 ± 0.10 and 70.9% ± 7.7 accuracy. The combination of soil and climate predictors resulted in better separation of vegetation in the Brazilian semiarid region. Soil attributes are key variables in large-scale biogeographic modelling. The so-called arboreal Caatinga is distributed over a wide edaphic and climatic range, with strong similarity to the Dry Forest distribution, confirmed by the great overlap in the multivariate space, which confirms the second hypothesis. The results point towards an urgent review of the Atlantic Forest Law. The environments where the arboreal Caatinga and the Dry Forest occur are very similar, so that the former may represent a degraded phase of the Atlantic Forest, currently without the due legal protection.

Keywords: Atlantic Forest Law, Caatinga, Climate, Environmental niche, Environmental policy, Soil, Seasonally Dry Tropical Forests

2.1 INTRODUCTION

The geographical distribution of natural vegetation and biodiversity on Earth can be understood at different scales (Willis and Whittaker 2002). On a continental scale, climate explains the vegetation distribution and defines transitions between biomes (Arruda *et al* 2017, Langan *et al* 2017, Dionizio *et al* 2018, Casalini *et al* 2019, Woodward *et al* 2004). On a local scale, one can expect a lower explanatory power of climate and a greater importance of soil and topographic factors (Trejo and Dirzo 2002, Arruda *et al* 2015a).

Soil attributes have long been recognized as an important factor in explaining plant distribution. However, the magnitude of its contribution to the improvement of vegetation distribution models compared to climate or topography is little addressed (but see Dubuis *et al* 2013, Santos *et al* 2012, Neves *et al* 2015). With regional particularities, different soil variables are crucial for determining the plant community (Almeida *et al* 2018, Arruda *et al* 2015a, Catorci *et al* 2014, Dubuis *et al* 2013, Ferreira-Júnior *et al* 2007, Neri *et al* 2012, Nunes *et al* 2015, Saporetti-Junior *et al* 2012, Silva *et al* 2015), such as the sum of bases, acidity, organic matter, aluminium saturation, texture and others. The regional particularities of soil-vegetation relationship mean that their predictive potential is also restricted to each region, as opposed to climate attributes, that can serve to outline large-scale patterns (*e.g*, Holdridge 1967, Woodward *et al* 2004), as annual temperature range, annual precipitation, precipitation seasonality and others. Hence, understanding the regional pattern of the soil-vegetation relationship is fundamental to allow the adjustment of more complete vegetation prediction models. These models can provide a great contribution to understanding the geographical distribution of complex vegetation, where intricate interactions between soil, climate, topography and human action occur.

The Caatinga is a complex domain present in the Brazilian semiarid climate (IBGE 2004, Santos *et al* 2011, Velloso *et al* 2002). This complexity is the result of its wide climatic, soil and topographic heterogeneity, as well as the cumulative impacts of human activity since pre-Columbian times (Andrade-Lima 1981, Velloso *et al* 2002). More precisely, the earliest human occupations in the northeastern region of Brazil date from the late Pleistocene, more than 20,000 y B.P (Lahaye *et al* 2015, 2019). Among the various faces of Caatinga vegetation (see Andrade-Lima 1981), the herbaceous stratum is the one that concentrates the greatest diversity of species (Costa *et al* 2007, Linares-Palomino *et al* 2015). However, most of the studies on the environment-vegetation relationship focus in the tree stratum. Therefore, they provide great terminological confusion regarding the forest physiognomies of Caatinga. These are described as tall Caatinga forest (Andrade-Lima 1981, Silva *et al* 2018), hypoxerophilic Caatinga (Brandão 1994, Arruda *et al* 2015b, Araújo Filho *et al* 2017), crystalline Caatinga (Queiroz 2006), arboreal Caatinga (Moro *et al* 2016, Santos *et al* 2012), deciduous stiff-leaved dwarf forest (Oliveira-Filho 2009) and forested steppic-savannah (IBGE 2004, 2012).

However, studies have shown that the arboreal Caatinga resembles floristically and environmentally the deciduous seasonal forest, or Dry Forest (Andrade-Lima 1981, Arruda *et al* 2015b; Santos *et al* 2012), the most hinterland and seasonal of the Atlantic Forest domain (Oliveira-Filho *et al* 2006a). This similarity raises the question of whether arboreal Caatinga is a successional stage of Dry Forest (Arruda *et al* 2015b). If this hypothesis is confirmed, there are obvious implications for biodiversity protection. This issue is of paramount importance in the enforcement of the Atlantic Forest Law (Brasil 2006b), which grants protection to this biome, but does not consider zones of ecological tension where the arboreal Caatinga and the Dry Forest are found, closely associated (IBGE 2006).

In addition to the deciduous forest physiognomies, the Caatinga domain also includes humid forests (semi-deciduous and ombrophilous), Cerrado (savannah) and the Caatinga *stricto sensu* (or steppic-savannah *sensu* IBGE 2004, 2012). Despite peculiarities derived from small-scale analyses, on a large scale, the Caatinga domain and the Dry Forest are included along with the Neotropical Seasonally Dry Forests. (Prado 2000, Neves *et al* 2015, Pennington *et al* 2018, DRYFLOR 2016). Although the official Brazilian classification does not adopt the terms ‘arboreal Caatinga’ and ‘Dry Forest’, the present study opted for this nomenclature for the best compatibility with the international literature.

In this context, the present study assessed environmental aspects of the main vegetation of the semiarid domain and modelled their distributions based on environmental suitability. Considering the extensive area of the semiarid region of Brazil (993,604 km²) and the possibility that the arboreal Caatinga is a physiognomic variation of the Dry Forest, we tested two hypotheses: i) on a large scale, the climate has a greater contribution as a driver of plant formations than the soil and, ii) the arboreal Caatinga is a vegetation with environmental attributes similar to the Dry Forest, in terms of soil and climate.

2.2 MATERIAL AND METHODS

2.2.1 Data collection

Soil data were obtained from the selection of 156 standardized soil profiles scattered throughout the climatic domain of the semiarid region (Figure 1). These profiles were obtained from the Brazilian Soil Information System (EMBRAPA 2019). The standardization was made by EMBRAPA to make compatible the analyses made in different periods with different methods. We analyzed 18 topsoil attributes, namely: percentage of fine earth (TF, %), contents of clay, silt and sand (g/kg), pH in H_2O, K, $Ca^{2+} + Mg^{2+}$, Na^+, H^+, Al^{3+}, cation exchange capacity (t , $cmol_c.kg^{-1}$), sum of bases (sb, %), base saturation (v, %), total organic carbon (co, $g.kg^{-1}$), Al^{3+} saturation (m, %), Fe_2O_3 content and Ki (SiO_2 / Al_2O_3) and Kr (SiO_2 / $Al_2O_3 + Fe_2O_3$) ratios. The A horizon was considered as a whole regardless of its depth. Therefore, no interpolation method was applied.

The criterion for selecting soil profiles from the large database was the clear identification of the local vegetation. Profiles whose associated vegetation was reportedly dubious in their description, or related to any transitional vegetation type, were not considered. Four types of vegetation were analyzed: i) Dry Forest (deciduous forest with two to three strata and partly continuous to continuous canopy), ii) arboreal Caatinga (hypoxerophilous low forest with two strata and discontinuous canopy), iii) Caatinga (savannah-like hyperxerophilic physiognomy, with partially developed non-grass herbaceous stratum), and iv) Cerrado (savannah physiognomy with well-developed grassy herbaceous stratum). To avoid changes resulting from land use, we included only profiles described under natural vegetation.

From each soil profile coordinates, 19 bioclimatic attributes were extracted from WorldClim version 2 (Fick and Hijmans 2017): mean annual temperature, mean diurnal range, isothermality, temperature seasonality, maximum temperature of warmest month, minimum temperature of coldest month, temperature annual range, mean temperature of wettest quarter, mean temperature of driest quarter, mean temperature of warmest quarter, mean temperature of coldest quarter, annual precipitation, precipitation of wettest month, precipitation of driest month, precipitation seasonality, precipitation of wettest quarter, precipitation of driest quarter, precipitation of warmest quarter and precipitation of coldest quarter. The data represent mean values recorded in the 1970-2000 period by meteorological stations and interpolated globally. The high density of stations present in the area of this study ensures good data reliability (see Figures 2 and 4 in Fick and Hijmans, 2017). The extraction of climate data was performed with ArcMap software, version 10.3 (ESRI 2016). The soil and climate data used are at different scales. While soil profiles were sampled in the field, climate data were interpolated to a 1 km resolution.

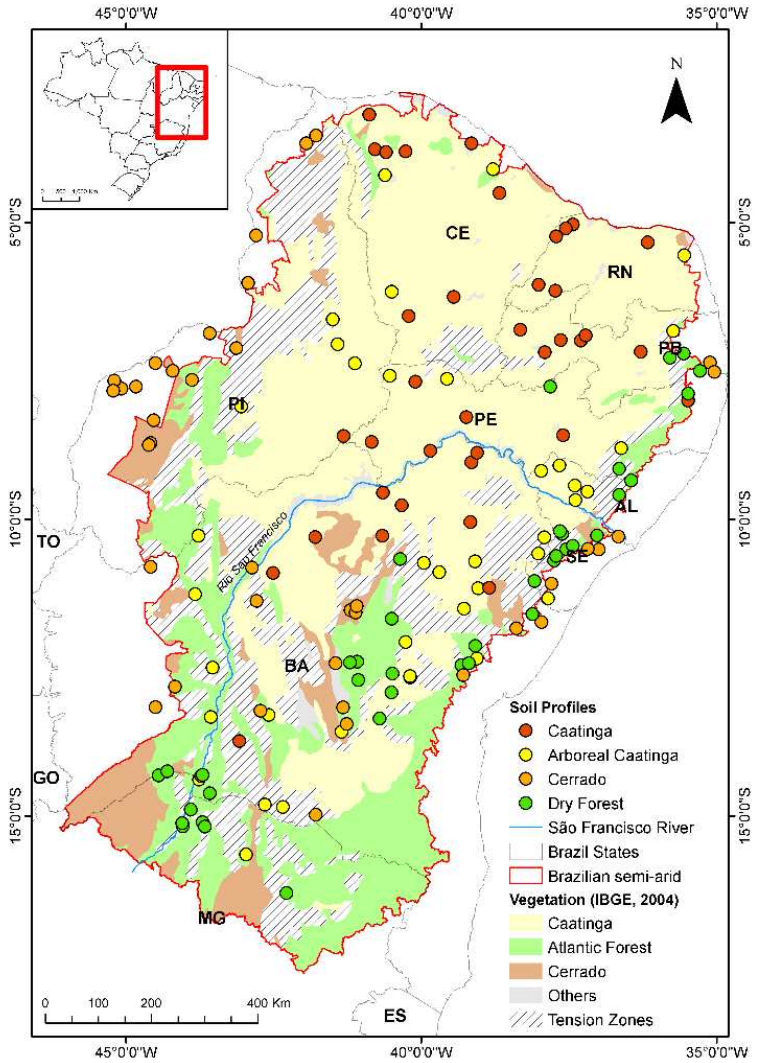

Figure 1. Location of the study area and distribution of soil profiles selected.

2.2.2 Data analysis

All analyses were processed using R version 3.5.1 (R Core Team, 2016). Initially, a hierarchical correlation dendrogram was used to find groups of highly correlated variables ($|r| > 0.95$) with the *varclus* function from 'Hmisc' package (Harrell Jr 2015). For each of these clusters, the variable with the lowest correlation (i.e, less redundancy) with all variables present in the data set was selected.

The data were divided into three sets: a) soil variables, b) climate variables, and c) soil and climate together. Next, the recursive feature elimination – RFE algorithm was used with the *rfe* function from 'caret' package (Kuhn 2008) to eliminate collinear variables and variables with little explanatory power (Genuer *et al* 2010, Ramasubramanian and Singh 2017). This procedure was performed individually for the three datasets. To create a parsimonious model, we selected only the best variables considering a 10% tolerance threshold. In short, tolerance expresses how much is lost in performance to build a parsimonious model, with a smaller number of variables.

To test the hypotheses, two approaches were used. First, we used the Linear Discriminant Analysis (LDA) to maximize the separation of vegetation in the multivariate space (Williams 1983). The discriminant function was also used to predict the vegetation classes. The LDA was performed for the three data sets. The results allowed comparing the contribution of the two groups of predictors individually (only soil and only climate) and jointly (soil and climate combined), and evaluating how the vegetation is separated. The second approach was accomplished with the Random Forests (RF) algorithm (Breiman 2001), which was also used to predict the vegetation classes with the combined soil and climate dataset.

The LDA was used to test the contribution of soil and climate predictors and better representation of data in multivariate space. The LDA seeks to determine the extent to which a set of independent variables can explain the groups (Borcard *et al* 2018), maximizing the separability among pre-defined classes. Multivariate homogeneity of group dispersions (Anderson 2006) was verified with the *betadisper* function and tested with the *permutest* function, both from 'vegan' package. Variances within not homogeneous groups were standardized with the *decostand* function from ‘vegan’ package. The Wilk's lambda test (Todorov and Filzmoser 2010) was applied to verify if the explanatory variables had different means. For this, we used the *Wilks.test* function from 'rrcov' package. Finally, the LDA was performed with the *lda* function from 'MASS' package. With the standardized data for each group of predictors, the discriminant functions for classifying the vegetation were computed. LDA cross-validation was performed with Jackknife (leave-one-out) method and the proportion of correct classifications by class was compared for each set of predictors.

The selected soil and climate variables were also used to predict the vegetation with the RF classifier (Breiman 2001). The data were split into training (80%) and validation (20%) sets. We repeat the procedures of sample selection, model training, prediction and validation 100 times to get the model parameters from the confusion matrix. The model performance were evaluated by the mean Kappa - K, accuracy, sensitivity and specificity parameters. The K statistic is a measure of agreement between the predictions of a model and the observed value, in comparison to what one could expect mathematically by chance. Accuracy measures the overall success rate of the classifier. Sensitivity represents the percentage of correctly classified presences, while specificity indicates the percentage of correctly classified absences (Cutler *et al* 2007). These parameters should be used together to better interpret the model performance (Ramasubramanian and Singh 2017).

2.3 RESULTS

From the hierarchical correlogram analysis, six variables from the first 37 were eliminated, leaving 16 soil and 15 bioclimatic attributes (Figure A.1, Appendix A). Following the 10% tolerance criterion over RFE results, we selected six variables from climate predictors, nine from soil and eight from the joint dataset (Figure A.2). The selected variables are presented in Table 1.

2.3.1 Linear Discriminant Analysis

The test for homogeneity of variances within the groups showed that the groups of predictors were not homogeneous. Subsequently, the data were standardized, allowing homogeneity to be confirmed by the permutational ANOVA. The Wilk's lambda test showed that the explanatory variables have different means among the vegetations for the three data sets. Thus, all assumptions for the LDA were met (Borcard *et al* 2018, Williams 1983).

For the three sets of predictors, the first two functions of LDA have contributed to explaining more than 90% of the variance between the classes. The LDA coefficients are presented in Table A.1, Table A.2 and Table A. 3. As for the climatic niche, Cerrado, Caatinga and Dry Forest were organized into well-defined groups (). Caatinga and Cerrado are distinguished by annual precipitation and by precipitation in the wettest month (LDA axis 1). The Dry Forest is distinguished from these two mainly by the seasonality of precipitation, annual precipitation and temperature seasonality (LDA axis 2). Climatically, the arboreal Caatinga is very similar to Dry Forest, being closer to it than to any other vegetation.

Concerning soil attributes (Figure 2b), the first axis of LDA separated the vegetations in terms of saturation of exchangeable bases and aluminium saturation (Table A.2). Thus, Caatinga and Dry Forest are positioned in the negative dimension of axis 1 (eutrophic and low Al^{3+} saturation) and the Cerrado to the positive dimension (dystrophic and high Al^{3+} saturation). The second LDA axis separates vegetation mainly in terms of organic carbon content and soil pH. Thus, there is an increase of soil pH and a reduction of organic carbon content in the Dry Forest-Caatinga direction. Arboreal Caatinga holds an intermediate position in this edaphic gradient between the two vegetation. This subtle gradient is also controlled by soil texture, more clayey in the Dry Forest and more sandy in the Caatinga. However, the sand content had a relatively small contribution to the model (Table A.2), as it does not serve to differentiate the arboreal Caatinga from other vegetation.

Table 1. Subset of variables selected by recursive feature elimination algorithm for each group of vegetation predictors in the Brazilian semiarid region

Predictors set		
Soil	Climate	Climate and soil
k	ann.pre	ann.pre
v	se.pre	m
m	se.temp	v
co	dry.m.pre	se.pre
fe2o3	wet.m.pre	k
h	wet.q.temp	se.temp
al		dry.m.pre
ph_h2o		wet.q.temp
sand		

k = exchangeable K, v = base saturation; m = Al^{3+} saturation, co = organic carbon, fe2o3 = Fe_2O_3 content by sulfuric attack, h = H^+, al = Al^{3+}, ph_h2o = pH in water, sand = content of sand, ann.pre = annual precipitation, se.pre = precipitation seasonality, se.temp = temperature seasonality,dry.m.pre = precipitation of driest month, wet.m.pre = precipitation of wettest month, wet.q.temp = temperature of wettest quater

The results of LDA cross-validation (Table 2) showed that classification success with climate predictors was slightly greater than with soil predictors (55 and 53%, respectively), although the values were very close. However, the best result was achieved with the combination of the two predictors, showing a synergistic interaction between them. While the soil was better predictor for Cerrado and Dry Forest, the climate was better for Caatinga and arboreal Caatinga. Thus, the different groups of predictors are complementary (Arruda *et al* 2017), allowing a better separation of vegetation without increasing the number of variables.

Combining soil and climate predictors increased the distance between the centroids of the vegetation classes while maintaining dispersion within the groups (Figure 2c). It means that the combination of these predictors forms better-defined samples, allowing better separation of classes. With this deeper view of the ecological niche, the similarity between arboreal Caatinga and Dry Forest is evident.

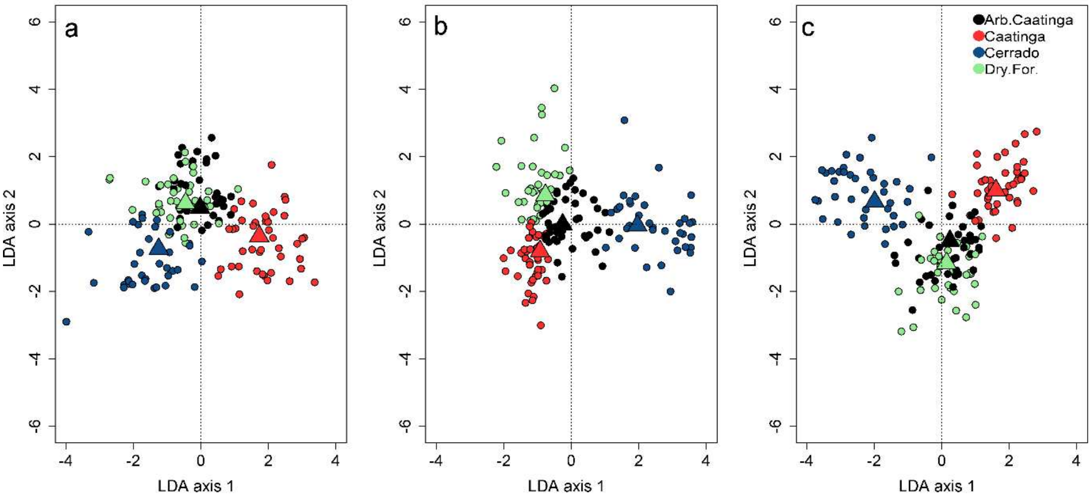

Figure 2. Linear Discriminant Analysis classification of vegetation in Brazilian semiarid; (a) climate predictors, (b) soil predictors; (c) climate and soil predictors combined.

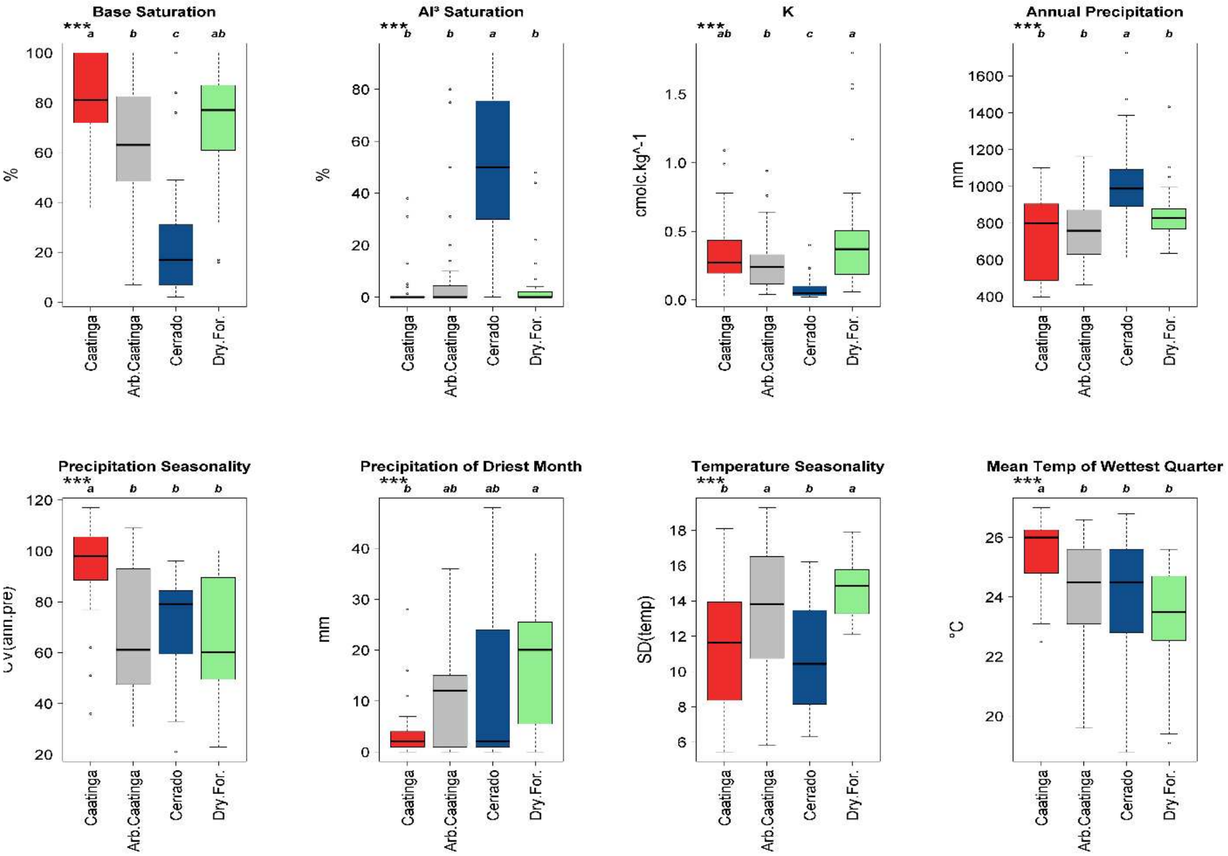

Figure 3. Boxplots of the eight soil and climate variables selected to compose the parsimonious model for vegetation prediction in the Brazilian semiarid region. Means followed with the same letter do not differ by Kruskall-Wallis test ($p < 0.05$).

Table 2. Classification success of Linear Discriminant Analysis – LDA for vegetation in Brazilian semiarid with three sets of predictors.

Predictors	**Arboreal Caatinga**	**Caatinga**	**Cerrado**	**Dry Forest**	**Mean**
Soil	0.31	0.54	0.74	0.54	0.53
Climate	0.38	0.82	0.56	0.44	0.55
Climate and soil	0.44	0.79	0.79	0.56	0.65

2.3.2 Random Forests

Once the best group of predictors was determined (Table 1), they were used for classification with the RF algorithm. The parsimonious RF model for vegetation class prediction with combined soil and climate predictors obtained an average K 0.61 ± 0.10. The overall accuracy was 70.9% ± 7.7 (Table A. 4 and Figure A. 3). The arboreal Caatinga had the lowest balanced accuracy per class and lower sensitivity among the classes, revealing the model's confusion between this class and the Dry Forest (Table 3). The low sensitivity means that the model was not able to place the arboreal Caatinga correctly since there are no environmental attributes that are characteristic of this vegetation (Figure 3).

For Caatinga, Cerrado, and Dry Forest classes, the model obtained an accuracy of 87.6, 87.5 and 81.4%, respectively (Table A. 4). As for specificity, the parsimonious model had high value (> 0.88) for all classes. The RF model corroborates the results of the LDA, confirming the similarity between arboreal Caatinga and Dry Forest. However, the RF classification was more successful, achieving more precise separation of the other classes than LDA.

Table 3. Random Forests correct classifications for combined climate and soil predictors. Percentages relative to the total number of predictions per class (39) after 100 repeats.

		Reference			
		Arboreal Caatinga	Caatinga	Cerrado	Dry Forest
Prediction	Arboreal Caatinga	**57%**	13%	8%	22%
	Caatinga	20%	**79%**	0%	0%
	Cerrado	14%	3%	**75%**	8%
	Dry Forest	19%	4%	9%	**68%**

2.4 DISCUSSION

The Brazilian semiarid is the most diverse and complex geographic space in the country (IBGE 2004, Santos et al 2011, Schaefer 2013). Considering the spatial scale covering roughly 15 degrees of latitude, the large climate contribution cannot be underestimated to explain the vegetation classes. However, the strong distinction between soils present in the semiarid nucleus and those of the peripheral zones are conditions that favour the use of soil attributes as a factor for enhancing the vegetation differentiation. Thus, although the soil has a slightly lower contribution, we consider that the difference presented (2%) is not ecologically relevant. With that, we reject the first hypothesis and assume that the use of the two groups of predictors best represents the environmental variability among classes of vegetation.

Soil attributes increased the multidimensional distance between groups while maintaining dispersion within them. Thus, allowed a better separation of vegetation classes (Figure 2 and Table 2). Therefore, the importance of soil is not limited to the landscape scale unlike what Willis and Whittaker (2002) suggest but is also an environmental factor that should not be neglected at regional scales (Arruda *et al* 2017, Langan *et al* 2017, Dionizio *et al* 2018, Casalini *et al* 2019). In the context of this study, Al^{3+} saturation, base saturation and K content were the most important soil attributes. The high Al^{3+} saturation associated with low soil fertility of Cerrado represents a barrier for Caatinga and Dry Forest, since these vegetations were not present on soils with this characteristic (Figure 3). Potassium content is related to a more efficient nutrient cycling in Dry Forest (Jaramillo and Sanford 1995). In the Caatinga, it is probably due to the high natural fertility of less weathered soils, where the presence of rich primary minerals and 2:1 clay minerals provides the replacement of this nutrient (Barré *et al* 2008).

The Cerrado stands out from other vegetation classes for its affinity to soils with high aluminium saturation and higher annual rainfall, associated with a moderate seasonality of precipitation (Figure 3), i.e., better-distributed rainfall. The Caatinga is matched by chemically rich soils with low aluminium saturation and warm semiarid climate. However, total precipitation does not differentiate it from other vegetation. The high precipitation seasonality, the lower precipitation in the driest period and the high temperatures in the wettest quarter were the best climatic predictors for this vegetation. Although the Dry Forest also presents affinity with eutrophic soils, the climatic aspects distinguish it from the Caatinga.

The similarity between the samples of arboreal Caatinga and Dry Forest, shown by both LDA and RF, proves the second hypothesis. Thus, it is likely that the difference between these vegetations is mainly structural (Arruda *et al* 2015b). The environmental similarity between the two vegetation can be explained in at least two ways. One possibility is that the arboreal Caatinga is a variation of the Dry Forest that has suffered chronic anthropogenic disturbance and is now in a stage of stagnant regeneration (Arruda *et al* 2015b), being incorrectly associated with the Caatinga biome only by its misleading structure. This does not mean that Dry Forest has not suffered such pressure. Nevertheless, minor environmental differences (Figure 3), such as slightly higher soil fertility, clay content and humidity in the Dry Forest give greater resilience to this vegetation, allowing its regeneration more quickly than in the arboreal Caatinga. The anthropic disturbance has more impact as the aridity increases (Rito *et al* 2017a).

Another possibility is that the arboreal Caatinga is reminiscent of seasonal forests that covered a larger area in the Brazilian semiarid region during the Pleistocene, and wetter phases in the Holocene (Arruda *et al* 2018, Behling *et al* 2000, Bouimetarhan *et al* 2018, Costa *et al* 2018, Medeiros *et al* 2018, Werneck *et al* 2011). Nowadays, they are the result of the combination of vestigial Dry Forest with species of the Caatinga, which have advanced with the dryness increase in the region (Silva and Souza 2018), which justifies its greater distribution in the border region of the Caatinga biome, in contact with Dry Forests.

The two possibilities above mentioned are not mutually exclusive. It is plausible that colonization by xerophytic shrub species has been favoured by human activity (Sagar *et al* 2003). Pereira *et al* (2005) found that arboreal individuals in the highest height class (> 3 m) were only present in the least disturbed environment. In the environments that suffered the greatest disturbance, they observed a reduction in vegetation size, lower floristic diversity and higher density of disturbed area indicator species. Grazing on natural vegetation, a common activity in the Caatinga, also reduces the plant diversity. Areas subjected to more intense grazing become less diverse and more homogeneous among themselves (Schulz *et al* 2019).

Regarding the floristic pattern of the tree component, different studies have shown that arboreal Caatinga is very similar to Dry Forest (Moro *et al* 2016, Santos *et al* 2012). Among nine biogeographic sub-regions of the Caatinga biome identified by Silva and Souza (Silva and Souza 2018), those located to the south, where they border the Dry Forest, were grouped into a single cluster. The authors recognize that the expansion and contraction of the surrounding Atlantic forest may influence the floristic of this group. Moro *et al* (2016) also observed that the arboreal Caatinga of northern Minas Gerais and southern Bahia are distinct from the other Caatinga vegetation, suggesting that this group should be appropriately treated as a peripheral subgroup within the crystalline Caatinga.

In addition to the historical and natural processes, human interventions should also be taken into consideration as a driver for differentiation of communities and vegetation physiognomies. Ever since the pre-colonial period, human dispersed plant species of interest in the tropics, enhancing the dominance of some species (Ter Steege *et al* 2013). In the same period, farmers using slash–and–burn methods for clearing vegetation in seasonal climates began landscape conversion. Thus, the use and alteration of the landscape by man, mainly after 1850, led to an intense fragmentation of dry forests in Brazil (Costa 2005, Espírito-Santo *et al* 2009), strongly affecting the species turnover between the remaining paths of different landscapes. As a result, a mosaic of vegetation of different successional stages remains in the landscape. Thus, we assume that soil attributes can be good proxies for estimating the original cover of these anthropized environments since the edaphic variability associated with different stages of the same vegetation class should not be sufficiently broad.

In this context, in the Middle São Francisco region (north of Minas Gerais and west of Bahia), arboreal Caatinga and Dry Forest also have great similarities with subtle difference only in soil texture (Arruda *et al* 2015b). The former is associated with soils slightly more sandy than the latter. This suggests that the difference between arboreal Caatinga and Dry Forest is locally controlled by a pedoclimatic gradient, as shown by Santos *et al* (Santos *et al* 2012). However, the same authors also showed that this gradient does not differentiate these vegetations in terms of floristic.

For the set of environmental predictors used in this study, the model also shows that the arboreal Caatinga is more similar to Dry Forest than to the Caatinga *stricto sensu*. Hence, there is strong evidence that the arboreal Caatinga is not a climax formation of the Caatinga domain, but an indistinguishable continuum of the Atlantic Dry Forest, which points to an urgent review of the protection offered by the Atlantic Forest Law (IBGE 2006). This discussion needs to be fostered with more data for a conclusion and, in this regard, the work on ecological niche modelling, floristic and phytosociology can make a great contribution. We highlight the importance of works that fill the sampling gaps present for the Caatinga in southern Bahia and northern Minas Gerais, as emphasized by Moro *et al* (2016).

Studies aiming to model the niche of vegetation in this region must consider that errors in the vegetation classification may generate noise in the models. Thus, disfiguring the multidimensional space that defines these niches and leading to inaccurate results. We built a parsimonious model with only eight variables (three soil and five climate variables), from which it was possible to predict the vegetation with 71% average accuracy using the Random Forests algorithm. The methodological framework applied in this study allowed the creation of a comprehensible model to explain the occurrence of the main vegetations found in the Brazilian semiarid region.

2.5 CONCLUSION

The hypothesis that the climate is the main driver to the vegetation class pattern found in the Brazilian semiarid was rejected. Although the contribution of the soil was slightly smaller than the climate, the combination of both provided better class separation, showing that ecological niche modelling, even at a large scale, should not neglect the interaction between the two groups of predictors.

The striking environmental similarity of arboreal Caatinga to Dry Forest allows us to assume that this may not be a distinct vegetation unit from deciduous forest formations. This point towards an urgent review of the Atlantic Forest Law, which currently does not protect the arboreal Caatinga, and faces increasing pressures from deforestation. The hypothesis that this vegetation represents the effect of long-term human activity should be addressed in future work.

3 CHAPTER II

Atlantic Forest or Arboreal Caatinga? Using soil and climate attributes to distinguish dry forests in a semiarid ecotone

Abstract

The southern ecotone of the Caatinga dry forest represents a gap in the knowledge of the dry forests phytogeography. In this poorly sampled transitional zone, the differentiation between the Arboreal Caatinga (AC) and the Atlantic Dry Forest (ADF) is still unclear. Most studies and mapping are based on physiognomic criteria, though it is unknown how much this reflects the species composition of these vegetations. In this context, herein we tested three hypotheses: i) the Arboreal Caatinga and Atlantic Dry Forest have distinct species composition; ii) abiotic attributes (soil and climate) have a greater contribution to the organization of communities and, iii) the variability in aboveground biomass is explained by climatic and edaphic factors. We used non-metric multidimensional scaling (NMDS), Redundancy Analysis (RDA), variance partitioning and multiple linear regression to analyse data from 16 communities. Our results show that the physiognomic classification had a poor relationship with both species composition and environment. Climatic and edaphic factors governed the species composition, explaining half of the total variance and confirming the importance of niche control in the SDTF. We found three main environmental and floristic groups. The ADF was predominant in areas with nutrient-rich and clayey soils and higher rainfall, whereas AC prevailed in sandy and nutrient-poor soils, with higher water stress. Soil clay content and cation exchange capacity were the factors that most explained most of the variability in aboveground biomass. Based on the results, we argue that the classification of vegetation in this region can be improved if more importance is given to niche control. Niche models trained with physiognomic maps should be interpreted with discretion. We predict that they underestimate the impact of aridization on the wetter formations of the Brazilian SDTF domain.

Keywords: Seasonally Dry Tropical Forests, niche modelling, niche conservatism, variance partitioning, Brazilian semiarid.

3.1 INTRODUCTION

Seasonally Dry Tropical Forests (SDTF) are severely threatened biomes across the world (Hoekstra *et al* 2005). Commonly associated with nutrient-rich soils (DRYFLOR 2016, Blackie *et al* 2014), they have been largely converted to agricultural use over the latest centuries resulting in a species-impoverished and spatially fragmented vegetation (Silva and Barbosa 2018, Albuquerque *et al* 2018a, Ribeiro *et al* 2015). These forests are distributed in the tropical zone and more than half of them are found throughout the Americas (Miles *et al* 2006), with the largest unit located in northeast Brazil and surrounding areas (Miles et al., 2006; Silva, Leal, & Tabarelli, 2018). The SDTF are plant formations with high rates of endemism and more diverse than previously thought (Linares-Palomino *et al* 2011a, Silva *et al* 2018), although their importance has been belatedly recognized in comparison to rainforests (Prado, 2000). Dry forests also provide resources for many low-income populations (Blackie *et al* 2014, Djoudi *et al* 2015), so that the demand on local forest resources is ubiquitous. In this context, the provision of ecosystem services is threatened, *vis-a-vis* population growth, reduction of natural vegetation area and the losses of biodiversity under a changing climate (Blackie *et al* 2014, Djoudi *et al* 2015).

Caatinga and Atlantic Forest are the main biomes are encompassed in the Dry Forests domain of northeast Brazil (IBGE 2004). The Caatinga occupies the largest part of the semiarid domain, representing the most characteristic vegetation (Silva *et al* 2018). The several Caatinga deciduous vegetation types vary from open thorny woodland to dense forest, expressing either the regional environmental diversity and chronic anthropogenic disturbances (Andrade-Lima 1981, Sfair *et al* 2018, Ribeiro *et al* 2015, Santos *et al* 2012, IBGE 2004). The Caatinga biome extends from the coast of Ceará and Rio Grande do Norte to northern Minas Gerais states, where the Atlantic Forest gradually replaces it in a complex climatic and edaphic gradient (IBGE 2004, Santos *et al* 2011). In this ecotonal region, predominates a forest physiognomy with intense deciduousness in the dry season, called dry forest. This ecotone is an acutely disturbed region, where natural vegetation remnants are found as scattered fragments in the landscape in a mosaic of succession stages. Despite the threatened status, the southern Caatinga ecotone has very little conservation units and no legal protection at the regional level. Currently, fragments that represent the original vegetation structure are rare. The dry forests in this region are among the most threatened globally (Miles *et al* 2006).

The dry forests of the southern Caatinga - Atlantic Forest transition is an old and unresolved debate in the context of SDTF in Brazil (Silva and Souza 2018, Andrade-Lima 1981, Santos *et al* 2012, Moro *et al* 2016, Oliveira *et al* 2019). There, the so-called Arboreal Caatinga (or Caatinga Forest, Andrade-Lima, 1981a; IBGE, 2004; Santos et al., 2012) presents a similar physiognomy to the Atlantic Dry Forest (Andrade-Lima 1981). Therefore, to distinguish these vegetations is a complex task, which becomes even more intricate with the historic of chronic anthropogenic disturbances that changed the natural environment over the last centuries (Ribeiro *et al* 2015, Silva and Barbosa 2018). Ultimately, for practical purposes of vegetation classification and mapping, the differentiation of these vegetations in field-scale is usually based on two features: the more developed structure in the Atlantic Dry Forest (both higher stands and higher basal area) and the common presence of succulent plants and thorny shrubs in the Arboreal Caatinga, along with a less developed vegetation structure.

Broad-scale studies demonstrated that the Arboreal Caatinga occupies an intermediate position in the environmental and floristic gradient between the driest Caatinga core and the surrounding Atlantic Forest and Cerrado formations (Oliveira *et al* 2019, Silva and Souza 2018, Moro *et al* 2016, Santos *et al* 2012, Neves *et al* 2015). However, there is no agreement on the separation between the Arboreal Caatinga and the Atlantic Dry Forest. Some authors consider these dry forests of northern Minas Gerais and central southern Bahia states as Arboreal Caatinga, a phytogeographic unit of the Caatinga Domain (Santos *et al* 2012, Silva and Souza 2018, Moro *et al* 2016). Others include it as a seasonally dry component of the Atlantic Forest (IBGE 2004, Arruda *et al* 2017). Some even include it as a part of the Cerrado biome – Brazilian savannah (Ribeiro and Walter 2008). This terminological inaccuracy has important consequences for biodiversity protection and knowledge on the biogeography of neotropics. First, since this vegetation is associated with the Caatinga biome, it is excluded from Law 11,428 (Brasil 2006a), which protects the natural vegetation of the Atlantic Forest (IBGE 2006). Secondly, the variety of terms to classify these vegetations hinders a consistent comparison of data from different studies and consequently a better understanding of the SDTF phytogeography in the neotropics.

The official vegetation classification system used in Brazil is physiognomic-based (IBGE 2012, 2004, Veloso *et al* 1991). However, the physiognomic variation in the Caatinga domain does not imply different species assemblages (Silva and Souza 2018). Recent work has shown that the species distribution in the Brazilian semiarid domain is strongly driven by phylogenetic niche conservatism (Queiroz *et al* 2018, Moro *et al* 2015, Oliveira-Filho *et al* 2013), which is a pattern observed in SDTF throughout the planet (Pennington *et al* 2009). Thus, environmental filters (climate and soil) are key attributes to explain the spatially-structured species composition in this region (Silva and Souza 2018, Neves *et al* 2015, Santos *et al* 2012, Arruda *et al* 2015a), where the environmental heterogeneity results in high beta diversity (Arruda *et al* 2020, Aguiar-Campos *et al* 2020). Accordingly, we argue that the classification of dry forests based solely on the structure can be deficient. They can be improved combining floristic and environmental data through niche modelling (Silva and Souza 2018, Santos *et al* 2012). Remarkably, despite the direct consequences for law enforcement and biodiversity conservation, a lack of comparative studies makes it impossible to identify the drivers of species distribution across the southern semiarid ecotone.

In this context, if the structure is the main difference between the Arboreal Caatinga and the Atlantic Dry Forest, what environmental factors explain its variability? In addition, how reliable are the physiognomic criteria to differentiate these vegetations in terms of species composition? Specifically, we hypothesized: i) the Arboreal Caatinga and Atlantic Dry Forest have distinct species composition; ii) abiotic attributes (soil and climate) have a greater contribution to the organization of communities and, iii) the variation in aboveground biomass is explained by climatic and edaphic factors. To test these hypotheses, we used a sample design covering different dry forest communities on the southern ecotone of the semi-arid region, identified as Caatinga or Atlantic Forest by the official vegetation map of Brazil.

3.2 MATERIAL AND METHODS

3.2.1 Study Area

The study area is located between the latitudes 12ºS and 16ºS, south of the Brazilian semiarid region (Figure 4). This region represents a climatic transition between hot semiarid (BSh, *sensu* Köppen) to the northeast and tropical with dry winter (Aw) to the south and west (Peel *et al* 2007). Annual rainfall varies between 600 mm and 1000 mm in a northeast-southwest gradient (Figure 1). In the driest quarter, the accumulated rainfall is less than 20 mm (Fick and Hijmans 2017). Site 10 (Joaíma-MG; plots 31-33) was the only exception, with rainfall exceeding 60 mm in the driest quarter.

3.2.2 Data collection

We sampled Atlantic Dry Forest (ADF) and Arboreal Caatinga (AC) communities at the edges of the southern Caatinga – Atlantic Forest ecotone (Figure 4). The field-level classification followed the same parameters used for vegetation mapping (IBGE 2012). We considered as ADF the physiognomies with two to three strata, continuous to partially discontinuous canopy and an occasional presence of shrubs and succulents. As AC, we considered the arboreal to bush vegetation with partially discontinuous canopy, in which succulents and thorny plants are frequent (Figure A. 4 - Appendix B).

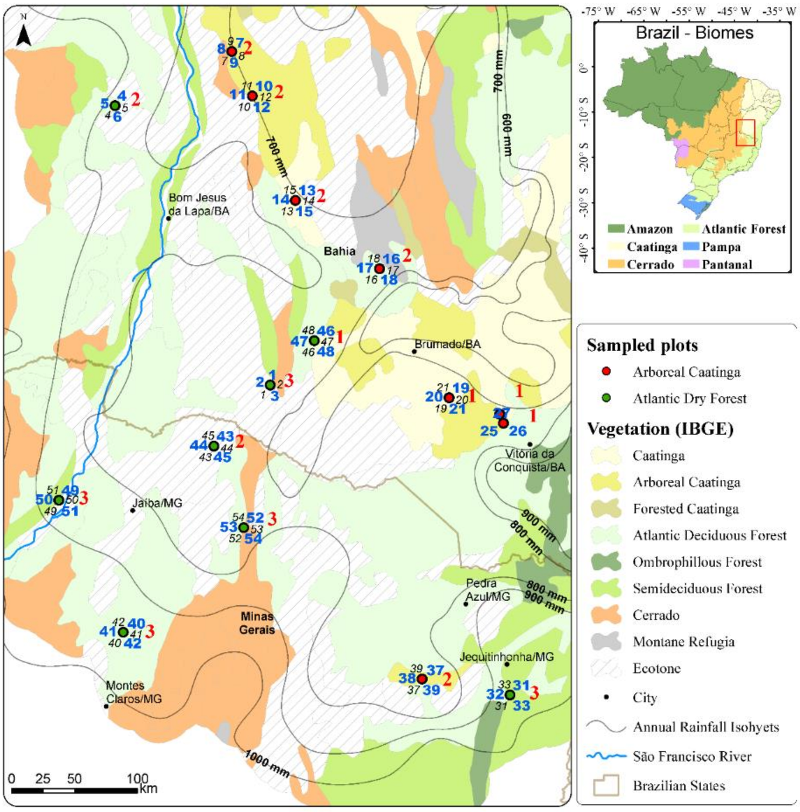

Figure 4. Location of the Atlantic Dry Forest and Arboreal Caatinga communities sampled. The numbers in blue correspond to the plot index. Numbers in red correspond to the environmental groups. Vegetation map adapted from (IBGE 2004). Annual rainfall isohyets reproduced from '*Atlas Pluviométrico do Brasil*' (ANA/CPRM).

The sites selection was based on the official Vegetation Map of Brazil (IBGE 2004). With the sampling scheme, we included communities outside the region mapped as ecotone, to highlight the contrast in the species composition (Figure 4). Besides, we aimed to increase the sampling density in a poorly sampled region (Moro *et al* 2016, Silva and Souza 2018). We sampled plant communities with the least disturbance and the largest area as possible, also considering that they were representative in terms of regional soil type and landscape. We also included data of five ADF communities from previous surveys (Table 4). The locations of the sampled communities are shown in Figure 4.

In each site, we sampled three plots of 20 x 20 m totalling 1.2 ha. We included tree and shrub species with a circumference at breast height (CBH) equal or greater than 15 cm in the ADF and circumference at soil height (CSH) > 10 cm in the AC (Moro and Martins, 2011). The sampled individuals were identified at the species level in the field, or later in the herbarium with the support of specialists. All botanical material was deposited in the Institute of Agricultural Sciences - UFMG (MCCA, Montes Claros). Additionally, a soil profile was dug, described and classified according to the Brazilian Soil Classification System (EMBRAPA 2018, Santos *et al* 2015) and World Reference Base for Soil Resource (WRB 2014). The soil colour was determined by the Münsell chart. For each plot, we collected three topsoil samples (0-20cm) and homogenized them in a single composite one.

The soil samples were air-dried, sieved (ø < 2 mm) and submitted to routine analysis according to the methods described by EMBRAPA (2017). The textural analysis of fine earth was performed by sieving and pipette method, but using slow stirring of 50 rpm for 16 hours followed by determination of the silt by pipetting. The soil pH was determined both in water and KCl solution (1.0 mol.L^{-1}), with a soil:solution ratio of 1:2.5 . The exchangeable cations were extracted in KCl 1.0 mol.L^{-1} and quantified by atomic absorption spectrometer (Ca^{2+} and Mg^{2+}) and titration with NaOH (Al^{3+}). The potential soil acidity ($H^+ + Al^{3+}$) was extracted with Calcium acetate 0.5 mol.L^{-1} in pH 7.0 and quantified by titration with NaOH. The Mehlich-1 method was used to extract available P, Na^+ and K^+. The P content was measured by the ascorbic acid method and K^+ with a flame photometer. The exchangeable Al^{3+} was extracted with 1.0 mol.L^{-1} ammonium acetate solution at pH 7.0 and measured by a flame photometer. Organic C was determined by the Walkley-Black method without heating. All analysis were performed in the Soil Science Department at the University of Viçosa - Brazil. In total, 15 soil attributes were analysed (Table S1).

We used bioclimatic data to represent the climatic patterns of the vegetations analysed. The bioclimatic variables with 1 km resolution were obtained from the Worldclim 2 database (Fick and Hijmans 2017), which consists of interpolated data from climate stations, recorded in the 1990-2010 period. We extracted the 19 variables (Table S2) for the plot locations with the ArcMap Geographic Information System, version 10.3 (ESRI 2016).

3.2.3 Data analysis

We organized the data in four matrices: environmental data (soil and bioclimatic variables), species abundance, spatial data (latitude and longitude), and basal area per individual. We used Hellinger transformation on the species abundance matrix to minimize the effect of rare species (Borcard *et al* 2018, Legendre and Gallagher 2001) with the *decostand* function from 'vegan' package (Oksanen *et al* 2008, Oksanen 2017). For species composition analyses all individuals were included. The environmental data matrix was standardized to zero mean and unit standard deviation. We removed highly correlated variables to reduce the data volume and avoid collinearity. The pairwise correlations were calculated and a cluster dendrogram was built with the *varclus* function from 'Hmisc' package (Harrell Jr 2015). For each cluster of highly correlated variables (Pearson > 0.90), the one with the lowest redundancy measured by the overall mean correlation was selected for all subsequent analyses (Figure A.5).

Hypothesis *i* - To verify the similarity in species composition between the ADF and the AC physiognomies, we performed a Multidimensional Non-metric Scaling (NMDS). This non-canonical procedure aims to represent the species composition in a reduced n-dimensional space (Kenkel and Orloci 1986). We calculated the number of dimensions for the NMDS convergence with stress < 0.20, with the *dimcheckMDS* function from the 'goeveg' package (Goral and Schellenberg 2018). Then, we performed the NMDS with the *metaMDS* function from 'vegan' package (Oksanen *et al* 2008). The Euclidean dissimilarities in the NMDS were calculated from the Hellinger-transformed species abundance matrix. We used Venn diagrams to represent the shared taxa between the two vegetations. To assess the dissimilarity between communities represented by species turnover, we computed the pairwise dissimilarity matrix using the Simpson index with the *beta.pair* function from 'betapart' package.

Table 4. Description of the sampled sites in the Caatinga – Atlantic Forest transition zone in northern Minas Gerais and southwest Bahia, Brazil. Vegetation: ADF - Atlantic Dry Forest; AC - Arboreal Caatinga. Lithology: Cr – Crystalline rocks, Sd – Sedimentary; Lm – Limestone. Köppen climate types: Aw - Tropical with dry winter; Bsh – Hot semi-arid. Elev. – Elevation above sea level.

Site	Veg.	Soil type - WRB	Lit.	Clim.	Lat.	Long.	Elev.	Source
1	ADF	Eutric Rhodic Ferralic Cambisol (Clayic, Colluvic)	Cr	Aw	-14.44	-42.69	760	1*
2	ADF	Xanthic Ferrasol (Clayic, Oligeoeutric)	Sd	Aw	-12.45	-43.79	490	1
3	AC	Ferralsol (Loamic, Epihypereutric, Ochric)	Cr	Aw	-12.06	-42.96	520	1
4	AC	Hyperdystric Rubic Ferralic Arenosols	Sd	Aw	-12.38	-42.82	488	1
5	AC	Lixic Xanthic Ferrasols (Clayic, Eutric, Ochric)	Cr	Aw	-13.12	-42.51	600	1
6	AC	Acric Xanthic Ferrasols (Loamic,Hyperdystric,Vetic)	Sd	Aw	-13.61	-41.91	510	1
7	AC	Rhodic Ferritic Ferrasols (Clayic, Oligeoeutric)	Cr	Bsh	-14.53	-41.41	698	1
8	AC	Acric Xanthic Ferralsols (Clayic, Orthodystric, Vetic)	Cr	Bsh	-14.65	-41.05	746	1
9	AC	Acric Rhodic Ferric Ferralsols (Clayic, Orthodystric, Vetic)	Cr	Bsh	-14.71	-41.03	803	1
10	ADF	Acric Rhodic Ferritic Ferrasols (Clayic, Orthodystric, Vetic)	Cr	Aw	-16.65	-40.98	370	1
11	AC	Acric Xanthic Ferralsols (Clayic, Orthodystric, Vetic)	Cr	Aw	-16.54	-41.61	283	1
12	ADF	Latossolo Vermelho eutrófico	Lm	Aw	-16.20	-43.74	568	2
13	ADF	Distric Yellow Argisol	Sd	Aw	-14.88	-43.09	564	2
14	ADF	Latossolo Vermelho distrófico	Cr	Aw	-14.13	-42.38	889	2
15	ADF	Eutric Latosolic Red Argisol	Lm	Aw	-15.26	-44.20	480	2
16	ADF	Eutric Latosolic Cambisol	Cr	Aw	-15.46	-42.88	580	2

*1: This study. ; 2: Arruda et al 2020

Hypothesis *ii* – To test the second hypothesis, we used two complementary approaches. First, we tested whether the environmental variables (climate and soil) or space (neutral processes) explained the species composition. For this, we proceeded to a Redundancy Analysis (RDA) followed by variance partitioning. The existence of a spatial trend in the data was tested before the RDA by Distance-based Moran's Eigenvector Maps (dbMEM) (Borcard *et al* 2018). We used the *dbmem* function of 'adespatial' package (Dray *et al* 2018) to calculate the eigenvector maps based on Moran's distance. We tested the overall significance of the dbMEM variables by Analysis of Variance (ANOVA) and subsequently we used forward selection to retain the significant spatial eigenvectors. Finally, an RDA was performed with the selected environmental and spatial variables combined. The RDA was executed with the RDA function of the 'vegan' package. Additional information about the RDA analysis is available in Supplementary Information (Supplementary Material). To evaluate the individual contribution of climate, soil and space in the species composition, we proceeded to variance partitioning. We used the *varpart* function from 'vegan' package to calculate the adjusted R^2 of each group of variables. The significance of the models and RDA axis were tested by ANOVA at 95% confidence level, with 9,999 permutations.

Secondly, we grouped the sites with similar environmental attributes and verified if these clusters corresponded to distinct groups in terms of species composition. To this end, we used the K-means clustering method followed by the NMDS. The optimal number of clusters was previously determined by two criteria: i) the sum of squares within clusters concerning the number of clusters, and ii) the distance between the cluster centres in the first two principal components. We used a supplementary Principal Component Analysis (PCA) to permit the visualization of the environmental attributes in the clusters. Significant differences in distributions of the environmental variables were verified by Kruskal-Wallis test (non-parametric). Additionally, to assist in the recognition of the above-mentioned environmental groups in the field, we have identified combinations of species as indicators (see Sup.Mat.).

Hypothesis iii – We used the basal area as a proxy of the aboveground biomass and verified whether the environment explained its variability. The DBH and DSH values were converted to basal area per plot and then to $m^2.ha^{-1}$. For individuals with multiple stems, the areas were merged. As we used different inclusion criteria to sample each physiognomy, we removed individuals with CSH < 15 cm from the areas classified as AC for this analysis. This was necessary to obtain greater equivalence and avoid overestimation of the basal area in the AC by including small individuals, which were not sampled in the ADF communities.

The difference between the two vegetation classes in terms of biomass was tested by t-test. Then, we assessed the influence of environmental factors on the aboveground biomass with multiple linear regression. Previously, we adjusted a global model with all environmental variables and then we proceeded to predictor selection. Non-significant variables were removed in an iterative process to adjust a parsimonious model. As stopping criteria, we have set a limit of a maximum 10% loss, in relation to the adjusted R^2 calculated for the global model. The normality of the multiple linear regression residuals was verified with the *shapiro.test* function from R package. We used the Cook's D statistic (Cook 1977) to remove poor-fit plots and adjusted a final model.

3.3 RESULTS

In total, we sampled 3131 individuals from 219 species distributed in 37 botanical families. In terms of abundance, Fabaceae was the most important family (962 individuals), followed by Euphorbiaceae (456), Bignoniaceae (377), Combretaceae (238) and Rutaceae (203). We identified 146 species in the ADF and 126 in the AC (Figure 5). We removed the species with a single occurrence (unicates) for comparison, totalling 3071 individuals of 159 species, of which 40 were present in both vegetation classes. Most of the rare ones were concentrated in the ADF (Figure 5c and 5d).

Regarding the difference in composition between the two vegetation classes (hypothesis *i*), the NMDS computed with three dimensions (stress = 0.19, R^2 linear fit = 0.68, Figure A. 6) showed a high overlapping, indicating that they share similar floristic assemblages (Figure 6). At the community level, the mean overall Simpson dissimilarity was 0.74. This value is consistent with those reported in other studies (Apgaua *et al* 2014, Arruda *et al* 2020). The dissimilarity matrix revealed lower values for the pairwise comparisons between AC communities (mean = 0.63) than between ADF communities (0.79) (Table A. 7).

Results of the preliminary RDA showed significance of the environmental predictors on the species composition (hypothesis *ii*) ($R^2_{adj.} = 0.52$, $F = 3.74$, p-value < 0.01). The final RDA model with environmental and spatial predictors (dbMEM) obtained greater explanatory power ($R^2_{adj.} = 0.586$) than the former. The overall significance was confirmed by ANOVA ($F = 4.70$, $p < 0.001$). Variance partitioning showed that climatic factors contributed for the most of the explained variance in species composition, followed by soil and space (Figure 7b). Non-explained variance (residuals) accounts for 40.8% of the total variance.

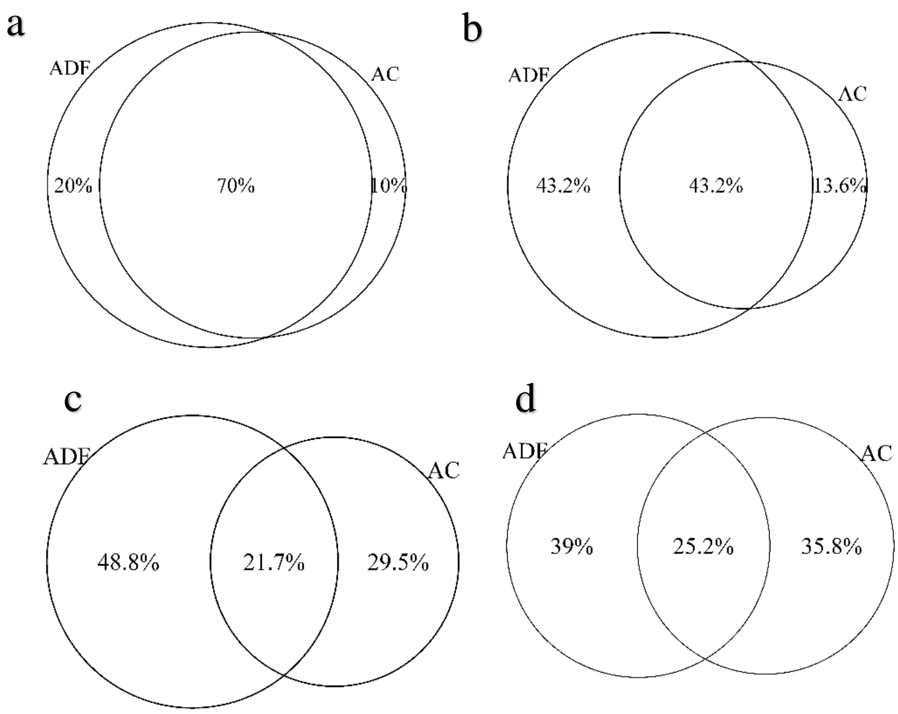

Figure 5. Venn diagrams with percentages of families (a, n=39), genera (b, n =133), species (c, n=219) and species without unicates (d, n = 159) distributed in each type of vegetation in the southern ecotone of the Brazilian semiarid. AC: Arboreal Caatinga; ADF: Atlantic Dry Forest.

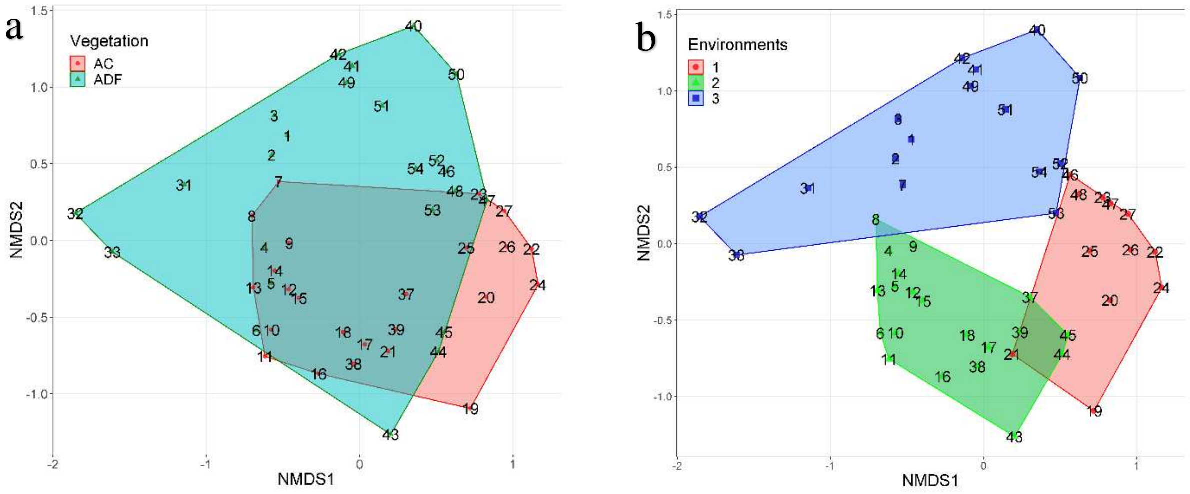

Figure 6. Non-metric multidimensional scaling (NMDS), with groups according to physiognomic classification (a); and environmental groups from cluster analysis (b). Vegetation: AC - Arboreal Caatinga; ADF - Atlantic Dry Forest. Environments: 1 – Less seasonal and cooler; 2 – Warmer and drier with nutrient-poor soils; 3 – Tropical with dry summer, high seasonality and nutrient-rich soils.

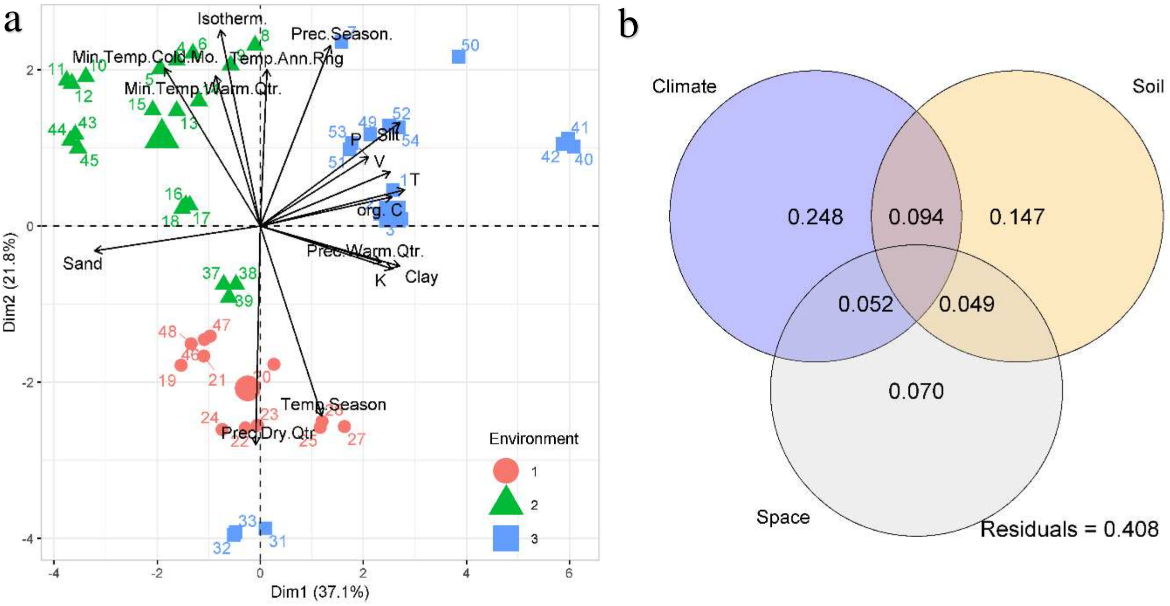

Figure 7. Principal Component Analysis of environmental variables by clusters (a) and variance partitioning results (b). Abbreviations: Min.: minimum, Prec.: precipitation, Temp.: temperature, Warm.: warmest, Season.: seasonality, Qtr.: quarter, V: base saturation, T: cation exchange capacity, P: available phosphorous, org. C: organic Carbon.

We identified three distinct environments (Figure 7a). The spatial distribution of these groups are presented in Figure 4. The PCA showed that the environments were separated mainly by soil (texture and nutrient richness) in Dimension 1 and by the climate in Dimension 2 (Figure 7a and Figure A. 7, Appendix B). Results of Kruskal-Wallis tests for environmental attributes are presented in Figure A. 8 and Venn diagrams with taxa distribution per environment in Figure A. 9. Henceforth, we will refer to the environmental clusters as Env.1, .2 and .3 for greater objectivity. Below, we highlight the main attributes of each.

Env.1 was the coolest and least seasonal (Figure A. 8), with a predominance of the vegetation classified as AC (Figure 4). The soils had intermediate characteristics among the other environments, standing only by the lower silt content (Figure A. 8). There was no significant difference in rainfall between Env.1 and Env.2. However, in the former, there was higher precipitation in the driest quarter and lower temperatures (Figure A. 8). This indicated better rainfall distribution with a dry period with milder temperatures, though the annual rainfall is low (*c.* 650 mm).

Env.2 was characterized by a warmer and drier climate throughout the year, with low annual precipitation (*c.* 750mm) and lower precipitation in the warmest quarter (Figure A. 8). Most of the Env.2 sites were located in the São Francisco River depression on Quaternary sedimentary surfaces. The vegetations classified as AC predominated (Figure 4). Soils were sandier, with low nutrient content, low CEC and organic matter (Figure A. 8). The Al^{3+} saturation was the highest among the three environments (Figure A. 8).

Env.3 stood out by its edaphic and climatic attributes, with nutrient-richer and clayey soils and higher annual precipitation (Figure A. 8). This group was associated with high seasonality, with a well-defined dry period (Figure A. 8). However, the higher rainfall during the warmest quarter suggests less aridity. The Al^{3+} saturation was virtually null. Most of the sites included in this group were classified as ADF (Figure 4).

The indicator species analysis identified significant pairs for the three environments (Table 5). However, many of the indicator species have a wide distribution in the SDTF domain in Brazil (Figure A. 10). Thus, the presence of a single species of each pair is not valid as an environmental indicator. They are meaningful when found co-occurring in the communities.

Table 5. Indicator species combinations of the three environments identified in the south ecotone of Brazilian semiarid. The environmental descriptions are relative to each other.

Environment	**Description**	**Indicator species combinations**		
1	Less seasonal and cooler	*Schinopsis brasiliensis* + *Mimosa sp.*	*Diplotropis ferrugínea* + *Schinopsis brasiliensis*	*Machaerium acutifolium* + *Senegalia langsdorffii*
2	Warmer and drier climate. Nutrient-poor and sandy soils	*Handroanthus spongiosus* + *Mimosa tenuiflora*	*Handroanthus spongiosus* + *Cnidoscolus bahianus*	
3	Tropical with dry summer (high seasonality). Nutrient-rich and clayey soils	*Commiphora leptophloeos* + *Myracrodruon urundeuva*	*Commiphora leptophloeos* + *Sapium glandulosum*	

The environmental clustering resulted in a better separation of the communities in terms of species composition, as showed in the NMDS (Figure 6b), and by the lower number of shared species between groups (Figure A. 9). In relation to the physiognomic classification, 95.8% of the AC communities were divided in the Env.1 (37.5%) and Env.2 (58.3%), whereas 62% of the ADF sites were included in Env.3.

Regarding aboveground biomass, the ADF physiognomy showed higher averages for basal area than the AC (2.95 ± 0.34 m^2 and 2.41 ± 0.43 m^2 at 95% C.I; Kruskal-Wallis $p = 0.04$)

confirming a more developed structure, consistent with the physiognomic criteria used in the survey. As for environmental groups, Env.3 presented the highest basal area (3.28 ± 0.42 m²) and Env.2 the lowest one (2.17 ± 0.36 m²; Kruskal-Wallis $p < 0.01$). Env.1 presented intermediate values between the previous ones (2.71 ± 0.60 m²). The distribution of basal area by groups showed a higher density of larger individuals in the Env.3 (Figure A. 11). The multiple linear regression (Figure 8) indicated that clay content (ANOVA: F-value = 13.81) and CEC (ANOVA: F-value = 13.01) predictors were the ones with the highest explanatory power. Soil variables represented the vast majority of environmental predictors to explain the variation in aboveground biomass, with isothermality as the only significant climatic variable (Table A. 8).

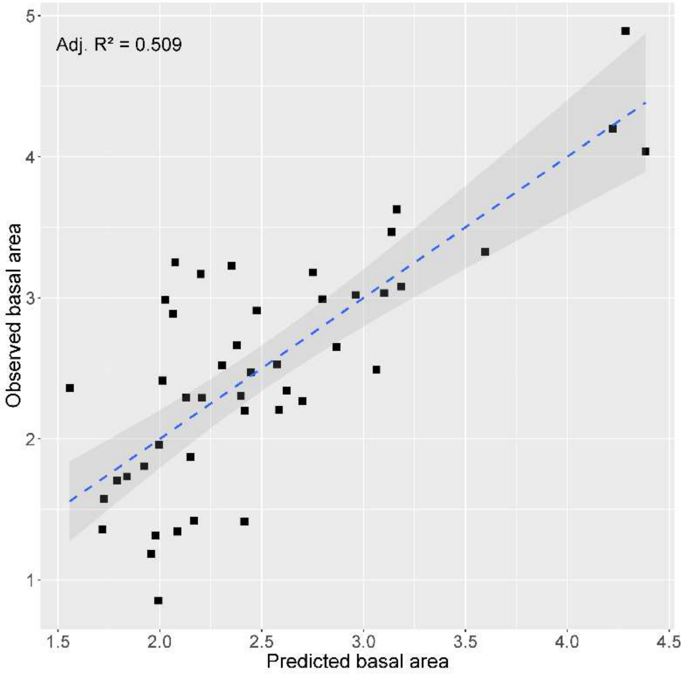

Figure 8. Basal area predicted by multiple linear regression model versus observed (ANOVA: F= 6.01, P < 0.01) (b). Plots 3, 11 and 25 were removed based on Cook's distance.

3.4 DISCUSSION

One chief question in plant ecology is to identify the extent to which the physical environment determines the species distribution in terrestrial ecosystems (Brown 1984, Elith and Leathwick 2009). Quantifying the relative importance of niche and neutral processes has practical implications for biodiversity conservation, allocation of protected areas and modelling species responses to environmental changes. In this regard, niche conservatism is an important driver of species distribution in SDTF globally (Pennington *et al* 2009), resulting in high beta-diversity among communities (Arruda *et al* 2020, Apgaua *et al* 2014).

Our results do not confirm the hypothesis that ADF and AC have distinct compositions. At the class-level, ADF and AC showed a remarkable floristic similarity sharing 25% of the species. If we remove infrequent taxa (< 5 occurrences), this sharing is for almost half of the species. These values are relatively high in the context of the dry forests (Oliveira-Filho *et al* 2006b), where there is great dissimilarity (beta-diversity) between communities. On the other hand, considering the species turnover at the community level, we found distinct patterns for the two vegetation classes. While the ADF showed higher intra-class dissimilarity, the AC communities were more homogeneous. This suggests that the AC communities may have undergone abiotic homogenization (Rito *et al* 2017c, Ribeiro *et al* 2016), which explains the difference in terms of physiognomy. We sampled communities with very distinct species compositions, but this variation was more related to the environment rather than to the physiognomic type.

Regarding the second question, we found that most of the variability in species composition was explained by abiotic factors (48.9% for soil and climate together), while space represented only 7%. In agreement, we found that the three environmental groups were associated with distinct species assemblages. Thus, we confirmed the second hypothesis, corroborating other studies that show the predominance of niche control over neutral processes in SDTF (Arruda *et al* 2020, Santos *et al* 2012, Neves *et al* 2015, Souza *et al* 2019a). In this regard, our results support the importance of two main drivers of the species composition in the SDTF: water stress - jointly represented by soil texture and volume and seasonality of rainfall - and soil fertility (Rito *et al* 2017a, Santos *et al* 2012, Silva and Souza 2018). The environmental factors, namely soil attributes, also influenced significantly the structure of the communities ($r^2 = 0.509$), confirming our third hypothesis.

Climatic factors were the main drivers of species assemblage since they alone explained 24.8% of the total variance. Neutral processes represented by spatial trends were significant but of lesser importance. It means that niche control prevails over processes such as limitations in species dispersal. These results corroborate other studies developed in the same region (Arruda *et al* 2020, 2015a), although the AC was not included in them. As shown in Arruda et al. (2020), soil and climatic factors equally contributed to the species turnover in the region that encompasses the ADF in a 300 km transect. In the present work, by expanding this transect to about 500 km in the latitudinal direction and including the AC, climatic predictors were more important for species composition, confirming the transitional character of this region.

We have not addressed the role of biogeographical history, anthropogenic disturbances or biotic factors in this study, although we recognize their importance. For instance, Carrión et al. (2017) showed that facilitation by nurse species influences the diversity of herbaceous plants in the dry Caatinga of northern Bahia. However, it is still unclear how much this kind of biotic interaction is relevant to the diversity and composition in the forest-type formations (but see Lasky et al., 2016 and Teixeira et al., 2020).

Concerning the biogeographical history, Queiroz et al. (2018) showed that three (main) phylogenetic lineages occur in the Caatinga domain. The older one, whose speciation occurred from the Mid to Late Miocene and Pliocene, is associated with the crystalline basement surfaces. The second and third ones emerged by *in situ* speciation from the crystalline areas in the last 1.5 M yr. They are related to the sandy and nutrient-poor sedimentary surfaces (Lemos and Rodal 2002) and karstic areas (Aguiar-Campos *et al* 2020). In the present study, we verified a similar trend in the distribution of lithological types within environmental groups. Nonetheless, this was not a determinant factor for all of them. Only Env.1 was associated with a single lithology (crystalline rocks). Most plots included in Env.2 (60%) were associated with sedimentary areas. However, sites on crystalline basement rocks have also been included whenever they were in a similar climatic type. Env.3 clustered both limestone and crystalline rock communities, provided they were in a similar climate. No community of the sedimentary areas was included in the Environment 3. This suggests that biogeographical history is an underlying factor influencing species composition in the region. We consider that biogeographical and land-use history and biotic interactions are encompassed in the 40.8% non-explained variance.

Rainfall, soil fertility and chronic anthropogenic disturbances are known drivers of functional composition in dry tropical forests (Pinho *et al* 2019, Sfair *et al* 2018, Zorger *et al* 2019). Dry environments select traits related to drought avoidance, tolerance or resistance (Lohbeck *et al* 2013, Chaturvedi *et al* 2011, Markesteijn and Poorter 2009). For example, increasing xylem vessels density reduces the chance of collapse and cavitation under intense drought events (Markesteijn and Poorter 2009), thus resulting in high-density woods. Corroborating with these findings, we verified that the indicator species of the drier environments (1 and 2) have high-density woods. On the other hand, *C. leptophloeos* and *S. glandulosum*, two out of the three indicators of Env.3 are species with very low-density woods. These results suggest that the functional traits filtering were different between Env.1-Env.2 and Env.3. The effects of environment in traits composition should be further assessed in future work.

Many authors have shown that anthropogenic disturbance changes the floristic composition in the Brazilian SDTF (Ribeiro *et al* 2019, Rito *et al* 2017c, Pegado *et al* 2006, Andrade *et al* 2010, Pereira *et al* 2001, Souza *et al* 2015, Ribeiro *et al* 2015, Sfair *et al* 2018). In short, the disturbances leads to a reduction in the abundance of less tolerant species and favours groups resistant to drought, herbivory and able to sprout after logging. Additionally, Rito et al. (2017b) and Zorger et al. (2019) showed that the effects of anthropogenic disturbance are stronger as precipitation decreases. In this context, we verified that the indicator species of Env.2 (the driest one) are pioneer species with high invasive potential (*M. tenuiflora*) (Robbins 2004) and non-palatable, therefore resistant to herbivory (*C. bahianus*). In fact, *M. tenuiflora* is abundant even in environments undergoing desertification processes (Souza *et al* 2015) and affected by fires (Sampaio *et al* 1993). In addition, the low pairwise dissimilarities among AC communities is a strong evidence of abiotic homogenization. Thus, our results support the hypothesis that part of the so-called AC represent a disturbed ADF in a drier environment with nutrient-poor soils (Arruda *et al* 2015b, Oliveira *et al* 2019). We emphasize that the absence of natural reserves in the region precludes the confirmation of this hypothesis, as the references to the structure and composition of the original vegetation do not exist.

Unlike species composition, mostly influenced by climate, the variability in aboveground biomass was explained by soil attributes. Clay content and CEC were the most important variables, showing a relationship between vegetation structure and soil nutrient richness, capacity to hold nutrients, and water storage capacity. A considerable part of the CEC in highly-weathered tropical soils is attributed to soil organic matter (Ramos *et al* 2018). Indeed, we observed a high correlation ($r^2 = 0.73$) between soil organic matter and CEC in our dataset. In turn, the organic matter tends to increase with more biomass and species diversity (Souza et al., 2019). Biogeochemical cycling is responsible for the concentration and redistribution of nutrients in Dry Forests (Campo *et al* 2000, 2001, Jaramillo and Sanford 1995, Vitousek 1984) and contributes to the increase of soil CEC. The CEC upkeep is important for species with acquisitive strategy (Maracahipes *et al* 2018) as the soil can retain nutrients that are released by litterfall and accumulated in the dry season (Campo *et al* 2000). Otherwise, they can be leached out of the system before the plants begin the uptake in the growing season (Campo *et al* 2007). Therefore, the soil conservation is crucial in the Dry Forests, once the interruption of the biogeochemical cycling and soil depletion has serious consequences for its ecology (Lawrence *et al* 2007, Berdugo *et al* 2020). In this regard, we consider that soil degradation is of particular concern in the sedimentary surfaces in the study area, where the limited nutrients were concentrated in the topsoil (Jobbágy and Jackson 2004), what makes them highly dependent on organic matter and nutrient cycling.

Soil P had minor importance on the structure of the communities. Phosphorus is a limiting macronutrient in tropical soils (Sollins *et al* 1988, Vitousek 1984, Wang *et al* 2010, Li *et al* 2016) and a key element for primary production in dry forests (Campo *et al* 2007). Thus, we expected that it would present a major influence on the vegetation structure. In this sense, a few remarks must be made for further research. First, the method used for P extraction (Mehlich-1) is likely to underestimate what the natural vegetation can absorb. Still, it is known that most of the P in tropical ecosystems is allocated to biomass and present in much smaller quantities in the soil (Li *et al* 2016, Vitousek 1984, Campo *et al* 2001). Thus, a better approach of the relationship between P and community structure should consider the content of such nutrient in the plants and litter as well. Second, we were unable to assess the structure variability over a full range of P availability. The sampled communities were restricted to soils with lower agricultural potential, thus, P was an equally limiting element for all communities sampled. Consequently, the narrow and very low P range sampled (0.4 – 5.97 $mg.dm^{-3}$) was below a threshold at which it starts to influence the growth of plants (phosphate starvation). At landscape-scale, organic P is concentrated in the bottom slope (Cheng *et al* 2016, Roberts *et al* 1985, Abrams and Jarrell 1995). In the Brazilian semiarid region, these flat and fertile areas were largely converted to croplands and pastures over the last centuries (Coimbra-Filho and Camara 1996). Consequently, the remaining secondary forests are located on the slopes or potentially affected by the disruption in P dynamics (Lawrence *et al* 2007) when regenerating in the lowlands.

Our results have practical consequences for biodiversity protection and for modelling the response of SDTF to climate changes. Based on species composition and floristic similarity, we argue that the southern semiarid ecotone should be encompassed in the Atlantic Forest Law enforcement (IBGE 2006). Given that the purpose is to protect the biodiversity of the Atlantic Forest Biome (Brasil 2006a), this transition with remarkable floristic similarity should be also encompassed. As our sampling scheme sought to maximize the difference between these physiognomies at the ecotone outskirts, we expect that the similarity is even higher inside the ecotone. This region represents an important area for buffering anthropogenic and climate change impacts on dry forests (Acosta Salvatierra *et al* 2017). Concerning allocation of legally protected areas, the fact that niche control drives the species composition has also major implications. Broad knowledge of regional environmental variability is crucial to enfold the largest range of species as possible. An effective network of protected areas should include the various types of environments found in the region (DRYFLOR 2016).

Furthermore, niche models trained with physiognomic types does not represent the floristic assemblage accurately. As shown here, the physiognomic-based classification mixes communities with different species compositions, which occur in distinct environments. Consequently, it inflates the multidimensional niche space of each vegetation. We predict that such models underestimate the impact of environmental changes on wetter vegetation, because the new (more arid) conditions were incorporated in the current multidimensional niche at the time of model training. Soil niche inflation is also of concern, because it overestimates the geographic space in which some species are able to move during climate changes (Corlett and Tomlinson 2020). The response of plants to environmental changes occurs at the species and functional composition level (Román-Palacios and Wiens 2020). For that reason, the physiognomy in the study area does not represent the features that ultimately determines the vegetation response to the environmental changes.

Niche conservatism is recognized as a driver of species and traits composition in the SDTF (Arruda *et al* 2020, Santos *et al* 2012, Neves *et al* 2015, Queiroz *et al* 2018, Rodrigues *et al* 2019). Thus, similar environments are expected to share analogous species composition (Arruda *et al* 2015a). From these findings, we conclude that it is urgent to develop phytogeographic models based on species composition (Silva & Souza, 2018), environment (Dubuis *et al* 2013, Rodrigues *et al* 2019) and phylogeny (Queiroz 2006, Queiroz *et al* 2018), besides the physiognomic bias. We expect such models to have a higher correlation with traits composition. Consequently, they can produce consistent predictions of vegetation shifts and impacts on the species diversity.

This is the first study that specifically analyses the southern ecotone of the semiarid region, encompassing AC and ADF communities. In this preliminary approach, we aimed to investigate the validity of the physiognomic classification and the factors that govern species composition and vegetation structure in a broad-scale. Based on the results obtained, we can outline further studies in more detailed scales. New sampling should follow an aridity and soil richness and texture gradient, including other environments that were not analysed here, as the riparian forests and rock outcrops. In this sense, we suggest a thorough environmental stratification with soil, lithology and climate data to optimize the sampling. Expanding knowledge of SDTF is crucial to devising conservation strategies for this threatened biome.

3.5 CONCLUSION

We found three main types of dry forest communities in the southern semiarid ecotone. However, the physiognomic-based classification was inefficient to separate them, while it is more likely to reflect impacts of abiotic homogenization. Following the general pattern observed in dry forests, there was a strong environmental control in the organization of communities. We also confirmed the significant influence of the environment in the structural variation of the communities. Climate was the predominant factor to explain the variation in species composition, whereas soil attributes were more important to explain structural variation. Our results show that models calibrated with the physiognomic type should be interpreted with discretion. We predict that such models may underestimate the impact of aridization on the wetter formations of the Brazilian SDTF domain.

4 CHAPTER III

Beneath the dry forests: spatial distribution of topsoil attributes in the Brazilian semiarid region

Abstract

Soil attributes represent a set of key variables for ecological modelling. They led to the enhancement of niche models, either for plant species and biomes distribution. However, the lack of spatialized soil attributes in quantitative maps is still a hindrance. The inclusion of this data is essential to model the distribution of Seasonally Dry Tropical Forests (SDTF), where the soil is an important driver of species composition. In view of the increased aridity predicted by climate models for the semiarid region of Brazil, the largest SDTF unit in the Neotropics, the development of more robust models is crucial to steer effective conservation strategies. Aiming to contribute to biogeographical studies and a better comprehension of edaphic variability in this region, we produced a database of 14 topsoil attributes. We used data from soil maps of the RADAMBRASIL Project (1/1,000,000) to associate the soil profiles with the mapping units and spatialize the A horizon (topsoil) attributes in a raster grid. We used the database to group similar topsoil properties in soil Units and highlight important features for biogeographical modelling. We have identified six soil Units with very contrasting superficial attributes. These Units were clearly related to the vegetation distribution at large-scale. The Caatinga vegetation was mostly associated with low Al^{3+} saturation, both in sandy and silty soils. The Cerrado was concentrated in sandy and dystrophic soils. In turn, the Atlantic Forest occurred in a wide variety of soil types. The diverging soil properties where each vegetation type predominates confirms their importance in modelling the vegetation distribution in future climate scenarios. If the climate model projections are confirmed, one can expect that the southern and western Brazilian semiarid regions will have the most critical changes, since in them there will be the expansion of a dry and dystrophic environment, contrasting with the environmental niche where vegetations currently occur.

Keywords: Niche modelling, soil attributes distribution, Caatinga biome, climate change

4.1 INTRODUCTION

A remarkable breakthrough in environmental niche modelling was achieved in the last decades due to the development of more robust algorithms and databases (Qiao *et al* 2015, Kearney and Porter 2009). Among the models based on the Hutchinsonian niche concept (Hutchinson 1957, Holt 2009), the mechanistic and correlative approaches are the most widely used (Soberon and Peterson 2005, Kearney 2006). In the mechanistic approach, the physiological responses of plants to physicochemical environmental factors are measured (*e.g.*, moisture, temperature, soil fertility). Then, the likelihood of a species occurrence is predicted for combinations of these parameters in a region (Särkinen *et al* 2011, Collevatti *et al* 2013b, Bueno *et al* 2017, Leibold 1995). On the other hand, the correlative approach uses species or biome occurrences and correlates them with the environmental variables to model the realized niche (Franklin 1995, Arruda *et al* 2017, 2018, Huntley *et al* 1995, Peterson *et al* 2001, Bakkenes *et al* 2002, Pearson *et al* 2002). In both approaches, models predict the occurrence of either a species or plant formation to a broader region - or paleo/future climates - using spatialized environmental attributes. Despite the potentials and weaknesses of each, they have proved to be complementary rather than antagonistic (Kearney and Porter 2009).

Notwithstanding the progress achieved, most of the factors that explain the taxa distribution remain unclear. In this sense, the inclusion of layers representing the variability of key environmental attributes is essential (Mod *et al* 2016a, Diekmann *et al* 2015). Models often use climatic factors to characterize the ecological niche (Mod *et al* 2016a). Hence, they would be more precisely called 'climate envelope' or 'bioclimatic' models (Pearson and Dawson 2003). However, the climate is not detailed enough to explain the vegetation distribution at finer scales, where soil play a chief role (Casalini *et al* 2019, Arruda *et al* 2015a). Also, the distribution of soil-specialist species cannot be explained by climatic factors alone (Corlett and Tomlinson 2020). Consequently, the need for soil attributes in biogeographic modelling has been dearly recognized and urged by many research groups in recent years (Pearson and Dawson 2003, Arruda *et al* 2017, Gégout *et al* 2005, Schweiger *et al* 2008, Diekmann *et al* 2015, Dubuis *et al* 2013, Figueiredo *et al* 2018, Mod *et al* 2016a, Thuiller 2013), although a survey by Mod *et al.* (2016) showed that less than 40% of studies on correlative niche modelling published in the 2010-2015 period used soil predictors.

The infrequent use of soil attributes in niche modelling is a result of database lack rather than unawareness of their importance (Diekmann *et al* 2015). This is partly due to the increased availability of high-resolution climate (*e.g*. WorldClim, Fick & Hijmans 2017) and topographic data (*e.g* SRTM, Jarvis *et al.* 2015) at large scales. On the other hand, soil attributes data covering large extents at fine scales are scarce. Therefore, researchers tend to use categorical data (Prentice *et al* 1992, Särkinen *et al* 2011, Bueno *et al* 2017), limited in geographical extent (Gégout *et al.*, 2005; Wright *et al.*, 2006) or at less detailed scales (Neves *et al* 2015). Recently, digital soil mapping products emerged as a promising solution to this problem (Hengl *et al* 2017, 2014, Chagas *et al* 2016). However, their quality is uncertain for poorly sampled regions (Figueiredo *et al* 2018).

Soil is a factor of differentiation in natural ecosystems, influencing the organization of ecological communities (Prado, 2000; Ferreira-Júnior *et al.*, 2007; Pinheiro *et al.*, 2010; Neri *et al.*, 2012; Saporetti-Junior *et al.*, 2012; Nunes *et al.*, 2015; Almeida *et al.*, 2018, see also Chapter 2). Soil attributes enable the development of more consistent models, with a realistic representation of the multidimensional niche. Consequently, they provide better depiction in ecotonal regions (Arruda *et al* 2017) and vegetations strongly associated with specific soil characteristics (Oliveira *et al* 2019, Dubuis *et al* 2013, Corlett and Tomlinson 2020).

Neglecting the edaphic dimension, on the other hand, has important consequences. Considering the niche as an n-dimensional hypervolume (Blonder *et al* 2014), the absence of the edaphic environment leads to a 'niche inflation'. It causes the overestimation of the hypervolume by not taking into account relevant environmental filters of plants distribution. In turn, niche inflation hinders the prediction of current vegetation distribution under climate scenarios. For example, the Cerrado (Brazilian savannah) occurs in a wide climatic range, but in a far more restricted soil niche (Oliveira *et al* 2019, Arruda *et al* 2017). Consequently, the prediction of this biome distribution is prone to overestimation without including soil attributes (Arruda *et al* 2017, Maksic *et al* 2019). Concerning vegetation shifts under future climate scenarios, the bioclimatic envelope can overestimate the response (movement) of soil-specialist species (Corlett and Tomlinson 2020). Hence, soil attributes are central to model the distribution of taxa where niche conservationism prevails (Moro *et al* 2015, Oliveira-Filho *et al* 2013, Wiens and Graham 2005), like in the Seasonally Dry Tropical Forests (SDTF, Pennington et al., 2009).

In South America, the largest SDTF unit is situated in the semiarid region of northeastern Brazil (Miles et al., 2006; Silva, Leal, & Tabarelli, 2018). This is the most heterogeneous area in the country in terms of soil, with high variability at landscape-scale (Araújo Filho *et al* 2017, Santos *et al* 2011, Brasil 1981b, 1983). The great soil and topoclimatic variability account for a great diversity of environmental niches, resulting in a high beta-diversity in the region (Arruda *et al* 2020, Fernandes and Queiroz 2018, Lima *et al* 2012, Souza *et al* 2019a). Phylogenetic niche conservatism has been recognized as the cause of the spatially-structure distribution of species in SDTF (Queiroz *et al* 2018, Moro *et al* 2015, Oliveira-Filho *et al* 2013). Thus, combinations of soil and climate drive species composition (Santos *et al.*, 2012; Arruda *et al.*, 2015; Silva & Souza, 2018, see also Chapter II). For this reason, the availability of soil attributes is necessary to achieve better results in environmental niche modelling in the semiarid region of Brazil (Chapter IV).

Facing this need, herein we aimed to give a contribution from pedology to biogeographic modelling. Our goal was to produce a spatial database with quantitative topsoil attributes for the semiarid region of Brazil, with an area of circa 1 million km². We used soil maps from the RADAMBRASIL Project to spatialize 14 soil attributes from 298 soil profiles. The raster database is available in the Knowledge Network for Biocomplexity data repository (doi:10.5063/F1NC5ZK7). We provide a relational database to users for further updates. We used this database to create groups of topsoils with similar superficial properties and highlight the most important features for biogeographical modelling in the semiarid region.

4.2 MATERIAL AND METHODS

4.2.1 The Brazilian semiarid region

The geographical extension of the database corresponds to the new official delimitation of the Brazilian semiarid region (Figure 9, Brasil 2017). This boundary covers the states of the northeast region (except Maranhão) and the northern and Jequitinhonha Valley regions of Minas Gerais state. According to Brasil (2017), the following criteria were used to define this perimeter: average annual rainfall equal or less than 800 mm; Thornthwaite aridity index equal to or less than 0.5 and daily percentage of water deficit equal or greater than 60%. The data used for this delimitation were obtained from series with 30 years or more (SUDENE 2017). This limit encompassed all municipalities that met at least one of the criteria above-mentioned. We obtained the cartographic base from the SUDENE website (http://www.sudene.gov.br/delimitacao-do-semiarido) and applied a 20 km buffer to the official boundaries.

The Brazilian semiarid region is among the most humid drylands worldwide, with mean annual rainfall between 400 and 800 mm in most of the region (Silva *et al* 2003). However, the uneven rainfall distribution is more important: according to the WorldClim database (Fick and Hijmans 2017), in half of the semiarid region, 50% of total rainfall is concentrated in the wetter quarter. The Caatinga is the predominant vegetation (Figure 9b), with xerophytic arboreal to shrub-sized formations, characterized by functional traits related to tolerance to water stress and high solar radiation: small leaves, deciduousness, succulence, underground structures for water storage, thorns and small size (Andrade-Lima 1981, Silva *et al* 2018). The species composition in the Caatinga domain is strongly correlated with soil attributes, being grouped in three main surfaces: crystalline, sedimentary and karstic (Pinheiro *et al* 2010, Queiroz *et al* 2018, Moro *et al* 2016).

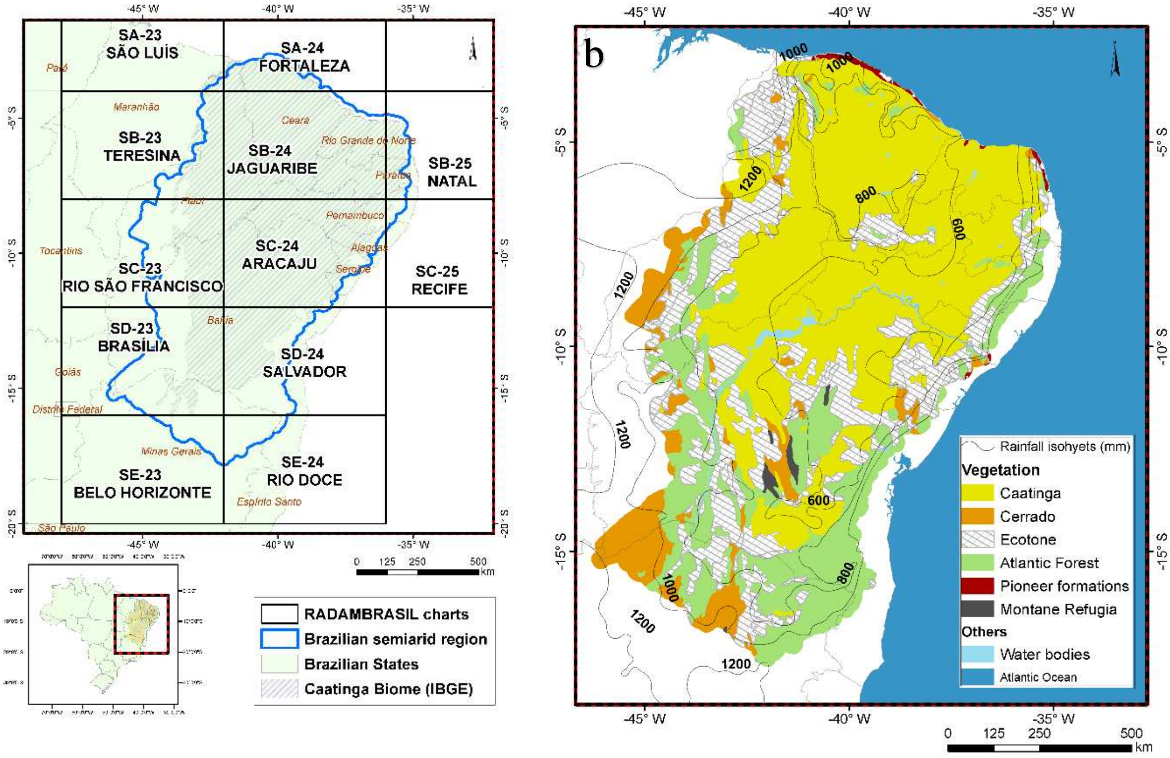

Figure 9. Location of the Brazilian semiarid region and the chart indexes from RADAMBRASIL Project maps included in the database (a). Vegetation map (adapted from IBGE, 2004) (b).

Along with the Caatinga, the Atlantic Dry Forest and the Cerrado are the vegetation types that cover more than 80% of the semiarid region (Figure 9b). Other minor plant formations also occur, located in its humid outskirts or as scattered disjunctions in the Caatinga domain (Figure 9b). The latter ones are associated with higher elevations and more humid climates, such as the '*Brejos de altitude*' broadleaf forests (Ferraz *et al* 1998, Rodal *et al* 2005, Silva *et al* 2018). The Caatinga and the Atlantic Dry Forest are encompassed in the SDTF biome (Mayle 2004, Pennington *et al* 2000b, Werneck *et al* 2011, Linares-Palomino *et al* 2011b, Särkinen *et al* 2011, Bawa *et al* 1997). In turn, the Cerrado is the Brazilian savannah analogue (Ribeiro *et al* 2006).

4.2.2 Data acquisition and consistency assessment

The RADAMBRASIL Project comprised the only systematic soil survey that covered the entire semiarid region in 1:1,000,000 scale to date (Brasil 1973a, 1973b, 1981b, 1973c, 1983, 1982, 1981a). It also included soil profiles described in the 1960s and 1970s in previous exploratory surveys conducted by the National Soil Survey and Conservation Service (SNLCS/EMBRAPA). Although RADAMBRASIL reports were published in 1:1,000,000 scale, the survey was made in 1:250,000 scale with support radar images. Consequently, these maps have an outline that matches high-resolution topographic data like SRTM DEM (Jarvis *et al* 2015).

The Brazilian Institute of Geography and Statistics (IBGE) digitalized and updated the RADAMBRASIL maps (IBGE 2007), converting the original classification to the current Brazilian Soil Classification System (Santos *et al* 2013). Vectorized maps and data tables of soil profiles were also produced. These data and more details care available at https://mapas.ibge.gov.br. To cover the entire semiarid region, we compiled 12 soil charts (Figure 9a). Following the data acquisition, we proceeded to thorough quality analysis. To correct some inconsistencies found we obtained the original RADAMBRASIL volumes in digital format at https://biblioteca.ibge.gov.br. We replaced the inconsistent data with the original publication values. We also performed a visual evaluation of the IBGE digital maps. For that, we georeferenced the original RADAMBRASIL soil maps and superimposed them with the vectorized maps (IBGE) to check the consistency of the updated mapping units.

4.2.3 Soil attributes database

To make the soil attributes database, the first step was to create a relationship table, whereby we linked each mapping unit (polygons) to a soil profile (alphanumeric table). This procedure was performed individually for each chart (Figure 9a). In profiles selection, we sought to achieve maximum similarity between the prevailing soil type in the mapping unit and the available profiles. This was needed because many mapping units did not have a soil profile. In such cases, we used the following criteria to choose profiles for replacement:

1) Have the same classification as described in the mapping unit, up to the third categorical level of the Brazilian Soil Classification system (Santos *et al* 2013);

2) Geographical proximity;

3) Parent material;
4) Vegetation;
5) Type of A Horizon.

Next, we merged the indexed vector maps into a single layer and clipped them with the boundaries of the study area. We dissolved small polygons (< 1 km^2) related to urban areas, water bodies and rock outcrops into the soil mapping-unit in which they were inserted. Polygons whose area was greater than this limit were used to make a non-soil mask. We aggregated mapping units represented by the same soil profile to eliminate divisions between the charts and reduce the database size. Only the surface horizon of each profile was included - except organic ones (O horizon).

We selected the soil attributes for spatialization according to their type and frequency in the database (Figure 10). We excluded those infrequent or presented as categorical variables. The values of Ca^{2+} and Mg^{2+} were represented in sum because they were published in this format for most of the profiles (Figure 10), which precluded their separation. Finally, we converted each of the soil attributes to a matrix format (*raster)* with a spatial resolution of 500 m.

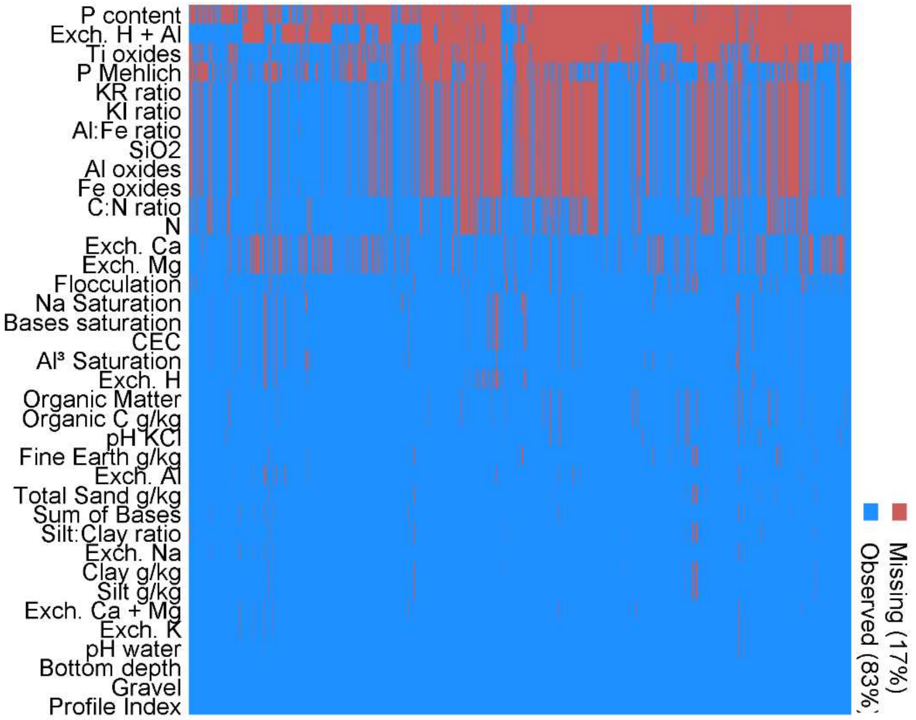

Figure 10. Missing data map.

We used the R package (R Development Core Team, 2016) to verify the consistency of the alphanumeric database and the ArcMap 10.3 geographic information system (ESRI 2016) for handling spatial data. The final maps were produced in Geographic Coordinate System and Datum World Geodetic System 1984 (EPSG: 4326).

4.2.4 Spatialization of topsoil properties

To spatialize the superficial chemical and physical variability of soils in the semiarid region and expose their importance for the vegetation distribution, we used the database to group regions with similar soil characteristics. First, we computed a correlation matrix among the 14 topsoil attributes, from which we identified and eliminated highly correlated variables. Then, we used the rasterPCA function from the ' RStoolbox' package to run a Principal Component Analysis (PCA) with the selected attributes. Four layers were created, corresponding to the first four dimensions of the PCA. Then we used these layers in the K-means cluster analysis to create units with similar topsoil properties.

4.3 RESULTS AND DISCUSSION

In total, we selected 14 topsoil attributes to compose the database (Table 6 and Figure 11). First, we present a general description of its properties in the semiarid region. Next, the units are discussed in detail.

Table 6. Soil attributes included in the database, units and statistics.

Attribute	**Unit**	**Min**	**Max**	**Mean**	**Std. Dev.**
Sand	g.kg^{-1}	0	970	645.59	220.92
Silt	g.kg^{-1}	0	650	180.31	134.85
Clay	g.kg^{-1}	0	710	120.45	124.60
Organic C	g.kg^{-1}	1	216	11.41	10.84
pH H2O	-	3.1	8.2	5.43	0.87
pH KCl	-	1.9	7.7	4.56	0.85
Ca^{2+}+ Mg^{2+}	cmol$_c$.kg	0.1	59.2	4.48	5.70
K$^+$	cmol$_c$.kg	0	3.34	0.24	0.21
Na$^+$	cmol$_c$.kg	0	8.63	0.069	0.10
Silt / Clay	-	0.07	8	1.37	1.24
Sum of Bases	cmol$_c$.kg	0.04	59.61	4.77	5.84
CEC	cmol$_c$.kg	1.1	87	7.91	6.67
Bases Saturation	%	1.4	100	51.22	27.93
Al^{3+} Saturation	%	0	95	17.59	23.39

4.3.1 Soils of the semiarid region

The semiarid region is divided into two main regions in terms of soil geography. In the north and northeast of the region, soils with low pedogenesis are concentrated, in accordance with the current drier climate: Luvisols, Leptsols, Phaeozems, Kastanozems, Regosols, Cambisols, Solonetz, Vertisols and Planosols (WRB 2014). To the south and west the Ferralsols, Lixisols, Acrisols and Alisols prevails. The latter, of advanced pedogenesis (more weathered), are inconsistent with the current semiarid climate, revealing their formation in wetter paleoclimate (Schaefer, 2013). The region in which they are found coincides approximately with the transition zone between the Caatinga biome and the surrounding ones (Figure 9b). These highly weathered soils are also found on sedimentary surfaces, both on the edges and in the dry core of the region (Araújo Filho et al., 2017). In such cases, they are formed from pre-weathered parent material, which contributes to the advanced stage of pedogenetic development in a drier climate. It is noteworthy in Latosols (Ferralsols) and Argisols (Acrisols) of the semiarid region the fact that many are epi-eutrophic. This is a result of the accumulation of bases under the current dry climate by the weak leaching and concentration of the biogeochemical cycling of nutrients on the surface.

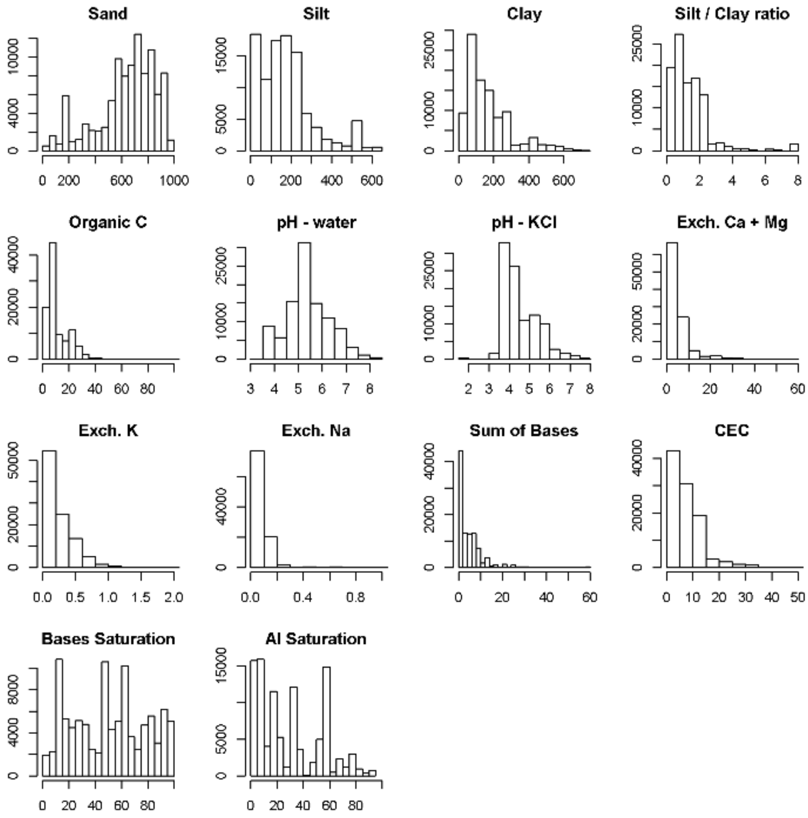

Figure 11. Distribution of the superficial horizon attributes of the soil present in the database. The histograms show the pixel count per class of the attribute. Cell size = 500 x 500 m.

Most of the soils in the semiarid region have a sandy or sandy loam texture on the topsoil (Figure 11 and Figure 12). Topsoils with a clay content above 300 g.kg^{-1} are relatively scarce (Figure 11), especially in the Caatinga domain. The low clay contents are a result of the differential erosion of fine soil particles (elutriation), due to intermittent and discontinuous vegetation cover, which brings less physical protection against rainfall. Also, due the occurrence of many soils with Argic horizon or clay-enriched subsoil. Clayey soils are found in the southern semiarid range, covered by seasonally dry forests and, to a lesser extent, the Cerrado. The silt content is higher (> 300 g.kg-1) in two cases: karstic surfaces, such as in northern Minas Gerais and western Bahia in soils derived from limestone from the Bambuí Group (Souza *et al* 2004) and in northeastern semiarid, on less weathered soils (Figure 13).

Low organic C levels (<10 g.kg-1) predominate in the semiarid region (Figure 11). The Caatinga biome holds the lowest C stocks in Brazil (Gomes *et al* 2019, Menezes *et al* 2012), due to low biomass input, high temperatures (Oades 1988, Zech *et al* 1997) and low clay contents, which favour fast mineralization of organic matter (Six *et al* 2002, Oades 1988, Zech *et al* 1997). The organic C content increases in soils with more clay ($r = 0.53$; $p < 0.001$), in karstic surfaces (Vertisols and Chernosols) and in areas with higher elevation, where the climate is milder. Very-high organic C levels (> 80 g.kg^{-1}) occur in a very limited way, with little geographical expression in Gleysols and Histosols located in floodplains in the Cerrado domain (Figure 9b). In this case, high organic C levels are explained by anoxic conditions, higher humidity and milder temperatures.

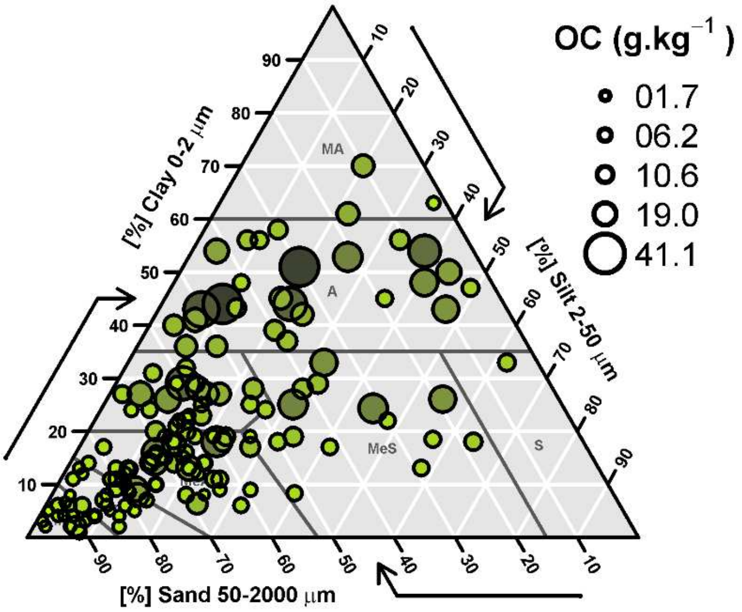

Figure 12. Textural triangle and organic C content in the superficial horizons of soils in the Brazilian semiarid region.

In the Caatinga domain (Figure 9b), the Al^{3+} saturation is null or very low (Figure 5), as a consequence of the soil pH normally above 5.5 and the low leaching rate, which retains the bases in the soil. The few exceptions are the sandy plateaus and sedimentary surfaces, where transitional vegetation predominate (Figure 9b). At the regional level, Al^{3+} saturation and base saturation (Figure 13) are the soil chemical attributes that best distinguish the Caatinga from the surrounding biomes (Figure 9b). In the transition to the Atlantic Dry Forest in the south and mainly to the Cerrado in the west, the Al^{3+} saturation is often higher than 50%.

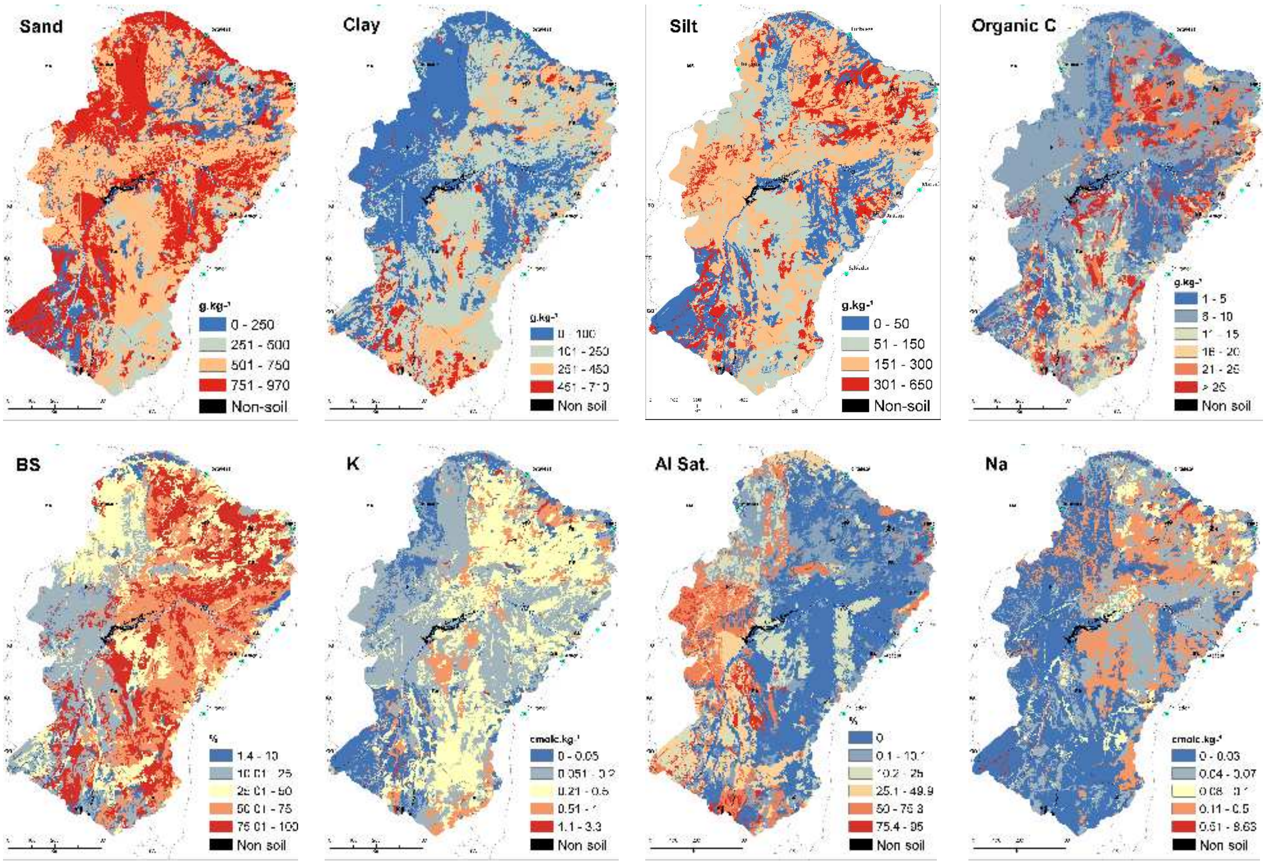

Figure 13. Maps of topsoil attributes in the semiarid region of Brazil. SB: sum of bases; CEC: cation exchange capacity; BS: base saturation; Al Sat: Aluminium saturation.

4.3.2 Soil Units

We selected eight out of 14 topsoil attributes to run a PCA. These were clay, silt and sand content, C-organic, base saturation, Al^{3+}, K^+ and Na^+ saturation (Figure 13). The first two PCA axes (Figure 14) explained 64% of the variation in the topsoil data. The first axis (41.6%) was positively correlated with silt ($r = 0.74$), clay ($r = 0.64$), K^+ ($r = 0.67$) and base saturation ($r = 0.63$) and negatively correlated with sand content ($r = -0.85$). The second axis explained 23%

of the variation in the data and was positively correlated with Al^{3+} saturation (r = 0.81) and negatively correlated with base saturation (r = -0.68). The third axis, which explained 12.5% of the data variation, was positively correlated with Na^+ (r = 0.70) and organic C (r = 0.46). With the first four components of the PCA (86% of variation explained), we identified six soil Units in cluster analysis (Figure 14 and Figure 15). We separated these units into two groups considering the cluster dendrogram: 1) Fine-textured soils and, 2) Coarse-textured soils. Geographically, these units are distributed throughout the region, forming large and homogeneous areas or complex mosaics (Figure 15). A detailed analysis of the units is presented below, integrating the topsoil attributes database, soil and geomorphological maps of the RADAMBRASIL Project (Brasil 1983, 1981b, 1973a) and the official vegetation map of Brazil (IBGE 2004).

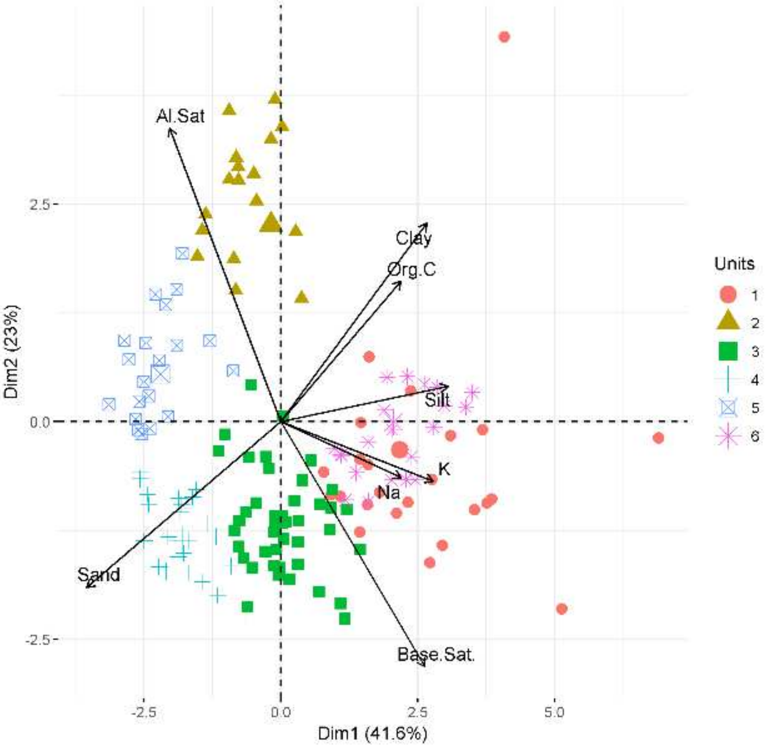

Figure 14. Principal Component Analysis of the topsoil attributes selected for clustering and respective units.

1.1.1.1 Group 1 – Fine-textured topsoils

4.3.2.1.1. Unit 1 – Silty Eutric (169,903 km^2)

With distribution concentrated in the northern *Sertaneja* depression, Unit 1 was related to three main geomorphological domains: a) depressions of uncovered pediment surfaces, b) mountain ranges or residual massifs of basic intrusions and c) karstic surfaces. This unit encompassed the soils with the highest silt contents in the semiarid region (360 g.kg^{-1}, on average), indicating low weathered soils. They are eutrophic, with an average base saturation of 64% and Al^{3+} saturation below 10%. Because of the combination of climate, topography and parent material, the soils of this Unit have the highest levels of readily leached ions (Na^+ and K^+) in the semiarid region (Figure 16). The organic C levels are also the highest, on average 25.5 g.kg^{-1}. These high values for a semiarid region are justified by the presence of carbonates and clay in the soil, which promote greater stability of organic matter, slowing down its mineralization (Fernández-Ugalde *et al* 2014, Virto *et al* 2018). This process is called carbonation, which ultimately leads to the genesis of Chernosols (Vysloužilova *et al* 2016).

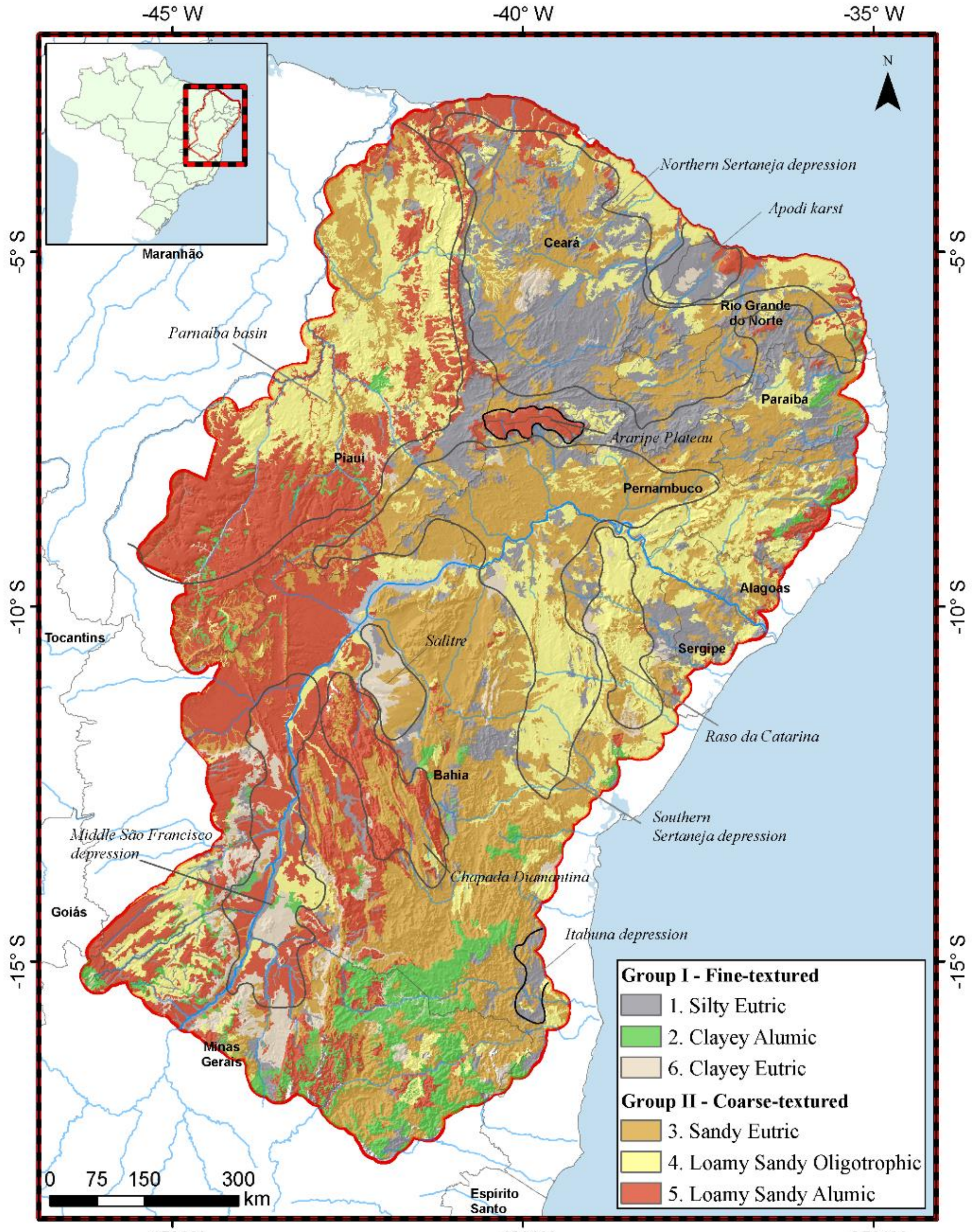

Figure 15. Distribution map of the six topsoil Units identified in the semiarid region of Brazil.

Concerning the soil types, in the residual massifs and mountain ranges of the *sertaneja* depression, predominate the Eutrophic Litolic Neosols (Eutric Leptosols) and Eutrophic Red Argisols (Rhodic Lixisols). On the karstic surfaces, one finds the Eutrophic Haplic Cambisols (some Carbonatic) (Eutric Cambisols). In the Apodi Plateau karst (Rio Grande do Norte) and in the Itabuna depression (Southeastern Bahia), Chernosols (Kastanozems and Phaeozems) occur in a lesser extent. The predominant vegetation in the Unit 1 was the Caatinga, which occupied 68.4% of its extent, followed by the Atlantic Forest (22.7%). The Cerrado vegetation occupies only 2% of Unit 1 (Figure 18).

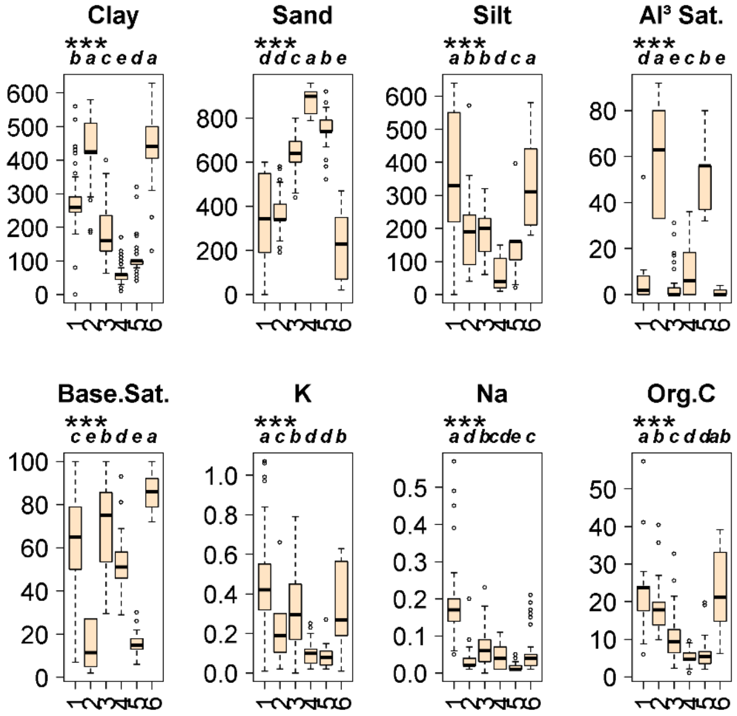

Figure 16. Soil attributes of the database selected for cluster analysis. Means followed by different letters are statistically different by Kruskal-Wallis test.

4.3.2.1.2. Unit 2 – Clayey Alumic (48,143 km ²)

Unit 2 represents clayey soils, with an average of 449 g.kg^{-1} of clay in the topsoil. Its distribution is centred in the south of the semiarid region, coinciding with plateaus and highlands of northeast Minas Gerais and southeast Bahia. They are chemically very poor, with an average of 14% base saturation and 59% of Al^{3+} saturation (Figure 16). The soil types that characterize this unit are very deep and highly weathered. Dystrophic Latosols (Ferralsols) cover 70% of its area (Figure 17). Regarding phytogeography, Unit 2 coincides precisely with the southern limit of the Caatinga biome (Figure 9b). In this sense, besides climate, chemical poverty and high Al^{3+} saturation seem to act as barriers to the vegetation of this biome. The typical vegetation of Unit 2 is the Atlantic Forest, which covers 70% of the area (Figure 18), mainly the dry forest. In second place is the Cerrado (14%). The Caatinga occupies only 2.5% of Unit 2.

4.3.2.1.3. Unit 6 – Clayey Eutric (45,959 km²)

This small and scattered Unit contains clayey soils (450 g.kg^{-1}, on average) with high base saturation (86%) and virtually null Al^{3+} saturation (0.6%). The soils have low Na^+ content, moderate to high K^+ content and relatively high organic C (21 g.kg^{-1}). Unit 6 is related to karstic areas correlated to the Bambuí Group in northern Minas Gerais and western Bahia. Smaller areas are located in the region of Salitre (Bahia) and associated with Unit 1 in the northern *Sertaneja* depression (Figure 15). Eutrophic Cambisols are predominant soil types in Unit 6, namely those with high activity clay (25%) and carbonatic (22%). Other chemically rich soils such as Red Latosols (Rhodic Ferralsols), Chernosols, Nitisols and Vertisols are also found in this unit, though covering a smaller extent. The typical vegetation cover is the Atlantic Forest, which takes place in 48% of Unit 6. It is noteworthy that the Dry Forest formation represents 87% of this total. In second place is the Caatinga (27.5%). The Cerrado occurs in only 9% of Unit 6.

4.3.2.2 Group 2 – Coarse-textured soils

4.3.2.2.1. Unit 3 – Sandy Eutric (358,340 km²)

Unit 3 is the largest in the semiarid region (Figure 15). Soils are superficially sandy (638 g.kg-1), eutrophic (69%) and with low organic C levels (10 g.kg-1) due to the sandy surface horizon. The Al^{3+} saturation is virtually null and K^+ levels are moderate to high (Figure 16). Due to its wide extension, Unit 3 encompasses soils present in different geomorphological units and climatic patterns, with contrasting pedogenetic characteristics. In the northern *Sertaneja* depression, the main soil types are the Chromic Luvisols and Rhodic Lixisols. To the south, this Unit encompasses highlands, plateaus and depressions, where Yellow Latosols (Xanthic Ferralsols) predominate. A remarkable characteristic of Unit 3, which is characterized by eutrophy and absence of Al^{3+} saturation, is the presence of highly weathered soils. However, their occurrence in a current dry climate favours the base concentration on the surface and consequently a high saturation, which justifies their inclusion in this Unit. Thus, for these highly weathered soils, the surface horizon better represents the steady-state with the vegetation than the diagnostic horizon, which reflects paleoclimatic conditions. Caatinga is the most representative vegetation of Unit 3, occupying 55% of its area (Figure 18). In the second place, there are plant formations related to the Atlantic Forest (20%) and ecotonal zones (21%). The Cerrado occurs in only 3% of Unit 3 area.

4.3.2.2.2. Unit 4 – Loamy Sandy Oligotrophic (225,729 km²)

The third-largest unit has the sandiest soils in the semiarid region with an average of 878 $g.kg^{-1}$ of sand in the A Horizon. Consequently, the CEC (3.35 $cmol_c.kg^{-1}$, on average) and organic C levels are very low (5.2 $g.kg^{-1}$). On surface, soils are nutrient-poor in absolute terms (mean $Ca^{2+} + Mg^{2+} = 1.6\ cmol_c.kg^{-1}$). Therefore, they have a mesotrophic to eutrophic status by low CEC and low Al^{3+} saturation rather than absolute richness in exchangeable bases, what label them as oligotrophic. Base saturation varies between 50 and 60% and Al^{3+} saturation is below 10%. The spatial distribution of this Unit is related to sedimentary surfaces in the southern *sertaneja* depression, the northern coast and the Middle Parnaíba Basin (Piauí state). The predominant soil types are the Dystric Arenosols, Eutric Planosols and Dystric Leptosols (Figure 17). In the semiarid climate, Caatinga is the main vegetation type. Ecotones were the second type of vegetation covering 25.5% of Unit 4. The Atlantic Forest occurred in only 10% of its area.

4.3.2.2.3. Unit 5 – Loamy Sandy Alumic (242,522 km²)

Unit 5 comprises sandy and aluminic soils covering 22% of the semiarid region and is the second-largest among those identified (Figure 15). In average, the topsoils have 50% Al^{3+} saturation, base saturation generally below 20% and very low levels of K^+ and Na^+ (0.07 and 0.01 $cmol_c.kg^{-1}$, respectively). Its geographical distribution is concentrated in the west, related to three main geomorphological regions: a) the sandy plateaus of western Bahia state (Urucuia Group, the upper Parnaiba Plateaus and the Araripe Plateau), b) the sedimentary surfaces of the Middle São Francisco Depression and c) the mountain ranges surrounding the Chapada Diamantina. The predominant soil types in the plateaus and sedimentary surfaces are the Yellow Latosols (Xanthic Ferralsols), which account for 45% of Unit 5 (Figure 17), followed by the Dystric Arenosols. These two soil classes, generally deep to very deep, are close in morphological terms since they are separated by a slight difference in sand content (EMBRAPA 2018). In the Chapada Diamantina region, the Dystric Leptosols are the main soil types. Concerning the vegetation, the occurrence of ecotones is remarkable in Unit 5 (31%). This Unit concentrates 48% of the Cerrado and 70% of the Montane Refuges occurring in the semiarid region, but only 13% of the Caatinga vegetation.

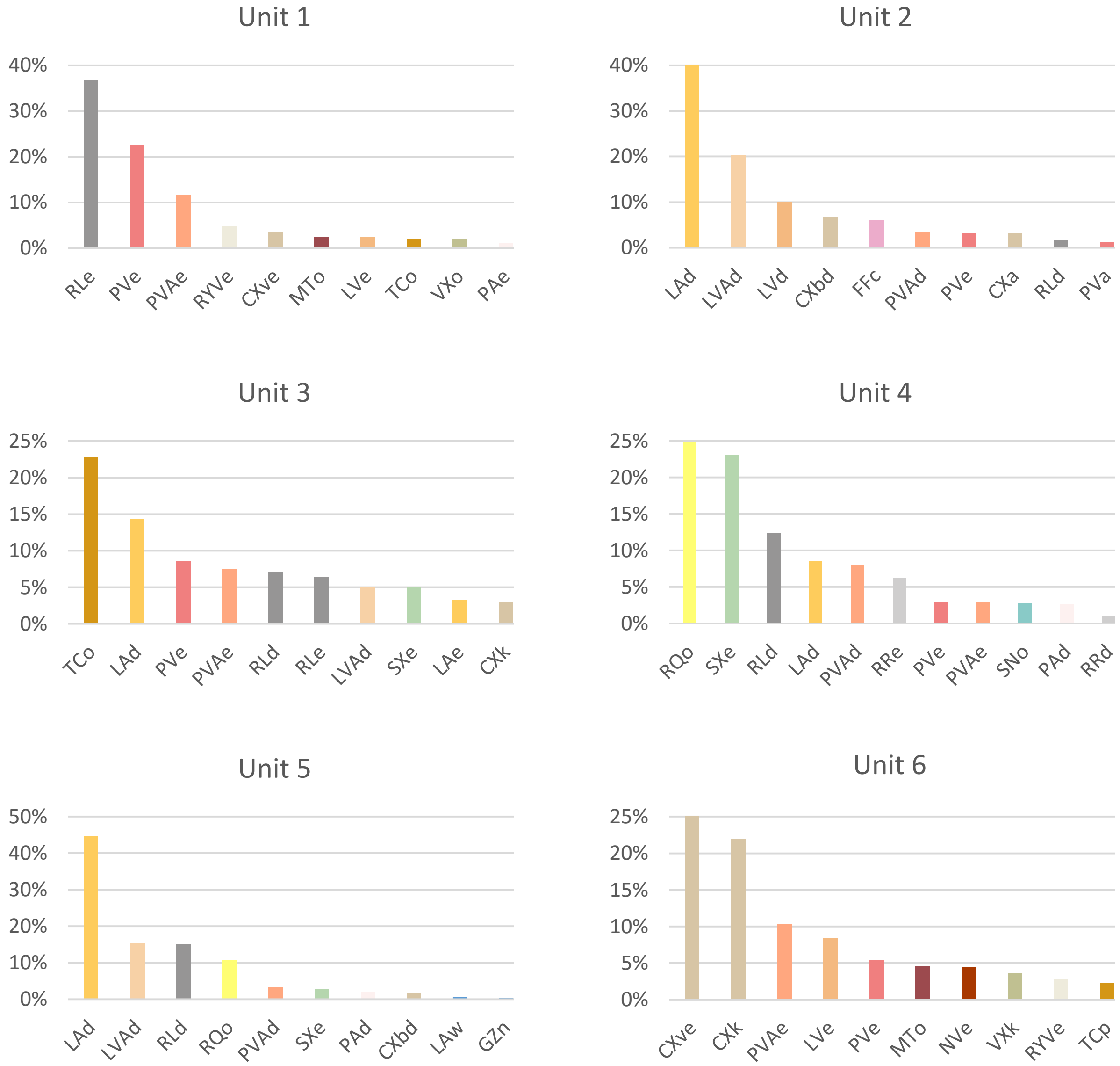

Figure 17. Top ten soil classes related to each soil Unit**.** CX: Haplic Cambisols - aluminic (a), Dystric (bd), Carbonatic (k); Eutric (ve). FFc: Petroplinthic Plinthosols. FTd: Plinthosols Acric. LA: Xanthic Ferrasols (Distric) (d), Dystric Densic (dx), Eutric (e), Geric (w). LVd:Rhodic Ferrasols (Dystric). LVAd: “Rhodic-Xanthic” Ferrasols (Dystric). MTo: Luvic Phaeozems. PAd: Xanthic Acrisols - Densic (x). PVa: Rhodic Alisols.PVe: Rhodic Lixisols.PVAd: Chromic Acrisols. PVAe: Chromic Lixisols. RL: Leptosols – Dystric (d), Eutric (e). RQo: Dystric Arenosols. RRe: Eutric Regosols; RYve: Eutric Fluvisols. SNo: Solonetz. SXe: Eutric Planosols. TCo: Chromic Luvisols.

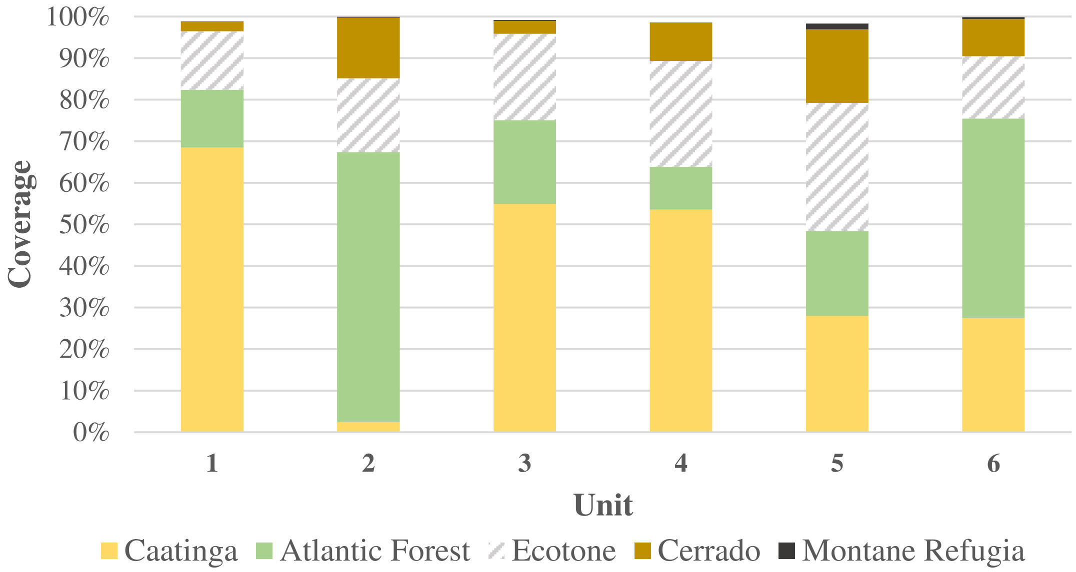

Figure 18. Relative coverage of each vegetation type in the Units.

4.4 CONCLUDING REMARKS

The semiarid region of Brazil encompasses great soil diversity, which should not be neglected in biogeographic modelling studies. The heterogeneous distribution of soil types in the region results in a multiplicity of contrasting environmental niches within similar climatic patterns. This remarkable heterogeneity contributes to the high beta-diversity found in the region. Moreover, the presence of small patches of vegetation like Cerrado within the current semiarid climate cannot be explained without taking into account the contrasting soil properties where they occur.

The data dimensionality reduction allowed us to synthesize the high soil variability, highlighting the key attributes that had better differentiate the soils in the surface and the soil-vegetation relationship at broad-scale in the semiarid region. The Caatinga vegetation predominated both in coarse and fine-textured topsoils within the semiarid climate, as long as the Al^{3+} saturation was low. In this sense, base saturation was a better indicator of its distribution than the absolute nutrient content. With the reduction of chemical richness and increasing rainfall, the Atlantic Dry Forests and the Cerrado replace the Caatinga. This occurs consistently within the Caatinga domain in the highlands, massifs and plateaus. In general, about 70% of the Cerrado present in the semiarid region is concentrated in sandy dystrophic or oligotrophic soils, whereas about 80% of the Caatinga is concentrated in non-aluminic soils. The transition zones Caatinga-Cerrado and Caatinga-Dry Forests were characterized by dystrophic soils that coincide approximately with the 800 mm rainfall isohyet. In this sense, the presence of transitional vegetation was explained by a combination of environmental conditions that do not favour any of the vegetations. That is, the Al^{3+} saturation is too high for the Caatinga vegetation and the climate is too dry for the Atlantic Forest and the Cerrado. In turn, the formations related to the Atlantic Forest occur in a wide variety of soils, revealing the preponderance of the climate in the distribution of these vegetations.

Climate models predict increased aridity in the semiarid region throughout this century. In this context, it is fundamental to consider soil variability for consistent modelling the environmental changes impacts on vegetation distribution. With the expansion of the dry climate zone, the dystrophic soils in the transition areas (namely the south and west) may be the areas most impacted by the expansion of a dry and dystrophic environment, which contrasts the niche occupied by the semiarid vegetation nowadays.

In this first version of the database, our focus was to spatialize the attributes of the A horizon. Many improvements can be made in further versions. In particular, the inclusion of diagnostic horizons, effective soil depth and morphological attributes. However, with the data available in the RADAM reports, many constraints were found. It was not possible to achieve the expected detailing for the 1:1,000,000 scale due to the absence of profiles for many mapping units and the impossibility to represent other soils occurring within them. In this aspect, pedological surveys with greater detail in the region are required. Also, important elements for vegetation such as N, P and micronutrients were scarce in the database. To fill these gaps, it is suggested to include data from other profiles described and published in the region, following standardization of analysis methods and units.

5 CHAPTER IV

Soil predictors are crucial for modelling dry vegetation distribution and responses to climate change

Abstract

Climate models forecast increasing aridity in semiarid regions over this century. However, the climate change impacts on the distribution of neotropical Caatinga and adjacent Seasonally Dry Forests lacks a detailed characterization to support conservation strategies. Bioclimatic envelope models have been largely used to this end, but they are prone to uncertainties coming from General Circulation Models. Novel research has mainly focused in the improvement of bioclimatic envelope models through combination of climate and soil predictors. In this context, our aim was to apply a combined edaphoclimatic envelope to predict the current and future vegetation distribution in the Brazilian semiarid region, using different machine learning algorithms. The models pointed to an expansion of the dry Caatinga vegetation, ranging from average 16% to 24% in RCP 4.5 and RCP 8.5 scenarios, respectively. The introduction of soil attributes improved the model outputs, both for current and future vegetation distribution. For the current vegetation, they provided more detail in the distribution at landscape scale. For future predictions, soil predictors led to greater agreement among the GCM in each RCP scenario. However, our results show that besides the use of soil predictors, the choice of algorithms that are capable of modelling the soil-vegetation interaction at local scale is crucial to achieve better outputs. Soil attributes imposed a buffer effect on vegetation shifts under climate changes, as they mitigated the overly predictions of the bioclimatic envelope.

Keywords: environmental niche modelling, SDTF, machine learning, Caatinga, Brazilian semiarid, environmental policy.

5.1 INTRODUCTION

Vegetation distribution models based on environmental niche are useful tools for biodiversity conservation. To date, a major focus has been placed on the distribution and dynamics at biome scale (Arruda *et al* 2017, Salazar *et al* 2007, Costa *et al* 2018, Maksic *et al* 2019, Oyama and Nobre 2003, Hengl *et al* 2018, Carnaval and Moritz 2008, Cook and Vizy 2008), using models mostly based on the bioclimatic envelope (Araújo and Peterson 2012). Nevertheless, it is known that the distribution of many species is locally conditioned by the substrate since they are soil-dependent. (Corlett and Tomlinson 2020, Saporetti-Junior *et al* 2012, Markesteijn *et al* 2010, Comita and Engelbrecht 2009). Hence, we argue that the bioclimatic envelope alone is not capable of representing the vegetation distribution and dynamics accurately (Iverson and Prasad 1998, Pearson and Dawson 2003, Diekmann *et al* 2015, but see Trindade *et al* 2020), particularly in dry regions at sub-continental scales ($< 10^6$ km^2), where soil plays a chief role (see Chapter 2). Under the forecasted impacts of climate changes in the tropical dry vegetations (Allen *et al* 2017, Salazar *et al* 2007), the dynamics of ecotones and vegetation refuges (Rodrigues *et al* 2019, Arruda *et al* 2015a) require better understanding to develop more efficient conservation strategies. Aiming to overcome these limitations, research performed in latter years has focused on the development of combined climate and soil envelope models (Diekmann *et al* 2015, Corlett and Tomlinson 2020, Arruda *et al* 2017, Stanton *et al* 2012, Thuiller 2013). In our study, these models will be considered as the ‘edaphoclimatic’ envelope.

General Circulation Models (GCMs) provides bioclimatic variables to develop environmental niche models, both for paleovegetation reconstruction (Arruda *et al* 2018, Costa *et al* 2018, Collevatti *et al* 2013b) and future vegetation predictions (Oyama and Nobre 2003, Salazar *et al* 2007). The biases of GCMs and classification algorithms have been widely highlighted (Maraun 2016, Elith and Graham 2009, Varela *et al* 2015, Phillips and Dudík 2008, Cannon *et al* 2015, Collevatti *et al* 2013b, Hemsing and Bryn 2012, Garcia *et al* 2012). The main uncertainties in the GCMs arise from the initialization parameters and the downscaling method (Maraun 2016, Seo *et al* 2009), resulting in inconsistent vegetation distribution maps (Salazar *et al* 2007). A solution to mitigate uncertainty is to consider the consensus among different GCMs and algorithms. However, the interaction between classification algorithms and GCMs when soil attributes are included in the model has not yet been addressed. In this context, the emerging question is whether the bioclimatic envelope models are overestimating the vegetation dynamics (Iverson and Prasad 1998). For example, under the expected aridity increase in the Brazilian semiarid region the impacts on dry vegetations distribution are inconsistent (Oyama and Nobre 2003, Salazar *et al* 2007). Including key soil attributes in the models could help to overcome this problem.

The Brazilian semiarid region, where Caatinga and Atlantic Dry forests coexist, has experienced intense climate shifts since the Last Glacial Maximum, with a general trend of increasing aridity on the long term (Arruda *et al* 2018). However, wetter fluctuations during and after the LGM (Wendt *et al* 2019) favoured the expansion of semideciduous Forests and Cerrado (savannah) in this region (Behling and De Oliveira 2018, Behling *et al* 2000, Queiroz *et al* 2018, Maksic *et al* 2019, Simões *et al* 2020, Wang *et al* 2004, Auler *et al* 2004). Relictual formations of these Pluvial vegetations are currently found in the Caatinga biome (Queiroz *et al* 2018, IBGE 2004), usually associated with local soil and topographic conditions inherited from past climates (Queiroz 2006, Sampaio 1995). The vegetation dynamics resulting from climatic fluctuations also left a complex ecological tension zone in the transition between the Caatinga and the surrounding biomes. Therefore, the vegetation maps in the semiarid region remain unclear and with considerable terminological confusion regarding the Caatinga phytogeography (Oliveira-Filho 2009, IBGE 2012, Velloso *et al* 2002, Andrade-Lima 1981). Consequently, 22.4% of the semiarid area is mapped as an ecotone in the Brazilian official vegetation map (IBGE 2004).

Modelling vegetation dynamics is troublesome due to the lack of precision in ecotones, especially for short-term projections (< 10^2 yr). Vegetation shifts are expected to occur more rapidly (or be more apparent) in ecotones (Allen and Breshears 1998, Arruda *et al* 2018), although such studies are scarce in the neotropics. The ecotone dynamics cannot be measured without sufficient detail in the current vegetation maps. Subsequently, the results lead to non-reliable information either for legislators, for conservation purposes or the identification of proxy areas for monitoring. Therefore, it is important to develop models that can predict the current distribution of environmental niches in ecotones. The importance of the soil regarding vegetation distribution in the semiarid region is well known (Oliveira-Filho *et al* 2013, Santos *et al* 2012, Andrade-Lima 1981, Pinheiro *et al* 2010, Oliveira *et al* 2019, Souza *et al* 2019a, Arruda *et al* 2015a). Thus, we expect that the inclusion of local soil attributes in this area can enhance the models to generate more reliable analysing tools (Oliveira *et al* 2019).

In this context, this study had two main objectives. First, we aimed to improve the vegetation map of the semiarid region, filling the ecotonal areas. Secondly, to predict the impacts of climate changes on the vegetation distribution. To this end, we used edaphoclimatic envelope models. In addition, we assessed the influence of soil predictors coupled with different classification algorithms and the differences among three GCMs under the Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios.

5.2 MATERIALS AND METHODS

5.2.1 Study area

The Brazilian semiarid zone comprises the Northeast region states (except Maranhão) plus the Northern and Jequitinhonha Valley regions in Minas Gerais. In total, 1262 municipalities are included in this delimitation, which meets at least one of the following criteria: average annual precipitation equal to or less than 800 mm; Thornthwaite aridity index equal to or less than 0.5 or daily percentage of water deficit equal to or greater than 60% (BRASIL 2017). A 20 km buffer was created from the original area obtained from the SUDENE website (www.sudene.gov.br/delimitacao-do-semiarido), resulting in an analysed territory of 1,101,391 km², which corresponds to about 13% of the total area of Brazil (Figure 19).

5.2.2 Sampling and data collection

To sample the environmental niche of the different vegetations in the semiarid region, we used the RADAMBRASIL vegetation maps in 1:1,000,000 scale (Brasil 1981a, 1982, 1973b, 1981b, 1973a, 1973c). These maps were used as a reference for the production of the official vegetation map of Brazil in 1:5,000,000 scale (IBGE 2004). The choice of RADAMBRASIL maps is justified by the appropriate scale at the studied area, allowing better compatibility with the other databases and resulting in a more accurate sampling of the multidimensional niche. The vectorized maps were obtained from the IBGE Maps website (www.mapas.ibge.gov.br) and compiled in Geographic Information System (GIS) (Figure 19).

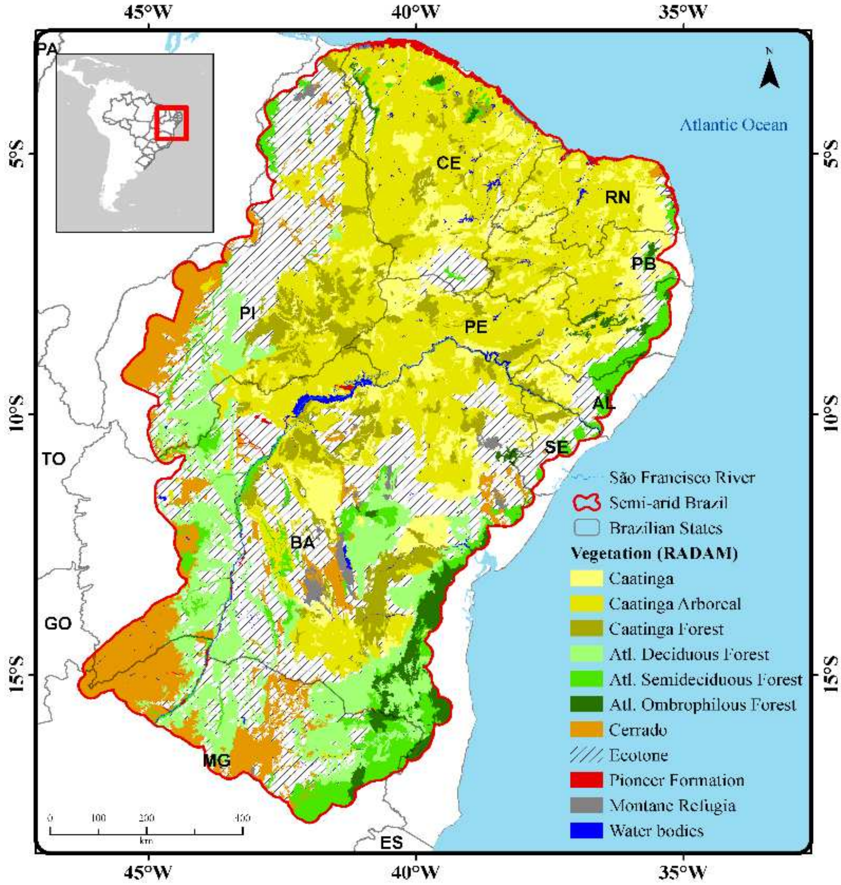

Figure 19. Location and vegetation of the Brazilian semiarid region. Vegetation map adapted from RADAMBRASIL.

The following vegetation types were sampled: Cerrado, Montane Refugia, Atlantic Semideciduous Forest, Atlantic Ombrophylous Forest, and the dry vegetations Atlantic Dry Forest, Caatinga Forest, Arboreal Caatinga and Caatinga. A detailed description of the vegetation types is presented in Table A. 9 - Appendix C. To achieve our objective of producing a more detailed map of the current vegetation in the ecotone, transitional and ecotone types were not included in the sampling. Thus, the models adjusted in the nuclear areas filled the transitional zones. To obtain the soil and climate attributes associated with the different vegetation types, we used a 0.05 degree (~ 5.5 km) point grid. From this grid, we randomly selected 1000 points for each one. Then, the environmental variables in raster format were extracted for the selected locations.

Three groups of variables were considered: bioclimatic (19 variables), soil (14 variables) and topographic (1 variable). We obtained the bioclimatic variables from the WorldClim 2 website (www.worldclim.org) (Fick and Hijmans 2017). This database was produced by interpolation of observations in the 1970-2000 period with 1 km spatial resolution. Therefore, what we define as current vegetation more precisely represents the potential distribution in this period. The bioclimatic variables used were: mean annual temperature, mean diurnal temperature range, isothermality, temperature seasonality, maximum temperature of the warmest month, minimum temperature of the coldest month, annual temperature range, mean temperature of the wettest quarter, mean temperature of the driest quarter, mean temperature of the coldest quarter, annual precipitation, precipitation of the wettest month, precipitation of the driest month, precipitation seasonality of the wettest quarter, precipitation of the driest quarter, precipitation of the warmest quarter and precipitation of the coldest quarter.

Soil attribute layers were produced from the RADAMBRASIL soil maps in 1:1,000,000 scale (Brasil 1981a, 1982, 1973b, 1981b, 1973a, 1973c). The attributes were converted to raster format for the entire study area with 500 m spatial resolution, considering a representative soil profile of each mapping unit (Chapter 3). Thirteen topsoil attributes were considered: pH in water, sand, silt and clay contents, silt-clay ratio, base saturation, sum of bases, Al^{3+} saturation, exchangeable Na^+, K^+ and $Ca^{2+} + Mg^{2+}$, organic C and cation exchange capacity (CEC). The soil depth was obtained from the SoilGrids system (www.soilgrids.org) with 250 m spatial resolution (Hengl *et al* 2017), summing up 14 soil attributes. Altitude was the topographic variable obtained from the SRTM digital elevation model with 90 m resolution (Jarvis *et al* 2015). In order to match databases with contrasting resolutions, all layers were re-sampled to meet the bioclimatic variables, with 1km spatial resolution.

5.2.3 Pre-processing and model training

After extraction of the environmental attributes to the sample units, the data was exported to the R software (R Core Team 2014) for subsequent analysis. To reduce data dimension, a correlation analysis with the *varclus* function from 'Hmisc' package was performed (Harrell Jr 2015). Hence, for highly correlated groups of variables ($P > 0.9$), it was considered only the one with less redundancy. Sampling was then performed using the Latin Hypercube method (Minasny and McBratney 2006, Zurell *et al* 2012) with the *clhs* function. This algorithm stratifies the n-dimensional sample space at equal intervals using cumulative distribution functions and randomly selects one sample for each stratum (Minasny and McBratney 2006). Thus, the representation of each vegetation environmental niche is enhanced by ensuring that all its distribution in multidimensional space is included in the sampling, in a reduced sample set.

Following sampling, we proceeded to selection of classification algorithms. We were interested in selecting the best ones to model the vegetation distribution in the semiarid region. In a previous screening, 36 algorithms of different categories available in the ‘caret’ package were tested (Kuhn 2008). The models were trained for a preliminary validation with all variables from the sample set optimized by the *clhs* function. We then selected those that achieved Kappa > 0.6. After this step, we used the Recursive Feature Elimination algorithm to remove variables of lesser importance with the rfe function from ‘caret’ package. We made this selection individually for each of the algorithms for model training.

5.2.4 Vegetation prediction

We used the selected models to predict current and future vegetation in the study area. A hundred predictions with random sample sets were performed with 80% and 20% of the data, respectively for training and validation. The prediction was performed with the *predict* function from the ‘caret’ package (Kuhn 2008). After processing, the results (100 predictions for each model) were collected in a single raster file, considering the most predicted vegetation in the cell. To process this large volume of data, we relied on the computer cluster of the University of Viçosa.

Two Greenhouse Gases concentration scenarios from the Coupled Model Intercomparison Project 5 (CMIP5) were considered for future vegetation prediction: RCP 4.5 and RCP 8.5 (Taylor *et al* 2012, Moss *et al* 2010). In the RCP 4.5 scenario, the radiative force is stabilized before the year 2100 through a set of strategies and technologies aiming emission reduction (Thomson *et al* 2011). In the RCP 8.5 scenario, there is an increase in radiative forcing throughout the whole horizon considered by the models (Riahi *et al* 2007). The RCP4.5 and RCP8.5 scenarios are currently considered the most plausible by the scientific community (He and Zhou 2015, Chou *et al* 2014, Tebaldi and Wehner 2018, Oleson *et al* 2018, Moore *et al* 2013). The RCP 2.6 (or RCP3-PD) scenario is already disregarded in most studies.

We considered three GCM broadly applied in modelling in South America (Chou *et al* 2014, Almagro *et al* 2017, Santos *et al* 2019, Arruda *et al* 2018): HadGEM2-ES (Jones *et al* 2011), CCSM4 (Gent *et al* 2011) and MIROC5 (Watanabe *et al* 2010). The data were obtained from the WorldClim database, bias corrected and downscaled to 1 km spatial resolution. The future simulations represent the climate in 2070 (average for the 2061-2080 period). Therefore, we analysed vegetation dynamics over nearly a century (1985 – 2070).

The prediction of potential vegetation in the RCP 4.5 and 8.5 scenarios was performed in the same way as for current vegetation, by replacing the layers of bioclimatic variables with the GCM simulations. A summary of the methodology is presented in Figure A. 12. To expose the effect of soil predictors, we selected the best performing algorithms and executed the predictions with bioclimatic and topographic predictors only. For the current vegetation, we compare the results of these models with the RADAMBRASIL vegetation map for the calculation of Kappa index and accuracy. For future vegetation, we calculate the agreement between the results of different GCM for the same RCP scenario and classification algorithm.

5.3 RESULTS

5.3.1 Algorithms selection

Out of the 36 algorithms tested, seven presented Kappa > 0.6 in cross-validation and were selected: kknn (K-nearest neighbors), treebag, rbfDDA, rf (random forests), svmRadialSigma, svmPoly and C5.0 (Figure A. 13). These algorithms were selected to predict the current and future vegetation distribution. The classified areas according to the vegetation type are shown in Table A. 10.

In order to determine the most accurate models to characterize the vegetation distribution at local-landscape scale, we performed a preliminary analysis. Comparison of the models showed a clear difference among the ones generated by the decision trees and the other algorithms (Figure A. 14). Decision trees (RF, treebag, C5.0) were restricted mostly to climatic attributes, meeting broad-scale distribution patterns (Figure A. 14). On the other hand, Support Vector Machine (svmRadialSigma e svmPoly), Nearest Neighbour (kknn) and Neural Networks (rbfDDA) algorithms considered more soil predictors and therefore resulted in models with greater local sensitivity (Figure A. 14). For example, the RF algorithm used 12 bioclimatic variables out of 14 (85.7%, Figure A. 15a) retained by recursive feature elimination. Soil pH was the only soil predictor selected by the RF algorithm. On the other hand, the svmPoly algorithm considered eight bioclimatic variables out of 19 (42%, Figure A. 15b). Therefore, the decision tree models resulted in less detailed outputs even with the availability of soil predictors. All models considered the mean annual precipitation (bio 12) as the most important variable. However, for the RF model it was much higher as compared to the other variables (Figure A. 15**a**).

Models within the same family of algorithms presented high correlation for current vegetation ($r > 0.93$), showing a high redundancy. To simplify the results of this study, we will only present the outputs from the RF and svmPoly models (from this point on SVM). For comparison purposes, we also used these algorithms to predict the vegetation with the bioclimatic envelope (hereafter Bioclim) from the current and future scenarios. Results from the other models for current vegetation distribution are summarized in Table A. 11 and Table A. 12.

5.3.2 Current vegetation distribution

Based on the predictors of the SVM edaphoclimatic model (Figure A. 15), we highlighted the key attributes to distinguish the vegetations analysed and construct a conceptual framework. The distribution of these attributes are shown in Figure A. 16 and Figure A. 17. The Cerrado vegetation was associated with an average annual precipitation around 1000 mm, wide temperature range and strong seasonality. Typically, the soils are sandy, acid, dystrophic, with low CEC and high Al^{3+} saturation (see Chapter 3). The K^+ content in Cerrado soils were particularly lower compared to the other vegetations. Among the Atlantic Forest formations, the Dry Forest presented higher seasonality, in contrast to the Ombrophylous Forest. These vegetations occurred in a wide range of climatic and soil settings. The Caatinga-related vegetation were distinguished from the others by the semiarid climate: lower rainfall (~600 mm), strong seasonality and high temperatures throughout the year. Regarding soil attributes, low Al^{3+}saturation and high base saturation stood out as typical of Caatinga soils. Finally, the Montane Refuges differed from all others by the colder climate and highly leached soils, resulting from the higher elevations in which they occur (>1000 m).

The RF models were less efficient to represent vegetations that occur due to local soil conditions (Figure 20). For instance, in the Middle São Francisco River region (southwest of the semiarid region) humid forests occupy the floodplains and valleys as corridors (riparian forests) and Cerrado patches occur occasionally (Figure 20) (Arruda *et al* 2015a, Rodrigues *et al* 2019, De Oliveira *et al* 1999). In the Araripe plateau region there is a mosaic that includes Caatinga, seasonal forests and Cerrado vegetations (Figure 20). In both cases, models that used more soil attributes produced better results. The enhancement resulting from the inclusion of soil predictors was more evident in the SVM model, since in the RF only one soil variable was included (Figure 20). However, in terms of overall model performance measured by Kappa and Accuracy, the inclusion of soil attributes had minor impact both in the SVM and RF models (Table 7).

The ecotone areas of the reference map (RADAM) were filled by the models (Figure 20). In the southern and western zone between Minas Gerais (MG) and Bahia (BA) the Atlantic Deciduous Forest prevailed (Figure 20 and Table A. 11). In the Chapada Diamantina region (BA), Montane Refuges and Cerrado occupied most of the ecotone. In the north-western transition zone (Piauí) the dominant vegetation in the predictions was the Cerrado. In the same area, there was a remarkable increase in the Atlantic Semideciduous Forest compared to the reference map. In the northeast Bahia, the ecotone was filled mostly by different Caatinga physiognomies.

All models predicted a larger Caatinga Forest area compared to the reference map (Figure 20 and Table A. 10), which represents this formation with a rather fragmented distribution (Figure 19). Furthermore, the Caatinga Forest was organized as response to a gradient, from the driest Caatinga core to the Atlantic Deciduous Forest along the São Francisco river basin (Figure 20). This distribution shows the Caatinga Forest as a transitional formation, closely related to the Atlantic Deciduous Forest.

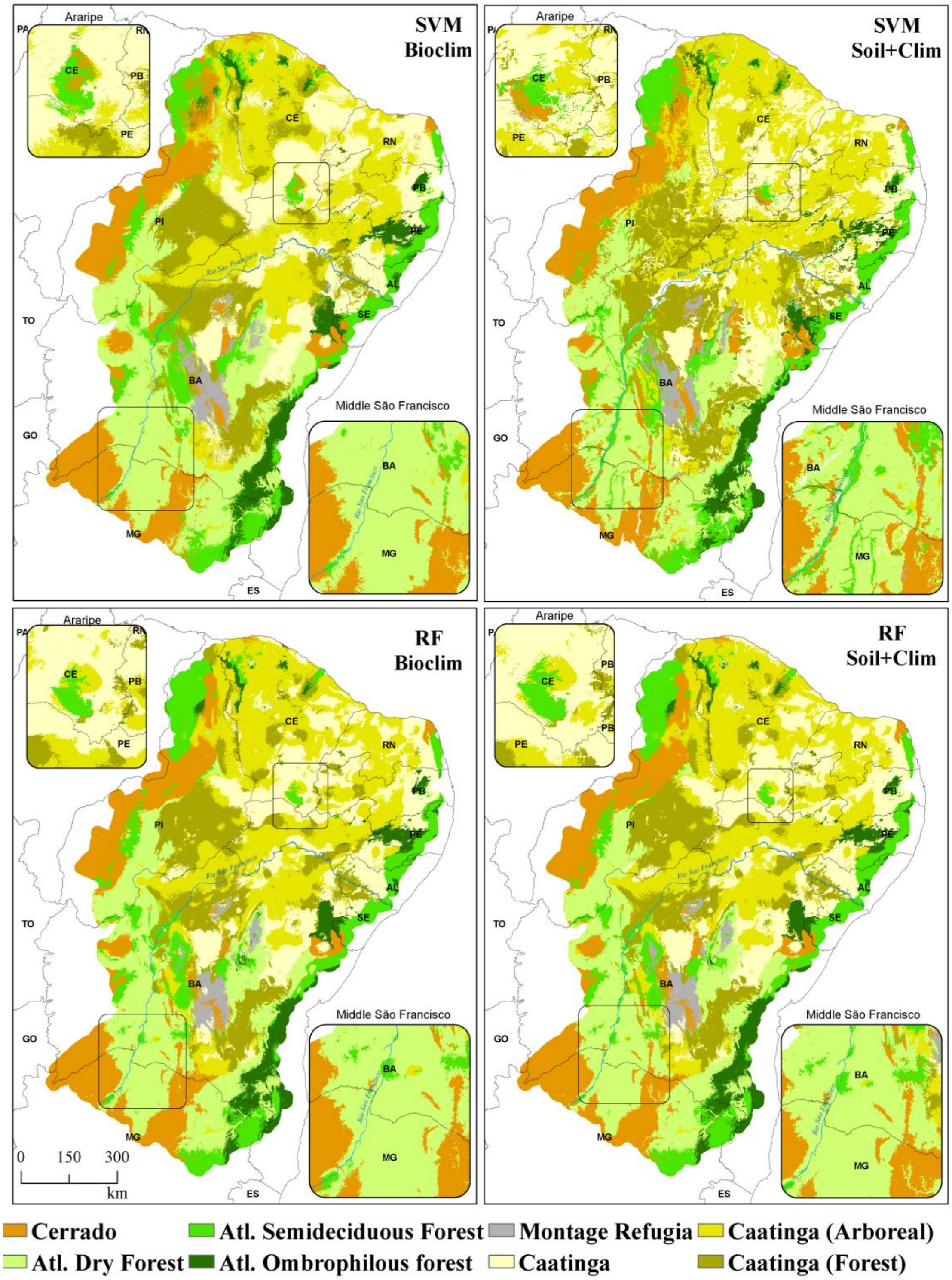

Figure 20. Potential current vegetation (1970-2000) in the Brazilian semiarid region predicted by bioclimatic and edaphoclimatic models. Support Vector Machine (SVM, above) and Random Forests (RF, below). Details of Middle São Francisco River and Araripe plateau in the boxes.

Table 7. Validation of Support Vector Machine (SVM) and Random Forests (RF) models with bioclimatic and edaphoclimatic predictors for current vegetation in the semiarid region of Brazil. The agreement expresses the number of cells with matching prediction in the future distribution models with the HadGEM, CCSM4 and MIROC5 General Circulation Models in each CMIP-5 scenario.

		Validation		Agreement	
Algorithm	Predictor set	Kappa	Accuracy	RCP 4.5	RCP 8.5
SVM	Bioclim	0.70	0.74	40%	43%
SVM	Soil+Bioclim	0.71	0.74	47%	57%
RF	Bioclim	0.74	0.77	9%	38%
RF	Soil+Bioclim	0.75	0.79	34%	41%

5.3.3 Vegetation distribution on future climate scenarios

The differences among GCM forecasts were the largest source of variation in the predictions within the same RCP scenario (Figure 21 and Figure 22). The use of soil predictors increased the agreement among GCM predictions, especially for the RF models in the RCP 4.5 scenario (Table 7 and Figure 23). Major impacts of the GCM inconsistencies in the vegetation distribution were detected in the bioclimatic models. Consequently, there was higher agreement among the SVM models than the RF ones for the different GCMs (Table 7). The predictions were systematically more consistent in the RCP 8.5 scenario than in the RCP 4.5 (Table 7 and Table 8).

Regarding the impacts on vegetation distribution, the GCM forecasts were ordered on a scale of increasing aridity in the semiarid region: HadGEM2-ES, CCSM4 and MIROC5 (Table 8, Figure 21 and Figure 22). All of them indicate an expansion of the dry Caatinga vegetation (Table 8). Major inconsistencies between GCM predictions were found in the RF model (Table 7 and Table 8). In the RCP 4.5 scenario, the Caatinga expansion ranged from 3.4 - 34.6% in RF models and from 5.0 - 30.5% in SVM models. In the RCP 8.5 scenario, this variation was 20.5 - 29.5% for RF models and 21.2 - 26.9% for SVM models.

HadGEM2-ES - In the RCP 4.5 scenario, the HadGEM2-ES forecast indicated a wetter (or less seasonal) climate in the western semiarid region, drier (more seasonal) in the east and less significant differences in the northern Minas Gerais and southwest Bahia. The expansion of the Caatinga-related vegetation ranged from 3.4 – 5.0% (Table 8). However, in the RCP 8.5 scenario, it showed increased aridity in the eastern, western and centre-south portions of the semiarid region leading the Caatinga to expand about 20.5 – 21.2% (Table 8). The Caatinga Forest and Arboreal Caatinga mostly occupied those areas, replacing the Atlantic Dry Forest.

Minor changes were also predicted for the southern semiarid zone in the RCP 8.5 scenario (Figure 22).

Table 8. Expansion of the Caatinga vegetation in the Brazilian semiarid region in the CMIP-5 models for the RCP 4.5 and RCP 8.5 scenarios. Percentages are relative to the current biome distribution predicted by each model. RF: Random Forests, SVM: Support Vector Machine.

	RCP 4.5		**RCP 8.5**	
GCM	**RF**	**SVM**	**RF**	**SVM**
HadGEM2-ES	3.4 %	5.0 %	20.5 %	21.2 %
CCSM4	13.2 %	10.9 %	27.0 %	21.3 %
MIROC5	34.6 %	30.5 %	29.5 %	26.9 %
Mean	**17.1 %**	**15.5 %**	**25.6%**	**23.1 %**

CCSM4 - The CCSM4 model pointed to an intermediate expansion of the dry Caatinga vegetations in the RCP 4.5 scenario (10.9 – 13.2 %). However, in the RCP 8.5 scenario, the Caatinga expanded from 21.3 to 27% concerning its current distribution. Also, the Forest and Arboreal Caatinga replaced the Atlantic Dry Forest in the southern and western ecotone.

MIROC5 - The MIROC5 model had the most drastic climate projections for the semiarid region (Figure 21 and Figure 22). Both in the RCP4.5 and RCP8.5 scenarios the Caatinga-associated vegetation covered more than 80% of the region, expanding mainly to western Bahia, Piauí and northern Minas Gerais beyond the limits of the current semiarid region. Furthermore, in the RCP 8.5 scenario, the Caatinga Forest and the Arboreal Caatinga replaced the Atlantic Dry Forest in the southern and western ecotones. The other vegetations were restricted to smaller areas at the semiarid region borders.

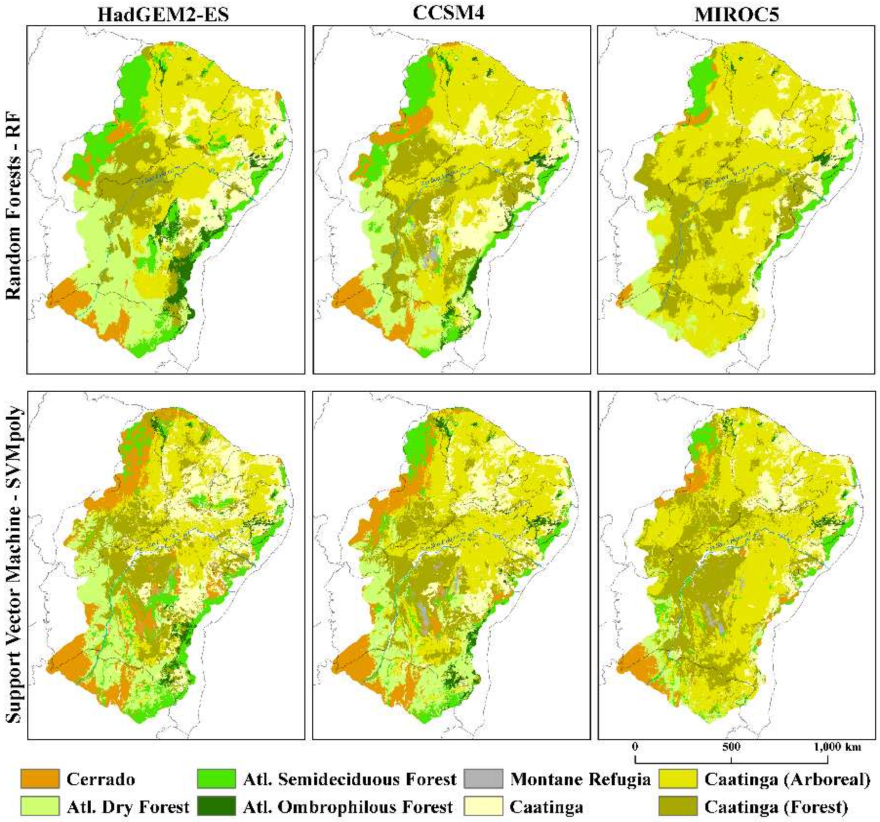

Figure 21. Potential vegetation distribution models with HadGEM2-ES, CCSM4 and MIROC5 general circulation models in the RCP 4.5 scenario.

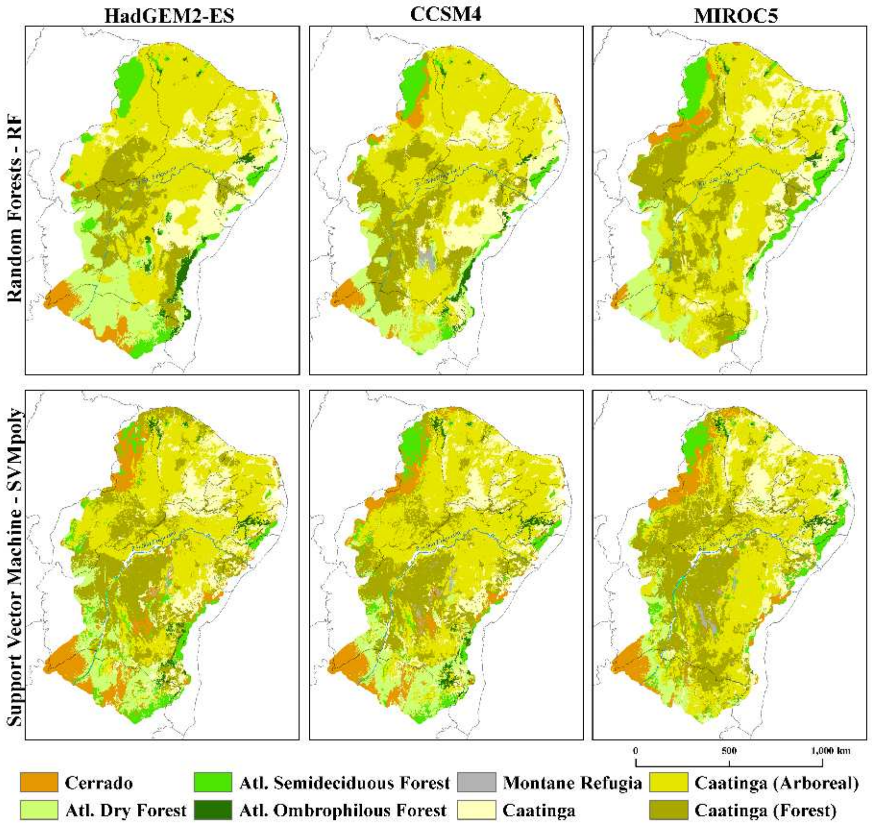

Figure 22. Potential vegetation distribution models with HadGEM2-ES, CCSM4 and MIROC5 general circulation models in the RCP 8.5 scenario.

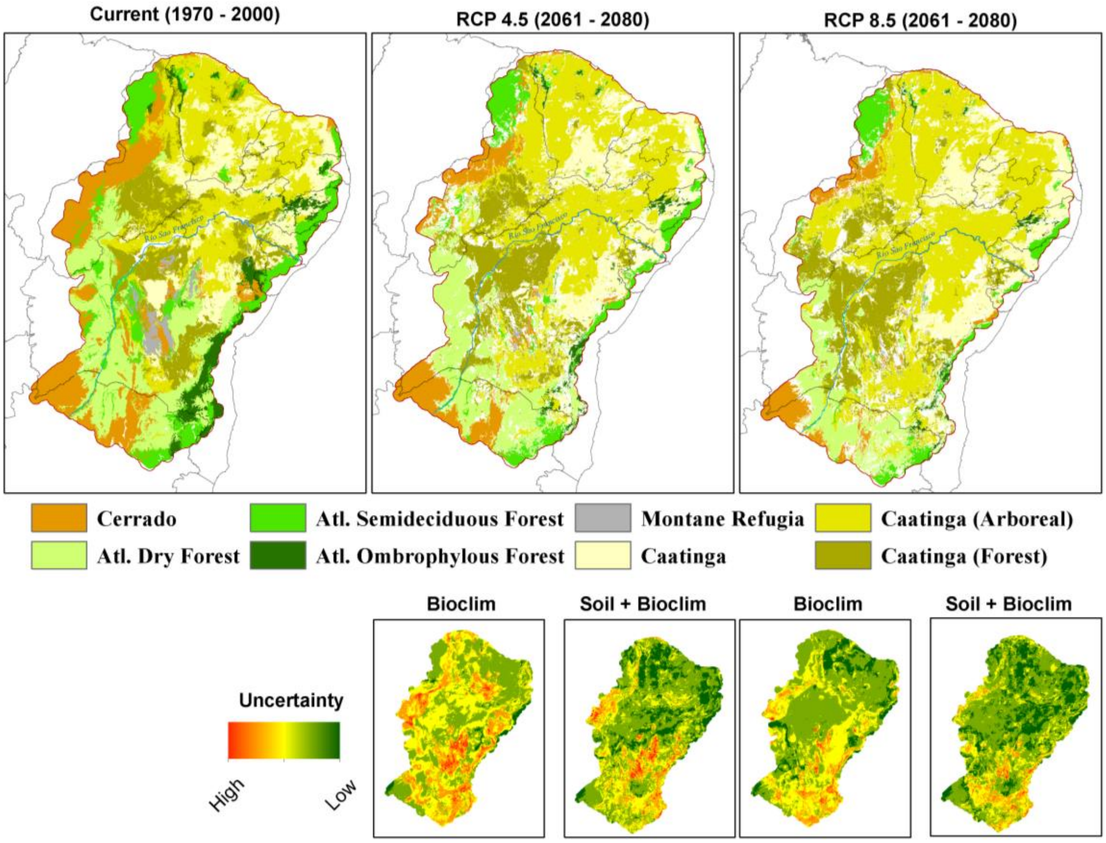

Figure 23. A synthesis of the simulations of the current and future distribution of vegetation in the Brazilian semiarid region. The vegetation maps (above) represent the predominant vegetation type in the predictions of HadGEM2-ES, CCSM4 and MIROC5 general circulation models with the classification algorithms SVM and RF. The uncertainty maps (below) are based on the number of distinct vegetations predicted in each cell with the bioclimatic and edaphoclimatic envelope models.

The areas occupied by each vegetation type in all models and scenarios are summarised in Table A. 13. In Figure 24, we present a summary of the vegetation dynamics in terms of area between the current climate and the RCP scenarios 4.5 and 8.5. To aid visualization, the vegetations were grouped by biome type.

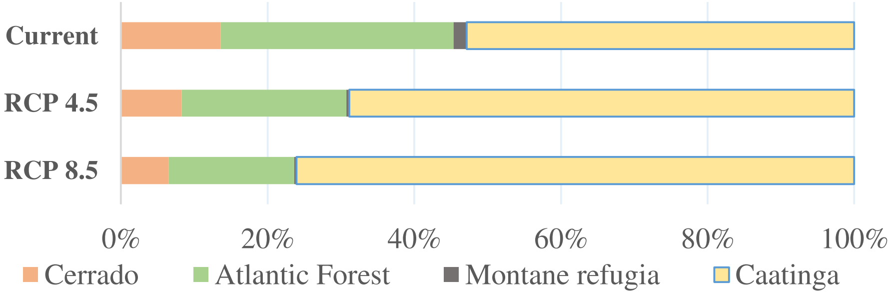

Figure 24. Percentage of the Brazilian semiarid area occupied by each type of vegetation in the current climate scenarios, RCP 4.5 and RCP 8.5. Each bar represents averages of the SVM and RF models.

5.4 DISCUSSION

About 28 million people inhabit the Brazilian semiarid region, making it the most populated semiarid worldwide (Tabarelli *et al* 2018). The region is among the ones with the lowest Human Development Index in Brazil (PNUD 2015) and has the highest concentration of rural population in the country. Consequently, there is a high dependence on rainfall and ecosystem services, which are directly affected by climate changes (Rito *et al* 2017b, Althoff *et al* 2016, Menezes *et al* 2012, Mooney *et al* 2009), putting at risk the permanence of populations, agricultural systems and biodiversity conservation. Therefore, the increasing aridity and the Caatinga expansion are indicators of potential threats to the semiarid region population in the areas that potentially will be most changed, such as the northern region of Minas Gerais and western Bahia.

In this context, developing accurate models is crucial to define strategies and guide decision-making at local scales. Although the use of soil predictors are currently urged in environmental niche modelling for this end (Thuiller 2013, Diekmann *et al* 2015, Arruda *et al* 2017, Mod *et al* 2016b), the classification algorithms performance with such predictors has not been objectively addressed in the literature. Our findings provide new insights regarding algorithms selection and highlight the importance of model assessment from an ecological perspective, in addition to ordinary validation.

5.4.1 Current vegetation distribution

Vegetation distribution models varied according to the algorithm and the predictors used. Among the most accurate models, the detailing level tends to be improved in the edaphoclimatic envelope. This novel approach was essential to generate more consistent results, which better resembled the actual vegetation distribution. For the current climate, the edaphoclimatic envelope was more efficient to predict the vegetation distribution at the landscape scale. However, the expected enhancement by adding soil predictors was not observed in all algorithms. The improving effect strongly depended on the algorithm used since many of them gave lesser importance to these variables. Despite the availability of soil predictors, decision trees like Random Forests were limited to macro-scale (bioclimatic) patterns.

Decision trees have been widely used in environmental niche modelling due to their better performance (Arruda *et al* 2017, Peters *et al* 2009, Wang *et al* 2016, Hengl *et al* 2018). Indeed, in our study, the RF, C5.0 and treebag algorithms were the ones that performed better, as showed by the highest Accuracy and Kappa. Nevertheless, they were deficient to represent the phytogeographic complexity in the Brazilian semiarid region, where the soil has an important role (Chapter 2). At regional scale (~ 10^6 km²) the contribution of climatic and soil attributes is more balanced (Arruda *et al* 2020, Oliveira *et al* 2019) when compared to the global one (Hengl *et al* 2018), where the climate is the chief driver of biomes distribution. In this regard, the use of appropriate algorithms for the analysis scale was critical to achieve ecologically consistent results.

The models organized the Caatinga Forest responding to an edaphoclimatic gradient, representing a clear transition between the dry core of the Caatinga and the surrounding Atlantic Dry Forest. It also occupied a larger area in all models in comparison to the reference map. This strongly suggests that the current Caatinga Forest patchy distribution is the result of a long-term anthropogenic disturbance, resulting in a fragmented landscape (Lôbo *et al* 2011, Antongiovanni *et al* 2018). Potentially, the transition zone between the Atlantic Forest and the Caatinga would originally be composed of a dry (deciduous) forests continuum.

To the south and west of the semiarid region, there are 76,508 km² currently mapped as Caatinga - Atlantic Dry Forest ecotone in the official vegetation map (IBGE 2004). Studies have shown a remarkable environmental and floristic similarity between these vegetations (Andrade-Lima, 1981a; Arruda, Schaefer, & Moraes, 2015; G. C. Oliveira et al., 2019; R. M. Santos et al., 2012, see also Chapter 2). Our results corroborate this, as the models classified 63.4% of this area as Atlantic Forest and only 20.6% with Caatinga vegetation (Table A. 11). Despite the greater similarity to the Atlantic Dry Forest, this transitional area is not currently protected by the Atlantic Forest Law (IBGE 2006), which regulates the biodiversity protection in this biome. According to most models, this region will undergo strong change in both CMIP5 scenarios. Considering the major importance of protected areas in mitigating the climate change impacts in the semiarid region (Acosta Salvatierra *et al* 2017, Oliveira *et al* 2012), the inclusion of the southern Caatinga ecotone in the Atlantic Forest Law protection is recommended as a strategic step for the Atlantic Forest conservation.

5.4.2 Future vegetation distribution

Regarding the forecast models, there was a significant variation due to the GCMs. In line with previous reports (Chou *et al* 2014), they were conflicting mainly regarding the rainfall distribution in the semiarid region. Whilst the HadGEM2-ES pointed to an increase in precipitation in the northern sector, the MIROC5 simulations showed a drier climate. In this sense, algorithms that were mostly oriented to bioclimatic attributes (especially rainfall), were also more subject to the GCMs uncertainties. However, it is consensual that both the number of consecutive dry days and temperature will increase in the semiarid region (Guimarães *et al* 2016, Almagro *et al* 2017, Chou *et al* 2014). Thus, even with high variability between GCM simulations, all models predicted an expansion of the dry Caatinga vegetation as a response to increased aridity at the regional level. The increase in the potential area was 16% in the RCP 4.5 scenario and 24% in the RCP 8.5 scenario (models average). These findings, besides corroborating previous studies (Chou *et al* 2014, Cook and Vizy 2008), provide the greatest detailed prediction of regions susceptible to vegetation cover changes to date.

The inclusion of soil attributes has increased the agreement between different GCM in predicting future vegetation. Hence, uncertainties derived from GCMs were mitigated, confirming the preliminary assumptions of our study. This is an evidence that the vegetation distribution models based on the bioclimatic envelope overestimate vegetation dynamics in short-term predictions. In addition to a higher consistency among predictions, soil attributes provided greater ecological coherence between models and our regional landscape rationale. The expansion of dry vegetations (usually related to nutrient-rich soils) towards strongly leached soils (Collevatti *et al* 2013a), is inconsistent for short-term vegetation dynamics. For instance, the replacement of the Cerrado by the Atlantic Dry Forest and Caatinga in the bioclimatic models was only sustained by climate changes, namely precipitation. However, it neglects the fact that these vegetations occurs in soils with very contrasting characteristics (Arruda et al., 2015a, 2015b; Oliveira et al., 2019), which imposes buffering attributes under changing climates. The Montane Refuges were strongly reduced in all future predictions, suggesting that these vegetations are important proxies of climate change in the semiarid region.

The high variability between the GCMs indicated that adopting a consensus within RCP scenarios is not feasible without a thorough analysis of its inconsistencies. Each GCM has its particularities, whose predictions may be further confirmed or not. Also, the GCM simulations for the global scale may not be sufficient to represent local climate variations even after downscaling. Therefore, it is recommended to analyse the results individually to include the GCMs uncertainties in the results (Varela *et al* 2015). In synthesis, the major differences between the GCMs are relative to the latitudinal extent of aridity expansion. This reflects the divergence among the GCMs in representing the dynamics of the Intertropical Convergence Zone (ITCZ) (Stanfield *et al* 2016, Chou *et al* 2014).

We have observed greater uncertainty in the RCP 4.5 scenario compared to the RCP 8.5. This can be explained by the fact that the initialization parameters in the RCP 4.5 scenario have intermediate conditions (Thomson *et al* 2011), which may have led to very different results. On the other hand, it is likely that on the RCP 8.5 scenario the more extreme climatic conditions resulted in the convergence of the simulations.

Further work in vegetation distribution modelling in the semiarid region should consider some constraints. (1) The distinction of the Caatinga vegetation types is one of the uncertainty sources, which is a consequence of the complexity in classifying them even on a local scale. The imprecise classification mixes the samples n-dimensional hyperspace and impairs the training of models, leading to classifiers confusion. Therefore, the interpretation of the Caatinga physiognomies distribution must consider this (Chapter II). (2) The lack of soil attributes database is a recurrent obstacle to niche modelling. The spatialization of soil attributes for large scales is laborious and time-consuming while requiring interpretation and correlation of pedological maps (Chapter III), often found in analogical format. (3) The models were unable to predict areas with potential desertification risk in the dry Caatinga core. In future work, sites with higher susceptibility, or where the desertification process is already occurring, should also be sampled (Tomasella *et al* 2018, Almagro *et al* 2017). Physiological critical/lethal temperature limits could also be used to compose a 'synthetic niche' of desertification. (4) We recommend the use of more variables that influence plant communities on a local to landscape scale. In particular, soil physical properties that can affect drought tolerance (*e.g.*, density and porosity), Nitrogen and Phosphorus. We emphasize that the inclusion of factors that provide local detail should be coupled with the use of algorithms that can model this variation.

Lithology has been used as a factor for niche differentiation in some studies (Goedecke *et al* 2020, Gastón *et al* 2009). We chose not to include it for two reasons: allochthonous soils would have little correlation with the underlying lithology and, on the other hand, highly weathered soils tend to have similar properties (e.g., high Al^{3+} saturation, low CEC, low pH), even derived from contrasting parent material. However, in some cases as in temperate regions, lithological variability can be important (D’Amico *et al* 2015). In the specific case of the Brazilian semiarid region, we considered that the topsoil variability (Jobbágy and Jackson 2004) was the best choice to model the soil-vegetation relationship on a regional scale in this first approach.

Our results confirm the need for a revision of the Caatinga phytogeography, in the light of several studies published in the last decades (Fernandes *et al* 2020, Silva *et al* 2018, Santos *et al* 2012, Queiroz *et al* 2018, Velloso *et al* 2002, Queiroz 2006, Rito *et al* 2017b). In this sense, we argue that classification systems of the SDTF should be closer to the environmental niche and floristic composition rather than to the physiognomic type (see Chapter 2), which is strongly changed by the chronic anthropogenic disturbance (Ribeiro *et al* 2015, Rito *et al* 2017b). The lack of a niche-compatible classification (Chapter 2) hinders an accurate model calibration. This affects the results leading to high uncertainty in the vegetation distribution, especially among the Caatinga formations.

5.5 CONCLUSION

The increase in aridity forecasted by different GCMs indicated major changes in the vegetation distribution in the Brazilian semiarid region both in RCP 4.5 and RCP 8.5 scenarios. However, there is high uncertainty concerning the GCM simulations. The inclusion of soil attributes mitigated those uncertainties in future predictions and, for the current vegetation, allowed the representation of smaller vegetation patches whose distribution is influenced by local edaphic and topographic factors. In this regard, the use of appropriate classification algorithms for the analysis scale is fundamental, since not all of them presented the expected performance with the inclusion of soil attributes.

6 GENERAL CONCLUSIONS

The global climate has always been changing. Large human migrations have occurred in response to prehistoric climatic events, which have often reconfigured the distribution of nomadic hunter-gatherer communities on the planet. However, in modern society, there is no possibility of free movement of individuals. Now, the population is incomparably larger, there are political boundaries and the nomadic way of life is an exception. Thus, we will face climate change without the option of simply migrating, as has happened several times over our history as human species. Consequently, the climate crisis can lead to global geopolitical conflicts if society is not properly prepared to deal with its impacts. In this context, science's role in assessing possible scenarios is crucial to guide impact mitigation strategies.

Based on the results found in this work, it is concluded that the climate changes predicted in the IPCC AR-5 scenarios will lead to substantial changes in the distribution of vegetations in the Brazilian semiarid region. On average, the models indicated a 26% increase in the current extent of Caatinga in the RCP 8.5 scenario and 16% in the RCP 4.5 scenario. According to the prediction models, this expansion will occur mainly in the northern regions of Minas Gerais and western Bahia. However, the degree of impact was variable and strongly dependent on the predictions of the General Circulation Models (GCM). In turn, the CCSM-4, HadGEM2-ES and MIROC5 models presented greater uncertainty in the RCP 4.5 scenario and greater convergence in the RCP 8.5 scenario. The uncertainty was significantly reduced with the approach that includes soil attributes in the modelling, leading to the adjustment of more consistent and realistic models. However, it was found that the choice of appropriate machine learning algorithms for the scale of analysis is critical for attaining better results.

The vegetation distribution in the semiarid region was related to rainfall volume and seasonality, in climatic terms. In the edaphic dimension, Al3+ saturation and base saturation were the key attributes. The texture of the topsoil was less important since the vegetations were distributed in fine and coarse-textured soils indistinctly. On the other hand, the presence of clay in the soil was important to explain the variation in vegetation structure at the community level. The importance of soil in explaining the vegetation distribution was shown both on the local (communities) and regional (biomes) scales.

The results also revealed the similarity between the Caatinga Arboreal and the Atlantic Dry Forest in environmental and floristic terms. This is a result of the physiognomy-based classification, which gathers many communities with distinct compositions without reflecting the species-environmental relationship accurately. As a result, at the vegetation-class level, these two formations were quite similar. Following the pattern observed for Seasonally Dry Tropical Forests, where niche control is predominant, most of the variation in species composition was explained by soil and climate. In this sense, different environments harboured different groups of species. The development of new phytogeographic classifications consistent with the inherent macro-ecological relationships in dry forests is necessary for the development of more robust models to assess climate change impacts in the Brazilian semiarid region.

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APPENDIX A – CHAPTER I

Climate and soils at the Brazilian semiarid and the forest-Caatinga problem: new insights and implications for conservation

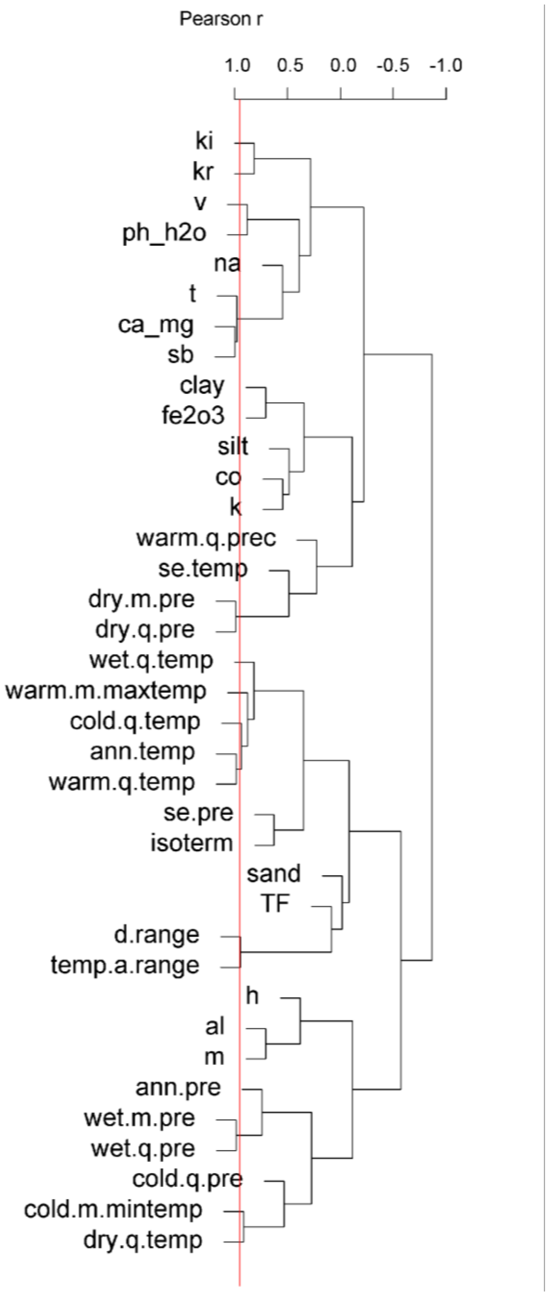

Figure A.1. Hierarchical correlation dendrogram of soil and climate variables. The 0.95 cut (red line) was applied to identify highly correlated clusters of variables. For each cluster, only the variable with the lowest redundancy was selected.

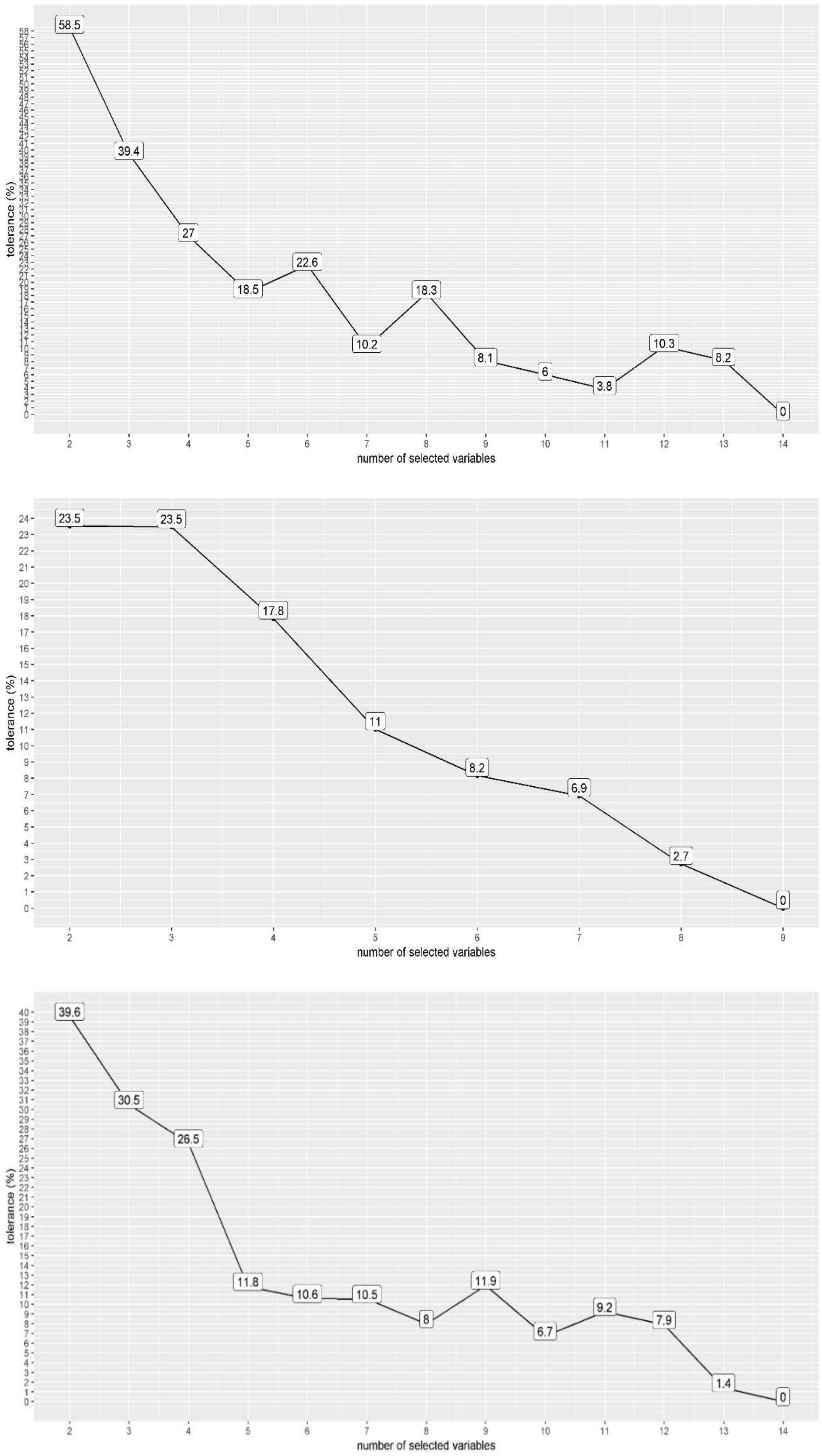

Figure A.2. Tolerance from recursive feature elimination. Soil dataset (above), climate dataset (middle) and combined soil and climate data set (bottom). A 10% tolerance threshold was set for the choice of the number of variables in the parsimonious model.

Table A.1. Coefficients of linear discriminants for climate predictors.

Variable	LD1	LD2	LD3
ann.pre	-2.268	-1.439	-0.491
se.pre	0.756	-1.888	-2.103
se.temp	-0.150	0.775	-0.449
dry.m.pre	1.176	-0.793	-1.701
wet.m.pre	1.374	2.065	0.604
wet.q.temp	0.360	-0.302	0.178
Proportion of trace	0.757	0.204	0.039

The explanation of the variable codes is in the main text.

Table A.2. Coefficients of linear discriminants for soil predictors.

Variable	LD1	LD2	LD3
k	-0.248	-0.122	0.319
v	-0.787	-0.125	1.117
m	0.923	-0.606	1.221
co	0.335	0.745	-0.691
fe2o3	-0.132	0.267	0.328
h	-0.058	-0.066	0.740
al	-0.046	-0.267	0.184
ph_h2o	0.234	-1.181	0.553
sand	0.074	-0.394	-0.185
Proportion of trace	0.746	0.193	0.061

The explanation of the variable codes is in the main text.

Table A. 3. Coefficients of linear discriminants for climate and soil predictors combined.

Variable	LD1	LD2	LD3
ann.pre	-0.760	-0.885	0.145
m	-0.771	0.959	1.058
v	0.402	0.369	0.872
se.pre	0.802	1.580	1.200
k	-0.033	-0.540	0.481
se.temp	-0.154	-0.451	0.185
dry.m.pre	0.458	1.477	1.229
wet.q.temp	0.144	0.437	-0.198
Proportion of trace	0.653	0.297	0.050

Table A. 4. Confusion Matrix and Statistics from Random Forests parsimonious model with combined climate and soil predictors, Accuracy: 0.7089, 95% CI: (0.6917, 0.7257), P-Value [Acc > NIR] : < 2.2^{-16}, Kappa: 0.6119, Mcnemar's Test P-Value: < 2.2^{-16}.

	Reference			
Prediction	Arb. Caatinga	Caatinga	Cerrado	Dry Forest
Arb.Caatinga	296	68	43	114
Caatinga	145	576	1	3
Cerrado	111	22	590	60
Dry.For.	148	34	66	523
Statistics by class				
	Arb.Caatinga	Caatinga	Cerrado	Dry Forest
Sensitivity	0.4229	0.8229	0.8429	0.7471
Specificity	0.8929	0.929	0.9081	0.8819
Pos Pred Value	0.5681	0.7945	0.7535	0.6783
Neg Pred Value	0.8227	0.9402	0.9455	0.9128
Prevalence	0.25	0.25	0.25	0.25
Detection Rate	0.1057	0.2057	0.2107	0.1868
Detection Prevalence	0.1861	0.2589	0.2796	0.2754
Balanced Accuracy	0.6579	0.876	0.8755	0.8145

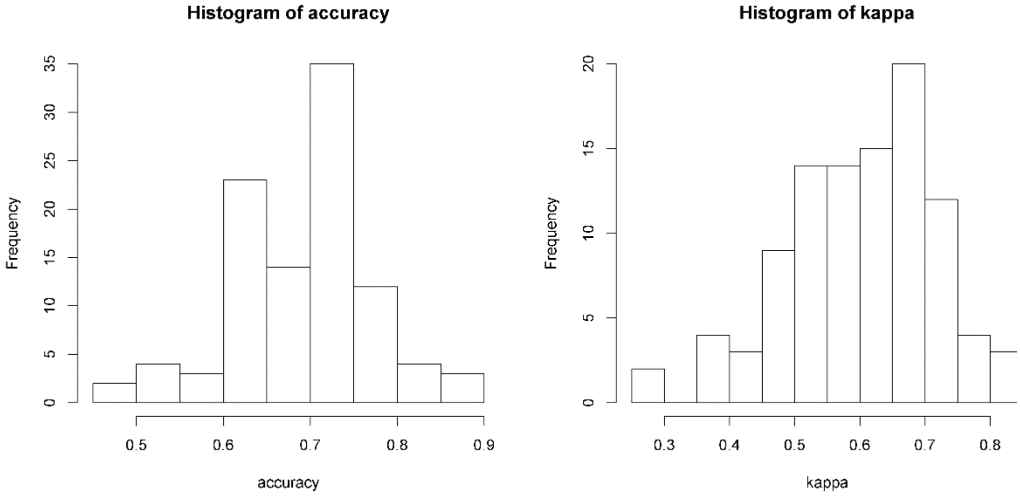

Figure A. 3. Kappa and accuracy histogram after 100 iterations of Random Forests parsimonious model.

APPENDIX B – CHAPTER II

Atlantic Forest or Arboreal Caatinga? Using soil and climate attributes to distinguish dry forests in a semiarid ecotone

Supplementary Information

Study Area

The plant communities sampled are located in the depressions of São Francisco, Paramirim and Jequitinhonha rivers. Precambrian crystalline rocks of the São Francisco craton and the Atlantic Mobile belt predominate in the region, occasionally covered with Quaternary sediments (Brasil 1982). The *Sete-Lagoas* and *Lagoa do Jacaré* formations of the Bambuí group (Drummond *et al* 2015, Perrella *et al* 2017, Iglesias and Uhlein 2009) on the east of the study area are another important features, though less expressive in terms of geographical extension. These Neoproterozoic formations are composed of carbonate rocks, representing islands of base-rich and null Al^{3+} saturation soils and influencing the chemical richness of the adjacent soils (Ferreira *et al* 2018, Arruda *et al* 2015a). On a broader scale, the study region comprises a domain of Latosols, Argisols and Cambisols (Santos *et al* 2011, Schaefer 2013), with more evolved pedogenesis compared to the dry core of the semiarid region (Santos *et al* 2011).

RDA Analysis

The RDA is a canonical ordering method which tests several linear combinations in the explanatory variables that best fit to the variation in the species data (Borcard *et al* 2018).

We tested the existence of a spatial trend in the data using Distance-based Moran's eingenvectors (dbMEM, Borcard et al., 2018). The aim was to use the detrended dbMEM eigenvectors as explanatory variables in the RDA and to quantify its explanatory power through variance partitioning (Smith and Lundholm 2010), whether the spatial trend in the data was confirmed.

The spatial eigenvectors were calculated from a Euclidean distance matrix using a Principal Coordinate Analysis (PCoA). The dbMEM analysis showed significant spatial trend (p-value < 0.01, $F = 3.14$), although with little explanatory power ($R^2_{adj.} = 0.08$). We calculated the residuals of the linear regression adjusted with the spatial matrix to generate a new detrended data matrix. The global dbMEM model resulted in six eigenvectors with positive spatial correlation. Of these, three significant eigenvectors were retained by Forward Selection for subsequent analysis.

Following the dbMEM variables selection, we executed a new RDA with the environmental predictors only. Once the significance of this preliminary RDA was confirmed, we proceeded to forward selection of environmental variables. The selection was made separately for each dataset (soil and climate) with the *forward.sel* function from 'adespatial' R package. Then, we proceeded to variance partitioning to assess the contribution of the environmental and spatial components. The significance of these components in the global RDA was confirmed by ANOVA. Finally, we adjusted a final RDA with the selected variables of the environmental and spatial components collected in a single explanatory matrix.

Indicator species groups

The analysis considered both the specificity and the frequency (parameters A and B, respectively) of a species combination in a given environment (De Cáceres and Legendre 2009). The species combinations were tested with the *indicators* function from 'indicspecies' R package (De Cáceres and Jansen 2019). We configured the function to test the significance of up to five species combinations per environmental group. We eliminated species combinations with a low indicator value, setting the A and B parameter thresholds to 0.5 and 0.4, respectively. The species combinations that showed p-value < 0.05 were then selected.

Multiple linear regression – aboveground biomass

Initially, we performed an outlier analysis to identify non-representative individuals (*e.g.*, *Spondias tuberosa* with a 2.2 m² basal area in plot 54, site 16). For these, we replaced the basal area value by the respective plot mean. The outlier removal was repeated until the distribution of basal area per plot reached the normal distribution, indicated by Shapiro-Wilk test at 95% confidence level. In total, we identified three individuals as outliers and replaced their values.

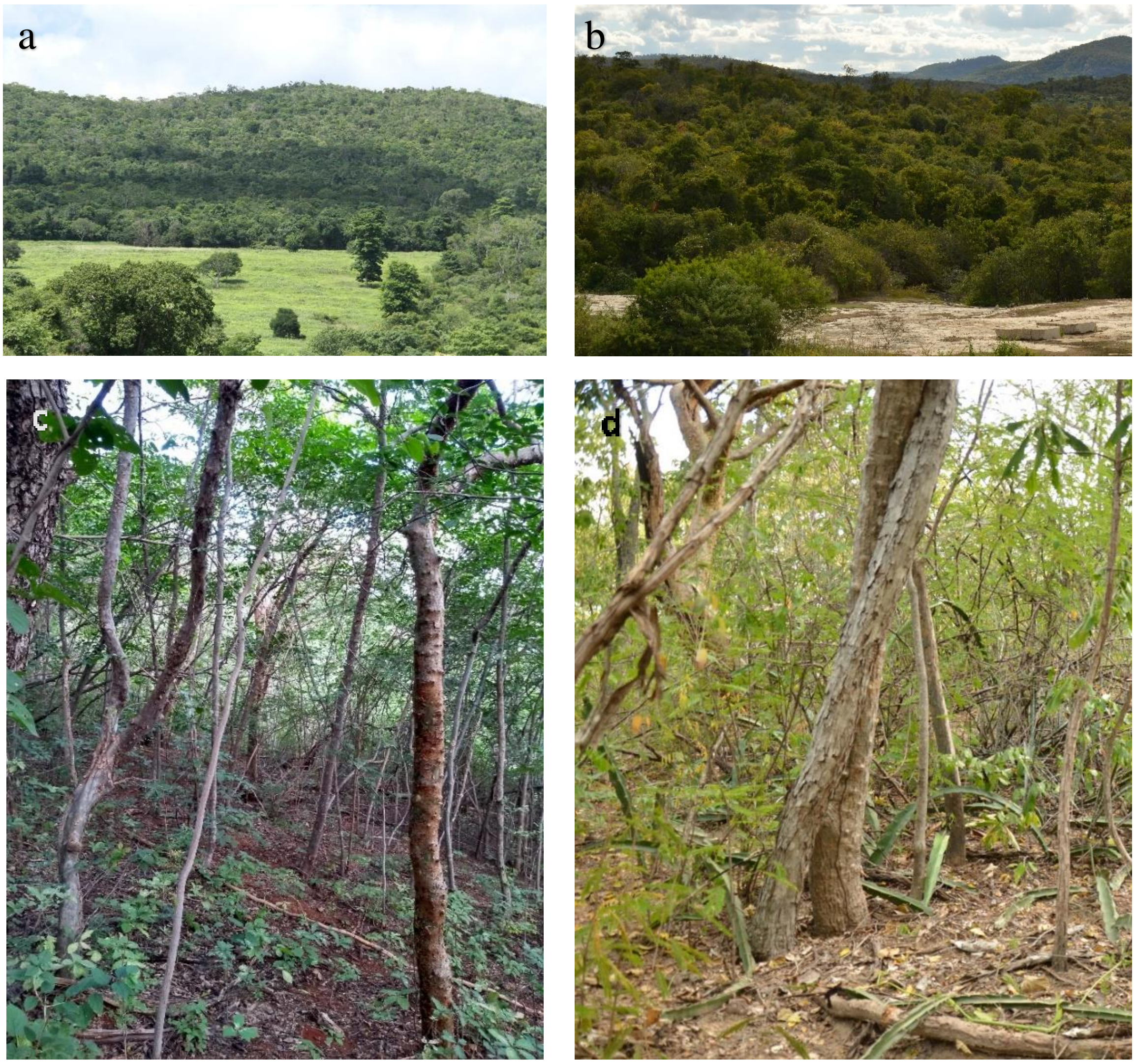

Figure A. 4. Illustration of the vegetations sampled: Atlantic Dry Forest (a, c) and Arboreal Caatinga (b, d), both in the wet season. Note the presence of succulents in the Arboreal Caatinga (d) and the absence of grass strata in both (c, d). Photos: Oliveira, G. C.

Table A. 5. Mean of surface soil attributes (0-20cm) per community. pH = soil pH in water; P , K and Na = content extracted by Mehlich-1; S.B. = sum of bases, CEC = cation exchange capacity; V = base saturation; SOM = soil organic matter; Silt clay and sand fractions in fine earth.

Site*	**Plots**	**pH**	**P**	**K^+**	**Na^+**	**Ca^{2+}**	**Mg^{2+}**	**Al^{3+}**	**S.B.**	**CEC**	**V**	**Al^{3+} Sat.**	**SOM**	**Silt**	**Clay**	**Sand**
			mg.dm^{-3}			cmol$_c$ .dm^{-3}					%		dag.kg-^{1}	%		
1	1-3	6.4	1.1	97.0	13.7	8.7	2.0	0.0	11.0	12.8	85.1	0.0	2.9	19.9	40.9	39.3
2	4-6	4.9	1.0	69.0	11.3	1.5	0.3	0.8	2.1	5.8	36.2	27.0	2.0	17.9	25.2	56.9
3	7-9	5.7	1.6	114.3	17.3	6.5	0.8	0.0	7.6	10.3	72.8	0.0	5.5	12.9	28.6	58.4
4	10-12	5.3	0.8	54.3	3.3	1.0	0.3	0.1	1.4	3.0	46.0	4.9	1.1	4.5	12.0	83.5
5	13-15	6.1	0.9	105.0	5.3	2.8	0.8	0.0	3.8	5.2	74.0	0.0	1.5	11.6	19.1	69.3
6	16-18	4.7	1.6	62.0	2.3	1.1	0.3	0.5	1.5	5.1	29.9	25.9	1.8	16.8	14.9	68.4
7	19-21	4.8	0.8	126.7	7.0	1.7	0.6	0.5	2.7	5.9	43.9	18.0	2.0	7.9	26.6	65.4
8	22-24	5.4	1.4	146.0	5.7	2.1	0.6	0.0	3.0	5.5	55.0	0.0	2.5	2.7	27.0	70.3
9	25-27	5.4	0.6	186.0	10.0	3.2	1.0	0.0	4.6	8.0	58.0	0.0	3.1	9.9	47.4	42.6
10	31-33	4.9	1.5	95.0	9.0	2.1	0.7	0.2	3.1	6.4	48.0	6.0	2.7	6.7	41.0	52.3
11	37-39	4.6	2.6	88.0	3.7	0.7	0.2	0.6	1.1	4.6	24.9	35.3	1.8	10.3	24.4	65.3
12	40-42	6.4	3.5	207.4	3.3	9.4	1.9	0.0	11.9	11.9	81.5	0.0	5.9	45.8	45.7	8.5
13	43-45	3.8	1.4	37.9	2.5	0.1	0.1	1.4	0.3	1.7	6.7	81.1	1.4	4.9	18.2	76.9
14	46-48	5.3	1.3	102.8	0.0	0.9	0.5	0.3	1.7	2.0	30.1	15.9	2.3	9.0	21.8	69.2
15	49-51	6.4	3.6	124.6	1.0	6.4	1.1	0.0	7.8	7.8	68.0	0.0	2.9	22.2	54.3	23.4
16	52-54	6.2	3.3	206.4	1.5	5.2	1.3	0.0	7.0	7.0	74.2	0.1	2.5	15.9	53.0	31.1

Table A.6. Description of the bioclimatic variables from WorldClim 2 (Fick and Hijmans 2017)

Variable	**Description**
BIO1	Annual Mean Temperature
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))
BIO3	Isothermality (BIO2/BIO7) (×100)
BIO4	Temperature Seasonality (standard deviation ×100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14	Precipitation of Driest Month
BIO15	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19	Precipitation of Coldest Quarter

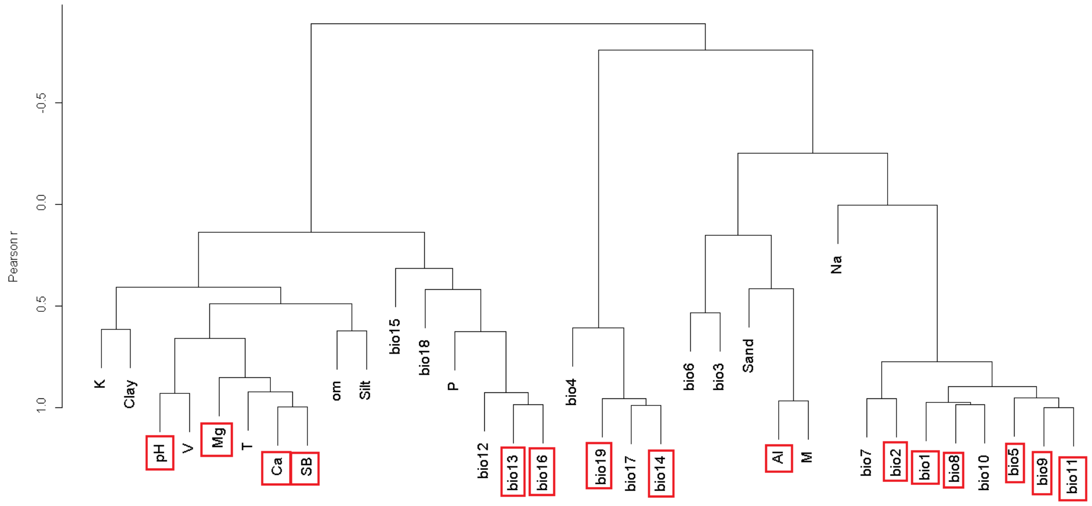

Figure A.5. Cluster dendrogram of environmental variables. The variables highlighted in red were removed for the analysis.

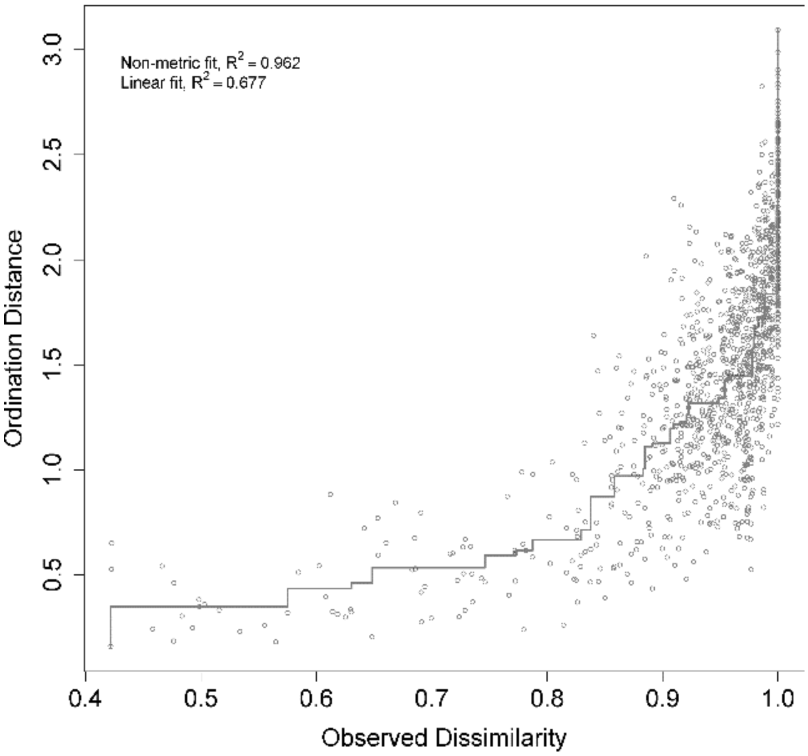

Figure A. 6 NMDS Stressplot.

Table A. 7. Simpson dissimilarity matrix. Pairwise comparisons between Arboreal Caatinga and Atlantic Dry Forest communities. Values greater than 0.7 are highlighted in bold.

	AC 11	AC 3	AC 4	AC 5	AC 6	AC 7	AC 8	AC 9	ADF 1	ADF 10	ADF 12	ADF 13	ADF 14	ADF 15	ADF 16	ADF 2
AC 11	0	**0.79**	0.68	0.70	0.64	**0.74**	**0.79**	**0.76**	**0.85**	**0.86**	**0.87**	**0.84**	**0.81**	**0.86**	**0.73**	**0.80**
AC 3	**0.79**	0	0.55	0.65	0.54	0.46	0.67	**0.75**	0.58	**0.92**	**0.75**	**0.74**	**0.88**	0.67	0.54	0.65
AC 4	0.68	0.55	0	0.55	0.45	0.55	0.59	**0.82**	0.68	**0.86**	**0.91**	0.68	**0.86**	**0.82**	**0.73**	0.65
AC 5	0.70	0.65	0.55	0	0.48	0.57	0.52	**0.74**	0.70	**0.78**	**0.83**	**0.79**	**0.87**	**0.78**	0.70	**0.80**
AC 6	0.64	0.54	0.45	0.48	0	0.40	0.60	**0.72**	**0.76**	**0.84**	**0.92**	**0.79**	**0.88**	**0.84**	**0.72**	**0.80**
AC 7	**0.74**	0.46	0.55	0.57	0.40	0	0.62	**0.73**	**0.73**	**0.86**	**0.84**	0.58	**0.75**	**0.74**	0.58	**0.75**
AC 8	**0.79**	0.67	0.59	0.52	0.60	0.62	0	0.55	**0.76**	**0.86**	**0.84**	0.58	**0.75**	0.66	0.69	**0.75**
AC 9	**0.76**	**0.75**	**0.82**	**0.74**	**0.72**	**0.73**	0.55	0	0.70	**0.93**	**0.81**	**0.74**	**0.91**	**0.76**	**0.73**	**0.80**
ADF 1	**0.85**	0.58	0.68	0.70	**0.76**	**0.73**	**0.76**	0.70	0	**0.83**	**0.71**	**0.74**	**0.84**	**0.73**	**0.73**	0.50
ADF 10	**0.86**	**0.92**	**0.86**	**0.78**	**0.84**	**0.86**	**0.86**	**0.93**	**0.83**	0	**0.97**	**0.84**	**0.86**	**0.83**	**0.92**	**0.90**
ADF 12	**0.87**	**0.75**	**0.91**	**0.83**	**0.92**	**0.84**	**0.84**	**0.81**	**0.71**	**0.97**	0	**0.84**	**0.87**	0.65	**0.73**	**0.90**
ADF 13	**0.84**	**0.74**	0.68	**0.79**	**0.79**	0.58	0.58	**0.74**	**0.74**	**0.84**	**0.84**	0	0.63	**0.74**	**0.79**	**0.84**
ADF 14	**0.81**	**0.88**	**0.86**	**0.87**	**0.88**	**0.75**	**0.75**	**0.91**	**0.84**	**0.86**	**0.87**	0.63	0	**0.81**	**0.85**	**0.85**
ADF 15	**0.86**	0.67	**0.82**	**0.78**	**0.84**	**0.74**	0.66	**0.76**	**0.73**	**0.83**	0.65	**0.74**	**0.81**	0	0.62	**0.85**
ADF 16	**0.73**	0.54	**0.73**	0.70	**0.72**	0.58	0.69	**0.73**	**0.73**	**0.92**	**0.73**	**0.79**	**0.85**	0.62	0	**0.85**
ADF 2	**0.80**	0.65	0.65	**0.80**	**0.80**	**0.75**	**0.75**	**0.80**	0.50	**0.90**	**0.90**	**0.84**	**0.85**	**0.85**	**0.85**	0

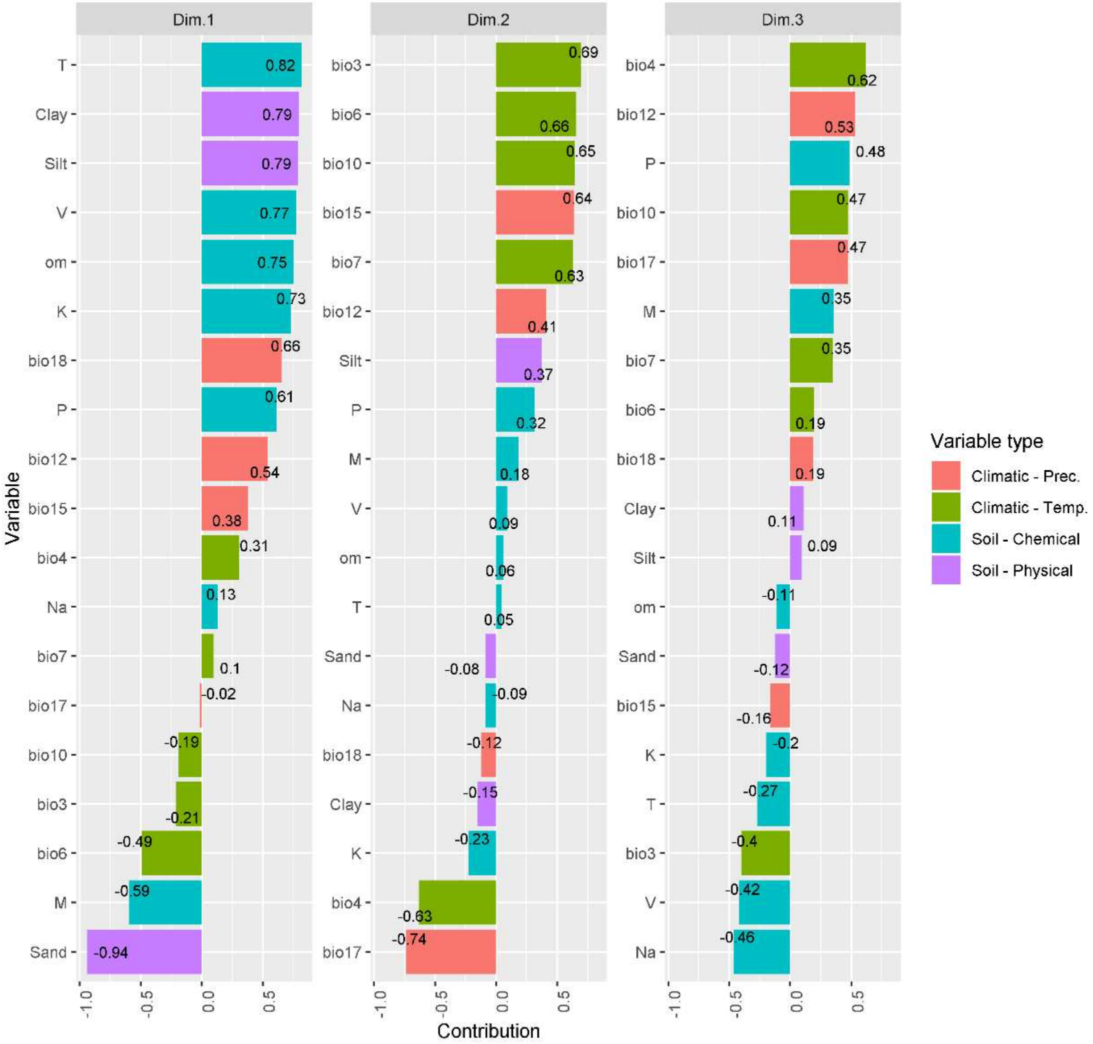

Figure A. 7. Contribution of environmental variables to each PCA dimension. The colours represent different types of variables (see legend). Prec.: Precipitation; Temp.: Temperature.

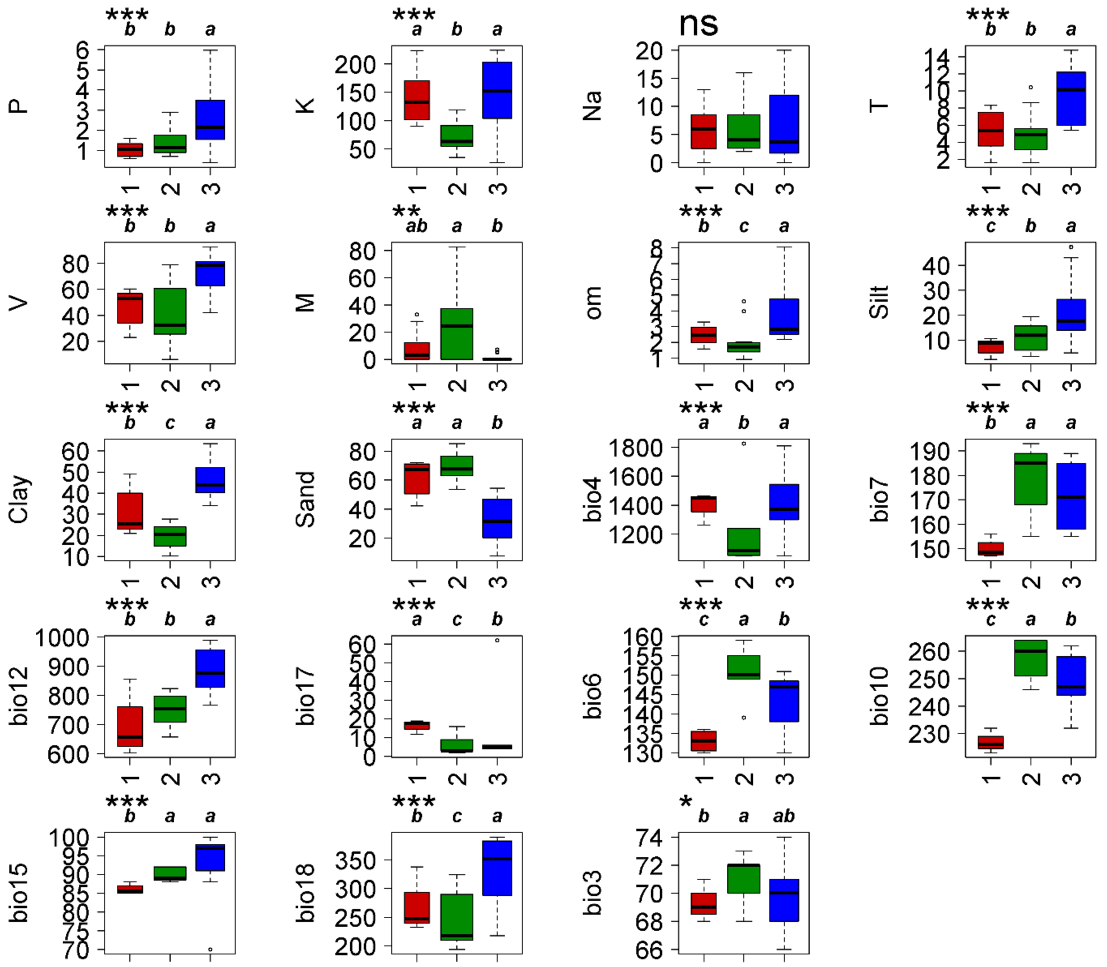

Figure A. 8. Distribution of environmental attributes in the groups identified by cluster analysis. Averages tested by Kruskal-Wallis.

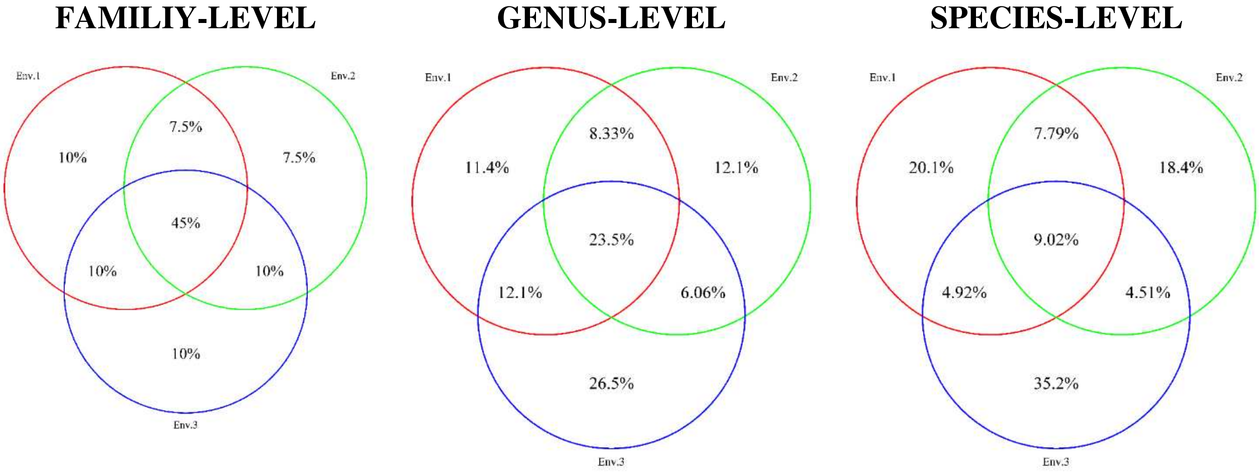

Figure A. 9. Shared taxa between the Environments 1, 2 and 3 in the southern ecotone of the Brazilian semiarid.

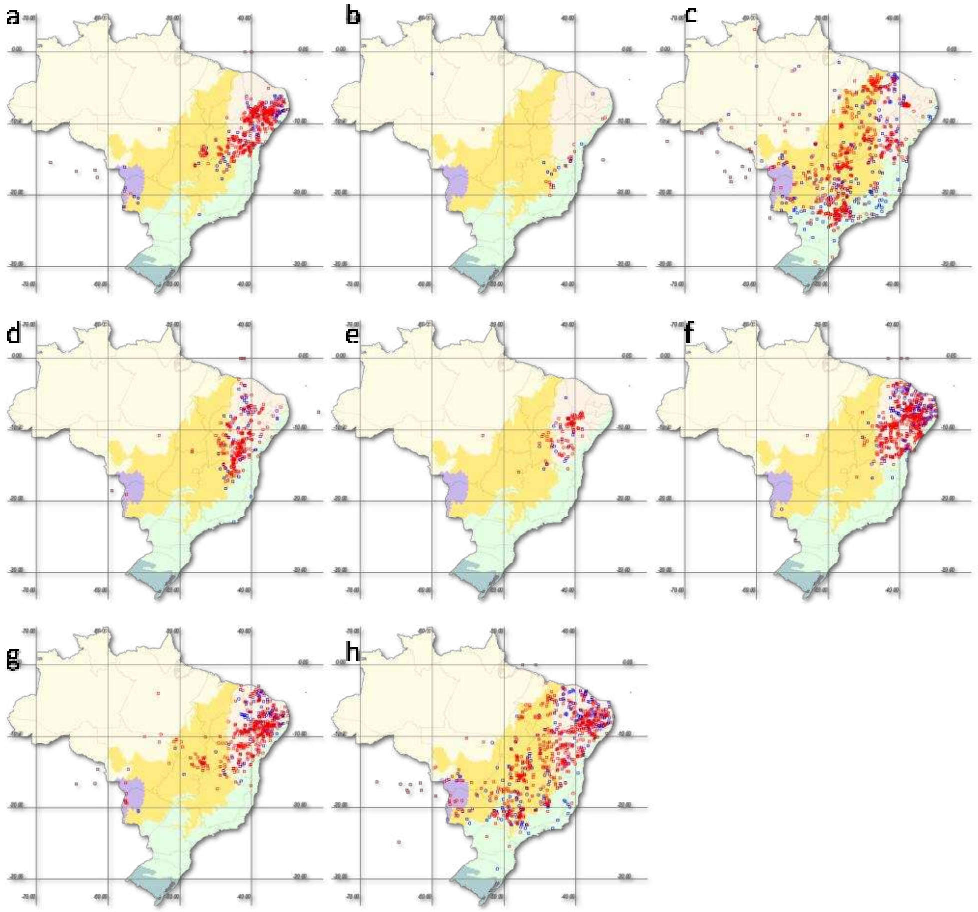

Figure A. 10. Distribution of the species identified as environment indicators, adapted from SpeciesLink database (http://splink.org.br/). (a) *Schinopsis brasiliensis*, (b) *Diplotropis ferruginea*, (c) *Machaerium acutifolium*, (d) *Senegalia langsdorffii*, (e) *Handroanthus spongiosus*, (f) *Cnidoscolus bahianus*, (g) *Commiphora leptophloeos*, (h) *Sapium glandulosum*.

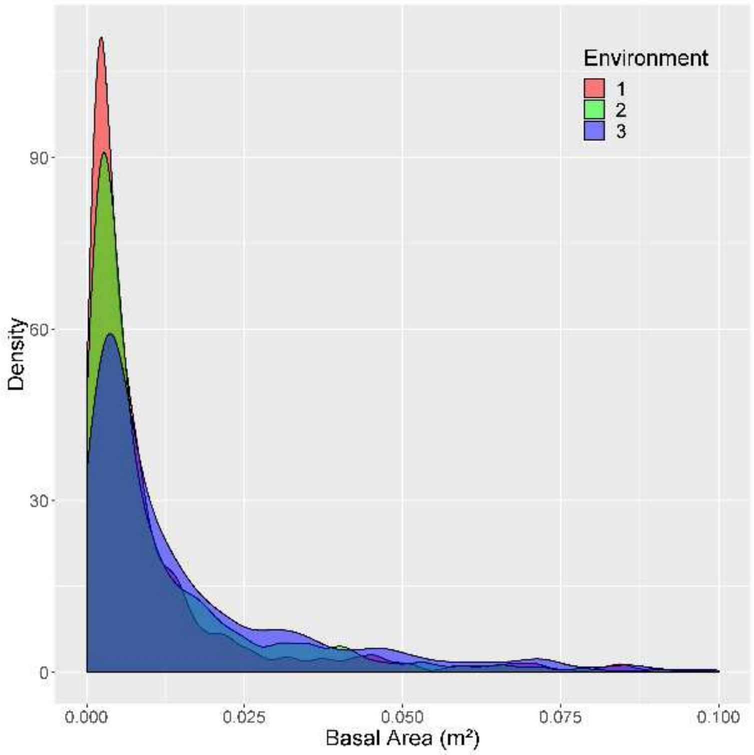

Figure A. 11. Density distribution of basal areal by environment group (a).

Table A. 8. Analysis of Variance (ANOVA) of the multiple linear regression model for aboveground biomass.

Variable	D.F	Sum Sq.	Mean Sq.	F value	Pr (>F)	Sig.[1]
K	1	0.4664	0.4664	1.304	0.261229	
Na	1	1.3259	1.3259	3.7075	0.062325	.
T	1	4.6553	4.6553	13.0169	0.000954	***
Silt	1	1.3874	1.3874	3.8793	0.05684	.
Clay	1	4.9398	4.9398	13.8123	0.000703	***
Sand	1	0.553	0.553	1.5461	0.221972	
bio3	1	2.7562	2.7562	7.7067	0.008775	**
P	1	2.0054	2.0054	5.6073	0.023541	*
V	1	1.4687	1.4687	4.1067	0.050386	.
Residuals	35	12.5173	0.3576			

Significance levels: *** 1%,

APPENDIX C – CHAPTER IV

Soil predictors are crucial for modelling dry vegetation responses to climate change

Table A. 9. Description of the vegetation types analysed.

Vegetation	Description	Remarks
Caatinga	Savannah physiognomy. Open dry vegetation mainly composed by scattered shrubs, small trees and succulents. Annual herbs fill the spaces between trees on the rainy season. This thorn bush vegetation is the most iconic of this Biome, also referred as 'Caatinga *stricto sensu*'. Is associated with semiarid climate, shallow and rocky chemically rich soils.	In this study, we grouped the open vegetations classified by RADAMBRASIL as ‘*Savana-Estépica*’, '*Savana-Estépica Parque*' and '*Savana-Estépica Gramíneo-Lenhosa*' as Caatinga. The Arboreal Caatinga was originally named as ‘*Savana-Estépica Arborizada*’ and the Forested Caatinga as ‘*Savana-Estépica Florestada*’.
Arboreal Caatinga	Woodland physiognomy, with two strata. Shrubs or small trees with scattered distribution form the upper one. Herbs and shrubs compose the lower stratum. Grasses are rare and sparse. Most of species lose theirs leaves during the dry season. Succulent species are common.	
Forested Caatinga	Two strata compose the Forested Caatinga subgroup: an upper one, with a predominance of periodically deciduous mesophanerophytes, generally thorny, and a lower woody-grass stratum of little expression. Among the Caatinga formations, this one is the most similar to the Atlantic Dry Forest, physiognomically and floristically. Succulents are present, however in lower density as compared to the other Caatinga vegetations.	
Atlantic Deciduous Forest	Forest physiognomy with upper stratum formed by macro and mesophanerophytes, where more than 50% of individuals completely lose their leaves during the dry period. This is the most seasonal vegetation of the Atlantic Forest, generally associated with eutrophic or mesotrophic soils.	The Atlantic Deciduous Forest is refered as '*Floresta Estacional Decidual*' in the RADAMBRASL maps. The Atlantic Semideciduous Forest is refered as ‘*Floresta Estacional Semidecidual*” and the Atlantic Ombrophillous Forest as ‘*Floresta Ombrófila*”.
Atlantic Semideciduous Forest	Forest physiognomy, stratified; associated to a lower seasonality in comparison to the Deciduous Forest. The canopy deciduousness range from 25–50%.	

Atlantic Ombrophillous Forest	Evergreen broad-leaf vegetation mainly composed by macrophanerophytes. In the context of the Brazilian semiarid region, it is associated to higher elevations and the higher humidity coming from the Atlantic Ocean on the east, with a limited territorial expression.	
Cerrado	Savannah physiognomy. The Cerrado is a xeromorphic, oligotrophic vegetation, with physiognomines varying from savanna to grassland with rare woods. In general, it is characterized by small trees, isolated or grouped on a grassy hemicryptophyte mat. The woody vegetation has thick bark, deep roots, constituting forms of life adapted to chemically poor, acid and aluminized soils.	The Cerrado group includes plant formations described by RADAMBRASIL as "*Savana Arbórea Aberta*", "*Savana Parque*" and "*Savana Gramíneo-Lenhosa*".
Montane Refugia	Grassland physiognomy composed of rupestrian, saxicolous and psamophilous species. Located in higher elevations, occupied by dwarf sclerophyllous, shrubby and/or herbaceous graminous vegetation. It is composed of many endemic species that reveal an ancient isolation.	

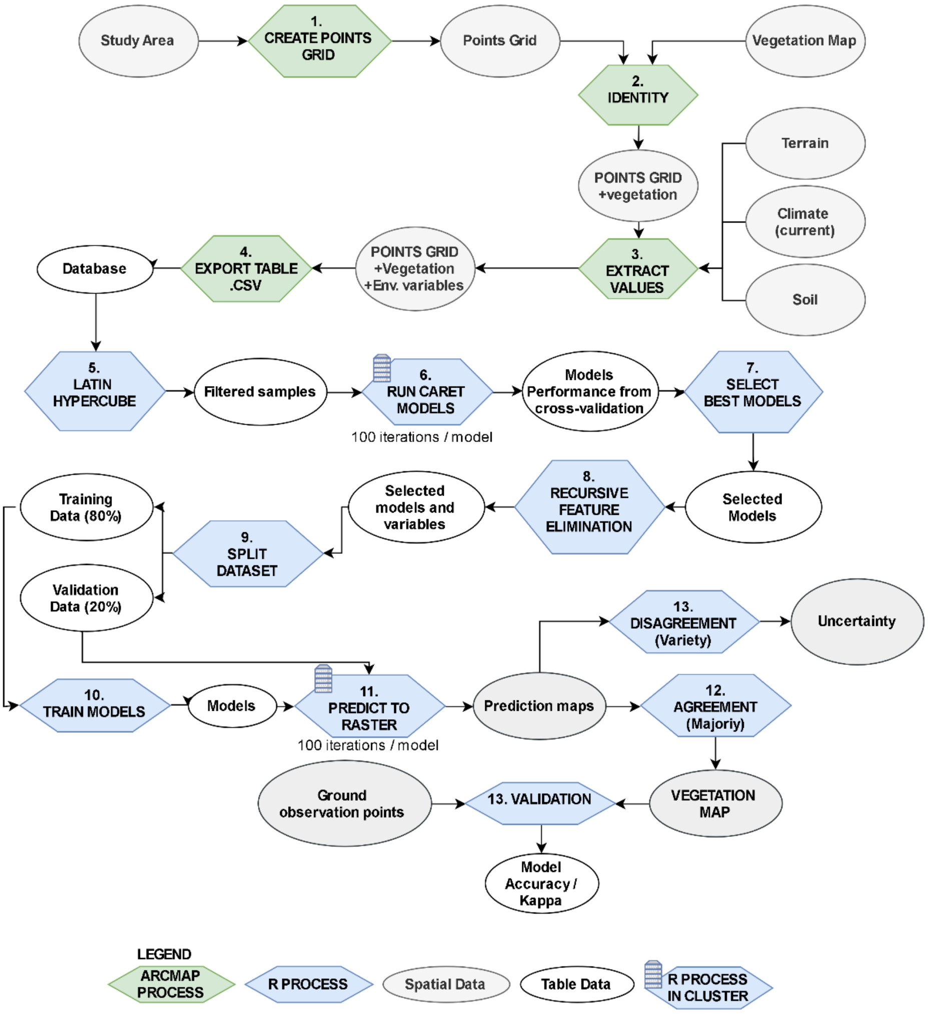

Figure A. 12. Methodological workflow

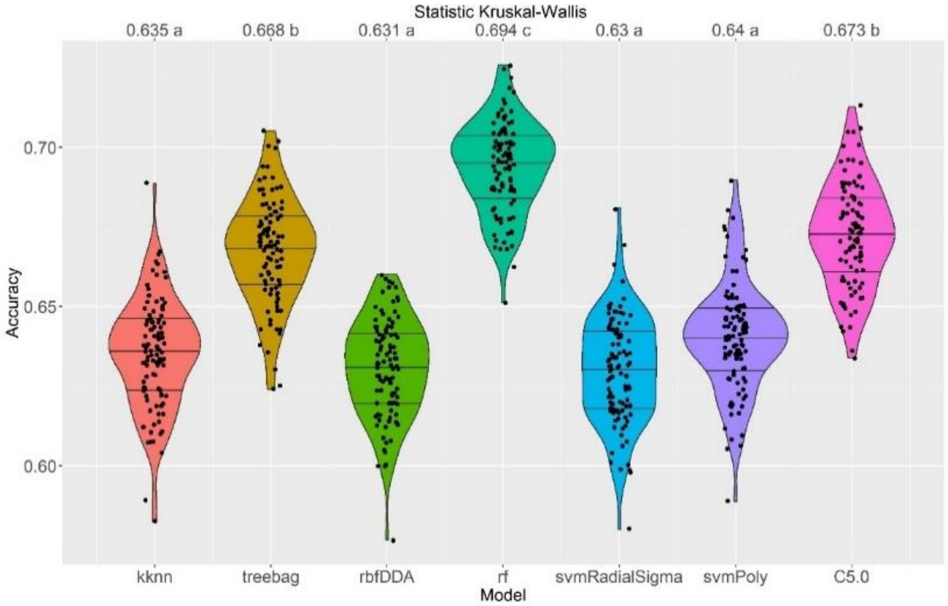

Figure A. 13. Model accuracy of the pre-selected algorithms.

Table A. 10. Total area in square kilometers predicted by each model to current potential vegetation in the Brazilian semiarid region. CE: Cerrado, ADF: Atlantic Dry Forest, ASF: Atlantic Semideciduous Forest, AOF: Atlantic Ombrphilous Forest, MR: Montane Refugia, CA: Caatinga, AC: Arboreal Caatinga, FC: Forested Caatinga.

Model	CE	ADF	ASF	AOF	MR	CA	AC	FC
RADAM	**98.2**	**124.3**	**66.9**	**25.6**	**5.7**	**134.7**	**337.4**	**77.2**
rf	152.1	202.5	118.2	52.6	19.1	196.9	268.2	146.9
treebag	151.6	200.1	119.8	53.1	19.9	198.9	264.9	148.2
C5.0	160.0	198.6	114.9	56.1	20.1	221.9	218.9	165.9
kknn	155.4	173.8	112.0	62.6	25.2	191.9	266.5	156.2
rbfDDA	191.6	169.8	122.7	52.8	20.7	185.2	251.8	148.8
svmPoly	160.1	192.4	111.8	50.7	22.5	181.0	265.5	159.6
svmRS	154.2	190.5	117.4	51.4	22.9	175.6	274.9	156.8

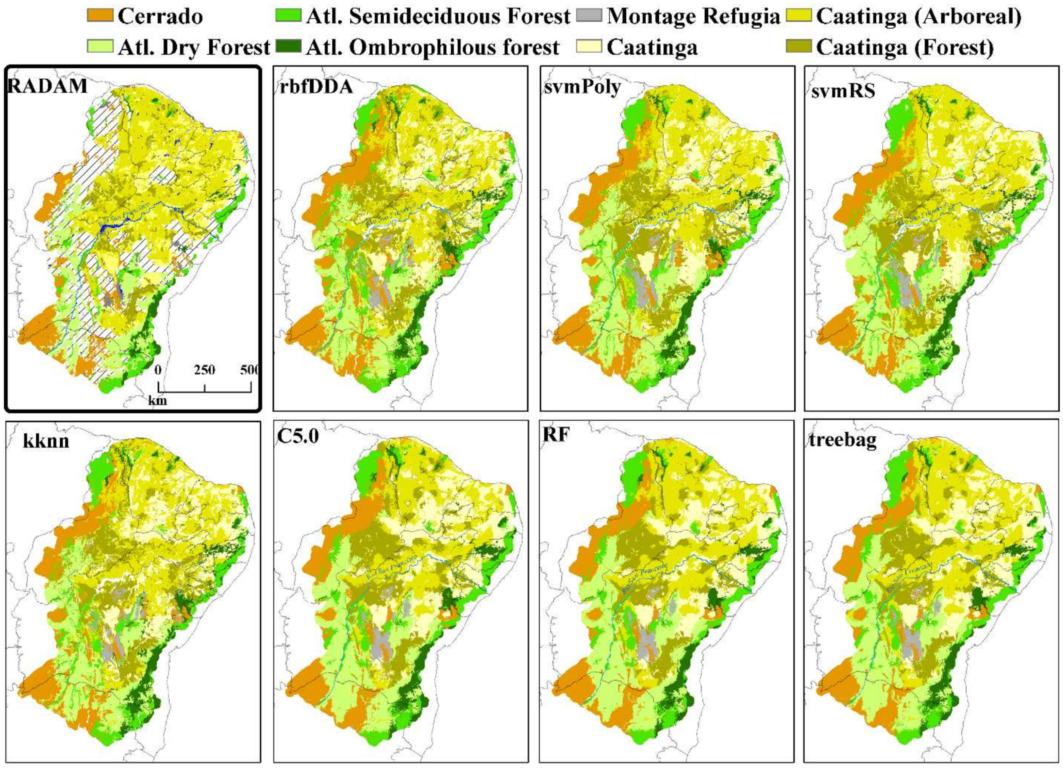

Figure A. 14. Model outputs for vegetation distribution in the Brazilian semiarid region. The RADAM map was used as reference for model calibration.

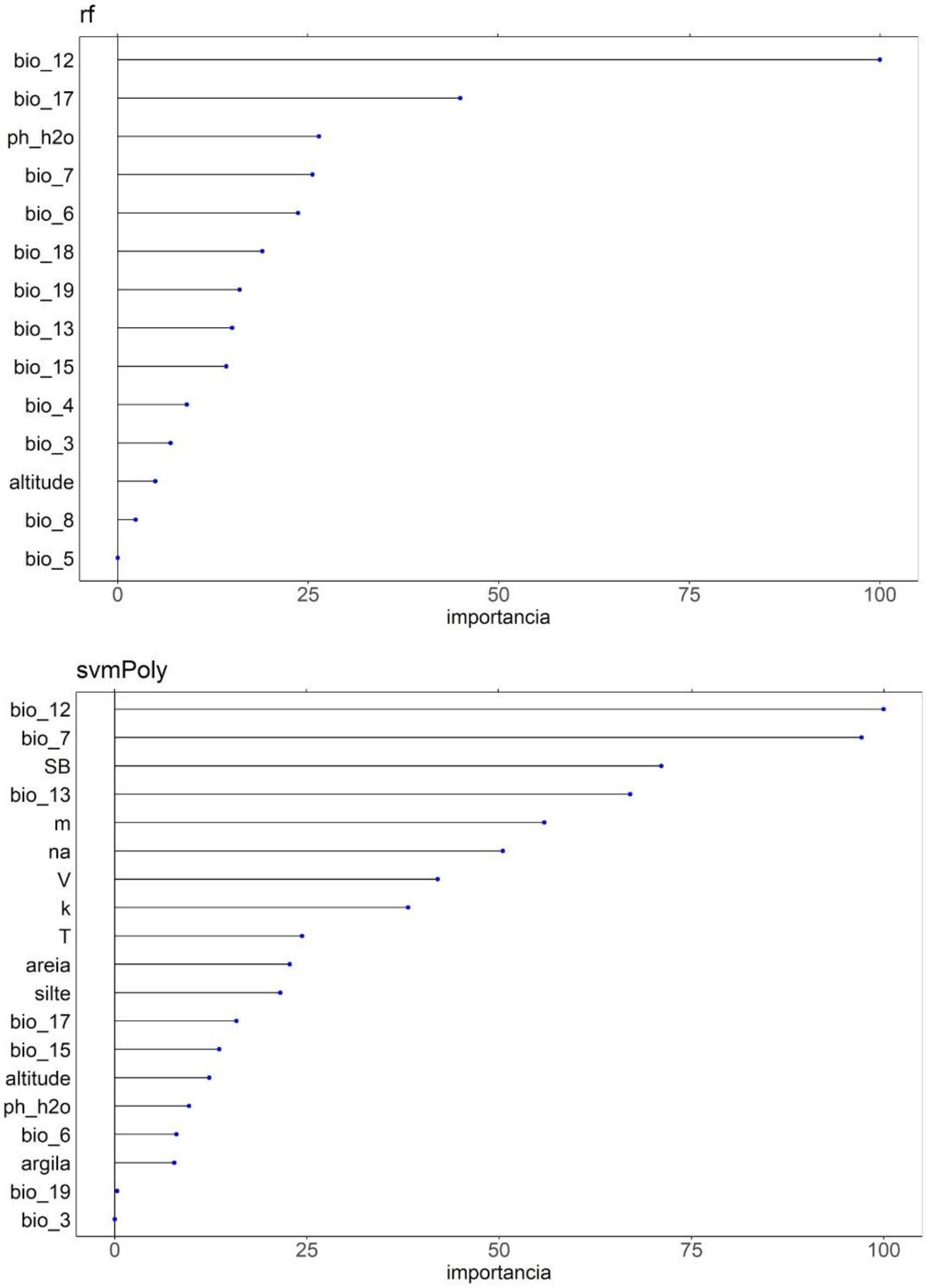

Figure A. 15. Variable importance for Random Forests (above) and svmPoly (below) algorithms.

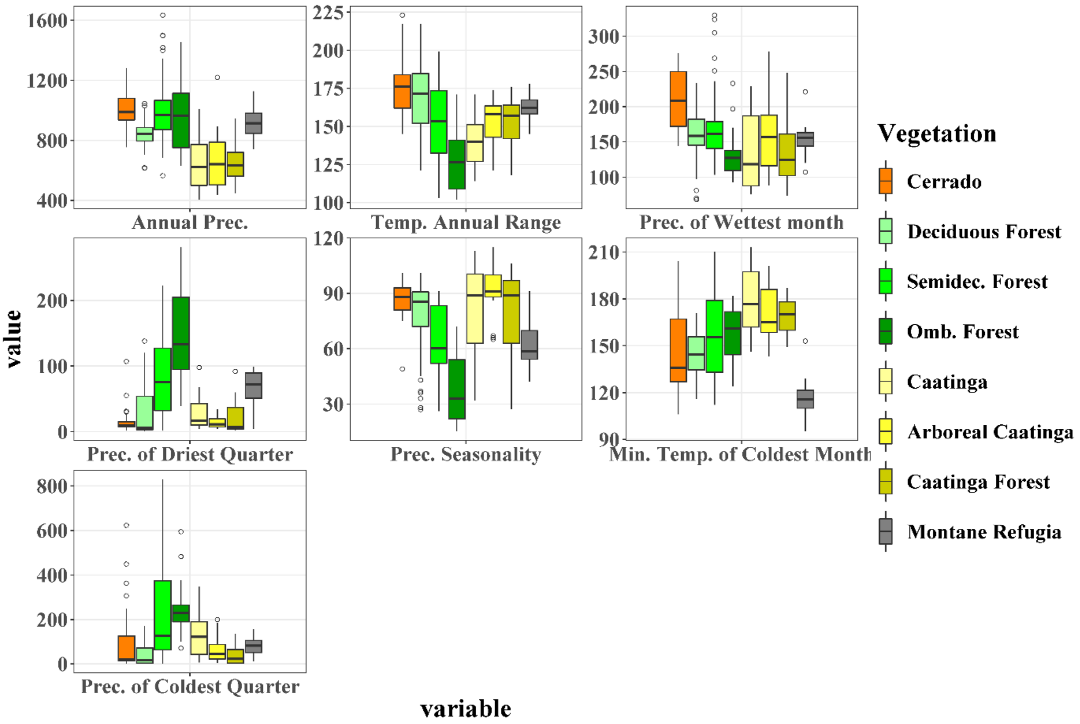

Figure A. 16. Bioclimatic variables distribution by vegetation type in the Brazilian semiarid region. Outliers were removed for a better visualization.

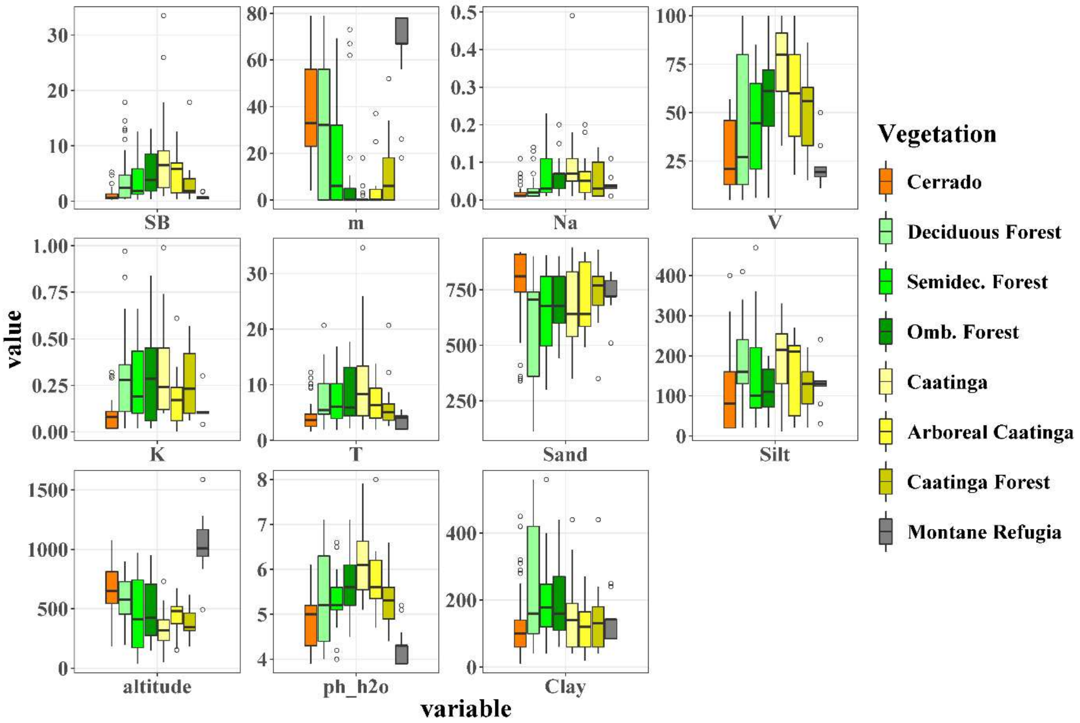

Figure A. 17. Soil variables distribution by vegetation type in the Brazilian semiarid region. Outliers were removed for a better visualization.

Table A. 11. Percentages of vegetations predicted by the models for the Caatinga-Atlantic Deciduous Forest ecotone in the south and west of the Brazilian semiarid. CE: Cerrado, ADF: Atlantic Dry Forest, ASF: Atlantic Semideciduous Forest, AOF: Atlantic Ombrphilous Forest, MR: Montane Refugia, CA: Caatinga, AC: Arboreal Caatinga, FC: Forest Caatinga

	Predicted vegetation							
Model	CE	ADF	ASF	AOF	MR	CA	AC	FC
C5.0	8.5	58.8	7.0	0.0	5.0	1.7	4.2	14.7
treebag	9.8	57.4	7.1	0.1	5.2	1.5	5.4	13.5
RF	8.8	59.2	7.3	0.1	4.8	1.6	4.9	13.4
kknn	11.0	46.7	10.8	1.6	5.3	4.4	7.5	12.8
rbfDDA	16.4	47.4	11.1	0.4	4.8	2.1	5.8	12.0
svmrRS	7.8	50.5	11.8	1.4	9.3	2.9	2.9	13.5
svmPoly	7.1	54.7	10.0	0.4	8.7	2.5	3.5	13.1
Mean	9.9	53.5	9.3	0.6	6.1	2.4	4.9	13.3

Table A. 12. Correlation between the vegetation distribution models in the Brazilian semiarid region, in the RCP 4.5 and RCP 8.5 scenarios. Mean values for the general circulation models HadGEM2-ES, CCSM4 and MIROC5.

	RCP4.5		**RCP 8.5**	
Model	**Mean**	**SD**	**Mean**	**SD**
svmRadialsigma	0.75	0.22	0.78	0.18
svmPoly	0.72	0.24	0.79	0.17
kknn	0.76	0.21	0.80	0.16
rbfDDA	0.66	0.27	0.69	0.23
RF	0.68	0.28	0.72	0.22
Treebag	0.65	0.30	0.70	0.24
C 5.0	0.67	0.28	0.71	0.23

Table A. 13. Results of all predictions. Percentages of the semiarid region occupied by each vegetation type.

Scenario	Algorithm	GCM	Predictors	Cerrado	Atl.Dry Forest	Atl. Sem.Forest	Atl. Omb.Forest	Montane Refugia	Caatinga	Arboreal Caatinga	Forest Caatinga
Current	SVM	-	BIOCLIM	13.5%	18.5%	10.1%	4.8%	1.8%	18.0%	20.9%	12.5%
Current	RF	-	BIOCLIM	13.0%	17.6%	10.4%	4.7%	1.6%	16.7%	23.2%	12.8%
Current	RF	-	SOIL+CLIM	13.2%	17.6%	10.2%	4.5%	1.7%	16.9%	23.1%	12.7%
Current	SVM	-	SOIL+CLIM	14.0%	16.9%	9.8%	4.4%	2.0%	15.7%	23.2%	14.0%
RCP 4.5	SVM	HadGEM	BIOCLIM	19.1%	6.1%	16.2%	2.6%	0.5%	13.8%	19.2%	22.4%
RCP 4.5	SVM	CCSM4	BIOCLIM	15.5%	9.9%	7.1%	1.9%	1.6%	16.9%	23.2%	24.0%
RCP 4.5	SVM	MIROC 5	BIOCLIM	9.9%	9.4%	5.5%	0.9%	0.2%	22.4%	13.8%	37.8%
RCP 4.5	RF	HadGEM	BIOCLIM	8.4%	18.3%	10.6%	2.8%	0.0%	13.8%	27.7%	18.3%
RCP 4.5	RF	CCSM4	BIOCLIM	6.7%	14.1%	9.3%	1.8%	0.2%	14.2%	36.0%	17.6%
RCP 4.5	RF	MIROC 5	BIOCLIM	1.4%	4.5%	5.1%	0.6%	0.0%	12.3%	57.2%	18.9%
RCP 4.5	SVM	HadGEM	SOIL+CLIM	15.3%	14.2%	10.6%	1.9%	0.4%	19.1%	21.0%	17.4%
RCP 4.5	SVM	CCSM4	SOIL+CLIM	12.4%	13.9%	7.2%	2.3%	0.8%	13.9%	32.7%	16.8%
RCP 4.5	SVM	MIROC 5	SOIL+CLIM	6.2%	4.2%	5.1%	0.8%	0.6%	12.0%	46.1%	24.9%
RCP 4.5	RF	HadGEM	SOIL+CLIM	6.4%	19.6%	13.9%	4.1%	0.0%	13.2%	28.5%	14.4%
RCP 4.5	RF	CCSM4	SOIL+CLIM	7.9%	14.9%	8.6%	2.2%	0.5%	14.5%	34.4%	16.9%
RCP 4.5	RF	MIROC 5	SOIL+CLIM	1.5%	5.2%	5.3%	0.7%	0.0%	11.9%	56.7%	18.6%
RCP 8.5	SVM	HadGEM	SOIL+CLIM	10.1%	8.7%	5.9%	1.4%	0.2%	14.9%	36.1%	22.8%
RCP 8.5	SVM	CCSM4	SOIL+CLIM	9.0%	9.4%	5.5%	1.8%	0.5%	12.1%	42.5%	19.2%
RCP 8.5	SVM	MIROC 5	SOIL+CLIM	9.0%	9.4%	5.5%	1.8%	0.5%	12.1%	42.5%	19.2%
RCP 8.5	RF	HadGEM	SOIL+CLIM	3.6%	14.8%	6.4%	2.0%	0.0%	14.9%	43.3%	14.8%
RCP 8.5	RF	CCSM4	SOIL+CLIM	4.0%	9.8%	4.6%	1.3%	0.6%	15.4%	44.9%	19.4%
RCP 8.5	RF	MIROC 5	SOIL+CLIM	3.0%	7.8%	6.3%	0.6%	0.0%	15.7%	47.8%	18.6%
RCP 8.5	SVM	HadGEM	BIOCLIM	16.6%	1.8%	7.0%	1.7%	1.3%	20.3%	24.4%	26.9%
RCP 8.5	SVM	CCSM4	BIOCLIM	13.3%	5.5%	4.5%	1.1%	2.2%	21.9%	27.8%	23.6%
RCP 8.5	SVM	MIROC 5	BIOCLIM	8.8%	7.3%	9.6%	0.8%	0.3%	13.2%	16.9%	43.1%
RCP 8.5	RF	HadGEM	BIOCLIM	3.7%	12.8%	5.6%	1.4%	0.0%	15.0%	42.9%	18.6%
RCP 8.5	RF	CCSM4	BIOCLIM	3.7%	8.8%	5.1%	1.0%	0.1%	15.2%	44.6%	21.5%
RCP 8.5	RF	MIROC 5	BIOCLIM	3.3%	6.5%	5.4%	0.8%	0.0%	17.8%	49.4%	16.7%

APPENDIX D – SOIL PROFILES

PERFIL 1

Data da descrição – 24/03/2018
Classificação SiBCS – Cambissolo Háplico Tb Eutrófico latossólico
Classificação FAO/WRB - Eutric Rhodic Ferralic Cambisol (Clayic, Colluvic)
Localização – Lat -14.589545; Long -42.640296, Pindaí-BA.
Situação e Declive – Corte de estrada em terço médio de encosta.
Altitude – 780m
Uso atual – Preservação
Litologia / Material de Origem – Complexo Santa Isabel, granodiorito
Relevo Local - Ondulado
Relevo Regional – Montanhoso
Vegetação Primária – Floresta Estacional Decidual
Erosão - Ligeira
Drenagem – Bem drenado
Pedregosidade – Ligeiramente pedregosa
Rochosidade – Não rochosa
Raízes – abundantes no A, Bi e Bi2 e comuns no BC
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-9 cm; 2.5YR 4/4 seco, 2.5YR 2.5/4 úmido; moderada pequena e média blocos subangulares, ligeiramente duro, friável, plástico e pegajoso; transição plana e gradual;

Bi 9-34cm; 2.5YR 3/6 seco, 2.5YR 2.5/3 úmido; moderada pequena e média blocos subangulares, dura, friável, plástico e pegajoso; cerosidade fraca e pouca; transição plana e gradual

Bi2 34-63cm; 2.5YR 3/6 seco, 2.5YR 2.5/4 úmido; fraca pequena e média blocos subangulares, dura, friável, plástico e pegajoso; cerosidade fraca e pouca; transição plana e gradual

BC 63-120+; 2.5YR 3/6 seco, 2.5YR 2.5/4 úmido; fraca pequena e média blocos subangulares, dura, friável, plástico e pegajoso; transição plana e gradual

Análises Físicas e Químicas – Perfil 1

Horizonte		**Composição granulométrica da terra fina (g/kg)**				**pH (1:2,5)**		
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**H_2O**	**KCl 1N**	**P** mg/dm³
A	0-9	433	66	156	345	6.55	5.99	5.2
Bi	9-34	283	100	181	436	6.47	5.74	1
Bi2	34-63	293	100	173	434	6.25	5.31	0.3
BC	63-120+	282	85	193	440	6.33	5.35	1.4

Horizonte	**Ca^{2+}** cmolc/dm³	**Mg^{2+}** cmolc/dm³	**K^+** cmolc/dm³	**Na^+** cmolc/dm³	**SB** cmolc/dm³	**Al^{3+}** cmolc/dm³	**$H^+ + Al^{3+}$** cmolc/dm³	**t** cmolc/dm³
A	11.06	1.93	0.07	0.03	13.09	0	1.6	13.09
Bi	8.46	2.63	0.40	0.06	11.55	0	1.6	11.55
Bi2	5.48	2.84	0.20	0.04	8.56	0	1.8	8.56
BC	5.28	2.72	0.08	0.05	8.14	0	1.1	8.14

Horizonte	**T** cmolc/dm³	**V** %	**m** %	**ISNa** %	**M.O** dag/kg	**P-Rem** mg/L
A	14.69	89.1	0	0.24	6.52	34.1
Bi	13.15	87.8	0	0.46	2.94	31.2
Bi2	10.36	82.6	0	0.42	1.41	35.1
BC	9.24	88.1	0	0.56	0.9	35.5

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K -- Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa - Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 2

Data da descrição – 25/03/2018
Classificação SiBCS – Latossolo Amarelo eutrófico típico
Classificação FAO/WRB - Xanthic Ferrasols (Clayic, Oligeoeutric)
Localização – Lat -12.618500; Long -43.751004, Brejolândia-BA
Situação e Declive – Trincheira aberta em fragmento de mata.
Altitude – 490m
Uso atual – Preservação
Litologia / Material de Origem – Depósitos cenozoicos / coluvial
Relevo Local – Plano
Relevo Regional – Plano
Vegetação Primária – Floresta Estacional Decidual
Erosão – Ligeira
Drenagem – Bem drenado
Pedregosidade – Não pedregosa
Rochosidade – Não rochosa
Raízes – muitas, muito finas e finas no A1; comuns, muito finas a médias no A2 e AB; comuns, médias a grossas no BA e poucas e médias a grossas no Bw1
Observações – Horizonte A2 com material de Bw bioturbado
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A1 0-5 cm; 10YR 5/4 seco, 10 YR 4/3 úmido; franco-argilo-arenosa; moderada pequena blocos subangulares e moderada média e pequena blocos angulares, ligeiramente duro, friável, plástico e pegajoso; transição plana e clara;

A2 5-12cm; 10YR 6/4 seco, 10YR 4/4 úmido; franco-argilo-arenosa; fraca média blocos subangulares e moderada pequena blocos angulares, dura, friável, plástico e pegajoso; transição plana e clara;

AB 12-22cm; 10YR 6/4 seco, 10YR 4/4 úmido; franco-arenosa; fraca média blocos subangulares e moderada pequena blocos angulares, dura, friável, plástico e pegajoso; transição plana e gradual

BA 22-45cm; 10YR 6/4 seco, 10YR 4/4 úmido; franco-arenosa; fraca pequena e média blocos subangulares e moderada pequena e média granular; dura, friável, plástico e pegajoso; transição plana e gradual

Bw1 45-75+cm; 10YR 6/6 seco, 10YR 5/6 úmido; franco-arenosa; fraca média blocos subangulares e forte pequena granular, dura, friável, plástico e pegajoso;

Análises Físicas e Químicas – Perfil 2

Horizonte		**Composição granulométrica da terra fina (g/kg)**				**pH (1:2,5)**		
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**H_2O**	**KCl 1N**	**P** mg/dm^3
A1	0-5	226	378	174	222	5.21	4.46	1.4
A2	5-12	186	354	198	262	5.38	4.47	0.8
AB	12-22	249	394	181	176	5.45	4.69	0.9
BA	22-45	223	377	203	197	5.63	4.84	0.5
Bw1	45-75+	159	294	172	374	5.2	4.35	0.1

Horizonte	**Ca^{2+}** cmolc/dm^3	**Mg^{2+}** cmolc/dm^3	**K^+** cmolc/dm^3	**Na^+** cmolc/dm^3	**SB** cmolc/dm^3	**Al^{3+}** cmolc/dm^3	**$H^+ + Al^{3+}$** cmolc/dm^3	**t** cmolc/dm^3
A1	2.46	0.45	0.24	0.07	3.21	0.1	3.2	3.31
A2	2.72	0.47	0.21	0.03	3.43	0	2.7	3.43
AB	2.07	0.33	0.14	0.03	2.58	0	2.3	2.58
BA	2.44	0.4	0.12	0.04	2.99	0	1.8	2.99
Bw1	3.26	0.72	0.09	0.09	4.16	0	1.6	4.16

Horizonte	**T** cmolc/dm^3	**V** %	**m** %	**ISNa** %	**M.O** dag/kg	**P-Rem** mg/L
A1	6.41	50.1	3	1.02	2.43	46.3
A2	6.13	56	0	0.5	1.92	45.1
AB	4.88	52.9	0	0.71	1.54	47.1
BA	4.79	62.4	0	0.82	1.28	45.1
Bw1	5.76	72.2	0	1.51	0.64	37.5

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K -- Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa - Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 3

Data da descrição – 26/03/2018
Classificação SiBCS – Latossolo Vermelho-Amarelo eutrófico típico
Classificação FAO/WRB - Ferralsols (Loamic, Epihypereutric, Ochric)
Localização – Lat -12.142120; Long -42.889104, Oliveira dos Brejinhos - BA
Situação e Declive – Trincheira aberta em fragmento de mata com relevo plano.
Altitude – 590m
Uso atual – Preservação
Litologia / Material de Origem – Quartzito e mármore / Formação Pajeú
Relevo Local – Plano
Relevo Regional – Suave ondulado / plano
Vegetação Primária – Caatinga Hipoxerófila
Erosão – Não aparente
Drenagem – Moderadamente drenado
Pedregosidade – Pedregosa
Rochosidade – Não rochosa
Raízes – comuns, muito finas a médias no A e AB; comuns, muito finas a finas no BA; poucas e muito finas no Bw.
Observações – Pavimento epipedregoso, presença de muitas galerias de cupins no perfil.
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-6 cm; 7.5YR 4/4 seco, 7.5YR 3/4 úmido; francoarenosa; moderada pequena e média blocos subangulares, dura, muito friável, ligeiramente plástico e ligeiramente pegajoso; transição plana e clara;

AB 6-12 cm; 7.5YR 5/8 seco, 7.5YR 4/6 úmido; franco-argilo-arenosa; moderada média blocos subangulares e fraca pequena granular, dura, muito friável, ligeiramente plástico e ligeiramente pegajoso; transição plana e clara;

BA 12-21 cm; 5YR 5/4 seco, 5YR 4/4 úmido; francoarenosa; fraca média blocos subangulares e moderada pequena granular; dura, friável, ligeiramente plástico e ligeiramente pegajoso; transição plana e gradual;

Bw 21-60+cm; 5YR 5/8 seco, 5YR 4/6 úmido; franco-argilo-arenosa; fraca média blocos subangulares e moderada pequena granular, muito dura, friável, ligeiramente plástico e ligeiramente pegajoso;

Análises Físicas e Químicas – Perfil 3

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm^3
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**pH H_2O**	**pH KCl**	**P**
A	0-6	397	291	134	177	6.37	6.04	3.9
AB	6-12	396	256	145	202	6.27	5.7	1
BA	12-21	387	266	157	190	6.04	5.26	0.6
Bw	21-60+	363	258	114	266	6.08	5.17	0.5

	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	$H^+ + Al^{3+}$
	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3
A	7.08	1.06	0.30	0.08	8.52	0	1.3
AB	3.67	0.69	0.37	0.05	4.78	0	1.6
BA	2.58	0.72	0.33	0.03	3.66	0	1.8
Bw	2.29	0.44	0.43	0.03	3.19	0	1.3

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm^3	cmolc/dm^3	%	%	%	dag/kg	mg/L
A	8.52	9.82	86.8	0	0.84	6.52	47.1
AB	4.78	6.38	74.9	0	0.82	2.56	48
BA	3.66	5.46	67	0	0.56	1.66	46.8
Bw	3.19	4.49	71	0	0.58	0.77	42.2

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva;
V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 4

Data da descrição – 27/03/2018
Classificação SiBCS – Neossolo Quartzarênico órtico latossólico
Classificação FAO/WRB - Hyperdystric Rubic Ferralic Arenosols
Localização – Lat -12.142120; Long -42.889104, Oliveira dos Brejinhos - BA
Situação e Declive – Trincheira aberta em fragmento de mata com relevo plano.
Altitude – 490m
Uso atual – Preservação
Litologia / Material de Origem – Sedimentos quaternários / Formação Vazante
Relevo Local – Plano
Relevo Regional – Plano
Vegetação Primária – Caatinga Hipoxerófila
Erosão – Não aparente
Drenagem – Excessivamente drenado
Pedregosidade – Não pedregosa
Rochosidade – Não rochosa
Raízes – Muitas, muito finas a médias no A, comuns, muito finas a grossas no C1; poucas, muito finas a médias no C2.
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-11 cm; 7.5YR 6/3 seco, 7.5YR 4/3 úmido; franco arenosa; grãos simples, solta, muito friável, não plástico e não pegajoso; transição plana e clara;

C1 11-48 cm; 7.5YR 6/6 seco 7.5YR 6/6 úmido; areia franca; grãos simples, solta, não plástico e não pegajoso; transição plana e clara

C2 48-100+ cm; 7.5YR 5/8 seco, 7.5YR 5/6 úmido; franco-arenosa; grãos simples, solta, ligeiramente plástico e ligeiramente pegajoso; transição plana e gradual

Análises Físicas e Químicas – Perfil 4

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm^3
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**pH H_2O**	**pH KCl**	**P**
A	0 -11	316	501	44	139	5.28	4.27	1.3
C1	11-48	351	481	48	120	4.98	3.89	0.3
C2	48-100+	330	483	26	160	5.15	3.98	0.2

	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	$H^+ + Al^{3+}$
	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3
A	1.04	0.33	0.18	0.02	1.57	0	2.2
C1	0.15	0.06	0.12	0.02	0.34	0.56	1.7
C2	0.51	0.22	0.09	0.02	0.84	0.28	0.9

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm^3	cmolc/dm^3	%	%	%	dag/kg	mg/L
A	1.57	3.77	41.6	0	0.58	1.58	45.8
C1	0.9	2.04	16.7	62.2	0.85	0.53	45.5
C2	1.12	1.74	48.3	25	1	0.26	46.1

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 5

Data da descrição – 28/03/2018
Classificação SiBCS – Latossolo Amarelo eutrófico argissólico
Classificação FAO/WRB - Lixic Xanthic Ferrasols (Clayic, Eutric, Ochric)
Localização – Lat -13.1248185, Long -42.52035694, Macaúbas-BA
Situação e Declive – Trincheira aberta em fragmento de mata com relevo plano.
Altitude – 600m
Uso atual – Vegetação natural em regeneração
Litologia / Material de Origem – Complexo Caraíba Paramirim (Arqueano)
Relevo Local – Plano
Relevo Regional – Suave ondulado
Vegetação Primária – Caatinga Hipoxerófila
Erosão – Ligeira
Drenagem – Bem drenado
Pedregosidade – Não Pedregosa
Rochosidade – Não rochosa
Raízes – Muito finas a grossas em todos os horizontes. Muitas no A, comuns no AB, e poucas no BA, Bw1 e Bw2.
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-10 cm; 7.5YR 4/4 seco 7.5YR 3/3 úmido; franco argilo-arenosa; grãos simples; solta; não plástico, não pegajoso; transição plana e clara.

AB 10-22 cm; 7.5YR 5/6 seco 7.5YR 4/6 úmido; franco argilo-arenosa; fraca pequena e média blocos subangulares; solta, não plástico, não pegajoso; transição plana e clara.

BA 22-45 cm; 7.5YR 6/6 seco 7.5YR 5/6 úmido; franco argilo-arenosa; fraca pequena e média blocos subangulares; macia, muito friável; lig. plástico, lig. pegajoso; transição plana e gradual;

Bw1 45-75 cm; 7.5YR 6/8 seco 7.5YR 5/8 úmido; franco argilo-arenosa; fraca pequena e média blocos subangulares; macia, muito friável, lig. plástico, lig. pegajoso; transição plana e gradual;

Bw2 75-120+ cm; 7.5YR 6/8 seco 7.5YR 5/8 úmido; fraca pequena e média blocos subangulares; macia, muito friável; lig. plástico, lig. pegajoso.

Análises Físicas e Químicas – Perfil 5

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm³
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**pH H_2O**	**pH KCl**	**P**
A	0-10	491	225	42	242	5.79	4.77	3.4
AB	10-22	319	356	52	273	5.37	4.06	1
BA	22-45	294	341	69	295	5.39	4.09	0.5
Bw1	45-75	259	314	83	344	5.05	4.1	0.4
Bw2	75-120+	217	292	114	378	4.9	4.35	0.1

	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	$H^+ + Al^{3+}$
	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³
A	3.8	0.92	0.49	0.01	5.23	0	3.1
AB	1.64	0.58	0.48	0.03	2.73	0.19	2.6
BA	2.33	0.72	0.37	0.03	3.45	0.28	2
Bw1	2.17	0.79	0.30	0.03	3.28	0.19	2
Bw2	1.86	1.02	0.41	0.03	3.33	0	1.4

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm³	cmolc/dm³	%	%	%	dag/kg	mg/L
A	5.23	8.33	62.8	0	0.16	3.29	42.7
AB	2.92	5.33	51.2	6.5	0.49	1.58	43.6
BA	3.73	5.45	63.3	7.5	0.48	1.19	43.7
Bw1	3.47	5.28	62.1	5.5	0.49	0.92	37.8
Bw2	3.33	4.73	70.4	0	0.64	0.53	30.8

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black.

PERFIL 6

Data da descrição – 29/03/2018
Classificação SiBCS - Latossolo Amarelo distrófico argissólico - fase murundu
Classificação FAO/WRB - Acric Xanthic Ferrasols (Loamic, Hyperdystric, Vetic)
Localização - Lat -13.700158; Long -41.861662. Livramento de N. Sra.- BA
Situação e Declive – Trincheira aberta em fragmento de mata com relevo plano.
Altitude – 510m
Uso atual – Vegetação natural em regeneração
Litologia / Material de Origem – Cobertura detrito-laterítica neogênica (Mioceno)
Relevo Local – Plano
Relevo Regional – Suave ondulado
Vegetação Primária – Caatinga Hipoxerófila
Erosão – Não aparente
Drenagem – Bem drenado
Pedregosidade – Não pedregosa
Rochosidade – Não rochosa
Raízes – muitas, muito finas a grossas no A; comuns, muito finas a grossas no BA; comuns, finas a grossas no Bw1; poucas, finas a grossas no Bw2
Observações – atividade de cupins no horizonte A. Murundus com1,5m de altura de 3,0m de diâmetro na região.
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-12 cm; 7.5YR 4/4 seco, 7.5YR 3/4 úmido; franco arenosa; fraca pequena blocos subangulares e moderada pequena granular; dura, friável; não plástico, não pegajoso; transição plana e clara.

BA 12-29 cm; 7.5YR 5/6 seco; franco argilo-arenosa; fraca pequena blocos subangulares e moderada média granular; dura, friável; lig. plástico, lig. pegajoso; transição plana e gradual.

Bw1 29-66 cm; 7.5YR 5/8 seco 7.5YR 5/6 úmido; franco argilo-arenosa; moderada pequena blocos subangulares e fraca pequena blocos subangulares; muito dura, friável; plástico, pegajoso; plana e gradual;

Bw2 66-90+ cm; 7.5YR 5/8 seco 7.5YR 5/6 úmido; franco argilo-arenosa; fraca pequena e média blocos subangulares e moderada pequena granular; muito dura, friável; transição plástico e pegajoso.

Análises Físicas e Químicas – Perfil 6

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm^3
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**pH H_2O**	**pH KCl**	**P**
A	0-12	374	313	158	155	4.85	4	1.5
BA	12-29	273	322	193	212	4.58	3.78	0.4
Bw1	29-66	256	279	207	258	4.56	3.8	0.2
Bw2	66-90+	210	280	244	266	4.6	3.83	0.1

	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	$H^+ + Al^{3+}$
	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3
A	1.97	0.42	0.19	0.01	2.59	0.19	3.9
BA	0.39	0.12	0.12	0.01	0.64	1.31	3.3
Bw1	0.52	0.2	0.10	0.02	0.85	1.13	2.8
Bw2	0.51	0.31	0.08	0.03	0.94	1.03	2.3

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm^3	cmolc/dm^3	%	%	%	dag/kg	mg/L
A	2.78	6.49	39.9	6.8	0.2	2.9	43.2
BA	1.95	3.94	16.2	67.2	0.33	0.92	34.7
Bw1	1.98	3.65	23.3	57.1	0.6	0.66	34.8
Bw2	1.97	3.24	29	52.3	1.07	0.26	32.5

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 7

Data da descrição – 30/03/2018
Classificação SiBCS – Latossolo Vermelho eutrófico cambissólico
Classificação FAO/WRB - Rhodic Ferritic Ferrasols (Clayic, Oligeoeutric)
Localização – Lat -14.533972; Long -41.416539**,** Aracatu-BA
Situação e Declive – Trincheira aberta em fragmento de vegetação natural.
Altitude – 690m
Uso atual – Vegetação natural em regeneração, presença de gado
Litologia / Material de Origem – Complexo Gavião - fácies ortognaisse migmatítico (Arqueano)
Relevo Local – Suave ondulado
Relevo Regional – Suave ondulado / Ondulado
Vegetação Primária – Caatinga Hipoxerófila
Erosão – Ligeira
Drenagem – Moderadamente drenado
Pedregosidade – Não pedregosa
Rochosidade – Não rochosa
Raízes – muitas, muito finas a médias no A e BA; comuns, finas a grossas no Bw e BC.
Observações - Cupins no horizonte A, estrutura biogênica, muita atividade biológica em todo o perfil. Perfil seco.
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-16 cm; 5YR 4/4 seco 5YR 3/4 úmido; franco argilo-arenosa; grãos simples e moderada pequena e média blocos subangulares; macia, muito friável; não plástico não pegajoso; transição plana e clara;

BA 16-25 cm; 2.5YR 4/6 seco 2.5YR 2.5/4 úmido; franco argilo-arenosa; grãos simples e fraca pequena e média blocos subangulares; ligeiramente dura, friável; lig plástico, não pegajoso; transição plana e clara;

Bw 25-48 cm; 2.5YR 4/6 seco 2.5YR 3/6 úmido; franco argilo-arenosa; grãos simples e moderada pequena e média blocos subangulares; muito dura, friável; lig plástico, lig pegajoso; transição plana e clara

BC 48-70+ cm; 2.5YR 4/6 seco 2.5YR 3/6 úmido; franco argilo-arenosa; grãos simples e moderada pequena e média blocos subangulares; dura, friável; lig plástico, lig pegajoso.

Análises Físicas e Químicas – Perfil 7

Horizonte Símbolo	Prof. (cm)	Composição granulométrica da terra fina (g/kg) Areia Grossa	Areia Fina	Silte	Argila	pH H_2O	pH KCl	mg/dm³ P
A	0-12	436	270	56	239	5.16	4.44	1.3
BA	12-29	467	260	32	241	5.02	4.02	0.6
Bw	29-66	433	248	35	284	5.38	4.32	0.4
BC	66-90+	356	243	63	338	5.39	4.42	0.3

	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	$H^+ + Al^{3+}$
	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³
A	3.34	0.73	0.44	0.03	4.53	0	3.6
BA	1.6	0.71	0.25	0.03	2.59	0.19	2.3
Bw	1.76	1.02	0.24	0.03	3.06	0.09	1.5
BC	1.69	1.41	0.19	0.04	3.33	0	1.4

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm³	cmolc/dm³	%	%	%	dag/kg	mg/L
A	4.53	8.13	55.7	0	0.32	3.95	45.1
BA	2.78	4.89	53	6.8	0.71	1.58	44.9
Bw	3.15	4.56	67.1	2.9	0.76	1.19	42.1
BC	3.33	4.73	70.4	0	0.83	0.79	41.3

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 8

Data da descrição – 19/04/2018
Classificação SiBCS– Latossolo Amarelo distrófico argissólico
Classficação FAO/WRB - Acric Xanthic Ferralsols (Clayic, Orthodystric, Vetic)
Localização – Lat -14.652015, Long -41.053578; Entre Vitória da Conquista e Anagé-BA
Situação e Declive – Trincheira aberta em fragmento de vegetação natural
Altitude – 749m
Uso atual – Vegetação natural com presença de gado
Litologia / Material de Origem – Granitóide Lagoa do Morro (Arqueano)
Relevo Local – Plano
Relevo Regional – Ondulado
Vegetação Primária – Caatinga hipoxerófila
Erosão – Não aparente
Drenagem – Bem drenado
Pedregosidade – Não pedregosa
Rochosidade – Não rochosa
Raízes – comuns em todos horizontes. Muito finas a finas no A e BA. Muito finas a grossas no Bw e BC
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-9 cm; 7.5YR 4/6 seco 7.5YR 3/4 úmido; franco argilo-arenosa; fraca pequena e média blocos subangulares; lig. dura, muito friável; lig. plástico, lig. pegajoso; transição plana e clara.

AB 9-20 cm; 7.5YR 5/6 seco 7.5YR 4/6 úmido; franco argilo-arenosa; moderada pequena e média blocos subangulares; dura, friável; lig. plástico, lig. pegajoso; transição plana e clara.

BA 20-37 cm; 7.5YR 6/6 seco 7.5YR 5/6 úmido; franco argilo-arenosa; moderada pequena e média blocos subangulares; dura, friável; lig. plástico, lig. pegajoso; transição plana e gradual.

Bw 37-65+ cm; 7.5YR 6/8 seco 5YR 5/8 úmido; argilo-arenosa; moderada pequena e média blocos subangulares; muito dura, friável; plástico pegajoso.

Análises Físicas e Químicas – Perfil 8

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm^3
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**pH H_2O**	**pH KCl**	**P**
A	0-9	539	180	46	234	5.98	5.18	1.8
AB	9-20	494	188	13	306	5.26	4.1	0.9
BA	20-37	456	193	24	327	4.88	3.97	0.7
Bw	37-65+	384	201	38	378	4.85	4.14	0.3

	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	$H^+ + Al^{3+}$
	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3
A	3	0.77	0.37	0.02	4.16	0	1.5
AB	0.85	0.43	0.36	0.02	1.66	0.19	2
BA	0.65	0.41	0.29	0.02	1.37	0.28	1.7
Bw	0.73	0.46	0.21	0.02	1.42	0.19	1.5

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm^3	cmolc/dm^3	%	%	%	dag/kg	mg/L
A	4.16	5.66	73.5	0	0.31	2.37	47.7
AB	1.85	3.66	45.4	10.3	0.48	1.32	48.2
BA	1.65	3.07	44.6	17	0.57	1.19	42.6
Bw	1.61	2.92	48.6	11.8	0.6	0.66	34.1

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 9

Data da descrição – 20/04/2018
Classificação SiBCS – Latossolo Vermelho distrófico típico
Classificação FAO/WRB - Acric Rhodic Ferric Ferralsols (Clayic, Orthodystric, Vetic)
Localização – Lat -14.722549, Long -41.025074 Long; Anagé-BA
Situação e Declive – Trincheira aberta em fragmento de vegetação natural.
Altitude – 798m
Uso atual – Vegetação natural em regeneração
Litologia / Material de Origem – Granitóide Lagoa do Morro (Arqueano)
Relevo Local – Suave ondulado
Relevo Regional – Ondulado
Vegetação Primária – Caatinga hipoxerófila
Erosão – Não aparente
Drenagem –
Pedregosidade – Não pedregosa
Rochosidade – Não rochosa
Raízes – comuns, muito finas a finas no A; abundantes, muito finas a médias no BA; comuns, muito finas a grossas no Bw
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-7 cm; 2.5YR 3/6 seco 2.5YR 2.5/3 úmido; argilo-arenosa; moderada pequena e média blocos subangulares e moderada pequena e média granular; macia, friável; lig. plástico, lig. pegajoso; transição plana e gradual.

BA 7-26 cm; 2.5YR 3/6 seco 2.5YR 2.5/4 úmido; argila; moderada pequena e média blocos subangulares e forte média e grande granular; macia, friável; lig. plástico, lig. pegajoso; transição plana e difusa.

Bw 26-80+ cm; 10R 3/6 seco 2.5YR 2.5/4 úmido; argila; moderada pequena e média blocos subangulares e forte média e grande granular; macia, friável; lig. plástico, lig. pegajoso.

Análises Físicas e Químicas – Perfil 9

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm³
Símbolo	Prof. (cm)	Areia Grossa	Areia Fina	Silte	Argila	pH H_2O	pH KCl	P
A	0-7	364	133	103	400	5.98	5.13	1.3
BA	7-26	308	119	97	476	4.69	3.77	0.4
Bw	26-80+	287	99	80	534	4.48	3.75	0.2

	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	SB	Al^{3+}	$H^{+} + Al^{3+}$
	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³
A	4.9	1.22	0.59	0.04	6.75	0	2.8
BA	0.58	0.5	0.17	0.03	1.29	1.13	4.2
Bw	0.71	0.4	0.15	0.07	1.33	1.13	3.3

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm³	cmolc/dm³	%	%	%	dag/kg	mg/L
A	6.75	9.55	70.7	0	0.41	5.27	33.9
BA	2.42	5.49	23.5	46.7	0.63	1.84	25.3
Bw	2.46	4.63	28.7	45.9	1.41	0.66	17.3

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 10

Data da descrição – 21/04/2018
Classificação SiBCS – Latossolo Amarelo distrófico típico
Classificação FAO/WRB - Geric Xanthic Ferralsols (Clayic, Hyperdystric, Ochric)
Localização – Lat -15.408032, Long -41.041076 Long; Vitória da Conquista/Cândido Sales-BA
Situação e Declive – Planalto de Vitória da Conquista, relevo plano
Altitude – 813m
Uso atual – Vegetação natural em regeneração
Litologia / Material de Origem – Cobertura detrito-laterítica paleogênica (Terciário)
Relevo Local – Plano
Relevo Regional – Suave ondulado
Vegetação Primária – Floresta Estacional Decidual (Mata de Cipó)
Erosão – Não aparente
Drenagem – Bem drenado
Pedregosidade – Não Pedregosa
Rochosidade – Não rochosa
Raízes – Muito finas a grossas e poucas no A, muito finas a finas e poucas no AB, muito finas e raras no Bw1, muito finas e raras no Bw2.
Observações – Atividade biológica em todos os horizontes
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-12cm; 7.5YR 4/4 seco 7.5YR 4/3 úmido; argilo-arenosa; grãos simples; solta muito friável, lig. plástico lig. pegajoso; transição plana e clara.

AB 12-24cm; 10YR 5/4 seco 10YR 4/3 úmido; argilo-arenosa; grãos simples; solta muito friável, lig. plástico lig. pegajoso; transição plana e gradual.

Bw1 24-48cm; 10YR 5/6 seco 10YR 4/6 úmido; argilo-arenosa; moderada média e grande blocos subangulares; lig. dura friável; plástico e pegajoso; transição plana e gradual.

Bw2 48-70+cm; 10YR 6/6 seco 10YR 5/6 úmido; argilo-arenosa; moderada média e grande blocos subangulares; lig. dura, friável; plástico e pegajoso;

Análises Físicas e Químicas – Perfil 10

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm^3
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**pH H_2O**	**pH KCl**	**P**
A	0-12	454	66	30	450	4	3.49	1.8
AB	12-24	482	108	15	395	3.75	3.58	1.7
Bw1	24-48	462	112	27	399	3.82	3.75	1
Bw2	48-70+	407	102	37	454	3.9	3.87	0.5

	Ca^{2+}	Mg^{2+}	K$^+$	Na$^+$	SB	Al^{3+}	H$^+$ + Al^{3+}
	cmol$_c$/dm^3	cmol$_c$/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3
A	0.74	0.19	0.14	0.04	1.11	1.13	8.2
AB	0.14	0.06	0.09	0.03	0.32	1.31	5.9
Bw1	0.07	0.03	0.07	0.01	0.19	1.13	4.6
Bw2	0.11	0.04	0.05	0.01	0.21	1.22	4

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm^3	cmolc/dm^3	%	%	%	dag/kg	mg/L
A	2.24	9.31	11.9	50.4	0.42	5.14	37.3
AB	1.63	6.22	5.1	80.4	0.42	2.9	33.8
Bw1	1.32	4.79	4	85.6	0.27	2.24	33.9
Bw2	1.43	4.21	5	85.3	0.31	1.58	28.3

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 11

Data da descrição – 23/04/2018
Classificação SiBCS – Latossolo Vermelho distrófico argissólico
Classificação FAO/WRB - Acric Rhodic Ferritic Ferrasols (Clayic, Orthodystric, Vetic)
Localização – Lat -16.654157, Long -40.982517 Long; Joaíma-MG
Situação e Declive – Trincheira aberta em fragmento de mata, terço médio da encosta.
Altitude – 373m
Uso atual – Preservação
Litologia / Material de Origem – Complexo Jequitinhonha; kingzito (Proterozóico)
Relevo Local – Ondulado
Relevo Regional – Ondulado
Vegetação Primária – Floresta Estacional Decidual
Erosão – Não aparente
Drenagem – Bem drenado
Pedregosidade – Não Pedregosa
Rochosidade – Não rochosa
Raízes – Muito finas a muito grossas em todos horizontes. Abundantes no A, muitas no BA e Bi, comuns no Bw.
Observações – Atividade biológica intensa no horizonte A. Carvão coletado a 80cm de profundidade. Aparentemente o horizonte B é proveniente de colúvio posterior a formação do Bw.
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-9cm; 2.5YR 4/4 seco 5YR 3/4 úmido; franco argilo-arenosa; moderada pequena e média granular; solta, plástico e pegajoso; transição plana e clara.

BA 9-26cm; 2.5YR 4/6 seco 2.5YR 3/6 úmido; argila; moderada pequena e média blocos subangulares e fraca pequena granular; ligeiramente dura friável plástico e pegajoso; transição plana e gradual.

Bi 26-64cm; 2.5YR 4/6 seco 2.5YR 3/6 úmido; argilo-arenosa; moderada média e grande blocos subangulares; ligeiramente dura friável; plástico e pegajoso; transição plana e clara.

Bw 64-90+cm; 2.5YR 4/6 seco 2.5YR 3/6 úmido; argila; forte pequena granular e fraca média blocos subangulares; macia muito friável; plástico e pegajoso;

Análises Físicas e Químicas – Perfil 11

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm³
Símbolo	Prof. (cm)	Areia Grossa	Areia Fina	Silte	Argila	pH H_2O	pH KCl	P
A	0-9	472	125	58	346	5.33	4.72	2
BA	9-26	322	121	73	483	4.8	4.07	0.6
Bi	26-64	327	136	49	489	4.66	3.92	0.9
Bw	64-90+	324	109	73	494	4.56	4.08	0.7

	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	$H^+ + Al^{3+}$
	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³	cmolc/dm³
A	2.8	0.78	0.35	0.03	3.96	0	3.1
BA	0.49	0.39	0.14	0.03	1.05	0.38	2.3
Bi	0.7	0.41	0.23	0.03	1.37	0.56	3.3
Bw	0.57	0.44	0.10	0.06	1.18	0.38	2

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm³	cmolc/dm³	%	%	%	dag/kg	mg/L
A	3.96	7.06	56.1	0	0.43	3.69	44.9
BA	1.43	3.35	31.3	26.6	0.91	0.92	27.9
Bi	1.93	4.67	29.3	29	0.65	1.58	30.4
Bw	1.56	3.18	37.1	24.4	1.91	0.26	27.5

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 12

Classificação SiBCS – Cambissolo Háplico Tb eutrófico latossólico
Classificação FAO/WRB - Oligeoeutric Chromic Ferralic Cambisols (Clayic)
Localização – Lat -16.527484, Long -41.017604; Jequitinhonha-MG
Situação e Declive – Trincheira aberta em fragmento de mata em terço médio de encosta
Altitude – 310m
Uso atual – Vegetação natural em regeneração
Litologia / Material de Origem – Granito Timorante, leucocrático
Relevo Local – Ondulado
Relevo Regional – Ondulado
Vegetação Primária – Floresta Estacional Decidual
Erosão – Ligeira
Drenagem – Moderadamente drenado
Pedregosidade – Não Pedregosa
Rochosidade – Não rochosa
Raízes – muitas, muito finas a muito grossas no A e AB; poucas, muito finas a grossas no Bi1 e Bi2
Data da descrição – 24/04/2018
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-17cm; 2.5YR 4/4 seco 5YR 3/4 úmido; franco argilo-arenosa; moderada pequena e média granular; solta, plástico e pegajoso; transição plana e clara.

AB 17-29 cm; 2.5YR 4/6 seco 2.5YR 3/6 úmido; argila; fraca e moderada pequena e média blocos subangulares e granular; ligeiramente dura friável plástico e pegajoso; transição plana e gradual.

Bi1 29-51 cm; 2.5YR 4/6 seco 2.5YR 3/6 úmido; argilo-arenosa; moderada média e grande blocos subangulares; ligeiramente dura friável plástico e pegajoso; transição plana e clara.

Bi2 51-70+cm; 2.5YR 4/6 seco 2.5YR 3/6 úmido; argila; forte e fraca pequena e média granular e blocos subangulares; macia muito friável plástico e pegajoso.

Análises Físicas e Químicas – Perfil 12

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm^3
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**pH H_2O**	**pH KCl**	**P**
A	0-17	516	76	86	322	5.7	5.14	1.6
AB	17-29	397	101	100	402	5.19	4.3	1.2
Bi1	29-51	375	85	98	443	4.92	3.99	0.6
Bi2	51-70+	375	82	78	465	5.05	4.14	0.5

	Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	Al^{3+}	$H^+ + Al^{3+}$
	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3
A	4.59	0.86	0.24	0.08	5.77	0	2.3
AB	2.82	0.56	0.12	0.06	3.56	0.38	2.8
Bi1	1.67	0.53	0.08	0.04	2.32	0.56	2.3
Bi2	1.46	0.61	0.06	0.04	2.17	0.38	1.5

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm^3	cmolc/dm^3	%	%	%	dag/kg	mg/L
A	5.77	8.07	71.5	0	0.97	3.29	49.3
AB	3.56	6.36	56	0	0.89	2.11	45.5
Bi1	2.41	4.62	50.2	3.7	0.85	0.92	43
Bi2	2.17	3.67	59.1	0	1.07	0.79	46.1

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black

PERFIL 13

Data da descrição –25/04/2018
Classificação SiBCS – Latossolo Amarelo distrófico argissólico
Classificação FAO/WRB - Acric Xanthic Ferralsols (Clayic, Orthodystric, Vetic)
Localização – Lat -16.555293, Long -41.581933; Itaobim-MG
Situação e Declive –
Altitude – 290m
Uso atual – Vegetação natural em regeneração
Litologia / Material de Origem – Granitóide Itaobim (Cambriano).
Relevo Local – Suave ondulado
Relevo Regional – Ondulado
Vegetação Primária – Caatinga hipoxerófila
Erosão – Ligeira
Drenagem – Bem drenado
Pedregosidade – Não pedregosa
Rochosidade – Não rochosa
Raízes – Comuns muito finas e finas no A; poucas e finas no BA; raras e finas no Bw1; raras, finas e muito finas Bw2.
Descrito e coletado por: Guilherme Resende Corrêa

DESCRIÇÃO MORFOLÓGICA

A 0-11cm; 7.5YR 5/3 seco 7.5YR 4/3 úmido; franco argilo-arenosa; moderada pequena e média blocos subangulares; dura muito friável; lig. plástico, lig. pegajoso; transição plana e gradual.

BA 11-28cm; 10YR 6/4 seco 10YR 5/4 úmido; franco argilo-arenosa; moderada e fraca pequena e média granular e blocos subangulares; dura muito friável; plástico e pegajoso; transição plana e clara.

Bw1 28-68cm; 10YR 7/3 seco 10YR 5/6 úmido; franco argilo-arenosa; moderada e fraca média e grande blocos subangulares e granular; dura muito friável; plástico e pegajoso; transição plana e gradual.

Bw2 68-80+cm; 10YR 7/4 seco 10YR 5/8 úmido; argilo-arenosa; moderada e fraca media e pequena blocos subangulares e granular; dura muito friável; plástico e pegajoso.

Análises Físicas e Químicas – Perfil 13

Horizonte		Composição granulométrica da terra fina (g/kg)						mg/dm^3
Símbolo	**Prof. (cm)**	**Areia Grossa**	**Areia Fina**	**Silte**	**Argila**	**pH H_2O**	**pH KCl**	**P**
A	0-11	477	224	61	238	5.09	4.29	5.7
BA	11-28	350	217	127	306	4.73	3.91	1.2
Bw1	28-60	293	220	153	334	4.84	3.87	1.7
Bw2	60-80+	262	216	134	389	4.83	3.88	2.1

	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	SB	Al^{3+}	$H^{+} + Al^{3+}$
	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3	cmolc/dm^3
A	1.95	0.47	0.24	0.01	2.67	0.19	3.4
BA	0.7	0.36	0.29	0.02	1.37	0.47	3.1
Bw1	0.3	0.5	0.25	0.02	1.07	0.66	2.3
Bw2	0.16	0.53	0.29	0.03	1.01	0.56	2

	t	T	V	m	ISNa	M.O	P-Rem
	cmolc/dm^3	cmolc/dm^3	%	%	%	dag/kg	mg/L
A	2.86	6.07	44	6.6	0.21	3.29	47.2
BA	1.84	4.47	30.6	25.5	0.49	1.58	37.6
Bw1	1.73	3.37	31.8	38.2	0.65	0.53	38.5
Bw2	1.57	3.01	33.6	35.7	0.87	0.26	38.1

pH em água, KCl e CaCl - Relação 1:2,5 ; P - Na - K - Extrator Mehlich-1; H + Al - Extrator Acetato de Cálcio 0,5 mol/L - pH 7,0 ; t - Capacidade de Troca Catiônica Efetiva; V= Índice de Saturacão por Bases; ISNa = Índice de Saturação por Sódio; P-rem = Fósforo Remanescente; Ca2+ - Mg2+ - Al3+ - Extrator: KCl - 1 mol/L; SB = Soma de Bases Trocáveis; T - Capacidade de Troca Catiônica a pH 7,0; m= Índice de Saturação por Aluminio; MO (Mat. Orgânica) = C.Org x 1,724 -Walkley-Black