Chapter 1
The Caatinga: Understanding the Challenges

José Maria Cardoso da Silva, Luis Cláudio Fernandes Barbosa, Inara R. Leal, and Marcelo Tabarelli

Abstract The Caatinga is a well-recognized ecological region that lies in the semiarid hinterland of northeastern Brazil and that covers 912,529 km^2. The term 'Caatinga' refers mostly to a seasonally dry tropical forest (SDTF) that presents a mosaic of different physiognomies. The Caatinga is a very heterogeneous region that can be divided into nine ecoregions. It was home to 28.6 million people in 2010. The region has an economy based mostly on public services, and its human development indicators are the lowest in Brazil. The interactions between humans and nature in the region have been marked by a frontier mindset in which natural resources are perceived as infinite. The combination of acute disturbances, chronic disturbances, the proliferation of exotic species, and climate change can lead to the disruption of critical ecological services. A significant regional shift toward sustainable development in this region is urgent. It will require persistence, creativity, consistent financial and political support, and a robust and evident connection between the improvement of human livelihoods and the conservation of natural landscapes.

Keywords Dry lands • Ecosystem services • Seasonally dry tropical forest • Socio-ecological system • Sustainable development

1.1 Introduction

The Caatinga is a well-recognized ecological region that lies in the semiarid hinterland of northeastern Brazil (Ab'Saber 1977; Prado 2003; IBGE 2004). The dominant vegetation type in the region is a seasonally dry tropical forest (SDTF) (sensu Pennington et al. 2009; see also Chap. 2) that exhibits at least 13 different physiognomies spanning a broad range of woody plant densities and is referred to

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J.M.C. da Silva et al. (eds.), *Caatinga*,
https://doi.org/10.1007/978-3-319-68339-3_1

collectively as the caatingas (Andrade-Lima 1981; Prado 2003). As in any other semiarid region, the Caatinga has an extended dry period in which rainfall is scarce. As a result, most of the vegetation is deciduous (Prado 2003). The deciduousness of the caatingas explains the name, which comes from Tupi, the language spoken by the Ameridians who still live in small numbers in the region, and means 'white forest', possibly because of the magnificent view offered by a 'sea' of leafless trees during the dry season (Prado 2003). In addition to being an ecological region, the Caatinga is also considered a well-defined social region. The Caatinga's human population is a product of the miscegenation of the native indigenous peoples with the Portuguese who colonized the area during the 1600s (Théry and Mello 2005). This population has developed strong and resilient cultural traditions based on cattle ranching and subsistence agriculture. However, political constraints have slowed human development in the Caatinga, making it Brazil's most underdeveloped region (Buainain and Garcia 2013).

Socio-ecological systems comprise ecological systems, human systems, and the interactions between them (Liu et al. 2007). They can be found in any spatial level, from local to global, and a good understanding of their spatial and temporal dynamics is fundamental for proposing sound sustainable development policies that seek to conciliate significant improvements in human welfare while conserving natural ecosystems. In fact, policies based on a reductionist approach have caused recurrent failures in semiarid regions, thus undermining human prosperity (Silva 2007). Here we propose that the Caatinga is a large-scale socio-ecological system that is predicted to exhibit the same properties that have been used to describe other socio-ecological systems worldwide: non-linear dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises (Liu et al. 2007). We suggest that understanding the principles of the processes that govern such a large-scale system is the first step toward a better framework that enables scientists and policy-makers to find sound solutions for the region. In this chapter, we provide a brief description of the Caatinga's socio-ecological system. We start by describing the boundaries of the region, and we then describe its ecological system, its human system, and the interactions between them. We close with a discussion of the relationship between science and policy in a region that requires immediate political actions to move toward a more sustainable and resilient development path.

1.2 Geographical Boundaries

Large socio-ecological systems, such as the Caatinga, do not have stable borders. In fact, they are under a permanent state of flow due to recurrent global changes. However, to understand the ecological and social processes that are operating within the region, it is necessary to delimit its boundaries. The position of the boundaries of an ecological region depends on both the dataset and the methods used to delimit it. In 2004, the IBGE (Instituto Brasileiro de Geografia e Estatística) identified six major ecological regions (or biomes) in Brazil, aiming to provide a guide for both

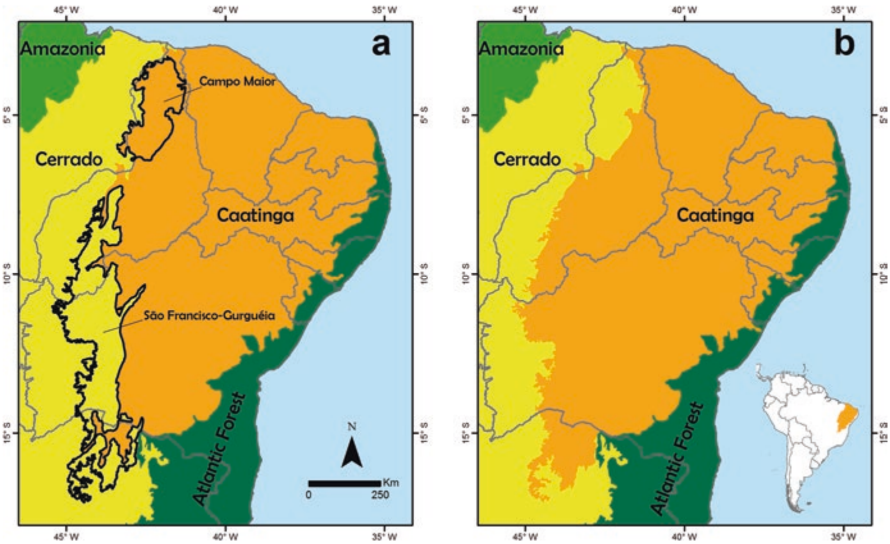

Fig. 1.1 Comparison of the Caatinga's limits proposed by the IBGE (Instituto Brasileiro de Geografia e Estatística) (2004) (**a**) with those proposed in this chapter (**b**). Note that we excluded Campo Maior from the Caatinga and included the seasonally tropical dry forests of the São Francisco-Gurgéia

environmental policies and research. These ecological regions were delimited based on the country's vegetation map at the scale of 1:5,000,000 (IBGE 2004). The following criteria were used: (a) the region should encompass a vast and continuous areas dominated by one vegetation type; (b) the enclaves of other vegetation types found within the region should be included within it; (c) the transition zones between ecological regions should be merged with one of the adjacent regions based on the vegetation type that dominates the transition zone; and (d) because of the mapping scale, all coastal environments had to be segmented and merged with the adjacent large ecological region.

In the IBGE's classification, the Caatinga was recognized as the ecological region that encompasses most of the hinterland of northeastern Brazil and that is delimited based on the distribution of the caatingas. Although dominated by the caatingas, the Caatinga as a region also encompasses all the enclaves of humid tropical forests, wetlands, transitional vegetation types, grasslands, and rupestrian grasslands found within it (for a full description, see Chap. 2). The IBGE's map included the region of Campo Maior within the Caatinga (Fig. 1.1). However, this region is dominated by grasslands, and the few patches of caatinga found there have limited floristic affinity to the remaining caatingas (Moro et al. 2014, 2016). In contrast, the IBGE's map excluded from the Caatinga a significant portion of the SDTFs found along the middle valley of the São Francisco River (Fig. 1.1). They were merged with the Cerrado, a region dominated by a savanna-like vegetation. This decision is not sound because the SDTFs of the São Francisco River have always been considered physiognomic units of the caatingas (Andrade-Lima 1981; Prado 2003; Chapter 2). Based on these two findings, we proposed a new limit for the Caatinga (Fig. 1.1). We maintained most of the boundaries suggested by the IBGE, but excluded from it the Campo Maior (which was transferred to the Cerrado) and included all the SDTFs along the Middle São Francisco River. According to the new boundaries, the Caatinga has an area of 912,529 km^2, which corresponds to 10.7% of the Brazilian territory or a region roughly equivalent to the areas of Italy, Germany, and the United Kingdom together.

1.3 Ecological System

The Caatinga has around 70% of its area in crystalline basements (Proterozoic) and 30% in sedimentary basins (Paleozoic and Mesozoic) forming flattened surfaces between 300 and 500 m above sea level (Cole 1986; Sampaio 1995, Chap. 2). Isolated mountain ranges and high-altitude plateaus (up to 1000 m) are scattered across the region, modifying the local climate and acting as present-day refuges for species assemblages well distinct from the ones found in the lowest terrains (Andrade-Lima 1982). The region has different soil types, ranging from shallow, rocky, and relatively fertile to profound, sandy, and unfertile ones (Sampaio 2010). Across most of the region, the climate is semiarid because the precipitation/potential evapotranspiration rate is <0.65 (Sampaio 2010). Average mean temperature is constant over the year, ranging from 25 to 30 °C. However, annual rainfall varies widely in time and space. Most of the region (68.8%) receives between 600 and 1000 mm of rain a year, with only 0.6% receiving less than 400 mm and 1.6% receiving more than 1200 mm (Chap. 10). In a few mountain areas, due to orographic effects, rainfall can go up to 1800 mm a year (Chap. 10).

Most of the rainfall is concentrated in three consecutive months, although wide annual variations and recurrent droughts are frequent (Nimer 1972). The number of dry months increases from the edges to the core of the region, with some areas experiencing periods of 7–10 months without water availability for plants (Prado 2003). An important feature of the Caatinga is the high inter-annual variability in rainfall, with droughts that can last for years (Nimer 1972). These long droughts impose severe conditions on the people living in the region and are the basis for the development of unique adaptations by the region's biota. Some mountain ranges benefit from orographic rains and reduced average temperatures, which provide mesic conditions for the maintenance of species from the adjacent biomes.

The dominant vegetation, the caatingas, ranges from open scrublands to tall, dry forests (see Chap. 2). These tall, dry forests were once the most dominant physiognomy along the rivers and mountain slopes, but, currently, most of the region is occupied by open physiognomies and woodlands, possibly due to human disturbances (Coimbra-Filho and Câmara 1996). Along the major rivers, wetlands and seasonally flooded grasslands were once common (Siqueira Filho 2012). Humid forests once covered the slopes of the mountains and high plateaus, creating ecological gradients found nowhere else. On the top of some plateaus, there are patches of cerrado and rupestrian grasslands, a unique vegetation type with a high level of endemism. In total, the flora of the Caatinga is very rich, with a relatively high proportion of endemic species compared with other SDTFs (Chap. 2). On a regional scale, vegetation dynamics, as measured by remote sensing and using vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), shows a wide variation across time and space and is strongly correlated with rainfall (Schucknecht et al. 2013). In fact, the plants of the caatingas usually grow and produce flowers and fruits during the wet season (Sampaio 2010).

The Caatinga has a dense river network composed of both perennial and intermittent rivers, both of which have been strongly disturbed by human activities (Fig. 1.2). Perennial rivers are few, and their headwaters are generally outside the Caatinga. The São Francisco is the largest and most important perennial river in the region, and its valley is where most of the energy and irrigation projects are located. The São Francisco River had large and productive wetlands along its valley in the past, but most of these ecosystems have been lost (Siqueira Filho 2012). Intermittent rivers are the ones that cease to flow every year or at least twice every 5 years (Steffan 1977). They experience flash floods and prolonged droughts, both of which act as agents of hydrologic disturbance and have a strong influence on aquatic plants and animals. In addition, when well-conserved, intermittent rivers help to maintain riparian forests along their valleys. These forests, in turn, act as refuges for plants and animals during the dry season. However, most of the riparian forests have been lost due to the expansion of cattle ranching and agriculture across the region.

The Caatinga is not a homogeneous region. Rodrigues and Silva et al. (2000) recognized at least 135 geo-environmental areas within the Caatinga. These units, in turn, can be grouped into nine ecoregions (Velloso et al. 2002). Here we propose a new map of the Caatinga ecoregions that seeks to align Velloso and colleague's map with the new map of the Caatinga (Fig. 1.3). The new ecoregion map differs from the previous one as follows: (a) the Campo Maior ecoregion has been removed from the Caatinga; and (b) a new ecoregion (São Francisco-Gurgéia) has been proposed to highlight the uniqueness of the SDTFs of this region (Fig. 1.3).

1.4 Human System

The Caatinga was the home of 28.6 million people in 2010, corresponding to 14.5% of the Brazilian population. This population lived in 1213 municipalities whose limits overlapped 50% or more with the Caatinga's boundaries (Fig. 1.4). These municipalities are nested into ten Brazilian states (Piaui, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Paraíba, Alagoas, Sergipe, Bahia, and Minas Gerais) (Fig. 1.4). The region includes two state capitals (Fortaleza and Natal) that are located in the segments of the coastline that were merged with the Caatinga by the IBGE (2004). The combined population of these two large urban centers was 11.4% of the Caatinga's population. Since the 1980s, the proportion of the population

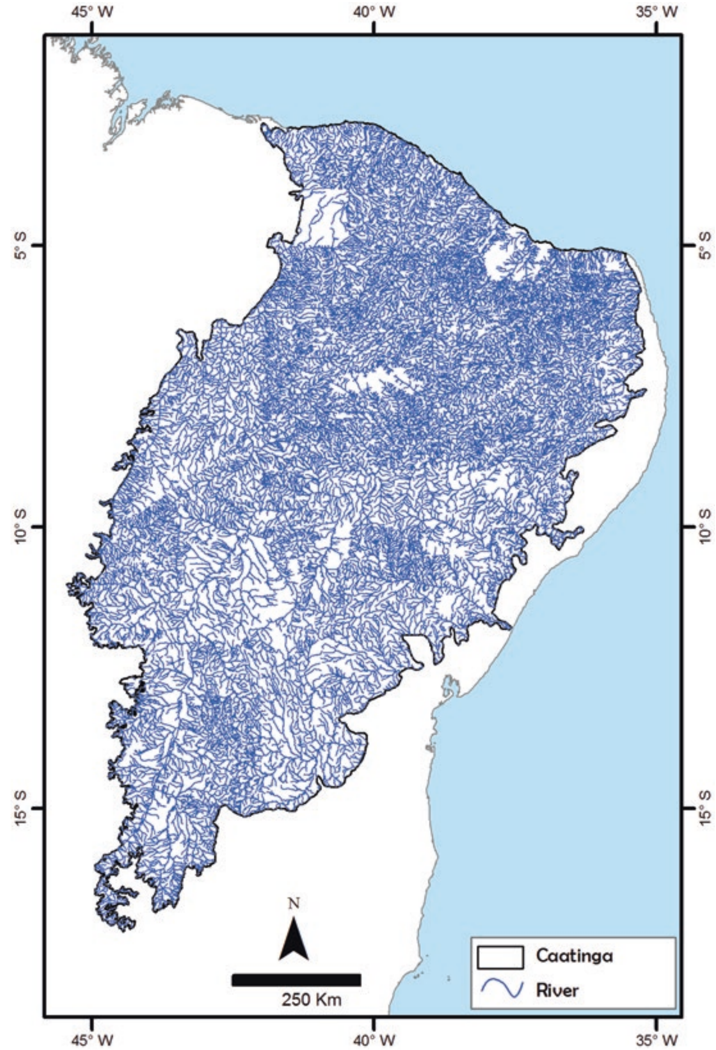

Fig. 1.2 Rivers of the Caatinga (Source: www.ana.gov.br)

living in cities within the Caatinga has been higher than that in rural settings (Théry and Mello 2005). In 2010, 66.7% of the population lived in cities.

The regional population density in 2010 was 33.1/km^2; however, if only the rural population is counted, this number declines to 10.4/km^2, which is a high rural density for a semiarid region (Ab'Saber 1999). The population density is not homogenous across the region. High densities are found along the eastern borders of the region as well as along the coastline (Fig. 1.5). In contrast, municipalities with low population densities are found mostly along the western borders in the transition to the Cerrado (Fig. 1.5). Few municipalities (6.3%) have population densities below

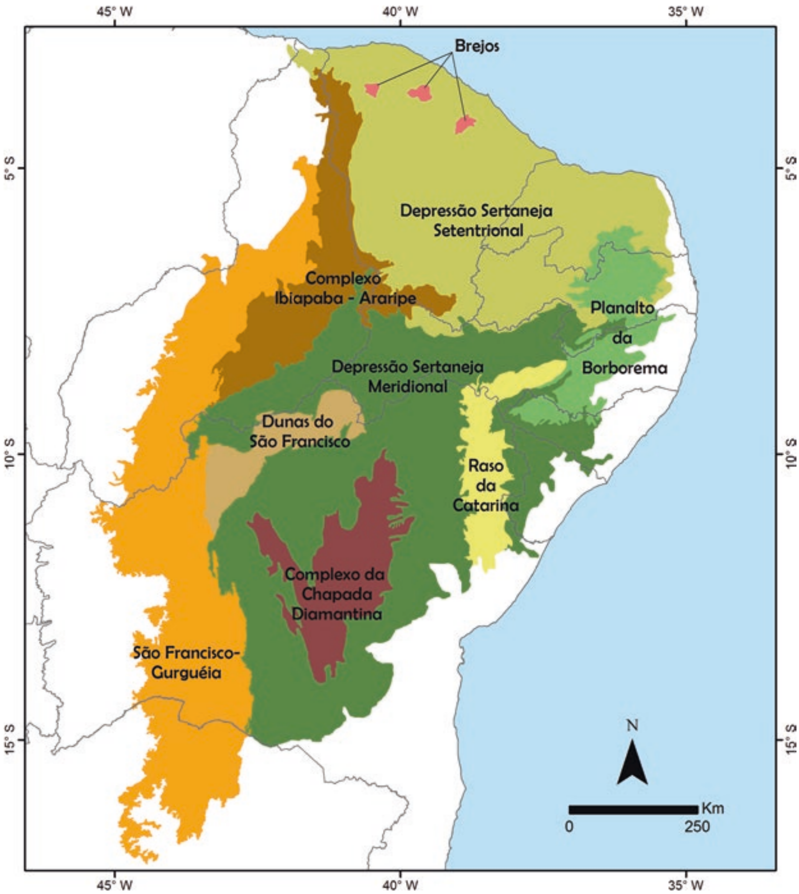

Fig. 1.3 Ecoregions of the Caatinga (Modified from Velloso et al. 2002)

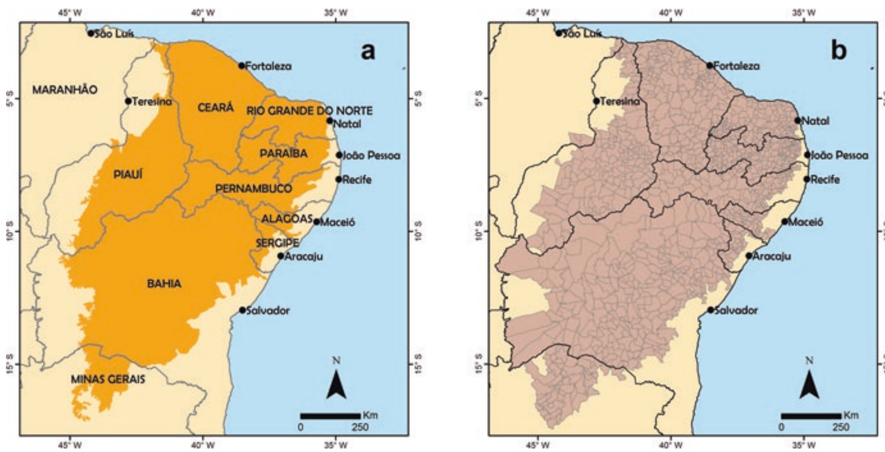

Fig. 1.4 Political map of the Caatinga: (**a**) division in states; (**b**) division in municipalities

5/km^2. However, these 77 municipalities are large and cover 23.2% of the region (Fig. 1.5). The percentage of the population living in rural settings presents a wide geographical variation, and a large number of municipalities (46.5%) have populations that are still mostly rural (Fig. 1.5). These rural municipalities cover 49.2% of the region and comprise 27.6% of the population.

In 2010, the Caatinga's gross domestic product (GDP) was around US$73 billion, corresponding to roughly 10% of Brazil's GDP. A total of 25% of the regional economic activity is centered around 11 municipalities in the states of Ceará (Fortaleza, Caucaia, Maracanaú, and Sobral), Rio Grande do Norte (Mossoró and Natal), Paraíba (Campina Grande), Pernambuco (Caruaru and Petrolina), Bahia (Feira de Santana), and Minas Gerais (Montes Claros) (Fig. 1.6). These municipalities together cover 1.61% of the region's area but are home to 21.5% of its population. The region's formal economy is based mostly on services (Fig. 1.7). On average, services contribute to 69.7% of the municipalities' GDP. An economy based on services would be considered good news if they were mostly provided by the private sector rather than by the governments. However, in the Caatinga, public services (e.g., pensions and government expenditures) are responsible, on average, for 44.4% of the local GDP. Although most of the Caatinga's rural population depends on agriculture (Buainain and Garcia 2013), it contributes only 11% of the local economic activity on average. This fact could be a consequence of the low

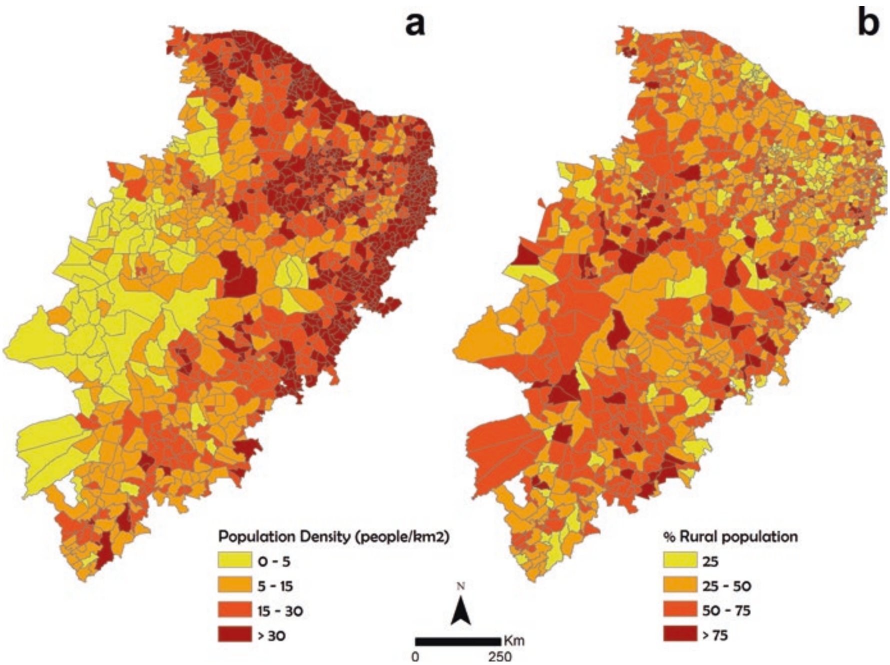

Fig. 1.5 Geographical variation in (**a**) population density (people/km^2) and (**b**) percentage of the rural population in the municipalities of the Caatinga (Source: http://seriesestatisticas.ibge.gov.br/)

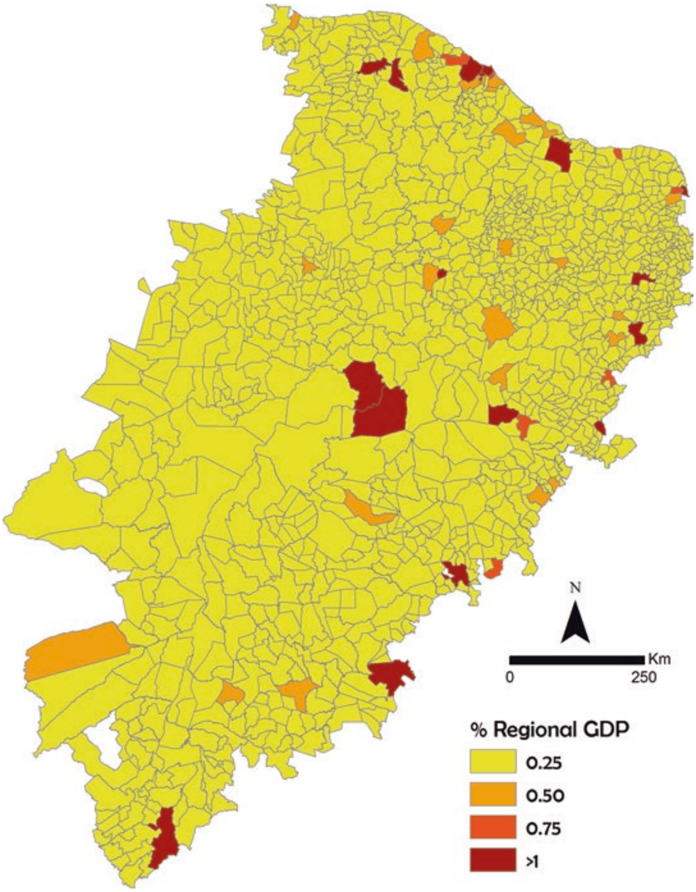

Fig. 1.6 Contribution of the different municipalities to the Caatinga's gross domestic product (GDP) (Source: http://seriesestatisticas.ibge.gov.br/)

productivity of the agriculture systems across the region but also because most of the agricultural output from the region is either for subsistence or traded on informal markets. The contribution of agriculture to the economy is high in a few municipalities along the border with the Cerrado and in the irrigated agriculture poles in Pernambuco and Bahia (Fig. 1.7). Industrial activities contribute on average slightly more (12.5%) to the local economies than agriculture. The importance of this sector to the economy is high in a few scattered major urban centers along the coastline and in central Bahia (Fig. 1.7).

The Caatinga has Brazil's lowest indicators of human development, as measured by the Human Development Index (HDI) at the municipality level. The HDI is a synthetic index that measures three basic dimensions of human well-being (health, education, and income) and ranges from 0 to 1. The municipalities can be classified into five categories according to their HDIs: very low (below 0.49), low (0.50–0.59),

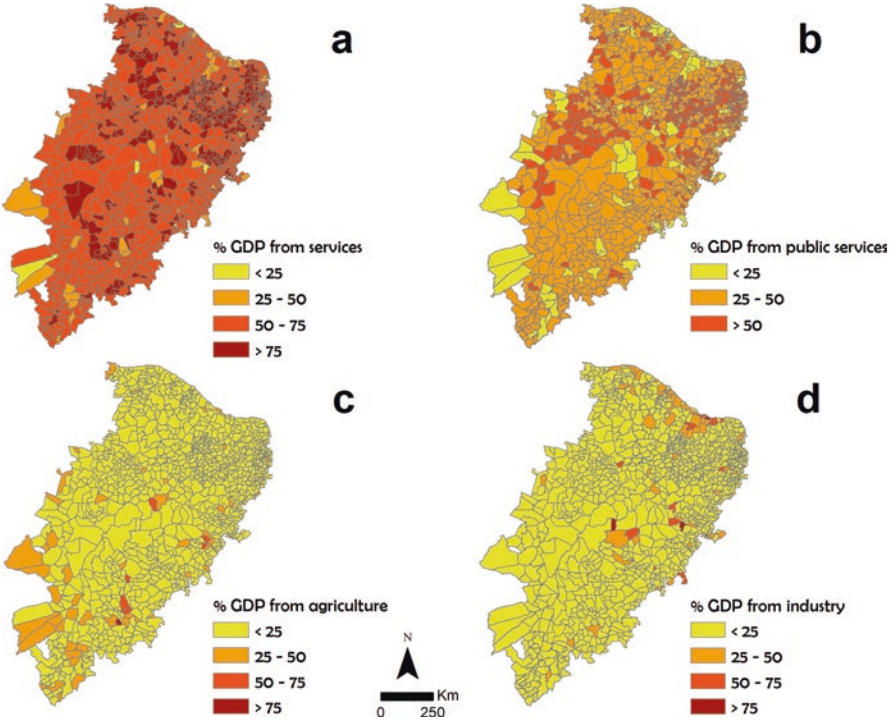

Fig. 1.7 Contribution of different economic sectors to the gross domestic product (GDP) of the Caatinga's municipalities (Source: http://seriesestatisticas.ibge.gov.br/)

medium (0.6–0.69), high (above 0.7–0.799), and very high (above 8). The proportion of the municipalities in each of these categories has changed over time (Fig. 1.8). In 1991, almost all municipalities had very low HDI. From 1991 to 2000, the situation did not change very much, but at least some municipalities (113) moved up to low and medium HDI. From 2000 to 2010, the region experienced a development burst that helped to move most of the municipalities to low and medium HDI. In addition, a few municipalities (20) moved up to high HDI (Fig. 1.8). In 2010, the HDI of the Caatinga's municipalities ranged from 0.48 to 0.77, with an average of 0.59. The regional average value is lower than the mean of all the municipalities in Brazil (0.66).

1.5 Interactions Between Natural and Human Systems

The interaction between humans and nature in the Caatinga began in the Late Pleistocene–Holocene, when the first populations arrived in the region, possibly following a coastal migratory route (Martin 2005; Bueno and Dias 2015). The indigenous people lived mostly along the major rivers and other humid spots, using

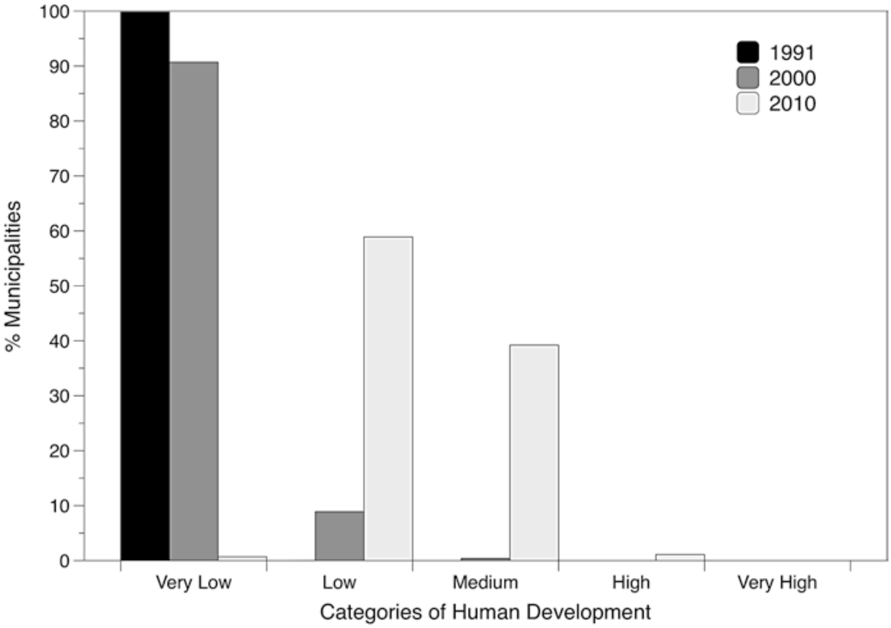

Fig. 1.8 Temporal changes in the classification of the Caatinga municipalities according to categories of the Human Development Index. Categories are as follows: very low (below 0.49), low (0.50–0.59), medium (0.6–0.69), high (above 0.7–0.799), and very high (above 8) (Source: http://atlasbrasil.org.br)

the caatingas during the wet season. When the Portuguese decided to colonize the Caatinga from their settlements along the coast, they opted to establish vast cattle ranches along the major rivers, such as São Francisco and Paraguaçu (Hemming 1978). This decision put the colonizers against the indigenous populations that had lived for thousands of years in such places. A long and cruel war took place, and thousands of indigenous people were slaughtered as a consequence (Puntoni 2002). With the venues opened to more intense colonization, cattle ranching expanded across the region, first, from the São Francisco to Parnaíba, and then to all other regions (Hemming 1978). Soon, the colonizers learned that it was possible to use the native vegetation to feed their cattle, which allowed them to move away from the major rivers (Hemming 1987). They had also begun to extract timber as construction material for their ranches and as firewood to provide the energy that they needed. Agriculture was mostly for subsistence and based on the traditional slash-and-burn method. In a few decades, the colonizers increased their dependency on the caatingas and developed a solid regional culture, with their leather clothes, food, music, poetry, traditions, and adaptations to the long droughts that eventually affected the region (Andrade 1998; Chaps. 11 and 12). Over time, losses caused by the recurrent droughts and competition with meat coming from elsewhere led to the decline of the regional cattle-ranching industry, which limited the growth of the regional economy when compared with other regions in Brazil (Prado-Júnior 1987).

For some time, cotton plantations in some areas generated good expectations (Silva 1977), but mismanagement of the land and weevils caused them to fail.

The negative impact of the long droughts on the population led to the adoption of emergency actions by the governments (Andrade 1998). However, these measures benefited only the wealthy and powerful and produced no long-term positive impact on the poor (Silva 2007). Inequalities that had always been high increased over time, deepening the regional social gap. Even today, millions have only a few hectares to produce and prosper, while a few control most of the land and other resources, including access to fresh water (Buainain and Garcia 2013b). Long droughts led to water scarcity. People unable to store water lost their farms and became hungry. Without food, they either moved to the main cities or stayed in the region and became vulnerable to all kinds of exploitation by the local elite, including exchanging hard work for poverty wages.

Because emergency programs were not successful, the governments decided to adopt a more permanent and scientifically based program to combat the droughts. The new program defined water shortage as the main obstacle to local development and determined that by building new reservoirs and creating water distribution mechanisms, such as new roads, the local population would thrive. The 'hydraulic solution' to the Caatinga's problems mobilized large sums of public funds over decades and transformed the Caatinga into a semiarid region with the world's greatest capacity to stock freshwater and with one with the densest road networks (Ab'Saber 1999). However, most of the reservoirs were built on private rather than public land; the water distribution mechanisms were not efficient and, as a consequence, chronic regional water shortages remained a challenge (Ab'Saber 1999; Silva 2007). Roads opened the few pristine areas for colonization, leading to more deforestation. In addition to the physical infrastructure, the programs to combat drought envisioned new rural economic activities, such as the replacement of cattle with sheep and goats (there are currently 19 million sheep and goats in the Caatinga) as well as the introduction of exotic plant species that could be consumed by both people and livestock during the droughts (Almeida et al. 2015). The perspective that large-scale infrastructure is favorable for the Caatinga and its habitants has not changed over time. For instance, in 2005, the Federal Government began a new project to transfer water from the São Francisco River to four rivers and several reservoirs in the north of the region. The idea was to ensure a permanent water supply to 12 million people at the cost of US$2 billion. Initially promised to be delivered in 2010, this massive infrastructure project has not been completed to date. Its final costs are now estimated at US$3 billion. In the meantime, outright protection of critical areas to ensure the conservation of the Caatinga has not advanced at the same pace as in other Brazilian regions. Only 7.4% of the region is within protected areas (Fig. 1.9), and most of these protected areas are not funded properly (Oliveira and Bernard 2017).

The interactions between people and nature in the Caatinga have been marked by a frontier mindset in which natural resources are perceived as infinite and exploited ruthlessly due to weak governance. Three types of human disturbances to the

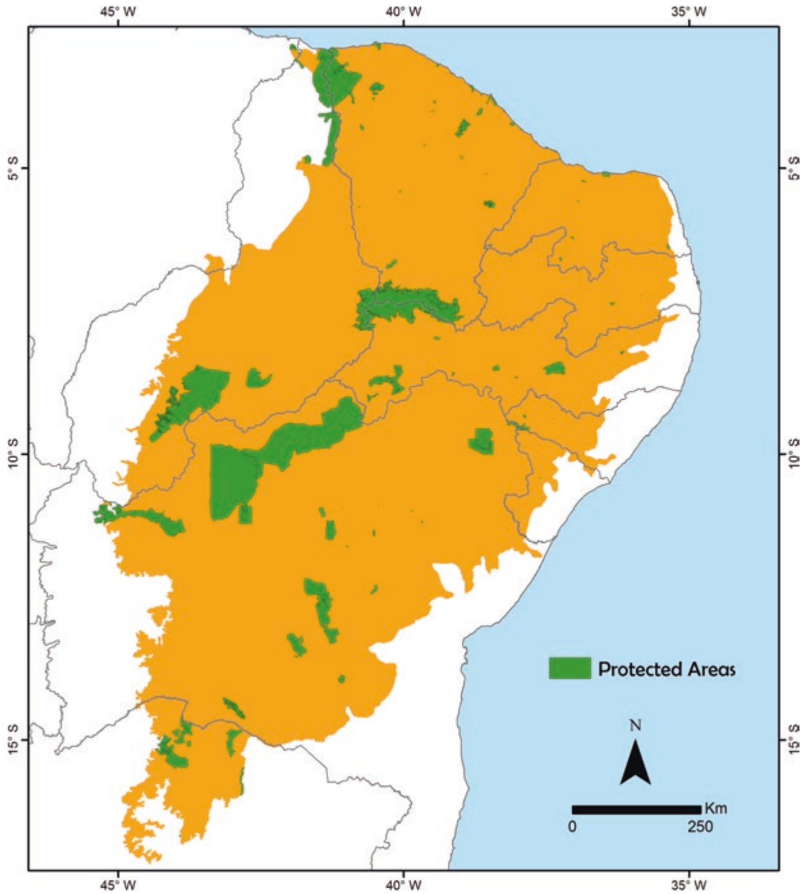

Fig. 1.9 Boundaries of the protected areas of the Caatinga (Source: http://www.mma.gov.br/areas-protegidas/cadastro-nacional-de-ucs/)

Caatinga's ecosystems have been detected. The first one is acute disturbances caused by the fast conversions of large areas of native vegetation into human-made ecosystems, with roads, reservoirs, or commercial agriculture. The second type is chronic disturbances caused by the slow but continuous overexploitation of the native vegetation, such as through establishing slash-and-burn agriculture, collecting firewood, and browsing by livestock (Singh 1998). Finally, the third type consists of the negative impacts caused by plant and animal exotic species that have been introduced into the region as a strategy to ensure food security for the rural population but that have reduced the populations of some native species (Nascimento et al. 2014). All three processes undermine the Caatinga's ecological systems that are so essential to sustaining the local populations but also to support globally relevant services.

1.6 The Challenges Ahead

The future of the Caatinga as a socio-ecological system will depend on how fast the regional society will move toward a new development paradigm that aims for the sustainable delivery of ecosystem services and benefits for human populations while simultaneously maintaining healthy, productive ecosystems. This paradigm requires the right mix of sound scientific knowledge and effective political action. In the last decade, knowledge about the Caatinga has increased exponentially (Fig. 1.10). We know more than ever about the biota of the Caatinga. It is now possible to model the ranges of the species, understand their evolution using DNA sequences, and use sophisticated computational methods to set priority areas for conservation. In addition, a new synthesis about regional archaeology, history, sociology, and economics has been produced, bringing new ideas and concepts about the Caatinga's past and current societies. In contrast, studies on the outcomes of the interaction between ecological and social systems are still in their infancy. Only recently, researchers have begun to estimate the magnitude of the impacts of the chronic disturbance on the Caatinga's biota (Ribeiro et al. 2015, 2016) and to understand how biodiversity loss can constrain the provision of the main ecosystem services (Leal et al. 2014, 2015; Sobrinho et al. 2016). There is still a long way to go to model how the Caatinga's biodiversity and ecosystem services are going to

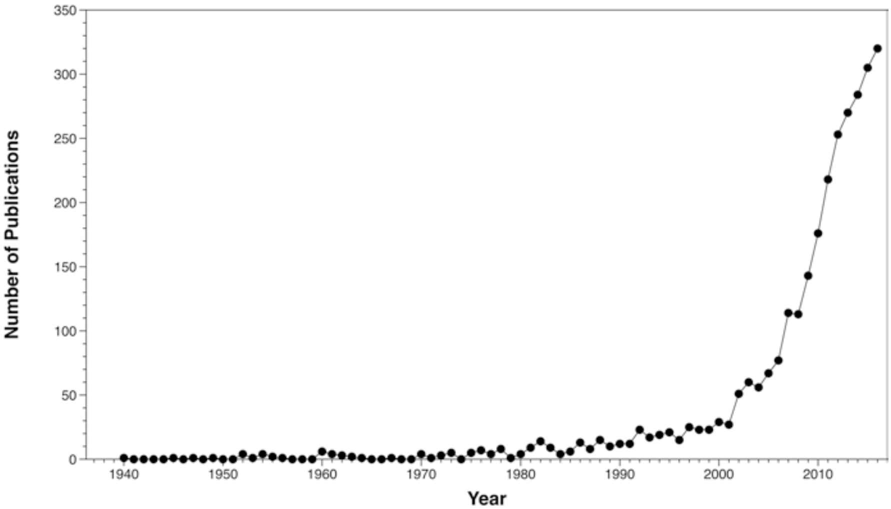

Fig. 1.10 Number of publications on the Caatinga in all citation databases in the Web of Knowledge, using 'caatinga' and 'caatingas' as topic search terms

simultaneously react to acute disturbances, chronic disturbances, exotic species, and climate change. Unfortunately, case studies describing the dynamics of local socio-ecological systems across the Caatinga are still scarce, possibly because the regional research teams have not yet cultivated and promoted transdisciplinary approaches in their graduate programs. We argue that more integrated studies combining the state-of-art from multiple disciplines are required to advance our knowledge on the Caatinga socio-ecological system and to support sound sustainable development policies. However, knowledge gaps cannot be used as an excuse to delay important political actions. We argue that in contrast with the scientific excitement that exists about the region, the political interest toward a major shift on how natural resources are managed in the Caatinga has vanished across all government levels in the last decade. Three facts seem to support our statement. First, despite all the awareness created by the importance of the Caatinga's biodiversity (Leal et al. 2003, 2005, Silva et al. 2004), protected areas remain inadequate to safeguard the region's biodiversity. Second, even though several studies have documented that 94% of the region has moderate to high risk of desertification due to intense and abusive land use practices (Sá and Angelotti 2009; Vieira et al. 2015), human disturbances across the region continue to increase and remain unchecked, as there is no system to monitor and evaluate the remaining native ecosystems. Finally, despite all the research demonstrating that the regional society is using the Caatinga's natural resources well beyond its carrying capacity (Gariglio et al. 2010), the most recent plans proposed to improve the regional economy continue to follow the same mindset that has dominated the region for centuries and that has failed miserably to deliver long-term prosperity for all. In spite of all these recent drawbacks in the political arena, we continue to be optimistic about a sustainable future for the Caatinga. As we stated 12 years ago (Leal et al. 2005), a significant regional shift toward sustainable development in this region will require persistence, creativity, consistent financial and political support, and a robust and evident connection between the improvement of human livelihoods and the conservation of natural landscapes. We hope all these enabling conditions will become available soon. Perhaps this book is another important step in this direction.

Acknowledgements We are grateful to Fábio Scarano for discussions about Caatinga development and sustainability. IRL and MT thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico for productivity grants (CNPq, process 305611/2014-3 and 310228/2016-6, respectively) and financial support from CNPq (PELD 403770/2012-2, Universal 477290/2009-4 and 470480/2013-0), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, PROBRAL CAPES-DAAD process 99999.008131/2015-05), and Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco (FACEPE, processes: APQ 0140-2.05/08 and 0738-2.05/12, PRONEX 0138-2.05/14). JMCS received support from the University of Miami and the Swift Action Fund.

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