



# Silvopasture in the Caatinga biome of Brazil: A review of its ecology, management, and development opportunities

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## Abstract

**Aim of study:** Silvopastoral system (SPS) involving numerous indigenous trees and shrubs is a traditional land-use system in the Caatinga, but it has little been studied scientifically. Given the importance of SPS as a sustainable land-use strategy in the drylands, this paper examines the attributes of the Caatinga SPS and their relevance to other arid and semiarid regions.

**Area of study:** Caatinga biome, with an area of 0.9 million km<sup>2</sup> and a population of 25 million, a unique dryland ecosystem of Brazil.

**Materials and methods:** The paper reviewed the literature on the main characteristics of SPS management of the Caatinga biome and the global perspectives of silvopastoral land-management in semiarid regions.

**Main results:** Guidelines for sustainable SPS management of the Caatinga include maintaining up to 400 trees/ha (40% tree cover) and allowing at least 40% of the available forage to dry up to provide mulch for soil protection. Opportunities for improving the low carrying capacity of the Caatinga are thinning, coppicing, and enrichment planting with desirable tree and understory species. Establishment of fodder banks, promotion of non-conventional feed sources such as cactus, and introduction of grazing animals to orchards and plantations are some other promising interventions.

**Research highlights:** The review highlights the importance of initiating new studies on Caatinga SPS, focusing on the role and potential of various native species and the ecosystem services they provide, in conjunction with relevant social, economic, and policy aspects to better exploit the benefits of the system and facilitate its wider adoption.

**Additional key words:** agroforestry; arid and semiarid lands; ecosystem management; fodder trees; food security; livestock production.

**Abbreviations used:** AFS (agroforestry systems); CC (cut and carry); CG (continuous grazing); LSU (life stock unit); SG (seasonal grazing); SPS (silvopastoral system).

**Authors' contributions:** FMP collected available information on the Caatinga system, especially from the numerous reports available in his native Brazilian Portuguese. PKRN contributed to discussing the results and completing the manuscript. The manuscript was prepared jointly by both authors.

**Citation:** Pinheiro, F. M.; Nair, P. K. R. (2018). Silvopasture in the Caatinga biome of Brazil: A review of its ecology, management, and development opportunities. *Forest Systems*, Volume 27, Issue 1, eR01S. <https://doi.org/10.5424/fs/2018271-12267>

**Received:** 15 Sep 2017. **Accepted:** 04 May 2018.

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**Funding:** FMP was supported by a fellowship of the Brazilian National Council for Scientific and Technological Development (CNPq).

**Competing interests:** The authors have declared that no competing interests exist.

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## Introduction

Drylands consist of hyper-arid, arid, semiarid, and dry subhumid categories of the aridity index classification, and occupy 60.95 million km<sup>2</sup> or 41% of the earth's land area. Out of the 2 billion inhabitants of the drylands, about 90% live in developing countries and are relatively more dependent on natural resources than other groups of populations. Between 6 million and 12 million km<sup>2</sup> of these areas are affected by desertification, reducing their capacity to sustain human livelihoods. Thus, tropical drylands are more

exposed than other ecological regions to the threat of environmental degradation (MEA, 2005). Designing land-use systems that are appropriate for productive use of land in perpetuity, which is a major challenge of land management everywhere, is particularly true for the drylands considering their fragile nature and inherently low productive capacity.

In this context, silvopasture, which is a major traditional agroforestry system (AFS) in the semiarid and dry subhumid regions of the world, merits special attention. In silvopastoral systems (SPS), various types of trees are grown in association with understory shrubs

and forage species to support livestock operations (Nair, 2014). Different forms of such systems are practiced in different parts of the world depending on local conditions; these are described in some detail later (Section SPS Management in Semiarid Regions Worldwide).

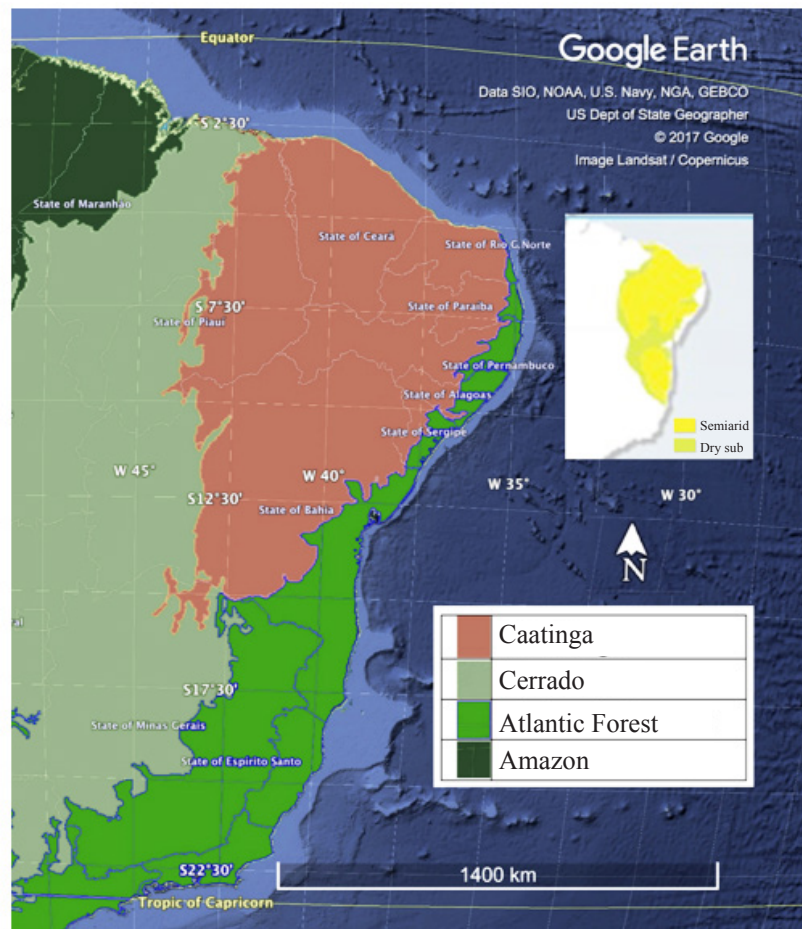
In Brazil, drylands extend over 900,000 km<sup>2</sup>, in the tropical biomes of Caatinga, Cerrado and Atlantic Forest. The Caatinga region that covers 10% of Brazil's land area and 1.4 % of total global area of drylands (MEA, 2005) represents a unique land formation, the ecological and land-management characteristics of which are of significant relevance to the management of drylands worldwide. Except in extremely arid regions, AFS of various types, especially SPS, are practiced in these drylands along with other types of agricultural and grazing systems. With this background, this paper first highlights the main characteristics of SPS management of the Caatinga biome and then examines the global perspectives of silvopastoral land-

management in semiarid regions globally. The overall objective is to identify the management opportunities for the Caatinga region and examine how developments in dryland and SPS management in other regions could be relevant to that. The Caatinga region includes both arid semiarid lands and the experiences from the region are relevant to all drylands; therefore, all these terms (arid-, semiarid-, and drylands) are used in this paper often synonymously.

## The Caatinga Region of Brazil

### Biogeography and climate

The semiarid Caatinga biome in the Northeast of Brazil that occupies about 845,000 km<sup>2</sup> is located between 3° to 17° S, and 35° to 45° W (IBGE, 2004), and spread over ten states (Fig. 1). The climatology of the region is one of the most complex in the world



**Figure 1.** Brazilian dryland biomes include mainly the Caatinga, but also parts of the Cerrado and the Atlantic Forest. The inset on right shows the spread of Brazilian drylands (semiarid and dry subhumid regions). Source: MEA (2005).

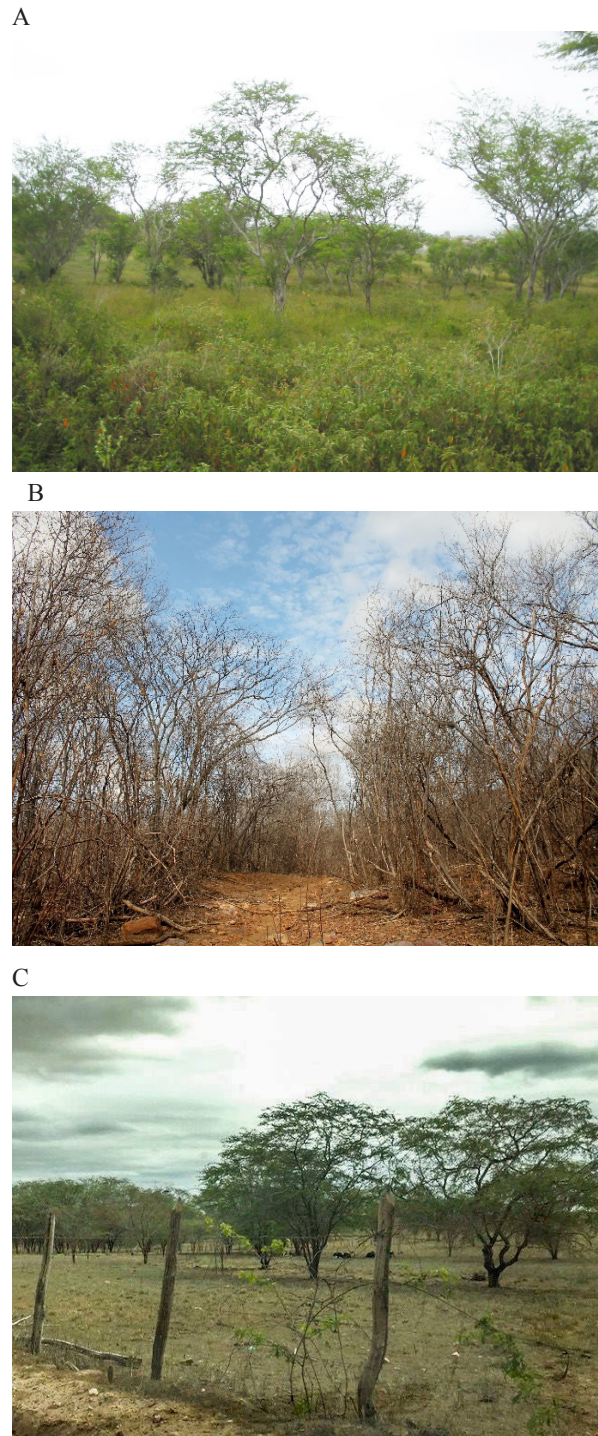


(Fernandes, 2003). Most of the area is located in a “depression,” which, due to the predominance of stable air masses, creates a unique environment of the rainfall being blocked from reaching the biome. As noted by Ab'Sáber (2003), the Caatinga region receives an annual average rainfall of 750–800 mm, the Cerrado and the Atlantic Forest biome that are adjacent to the Caatinga on two longitudinal sides receives much higher rainfall. Furthermore, there is a high degree of year-to-year variation in rainfall in the range of 260–800 mm in the Caatinga region, where rainy season lasts usually for 3 to 5 months, and severe drought periods lasting 3–5 years occur every three or four decades. High annual average temperatures are another striking feature of the Caatinga, with values between 25 to 29°C (Ab'Sáber, 2003). Compared with other regions of Brazil, this region has several extreme meteorological characteristics such as the highest solar radiation, low cloudiness, the highest annual average temperature, the lowest relative humidity, and the highest potential evapotranspiration (Fernandes, 2003).

### Ecology: Soils and vegetation

The soils of the Caatinga region are stony and shallow, with many outcrops of massive rocks. The main soil orders (US Soil Taxonomy) are Ultisols, Alfisols, and Oxisols (Argisol, Luvisol, and Latosol according to the Brazilian soil classification); in general, these soils are of average agricultural potential (Araújo Filho, 2013). Soil erosion is a serious problem in the biome, Utisols and Alfisols being particularly prone to severe erosion (Jacomine, 1996).

The main vegetation type of the biome is a deciduous woodland (Fig. 2), composed of arboreal or shrub forests, mainly low trees and shrubs. Many of them have spines and some xerophytic characteristics (Prado, 2003). The growth rate of a managed native vegetation is correlated mainly with the annual precipitation (61% to 89%), whereas other factors such as past use, soil quality, and grazing intensity, contribute 11% to 39% of growth (Pareyn *et al.*, 2015). The Caatinga has a rich diversity of plants. Forzza *et al.* (2010) described 4,320 species of angiosperms in the biome, 744 of which were described as endemic. According to Araújo Filho (2013), who has provided major descriptions of the ecology and land-use systems of the Caatinga region, the most frequent botanical families are Cactaceae, Caesalpinaceae, Mimosaceae, Euphorbiaceae, and Fabaceae, the major genera being *Senna*, *Mimosa* and *Pithecellobium*. The most common woody species are *Amburana cearensis*, *Anadenanthera colubrina*, *Aspidosperma pyriforme*, *Poincianella pyramidalis*, *Croton* spp., *Cnidocolus quercifolius*, *Commiphora leptophloeos*, *Mimosa* spp., *Myracrodruon urundeuva*, *Schinopsis brasiliensis*, and *Handroanthus impetiginosus* (Prado, 2003).



**Figure 2.** Caatinga in the wet (A) and dry (B) seasons. A smallholder silvopastoral farm in the Caatinga region (C). Sources: Allan Patrick in Rio Grande do Norte (A); Thiago Parente in Paraíba (B); Alisson Nascimento in Sergipe.

### Livestock and fodder availability

Livestock activities in the Caatinga biome are concentrated in a region that resembles a savannah, with an abundant herbaceous vegetation and arboreal shrub

covering about 20%, and the tree density varying from 0 to 300 plants/ha. About 70% of the tree species of the Caatinga are fodder trees, some better forage as leafy materials, and others as litter in dry periods (Araújo Filho *et al.*, 1998). The major fodder shrub/tree species that are browsed by the animals and their characteristics are included in Table 1.

Livestock in the biome are mainly cattle, sheep, and goats. In the native forests without management, they derive more than 70% of their diet from the woody vegetation (Araújo Filho *et al.*, 1996) (Table 2); but it is less than 10% of the biomass produced, because most of the leaf produced in the rainy season is not accessible to the animals and in the dry season the biomass is of lower quality and is less preferred by animals (Araújo Filho *et al.*, 2002). The management of the native vegetation can change the main feed source of these animals, mainly cattle (Table 2). A good comprehension of these animals' behavior in the biome and ways of improving forage availability/productivity of each species alone and in combination with other species is critically important for successful management of SPS.

During the dry season, which is the season of nutritional stress, the Caatinga vegetation has little or no forage in the "bipedal foraging zone" (accessible to animals while

standing up on two rear legs and leaning on to the tree) and leaf litter is the dominant component of the available forage. The quantity of leaf litter available during the dry season varies from 500 to 1,500 kg/ha, which constitutes 20–70% of the animal's annual diet (Pfister & Malechek, 1986). Leaf litter of most deciduous trees contain 10% crude protein throughout the dry season (Pfister, 1983), and goats are better adapted than other animals to take advantage of this resource.

In the Caatinga, more than 90% of the farms have herds of more than one animal species simultaneously (Araújo Filho, 2013). Reviewing pasture management practices of the region, Cândido *et al.* (2005) highlighted that the diet of goats and sheep (or cattle) are complementary due to different grazing preferences. The degree of dietary overlap between sheep and goats is greatest in the dry season and almost complementary in the wet season. During the year, sheep spend significantly longer time than goats foraging the herbaceous vegetation, while goats tend to prefer browse matter (Pfister *et al.*, 1988). Although the feeding behavior of goats compared to that of sheep changes more during the seasons, no evidence has been found to conclude if survival rate of goats was correspondingly higher in the region (Pfister & Malechek, 1986). It is likely that during the dry season when forage

**Table 1.** Common fodder trees and shrubs of the Caatinga region and their characteristics.

Species	Height and succession stage	Growth habits and coppicing ability	Fodder availability, animals' preference	Other possible uses
<i>Aroeira</i> ( <i>Myracrodruon urundeuva</i> )	Up to 25 m. End of secondary succession, near climax	Moderate growth. No coppicing	Leaves consumed either green or dried	Wood for construction. Medicinal. Bees (nectar and pollen)
<i>Catingueira</i> ( <i>Poincianella pyramidalis</i> )	Up to 10 m. Secondary succession (intermedium)	Slow growth. No coppicing	Leaves highly preferred when dry (dry season-up to 35% of the animal's diet)	Wood for construction. Bees (nectar and pollen)
<i>Juazeiro</i> ( <i>Ziziphus joazeiro</i> )	Up to 10 m. End of secondary succession, near climax	Slow growth. Inverted phenology, trees grow new leaves in the dry season. No coppicing	Leaves consumed when green in the dry season. Fruits consumed in wet season	Strategic fodder bank for drought periods. Medicinal. Fruit tree (human and animal consumption). Bees (nectar and pollen)
<i>Jurema-preta</i> ( <i>Mimosa tenuiflora</i> )	Up to 8 m. Beginning of the secondary succession	Fast growth. Leaves remain green during the dry season (even more if coppiced). Coppicing recommended	Leaves highly preferred when green (wet season). Fruits avidly consumed in the beginning of dry season	Strategic fodder bank for drought periods. Nitrogen fixing. Firewood. Medicinal. Bees (nectar and pollen)
<i>Mororó</i> ( <i>Bauhinia cheilantha</i> )	Up to 8 m. Pioneer and in secondary succession (intermedium)	Slow growth. Coppicing recommended	Consumed when green (wet season)	Firewood. Bees (nectar and pollen). Nitrogen fixing
<i>Sabiá</i> ( <i>Mimosa caesalpiniiifolia</i> )	Up to 9 m. Secondary succession (intermedium)	Fast growth. Coppicing recommended	Highly preferred when green (wet season)	Firewood. Bees (nectar and pollen). Easy to spread, roots may grow out of branches. Nitrogen fixing

Source: Adapted from Araújo Filho (2013).



**Table 2.** Contribution of different botanical groups of vegetation to the diet of cattle, goat, and sheep in a Caatinga forest without management and after the thinning treatment; average of dry and wet seasons.

Animal species	Proportion of botanical components (%) to the animals' diet					
	Native vegetation			Thinning treatment		
	Grass	Herbs	Trees	Grass	Herbs	Trees
Cattle	12	17.8	70.1	74.9	18.3	6.8
Goat	2.8	10.4	86.8	17.5	26.2	56.2
Sheep	9.4	12.9	77.6	34.1	51.8	14

Source: Adapted from Peter (1992).

supply is less, both species of animals tend to feed from the same forage sources.

### Land use systems and dynamics

Despite water limitations, more than 25 million people live in the Caatinga biome. Currently the main land-use systems of the biome are livestock and crop production and firewood collection from the native vegetation to support the industry and the local demand (IBGE, 2006).

Historically, livestock-related activities were the primary occupation of the inhabitants. That situation has not changed, and continues to be very important for local farmers. In a drought year, the agricultural production in the state of Ceará, a major state of the Caatinga region, declines by up to 84%, whereas livestock activity drops by only 20% (Araújo Filho, 2013). On the other hand, livestock activities using practices like slash-and-burn with a fallow period shorter than 50 years, overgrazing, and intense firewood gathering accounted for about 45% of deforestation and desertification in many regions in the biome (MMA, 2007; 2011). The recognition of the negative impact of livestock activities in the biome and recommendations on tree growing in the pasture for improving livestock productivity date back to the 1860s (Braga, 1962). Today, a substantial body of knowledge on sustainable land use systems in the biome, mainly SPS, is available as numerous reports and books that describe these practices (Araújo Filho, 2013; Cândido *et al.*, 2005).

## Silvopastoral management in the Caatinga Region

As mentioned, traditional management of the Caatinga biome includes site-specific silvopastoral activities of various intensities that are influenced by a multitude of ecological and sociocultural characteristics. Therefore, recommendations for management-

improvement opportunities have to be of a broad nature ranging from improvement opportunities for native forests to SPS opportunities. Some of the suggestions and recommendations given below have been implemented to varying degrees in the region, while others are innovative opportunities based on experience from elsewhere.

### Native forest management

The guidelines for sustainable management of the native Caatinga forest (Araújo Filho, 2013) include three important norms to be followed: 1) maintain up to 400 trees/ha (40% tree cover), 2) limit the use of available forage to a maximum of 60% per year, and 3) preserve the riparian forest (Araújo Filho, 2013). Allowing at least 40% of the available forage to dry up to provide mulch is important for soil protection. Araújo Filho *et al.* (2002) reported that maintaining 30% of tree cover in the Caatinga pastureland increased both forage and meat production.

The carrying capacity of the arboreal shrub vegetation without management for supporting animal production is very low: an area of about 10 ha is necessary to support one life stock unit (LSU) of cattle and 2 ha/animal for sheep or goat. Overall, in the native vegetation without management, goats and sheep perform better than cattle (Tables 3 and 4): goats can gain an annual live weight of up to 11.9 kg/ha, sheep 9.7 kg/ha, and cattle 5.6 kg/ha (Araújo Filho *et al.*, 2002). Thus, proper management of the native forest is an important step toward sustainable use of resources. Some of the management options for the Caatinga forest are described below.

### SPS opportunities

Four main SPS management practices have been suggested for increasing forage productivity or animals' accessibility to forage of the native vegetation of the Caatinga region. These are: thinning, coppicing, thinning + coppicing, and enrichment (Table 5).

#### Thinning

Thinning the tree stand opens up the overstory canopy and helps more sunlight to be transmitted to the understory and thus increase yield and availability of herbaceous understory plants for cattle and sheep (Tables 3 and 4). Goats under this management practice can gain an annual live weight of up to 33.8 kg/ha, sheep 32.6 kg/ha, and cattle 57.8 kg/ha consequent to improvement in their forage diet (Table 2). With this management, the area required to support one LSU of cattle is 3.5 ha and 0.5 ha for goat and sheep (Araújo Filho *et al.*, 2002).

**Table 3.** Influence of management treatments on the daily mean live weight gains of the different animal species in the dry and wet seasons.

Animal species	Management treatments and daily mean live weight gains (g/LSU)							
	None		Coppicing		Thinning		Enrichment <sup>[1]</sup>	
	D	W	D	W	D	W	D	W
Cattle	-155.7	275.5	-132.9	405.8	-11.5	621.0	25.0	650.0
Goat	14.9	36.1	27.8	54.0	26.8	57.7	18.0	47.0
Sheep	18.2	44.0	21.0	47.7	32.0	77.9	29.0	69.0

LSU= Life stock unit; D = Dry season; W = Wet season. Source: Adapted from Araújo Filho *et al.* (2002) and <sup>[1]</sup> from Araújo Filho (2013).

**Table 4.** Annual live-weight increase of cattle, goat, and sheep browsing and grazing on native Caatinga vegetation following different management treatments.

Animal species	Annual live-weight increase per animal (kg/ha) following treatments			
	No treatment	Coppicing	Thinning	Enrichment <sup>[1]</sup>
Cattle	5.6	22.3	57.8	172
Goat	11.9	41.3	33.8	120
Sheep	9.7	19.1	32.6	180

<sup>[1]</sup> Enrichment done with the grass species *Cynodon dactylon* and phosphate fertilization. Source: Adapted from Araújo Filho *et al.* (2002) and <sup>[1]</sup> from Araújo Filho (2013).

One important consideration for this management is to decide which trees (of different species as well as individuals of the same species) to be removed vs. retained. Examples of fodder trees that should be kept include: *mororó* (*Bauhinia cheilantha*), *pau-ferro* (*Libidibia ferrea*), and *sabiá* (*Mimosa caesalpiniiifolia*), and, on the other hand, tree species that are not accepted as forage can be considered for removal, or maintained for other purposes (*i.e.* conservation), like *Auxemma oncoalyx* one of the least consumed by sheep and goats (Kirmse *et al.*, 1987).

Some common norms to be observed are that 40% tree cover (around 400 medium size trees/ha) may be maintained, and thinning should be avoided in areas of slopes steeper than 25%. Thinning regimes should be designed such that the tree arrangements after thinning should result in one of the three configurations: (1) Savannah (trees dispersed on landscape); (2) tree clusters consisting of small groups of trees together as a cluster or group and the clusters scattered on the landscape; and (3) tree alleys in which trees are planted close together in single or double rows with wider distances between tree rows (as in alley cropping type of agroforestry). The alley type of arrangement is recommended for slopes of 10–25%, and the savannah and tree clusters for slopes less than 10%, for facilitating soil conservation (Araújo Filho, 2013).

### Coppicing

Coppicing refers to cutting the trees' branches or trunks at a low height, usually 20–30 cm above ground, to facilitate vigorous re-sprouting of new shoots in an accessible stratum for the animals, enhancing the quality of the animals' diet (Kirmse *et al.*, 1987; Araújo Filho *et al.*, 2002). Goats gain an annual live weight of up to 41.3 kg/ha, sheep 19.1 kg/ha, and cattle 22.3 kg/ha (Table 4). For this type of management, the area required to support one LSU of cattle is about 5 ha and 0.7 ha for goat and sheep. For the combination of cattle (or sheep) and goat is recommended, *i.e.*, one head of cattle/sheep for every six to eight heads of goat (Araújo Filho, 2013). Thinning and topping can also be done together.

Coppicing should not be done uniformly to all tree species; the rate at which the trees resprout varies considerably among species. Some resprout vigorously, while some do not resprout at all and they die off once they are cut. Species that are preferred by animals and can withstand coppicing include: *jurema-preta* (*Mimosa tenuiflora*), *jurema-branca* (*Piptadenia stipulacea*), *quebra-faca* (*Croton conduplicatus*), *feijão-bravo* (*Capparis cynophallophora*), *carquejo* (*Calliandra depauperata*), *camaratuba* (*Cratylia mollis*), *marmeleiro* (*Croton hemiargyreus*), *sabiá* and *mororó*. Some trees that are not forage but have contribution

**Table 5.** SPS Management treatments for the Caatinga native vegetation.

Management treatment	Purpose	Management and ecological considerations	Difficulties/ Concerns
Thinning	Increase herbaceous productivity; produce wood and firewood; support cattle or sheep production	Keep at least 30% of tree cover; retain fodder trees or trees with ecological values; trees that provide forage for longer periods during the year are preferred; the practice is preferred for cattle or sheep	Difficult to evaluate seed needed for optimum herbaceous productivity; identification of trees to be retained or removed could be problematic; not suitable for areas with more than 25% slope
Coppicing	Increase herbaceous productivity and accessibility of the animals to the tree foliage. Support goat production (potential for combination with cattle or sheep).	Reduce trunk height of fodder trees to about 30 cm above ground. Control the regrowth to about two branches per trunk	Identification of trees to be coppiced could pose challenge; animals may impact tree survival and regrowth after coppicing/ browsing
Thinning + Coppicing	Same as above, with higher level of animal productivity. Support production of all three groups of animals	Same as above. Ideal for integrating more than one animal species, like goat and cattle (or sheep)	Same as those above
Enrichment	Significantly increases the forage production. Focus could be on the tree or/and the grass component	Can be done in conjunction with any of the other three treatments. Potential use of native and non-native plants (trees/shrubs/ grasses), and integrating more than one animal species (goat/cattle/ sheep)	Ensuring soil conditions for optimum plant growth; selection of plants adapted to local conditions; seed availability (collection vs. purchase); tree seedlings may need to be protected possibly by intercropping when trees are young
Grazing	Opportunities for commercialization	Cows and sheep feed mainly on grasses while goats prefer tree leaves	Evaluation and adjustment to make the stock of grasses and fodder trees ideal to sustain the animals over the seasons

Source: Adapted from Araújo Filho (2013).

to the system ecologically, medicinally or economically should not be coppiced; the examples include *baraúna* (*Schinopsis brasiliensis*), *umbuzeiro* (*Spondias tuberosa*), *pereiro* (*Aspidosperma pyrifolium*), and *embiratanha* (*Pseudobombax marginatum*). Trees that are consumed when dry or used for hay production such as *catingueira* (*Poincianella pyramidalis*) should also not be coppiced (Araújo Filho, 2013).

### Enrichment planting

Enrichment or enrichment planting refers to the practice of introducing additional plants into an existing stand of plants, increasing the overall productivity from the land. Araújo Filho (2013) described that enrichment plantings in the Caatinga region can result in live-weight increases of up to 120 kg/ha for goats, 180 kg/ha for sheep and 172 kg/ha for cattle (Table 3). The LSU can be one cattle/ha and up to 10/ha for goats and sheep (Araújo Filho, 2013). The species used for enrichment of the grass component include: buffel (*Cenchrus ciliaris*), *capim-gramão* (*Cynodon*

*dactylon*), *capim-corrente* (*Urochloa mosambicensis*), and *capim-andropogon* (*Andropogon gayanus*).

The tree component to be used for such enrichment planting could be either exotic species such as leucaena (*Leucaena leucocephala*), *algaroba* (*Prosopis juliflora*) and *gliricidia* (*Gliricidia sepium*) or native multipurpose trees such as *juazeiro* (*Ziziphus joazeiro*), *umbuzeiro*, and *aroeira* (*Myracrodruon urundeuva*). *Umbuzeiro* produces a locally consumed fruit and the leaves are palatable to animals; *juazeiro* can be used as medicinal species and for production of fruit, wood, and forage; and *algaroba* is an excellent fodder species as a green fodder in rainy season and leaves and fruits in the dry season; it has high-quality timber and is a nitrogen-fixer too (Araújo Filho, 2013).

Reports on the survival of tree seedlings used for enrichment planting in the Caatinga are not available; this is an aspect that needs investigation. Furthermore, studies from two arid regions, northwestern India (Vishwanatham *et al.*, 1999) and northern China (Lai *et al.*, 2014), have pointed out the importance of

maintaining adequate distance between tree seedlings and grass patches to reduce belowground competition.

### Other vegetation management techniques

#### Fodder bank

Management of the native vegetation can and sometimes should be done with techniques and treatments that may be new yet relevant to the location. Introduction of a “fodder bank” is one such strategy. A fodder bank is an assemblage of tree and shrub species that are predominantly fodder species, but are multipurpose in nature, providing multiple products and services such as for forage, fruits, soil fertility improvement, and biodiversity habitats. They can be assembled as woodlots, live fences, wind breaks, soil conservation barriers, and for similar other purposes. Usually, the fodder is cut and carried to stall-feed the animals, but sometimes are allowed to graze on the fodder bank in a controlled manner for defined periods of time (Cândido *et al.*, 2005).

The Caatinga Research Institution of the Instituto Nacional do Semiárido, Campina Grande/PB, is studying native and exotic trees for fodder banks; the species include *canafistula* (*Peltophorum dubium*), gliricidia, leucaena and moringa (*Moringa oleifera*) (INSA, 2015). As an example, leucaena can produce 1.3 to 6 Mg/ha of dry biomass annually while also contributing to soil fertility (Duarte, 2002). *Gliricidia sepium* is adapted to a wide range of water (rainfall) regimes including under water-stress conditions. In a study using trees planted in 6 m × 1 m spacing between and within rows respectively at Campina Grande, Marin *et al.* (2006) found a higher soil concentration of nutrients (P and K) under the trees, and a temperature 6°C lower under the trees than away from the trees (middle of the rows). Additionally, the litterfall from trees was kg 1,390 kg/ha under the trees, compared with 270 kg/ha, 3 m away from the trees. A native tree species with potential as a fodder bank species is *catinguera* (*Caesalpinia pyramidalis*), which is drought tolerant. Although its green leaves are not palatable, animals relish the dry leaves that are nutritious and thus it has potential as a reserve feedstock in the late dry season (Pfister & Malechek, 1986). The protein-rich foliage of fodder trees such as leucaena and gliricidia can also be preserved by drying (hay) or fermentation (silage) for lean fodder-availability seasons (Cândido *et al.*, 2005).

#### Non-conventional feed resources

Another plant that is suitable for feed supplementation during the dry season or drought periods is cactus. In the Caatinga, goats grazing on native vegetation half year had their diet quality improved in the reproduction period with the cactus *Opuntia ficus-indica* (Soares *et al.*, 2012). The cactus *Nopalea cochenillifera* has also shown potential as forage for sheep (INSA, 2015).

Elephant grass (*Pennisetum purpureum*) could also be used more frequently (Araújo Filho, 2013).

Crop residues of common crops could also be used to feed animals, but with nutritional supplementation; such common crops include maniçoba (*Manihot glaziovii*), sugarcane (*Saccharum officinarum*), cassava (*Manihot esculenta*), maize (*Zea mays*), rice (*Oryza* spp.), and beans (*Phaseolus* spp. and *Vigna* spp.). One study in the Caatinga on goats fed on native vegetation with supplemental diet of maize and sorghum (*Sorghum bicolor*) in the dry season was reported to have increased the system resilience during drought periods (Moreira *et al.*, 2000). Another alternative to increase the protein content of feeding sources is the use of multi mixtures and salts with protein. For example, a mix of cassava tubers (low in protein) and the cassava leaves (high in protein) that should be dried in the sun to remove their toxic chemicals (cyanide) and then fed the animals (Cândido *et al.*, 2005). Schacht *et al.* (1992) studied the desirability of using urea and/or molasses as feed supplements to goats grazing on the Caatinga vegetation and found that the molasses + urea treatment resulted in average daily weight gains of nearly twice as high for other treatments. The more pronounced effect occurred in later in the dry season, when the quality of forage decreased.

#### Conversion of orchards

Another type of SPS being adopted in the biome is the introduction of animals in orchards and plantations to help in weed management and for the manure. This is being practiced in the irrigated fruit-orchards of mango (*Mangifera indica*), *Psidium guajava*, *Malpighia glabra*, and *Annona squamosa* and in non-irrigated stands of *Anacardium occidentale*, *Syagrus coronate*, and *algaroba*. In fruit orchards of vines (*Vitis* sp.) and mango, experiments with sheep showed satisfactory animal weight and weed control efficacy (Guimarães Filho *et al.*, 2000; Guimarães Filho & Soares, 2003). The conversion of the mango orchard reduced the cost of the production in about of 6% (Guimarães Filho & Soares, 2003).

#### Special systems for small and medium-sized farms

Considering all the possible management approaches described above, different systems have been recommended for the Caatinga region with the general objectives of improving nutrient cycling, forage availability and soil resilience. Two main systems are described below, but several other possibilities exist (Araújo Filho, 2013).

The Saf-Sobral system is one that focuses on food production. Food crops are grown in the rainy season in about 20% of the total land holding (which could be < 10 ha). After the crop, a fodder bank is established where the animals can graze in the dry season on both the crop residues and the leguminous fodder trees.



This is a promising option for smaller farms with land holdings of area > 3 ha. Considering that most of the farms in the biome are < 10 ha in area, this system has a great potential of adoption and can play an important role for food security (Araújo Filho, 2013).

Another promising system for the region is the Caatinga-Buffer-Leucaena System, for farms that are larger than 20 ha, but preferably larger than 100 ha. This system has three areas: an open pasture, a fodder bank, and the native vegetation. The native forest is 1/3 to 2/3 of the total area; animals can graze over the area mainly during the rainy seasons (3-4 months), when the native vegetation offers good forage of herbaceous and tree vegetation. The area of the open pasture should be no more than 80% of the area and the fodder bank 10-20% of the pasture area (Guimarães Filho *et al.*, 1995). The open pasture should have some grass species such as buffel, which can sustain the herd in the dry season. The fodder bank, with some multipurpose trees such as leucaena should either be allowed to be browsed by animals for short periods (2 h/day) or the foliage could be used in a cut and carry system (Cândido *et al.*, 2005); nutritional supplement with molasses could also be given to animals (Guimarães Filho *et al.*, 1995).

## SPS management in semiarid regions worldwide

### Main SPS in semiarid regions worldwide

Silvopastoral systems practiced in different parts of semiarid to arid regions of the world have been described in several publications (Nair, 1989; Boffa, 1999; Moreno & Pulido, 2009; Rojas *et al.*, 2016). In the Middle East and the Mediterranean, the most widespread SPS is the Dehesa system in the oak woodlands of Spain and Portugal, estimated to cover more than 3 million ha (Mosquera-Losada *et al.*, 2012; Moreno & Pulido, 2009). In this system, widely spaced natural oak trees (*Quercus rotundifolia*, *Q. suber*, and *Q. faginea*) are traditionally used mainly for rearing pigs and cattle and harvesting a variety of wood products (e.g., timber, charcoal, tannin, and cork) for local inhabitants for centuries. Today sheep is the main grazing animal, although goats, cattle, and pigs are also important components. Grazing management is flexible but includes moving animals to field stubble and fodder sources during dry summer months, with concomitant resting periods for grasslands (Joffre *et al.*, 1988). Open woodlands in other Mediterranean countries are also used as SPS, with either oaks or carob trees (*Ceratonia siliqua*). Various intercropping systems including silvopasture with olive trees (*Olea europaea*) are also

very common in the Mediterranean especially Greece (Papanastasis *et al.*, 2009) and Portugal (Castro, 2009).

In Chile, SPS management practices include fodder banks, grazing in croplands, family gardens; but due to the high aridity in many regions, only a few tree species are able to survive producing forage/food, *Acacia saligna*, *Prosopis tamarugo* and *Prosopis chilensis* being the most common (Rojas *et al.*, 2016). These species are also common in salt-affected soils and severely degraded arid regions in Peru, Bolivia, and Argentina. Throughout the arid and semiarid regions of these regions, these species are used in reforestation projects as well as a variety of other land-use systems that may not strictly fall under the category of SPS, including degraded-land reclamation, soil-erosion control, and supplemental human food items such as breads and biscuits and nutraceuticals (Rojas *et al.*, 2016).

In East and Central Africa, SPS are *Acacia*-dominated in the arid parts of Kenya, Somalia and Ethiopia; protein bank (cut and carry) and fodder production are also very common. In the arid and semiarid West Africa, the Parkland system (Boffa, 1999) is most common agroforestry system which also includes integrated crop and animal production in association with multipurpose trees yielding fodder and fuel. Numerous reports are available on this and similar extensive SPS in the region (Garrity *et al.*, 2010).

Overall, the nature of management of these systems is in accordance with the general land-use scenarios and socioeconomic conditions of the regions and countries concerned. Thus, in Africa and the Indian subcontinent, the SPS systems are more subsistence-oriented and labor-intensive than in the Mediterranean and southern regions of South America, where the system management is more capital-intensive and less labor-intensive. An overview of those systems and their characteristics is beyond the scope of this paper. Instead, some common features related to livestock production and SPS in the semiarid regions worldwide and the commonalities and contrasts between the Caatinga SPS and SPS in other parts of the world will be examined briefly in the following sections.

### Developments in SPS management worldwide with relevance to the Caatinga

#### *Calculations and estimations for the systems' resilience*

Estimations and calculations based on computer models are becoming popular in designing management options for sustainable of livestock activities. Detailed surveys and inventories of local conditions and stocks of natural resources including vegetation characteristics, species

composition, tree cover density, biomass productivity, litter production, forage consumption, and animal carrying capacity are some of the points need to be measured for the Caatinga. To the extent possible, farmers should be educated about these calculations and their experience taken into proper consideration. Araújo Filho (2013) has given a detailed account of the major factors to be taken into consideration.

Some computer models are available to estimate the productivity of arid environments. Mor-Mussery *et al.* (2013) developed a model to predict high yield on a sustainable basis in Israel's arid lands; it is reported to be flexible that allows for adjustment of various parameters (tree growth rate, the grazer's monthly consumption, animal species, and type of fodder) for optimum benefits. One model, for example, showed that grazing capacities for sheep and goats were two times higher in the woodland than in the adjacent sustainably managed shrub-lands, and four times higher than in degraded shrub-lands (Mor-Mussery *et al.*, 2013).

### **Soil resilience**

In the management of any native vegetation as well as anthropogenic grasslands for livestock activities in drylands, plant productivity/survival is a main concern, for which soil resilience plays a key role. Studies have shown SPS as the most efficient land-management system in the Caatinga to minimizing soil degradation processes, reducing water erosion and losses of nutrients and carbon (Menezes & Salcedo, 1999). Aguiar *et al.* (2010) compared SPS management in the Caatinga to many other practices commonly applied in the region such as intensive cropping, slash and burn, firewood collection, and secondary forest in natural stands, and found that SPS was always one of the best for reducing water and soil losses, and improving soil organic carbon and nutrient content. Additionally, the native vegetation and/or mulch is described to reduce loss of water and soil by more than 70%, compared to deforested areas and soils without mulch (Albuquerque *et al.*, 2002). Studies on the soil improvement potential of specific tree species and comparing to open areas in the Caatinga have reported that the soil near trees such as *algaroba*, *juazeiro*, and *umbuzeiro* increased the level of soil organic matter and nutrients (N, P, K, Ca, and Mg) (Menezes & Salcedo, 1999; Correia *et al.*, 2014; Pezzopane *et al.*, 2015).

In Jodhpur, Rajasthan state, India, an arid region, the tree litter from a SPS was reported to have increased soil fauna abundance and soil fertility (Tripathi *et al.*, 2013). In a semiarid highland in northern Ethiopia, seasonal "resting" of lands (avoiding livestock interference) on regular basis helped regain key vegetation attributes and soil properties (Habtemicael *et al.*, 2015).

### **Seasonality and grazing regimes**

Grazing limits are very important in the semiarid regions. Overgrazing can cause soil compaction, exterminate seed bank, and curtail the plant's capacity for regrowth. Management measures should be put in place to overcome the effects of dry season and drought years on the availability of forage and the impact of the animals on surviving plants as well as soil erosion. Grazing regimes can play an important role in that. Management of areas without animals can avoid effects of overgrazing and will be economically important; for example, by supporting those that require extra nutrients and energy such as pregnant or lactating animals.

In a study in Northern Oman, areas not grazed by goats had substantially higher species diversity and herbaceous mass yield compared to grazed areas (Schlecht *et al.*, 2009). In the same region, when goats were fed mainly from the native vegetation of generally low yet widely ranging nutritional quality, the productivity was limited. An alternative strategy that was suggested to overcome the problem was an intensive livestock feeding in zero-grazing systems, coupled with cut and carry (CC) the vegetation from ecologically fragile zones (Dickhoefer *et al.*, 2011). This example shows the potential use of recovering or sensitive areas, which may not be suitable for animal grazing, but still can produce forage that can be cut and carried.

A study in Ethiopia compared three grazing regimes: CC, seasonal grazing (SG), and continuous grazing (CG). The CG had the lowest species diversity and richness during the rainy season, and affected negatively the soil bulk density, total nitrogen, and the herbaceous basal cover which was 6.8 times smaller than CC. For the occurrence of not desirable or intended plants, like non-forage species, CC was also the best management for the dry season, although in general SG regime improved soil phosphorus (Habtemicael *et al.*, 2015).

### **Animal welfare**

The maintenance of source of animal feed can be considered the main focus, but the effect of strong light intensity without shades over the animals in hot regions may play a significant effect on their welfare and productivity. The potential of microclimate amelioration by the trees to cattle for example is described for the Cerrado biome (Paciullo *et al.*, 2014). Although there are no reports about the effect of tree shading on the animals in the Caatinga, in a homestead study, the shading provided by trees increased milk yield by 3.5 kg/day (Domingos *et al.*, 2013). The role of shading in increasing animal welfare and optimizing productivity should always be considered, but possible adverse effect of too much shading by trees on herbaceous productivity will also need to be weighed in.

### **Salinization**

Soil salinization is a major concern in many arid regions worldwide, and the Caatinga region is no exception to this (Lima *et al.*, 2001). A recommendation to address the problem, worldwide, is to grow salt-tolerant plants that can be used as forage (directly or after chemical process) (Gul *et al.*, 2014). In this context, it is also important to consider if the halophytes selected as forage species contains any toxic compounds that are harmful to the animals. In situations like that, the animals should gradually be conditioned to optimum water-intake (Gul *et al.*, 2014).

The best species for halophytic fodder crop preferably contain > 5% protein and < 10% ash. Many halophytes can fulfill the animals' protein requirement, but if the species has 10-15% ash, it may be used as supplements to regular feed (El Shaer, 2010). Before feeding the species with high ash and or toxic chemicals to animals, they are sometimes subjected to treatments such as chopping, soaking, washing with brackish water followed by washing with fresh water, air drying, and ensiling to help reduce or moderate the adverse effect (Gul *et al.*, 2014).

Ramirez-Restrepo *et al.* (2004) showed for a New Zealand region with soil moisture deficits that sheep fed on *Lotus corniculatus* had higher live weight gain and wool production, and the animals were free from internal parasites, saving expenses with medicines (attributed to the presence of 2.4-2.7% condensed tannins on dry weight basis). In a review of the use of halophytes for livestock feed in arid and semiarid regions of Pakistan, Gul *et al.* (2014) highlighted many benefits of using halophytes plants. Perennial halophyte grasses like *Distichlis palmerii* and *Leptochloa fusca* have a low cost since they do not require annual re-seeding and they are successfully used as forage for cattle worldwide. The review by Gul *et al.* (2014) also described many species capable of producing biomass of 40 to 50 Mg/ha annually providing high-quality fodder with low anti-nutrient compounds and low ash content.

### **Social aspects**

Social considerations are also very important for livestock and SPS activities in arid regions, especially when considering the adoption of new management strategies. Studies on the cost of implementation of SPS, economic evaluation and farmers perceptions should also receive more attention, both in the Caatinga and worldwide. Issues such as animal selection, educational level of farmers, gender role, land concentration, and local economy play important roles in land management in arid regions too as everywhere else.

In the Caatinga, for example, most farms are less than 10 ha in area and most farmers do not know the concept of overgrazing. In an effort to intensity land use, sometimes they adopt poor management practices that compromise the system's resilience, threatening food security (Araújo Filho, 2013). The lack of interest to adopt sustainable practices in a region in the Caatinga was reported to be associated with poor education level of farmers and smaller land-holding size (Nunes *et al.*, 2014). Educational projects and enabling land policies are of utmost importance in the region, which is, again, universally true.

Although some animal species may be preferred for ecological aspects, farmers may have important concerns that are not limited to just livestock productivity. In a study about decision models in a dryland in Zimbabwe, goats were almost always preferred compared to cattle, the opposite occurred only when cattle were used for draft power. Although cattle productivity decreased due to this activity, the considerable increase in crop production was reported to have compensated for that, especially by wealthier farmers (Milner-Gulland *et al.*, 1996).

Gender roles also should be considered for any future projects, and it may play a key role in rural projects. Nunes *et al.* (2014) found that in a region in the Caatinga, 90% of the farmers are male, whereas in Africa, poverty alleviation and rural business development programs were successful when women were involved in the programs. Consideration of gender roles may also be important in the semiarid regions in Brazil and elsewhere.

Economic activities in the region can also push farmers to adopting a specific activity. In the Caatinga, for example, the firewood activity generates about 90,000 direct jobs in the rural zone and have become attractive during the past few years. Although in general this practice causes deforestation, a different output is described when the firewood-gatherers received governmental support. In 2015, a total of 4,000 families in 468 sustainable forestry management plans were maintaining or increasing the biodiversity of plants, with positive impacts on fauna, and increasing their domestic income (Gariglio, 2015). These management plans supported by the government, by collecting wood in the dry season when the crop production stopped, could also integrate livestock activities, which could eventually lead to an economic development in the region.

### **The Caatinga SPS experience: Relevance to other regions**

In terms of ecological and land-use characteristics, the Caatinga region is distinctly different from and less studied than the two other ecological regions between which it is "sandwiched" – the Cerrado to the left and



the Atlantic Forest to the right – as described in Section The Caatinga Region of Brazil. Although some studies on the Caatinga region have been conducted as reviewed in the previous sections, the region is perhaps one of the least-studied and economically backward in Brazil. Little is recorded on its ecology and land-use history, resource utilization patterns, and development potential. Therefore, the relevance of the Caatinga experience to other regions has to be projected based more on intuition than on scientific background. Nevertheless, given that the world's drylands and the proportion of world population affected by water scarcity and severe drought conditions are projected to expand by 10% by the end of this century under a high greenhouse-gas-emission-and-global-warming scenario (Fu & Feng, 2014), the Caatinga experience would be increasingly relevant. To attain this, intensified efforts are needed on three fronts: development of a scientific body of knowledge, exploitation of ecosystem services, and design of innovative management techniques.

The lack of a rigorous body of scientific knowledge on the Caatinga is a serious deficiency, but also a major opportunity for future efforts. The seemingly vast biodiversity of the region is one such exciting opportunity. Biodiversity of ecosystems is proving to be one of the best defenses against extreme weather and rising temperatures (Duffy *et al.*, 2017). As reported earlier (Section Ecology: Soils and Vegetation), Forzza *et al.* (2010) described 4,320 species of angiosperms in the biome, 744 of which were described as endemic. What is known could be a small fraction of what is unknown. Furthermore, the potential attributes and uses of many of the species that have been identified have not been studied. Efforts to study and exploit the potential of those species could open up enormous opportunities for enhanced use of ecological knowledge for economic development not only locally but in other semiarid regions and drylands as well.

A major area of unexplored potential of the Caatinga biome in terms of the ecosystem services is related to soil carbon storage. Some of the studies from the Caatinga region on this aspect have been mentioned in Section Developments in SPS Management Worldwide with Relevance to the Caatinga. Additionally, numerous studies have recently been reported on enhanced soil carbon sequestration under SPS compared to woodlands, both natural and planted. Upson *et al.* (2016) reported from the UK that 14 years after tree planting, soil organic carbon in surface soil layer (0–10 cm) was higher in the SPS than under woodlands, and the SPS was predicted to achieve a higher level of carbon storage than equivalent areas of separate woodland and pasture. Based on a study from four spontaneous SPS in southern Ecuador, McGroddy *et al.* (2015) reported that

adding trees to pasture provided carbon sinks in woody biomass and suggested that having a low density of trees in pastures could substantially increase carbon sequestration without affecting cattle production. These and several other recent studies of this nature clearly indicate the potential of SPS in improving soil C stock, which is important from the soil-fertility-improvement as well as environmental-amelioration (carbon sequestration) points of view. Yet another recent study related to soil carbon stock under the native vegetation in such unexplored systems is that of Tonucci *et al.* (2017) from the Cerrado region (near the Caatinga region: see Fig. 1). Using carbon dating, the authors found relatively large deposits of “old” (>2,000 years) carbon in the soil irrespective of the current land-use systems (forest, silvopasture, pasture), suggesting that the forested land of the study site was cleared about 300 years ago. They further speculated that a natural calamity such as a massive fire might have destroyed the original grass-dominated ecosystem, which then was inhabited by a tree-dominated system, the typical vegetation of the Cerrado at present. This could well be applicable to the Caatinga region as well. If this is true, environmentally sustainable land-use systems such as silvopasture and other agroforestry systems could be much more appropriate than indiscriminate commercial systems that would lead to release of large masses of carbon stored in these soils. Evidently, rigorous and detailed studies are warranted on these unexplored biomes.

The SPS management practices in the Caatinga are basically similar to those of many arid regions; however, the inherently high level of biodiversity of the Caatinga offers several possibilities for arrangement of various tree/shrub/and grass components according to the needs and browsing/grazing habits of animals. Research-based knowledge of the local biodiversity and the specific management for each component while grown in combination with other plant species, and the scope for development of varieties from both the Caatinga and for other regions are two important management-related research priorities. Coppicing or/and thinning in a woodland with the adequate number of animals may create an even more sustainable system that would increase the growth of the grass component and accessibility of the fodder bank, and additional input of animal manure to the system.

Environmental and ecological specificity of the Caatinga biome is one of its unique features, which restricts the comparison and extrapolation of the management used in the biome to other hot semiarid regions. However, the limited studies in the region focusing on animal – vegetation interactions (behavior and response of animals to native vegetation, and vice

versa) have helped develop management strategies to improve the productivity and sustainability of the systems. The lessons learned from these experiences could be valuable for the design of productive and sustainable SPS in other semiarid and more humid regions too. The social aspects mentioned above, though not analyzed in detail, may present formidable challenges and barriers for SPS adoption. Nevertheless, given that the options for such ecologically challenged environments are limited, the experiences from Caatinga management deserve serious consideration in global development paradigms.

## Conclusions

Livestock production and management activities in drylands the world over play an important role in the livelihood and food security of local communities as well as sustainability of these fragile ecosystems. The traditional SPS of the Brazil's Caatinga region have stood the test of time as an excellent example of the resilience of the ecosystem and the ingenuity of the local farmers in managing it sustainably. The role of native trees in supporting animal production has been remarkably illustrated by this experience. The lack of any significant volume of scientific input in understanding the potential of these native species and opportunities for improving their productivity has, however, hampered the development of these systems for reaping substantial benefits that are feasible.

Relatively simple management interventions such as thinning, coppicing, and enrichment planting either alone or in combination could offer immediate benefits in the short term. In the longer term, careful introduction of desirable exotic species that are adaptable to local conditions biologically as well as socioeconomically could be a promising opportunity. Vegetation management techniques that allow at least 40% of biomass to be "reserved" for dry season forage have been shown to be extremely desirable for protecting the soils against forces degradation. Fodder banks and use of non-conventional fodder sources such as cactus, and introduction of fodder species into existing orchards and plantations are other management opportunities that deserve serious considerations.

The experience gained from other SPS systems in tropical semiarid regions such as system resilience in response to management, adjusting the seasonality of grazing regimes according to forage availability and weather conditions, and importance of animal welfare, could be adapted for the improvement of the Caatinga. Likewise, the Caatinga experience of SPS could be

valuable for other semiarid regions around the world. Biodiversity and climate-change mitigation are two unique aspects of ecosystem services provided by such traditional systems that are seldom recognized. For example, the power of biodiversity in the wild, with which the Caatinga is enormously endowed but the extent of which has not yet been studied, is now known to surpass what has been predicted by experiments and models. Understanding these systems and protecting them for long term benefits rather than "exploiting" them for short-term returns is a strategy that needs careful consideration and successful implementation. This applies to SPS not only in the Caatinga region, but in the entire drylands worldwide.

## Acknowledgments

The paper draws heavily from the results of the work of researchers and institutes of the Caatinga region that have been working for decades on developing SPS in the region. The authors are grateful to all of them.

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