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Low Carbon Technologies for Agriculture in Dryland: Brazilian Experience

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Abstract

Anthropogenic activities have altered the atmospheric composition since the industrial era, especially with the increasing greenhouse gas emission due to fossil fuel combustion, cement production, and land-use change. The Brazilian semiarid, covering approximately 969.589 km² with 21 million people, region has 1.6 million agricultural establishments and 95% are classified as family farms. The typical agricultural systems are characterized by high grazing density, slash and burn practices, and fruits and legumes by irrigated monocultures. Consequently, soil degradation occurs due unsustainable soil management, decreasing soil carbon stock, and the biodiversity. The soil carbon depletion is also associated with saline, water, and thermal stresses. Saline, water, and thermal stresses in dryland, the impact of the land-use change associated with climate change, and few technological resources available for use in agricultural systems are the main reasons responsible for low productivity in the Brazilian semiarid region. Low-cost agricultural practices can contribute to build healthy and sustainable agroecosystems: among these, the selection of plant species tolerant to saline, water, and thermal stresses, the use of rhizobial inoculants, adoption of no-tillage, sowing green manure, and adoption of technologies to stock water to improve its efficiency and productivity.

Keywords: climate change, land-use change, technologies, agroecosystems design

1. Introduction

All the governments of the world have been concerned about climate change and how they can ensure access to sufficient food, water, and energy resources to safeguard human well-being

[1–3]. The anthropogenic activities have altered the atmospheric composition since the industrial era, especially by the increasing of greenhouse gas emission due to fossil fuel combustion, cement production, land-use change, and land use [2, 4, 5]. Land use and land-use changes affect soil carbon stocks, which are particularly important because they are the largest and most stable active compartment of the planet that can be handled [5–7]. In Brazil, land use and land-use changes, caused by deforestation or agricultural practices, can have a large participation on total national greenhouse gas emission (GHG) having reached 58% of all CO₂eq emitted in 2005 [7].

The most optimistic greenhouse gas emission (GHG) scenarios projected that planet temperature will increase at least by 2°C until the year 2100 [8, 9]. Managing with different climate change scenarios, in December 2015, Parties of the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement to manage climate change. The Paris Agreement stipulated that it is necessary to limit temperature increase to 1.5°C above preindustrial levels by 2050 [10, 11]. Although, even if all national commitments in the Paris Agreement are accomplished, mean planet temperature is likely to increase at least by 2.6–3.1°C until the year 2100 compared to preindustrial levels [12]. Even at the face of difficulties, many Parties formulated and submitted Intended Nationally Determined Contributions or INDCs that outline the post-2020 climate action plans they intend to take under the Paris Agreement. On that basis, Brazil undertook to reduce until 2025 the greenhouse gas emissions by 37% below 2005 levels and until 2030 reduce greenhouse gas emissions to 43% below 2005 levels. All regions of the country will be developing local actions to achieve the national goal. As much of the country's emissions are linked to land-use change and agriculture, these themes are prominent in research, extension, and public policy actions [13, 14].

In that way, one of the main programs established by the country that will support the reach of the INDCs is the Sectorial Plan of Mitigation and Adaptation to the Climate Change for the Consolidation of a Low Carbon Economy in agriculture—ABC Plan—created in 2010 and whose objectives are to promote the reduction of greenhouse gas emissions in agricultural activities; reduce deforestation; increase agricultural production on a sustainable basis; adapt rural properties to environmental legislation; expand the area of cultivated forests; and stimulate the recovery of degraded areas. Thus, the ABC Plan represents a set of applied technologies in agriculture and livestock, able to promote the reduction of GHG emissions by improving management practices and increasing carbon retention in soil and vegetation, while raising rural farming income [15, 16].

The Brazilian semiarid region, covering approximately 969,589 km², is situated in the Northeastern part (**Figure 1**), with unique native dryland vegetation and adapted to the periodic droughts called Caatinga. With 21 million people, this region has 1.6 million agricultural establishments and 95% are classified as family farms [17, 18]. Much of this population still seeks their livelihood in agropastoral activities and based on natural resources existing on or around their properties. Consequently, the land-use change from woody plants used for energy production, together with the conversion of use aimed at agricultural production, is responsible for the removal of 46.38% of the Caatinga vegetation [10, 19]. The native vegetation, to produce firewood and charcoal, is more than 30% of the energy matrix of the Brazilian semiarid region, and the demand for these products increases the deforested areas to improve farmers' income.

The climatic scenarios point out an increase in average air temperature up to 4.8°C and a 50% reduction in rainfall distribution by the end of the century (2071–2100) [8]. Rising air

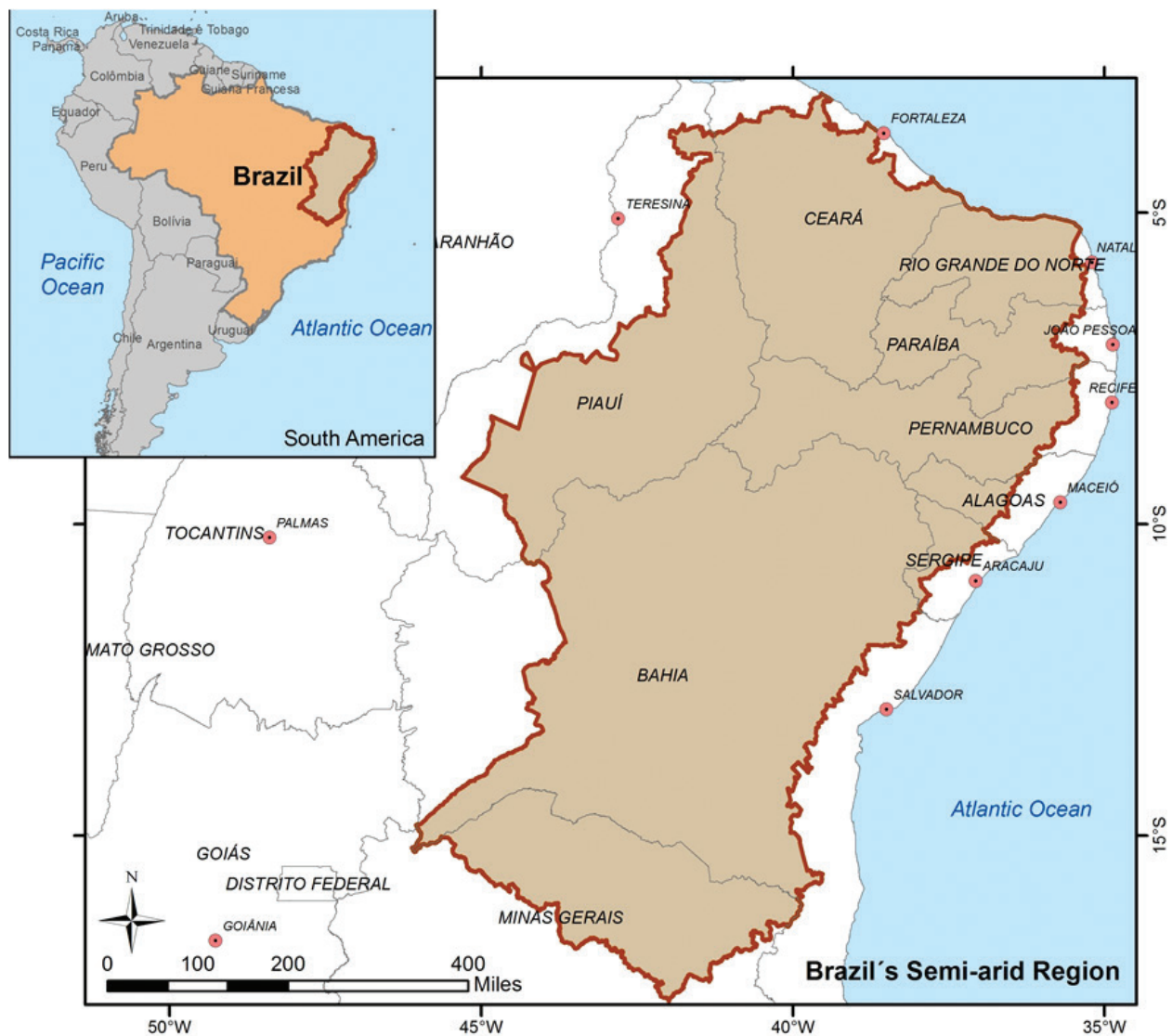


Figure 1. Map of Brazilian semiarid region.

temperatures can intensify hydric deficiency, affecting the availability of water for human consumption and for the rain-dependent agricultural activities. The increase of drought in the Northeast and changes in the characteristics and distribution of vegetation warn the risk of aridization of the region [20]. With these characteristics, the semiarid region is the most vulnerable Brazilian region to climate changes due to the increased difficulty of accessing water, food, and energy and due to the economic and social crisis [21].

This chapter aims to demonstrate the importance of low carbon agriculture to ensure access to food, energy, and water and to ensure human well-being facing the global climate change scenarios in the Brazilian semiarid region. In this regard, we understand that the way forward is to provide tools (technologies, products, processes, and knowledge) so that government, farmers, and private initiatives can create structures and links to implement sustainable agroecosystems, integrating concepts of resilience, adaptation, mitigation, and transformation of the biosphere in a unique approach to reflective and collaborative science.

2. Dryland characteristics and fragilities

It is important to highlight the large asymmetry between the geographic distributions of the CO₂ emissions and warming rates and work with indicators of corn yield, floods, drought, and climate suitability for malaria transmission. Researches point out over the past century that surface warming over global drylands has been 20–40% higher than that over humid lands, while anthropogenic CO₂ emissions from drylands have been only 30% of those generated from humid lands. For the twenty-first century, warming over global drylands could reach 3.2–4.0°C, while in humid lands warming of 2.4–2.6°C due to anthropogenic CO₂ emissions [22]. With this, it is evident that drylands should receive more attention because they are most sensitive and vulnerable to climate change. Additionally, we should consider that currently drylands represent 45.4% of the 147,000 km² of Earth's total terrestrial area [23]. Studies, based on aridity data analysis simulated under scenario RCP8.5, by the year 2100, estimate that the drylands will represent 56.10% of the Earth's total terrestrial area. Areas covered by hyperarid, arid, semiarid, and dry subhumid systems are expected to reach shares of 12.6, 14.9, 20.3, and 8.3%, respectively [22].

The Brazilian semiarid region, with 11% of the national territory (**Figure 1**), has average insolation of 2800 h year⁻¹, average annual temperatures of 23–27°C, average evaporation of 2000 mm year⁻¹ (**Figure 2**), relative humidity of about 50%, and maximum annual rainfall of 800 mm (**Figure 2**), with rainfall marked by scarcity, irregularity, and concentration of rainfall in a short period of the year, on average, from 3 to 4 months. The water volumes stored in lakes and reservoirs are often insufficient to achieve the needs of the population and to feed the animals [24], and farmers often become dependent on government water trucks [25, 26]. The Caatinga Biome is the main semiarid ecosystem. Botanically unique in the world, its vegetation is resilient due to the different adaptation strategies to the water, saline, and thermal stresses, due to the high temperatures and periodic droughts that characterize this region. Expressed in a multifaceted mosaic of fragments of small dimensions, with soils of extremely different characteristics occurring in close proximity, the soil diversity of the semiarid region is the largest in Brazil [27].

The land use and occupation in the semiarid region happened due to the expansion of the area for cattle breeding in the eighteenth century, the period of colonial Brazil. However, this occupation occurred in a disorderly way and without taking into consideration the fragility of natural resources. The management of these animals was carried out in an ultra-extensive way (animals released in the open field and having as food source the tree, shrub, and herbaceous species of the Caatinga) [28]. Thus, cattle ranching was responsible for the demographic occupation of the semiarid region, giving rise to settlements, which later became large cities. At that time, subsistence agriculture also began, characterized by exploitation during the rainy season, in small orchards surrounded by sticks, with cassava, corn, and beans.

The livestock and subsistence crops are still the main land uses. The most diverse arrangements can be observed in the Brazilian semiarid region, but all of them stand out due to the small area organized; approximately 95% of the establishments are family farms (**Table 1**) [17, 28]. The existing demand for firewood and charcoal extends the deforested areas of native vegetation to improve income from the sale of wood. The production of firewood and charcoal from native vegetation constitutes more than 30% of the energy matrix [29]. Subsistence agriculture, with cassava, beans, maize, and several annual crops, occupies small spaces and does not promote a

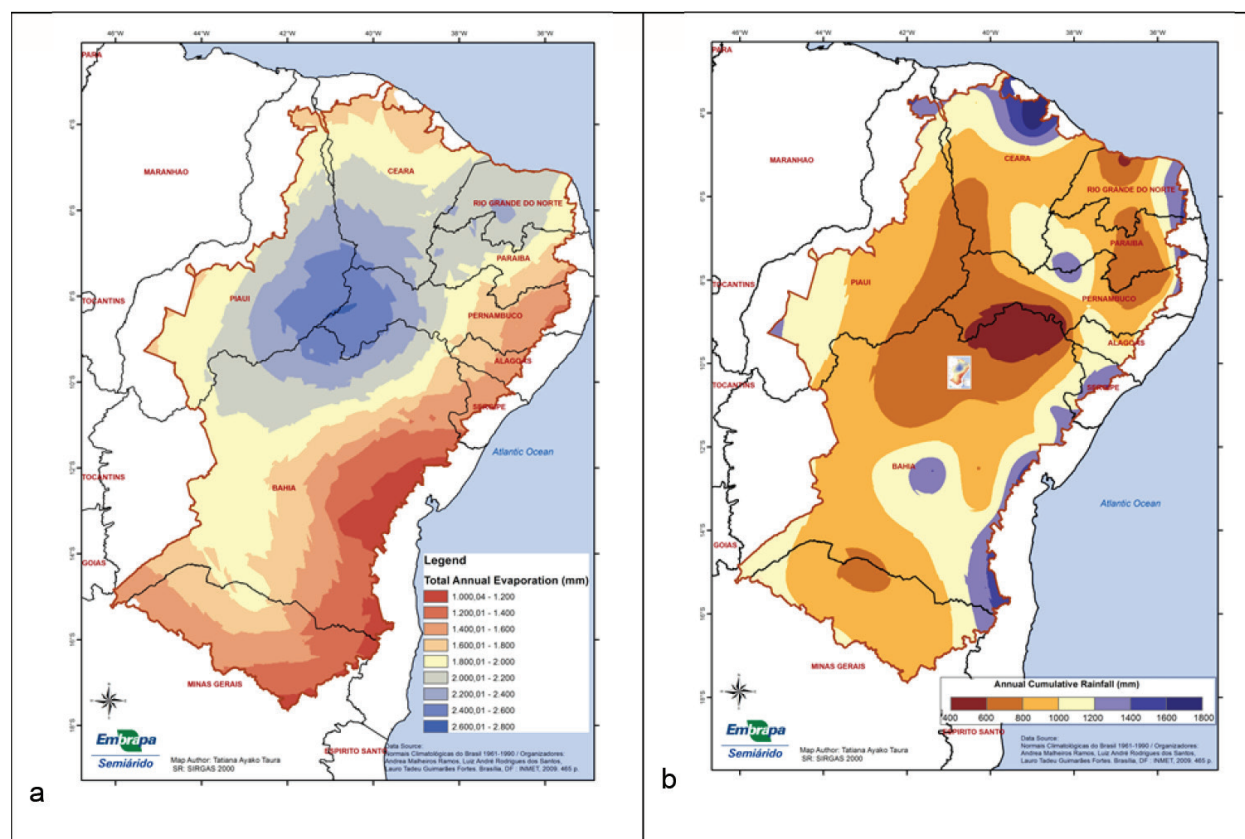


Figure 2. Evaporation (a) and precipitation (b) maps of the Brazilian semiarid region.

deforestation front. Small farming or pasture plots are exploited for a few years and abandoned for longer periods of time [30]. However, its itinerant characteristic increases deforested areas in a pulverized form. To a lesser extent, irrigation projects that produce fruits for export are responsible for the deforestation of the Caatinga [27, 28].

The livestock, characterized by overgrazing, itinerant subsistence agriculture, wood extraction, poorly designed irrigation projects, and increase of severe drought are contributing to enhance the water, thermal, and salt stresses (**Figure 3**).

Climate change, land-use change, and land use are expanding degraded and desertified areas, leading to loss of biodiversity, soil carbon stock, and vegetation [6], and, in general, degrading physical and chemical properties of soil that does not support primary productivity [6, 24, 31–33]. However, Brazilian semiarid region presents a great diversity of soil types and land use expressed in a multifaceted mosaic of small fragments occurring in the vicinity [27] (**Figure 4**).

Studies on the impact of land-use change and climate change on the Brazilian semiarid region show that resilience can be drastically affected by atrophic action and climate change. In a study by means of time series of difference vegetation index satellite normalized derivative (NDVI) 2008–2013 and weather data, the cleared areas had significantly lower normalized difference vegetation index (NDVI) and greening delay in response to precipitation. On the other hand, strictly protected areas presented higher productivity and considerable resilience at low levels of precipitation compared to sustainable use or unprotected areas [34]. Changes in the characteristics and distribution of vegetation associated with increased drought and

Production systems	Characteristics
Survival farming	<ul style="list-style-type: none"> - Crops for high consumption (rice, corn, beans, and fava beans) - Have no animal breeding
Subsistence farming	<ul style="list-style-type: none"> - Survival cultures - Maximum of 3 ha in crops of commercial value
Commercial agriculture	> 3 ha of commercial agriculture
Livestock production	<ul style="list-style-type: none"> - Maximum of five animal units - Self-consumption crops
Diversified livestock subsistence	<ul style="list-style-type: none"> - Up to five animal units - Maximum of 3 ha of commercial crops
Diversified livestock with commercial agriculture	<ul style="list-style-type: none"> - Up to five animal units - > 3 ha of commercial crops
Livestock	<ul style="list-style-type: none"> - Crops for self-consumption - Five animal units - Produce <7000 L milk/year
Diversified livestock	<ul style="list-style-type: none"> - Up to five animal units - Maximum of 3 ha of commercial crops - Produce <7000 L milk/year
Livestock with commercial agriculture	<ul style="list-style-type: none"> - >5 units animal - Maximum 7000 L milk/year - More than 3 ha of commercial crops
Livestock milk	<ul style="list-style-type: none"> - >5 animal units - Crops for self-consumption - Produce >7000 L/year milk
Diversified livestock milk	<ul style="list-style-type: none"> - >5 animal units - 3 ha of commercial crops - Produce >7000 L/year milk
Livestock milk with commercial agriculture	<ul style="list-style-type: none"> - >5 animal units - >3 ha of commercial crops - Produce >7000 L/year milk

Adapted from [28].

Table 1. Types of production systems in the Brazilian semiarid region.

temperatures and atrophic action point to the risk of degradation and aridization of the region [20]. These studies allow us to verify two important questions: first, the importance of preserved areas and second, the need to develop agricultural systems and to use natural



Figure 3. Images of the Caatinga in the dry period (a), current model of goat breeding, exploring native vegetation and degraded pastures (b), area in which vegetation was removed and burnt (c), and area cultivated with forage palm (d). Source: Embrapa image bank.

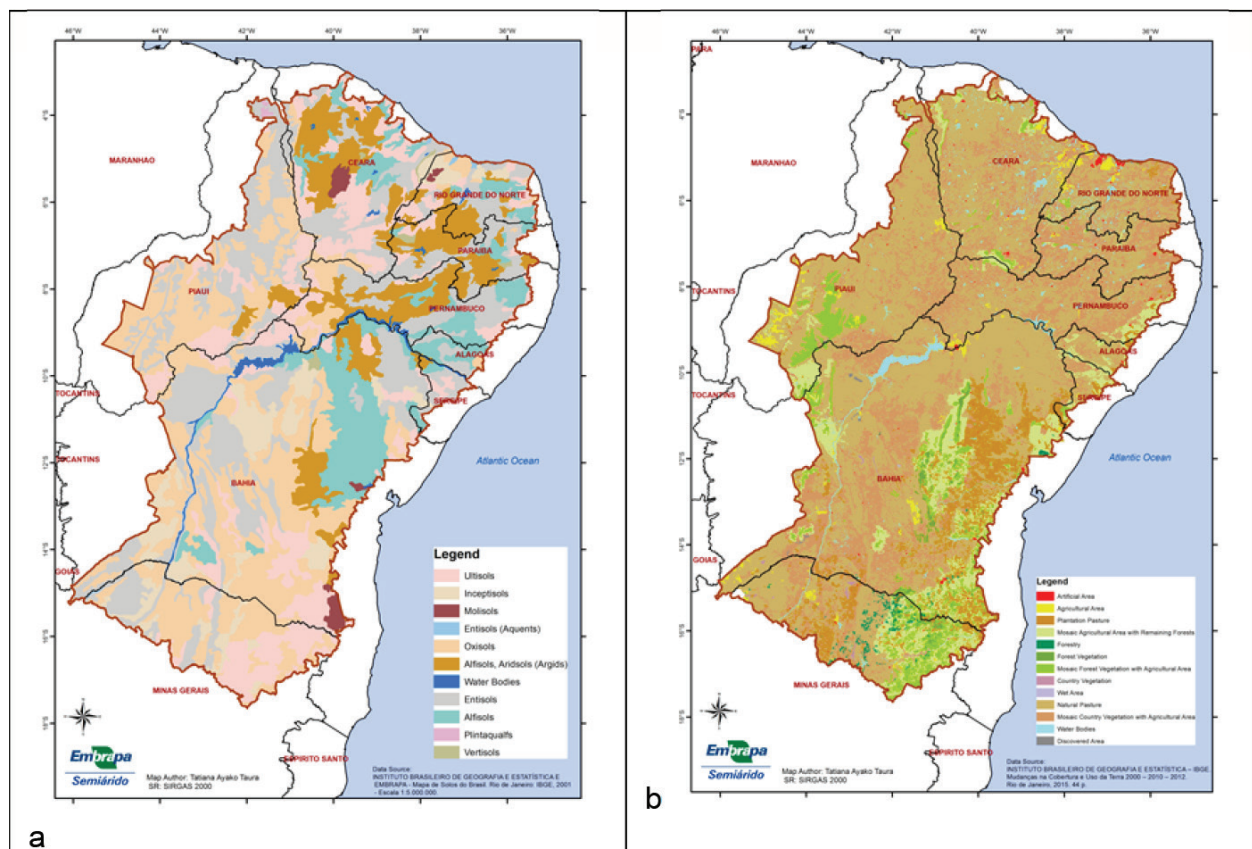


Figure 4. Soil (a) and vegetation (b) maps of the Brazilian semi-arid region.

resources that do not affect biodiversity and the regeneration capacity of Caatinga and that do not put pressure on the preserved areas while adapting to the impacts of climate change.

Impacts due to temperature rise and precipitation anomalies can cause socioeconomic and ecological damage. From the economic point of view, climatic variations have a direct impact on agricultural production, representing a challenge for food security. Similarly, in semiarid regions, climate change can further aggravate and accelerate the process of degradation/desertification, affecting ecosystem function and biodiversity, causing loss of landscape heterogeneity [35, 36] in addition to increasing emissions of greenhouse gases and decreasing the capacity to store carbon in soil and vegetation.

3. Direct impacts of climate change on productive systems

The increase in temperature and changes in precipitation patterns may cause significant impacts on the different types of production systems in the semi-arid region. This is because the air temperature is one of the main climatic elements for the growth and development of plants. It is known that high temperatures can reduce the metabolic activity and increase breathing [37]. Cowpea, for example, is a crop of great socioeconomic importance for the semiarid region and this leguminous develops well between temperatures of 20 and 30°C, being that high temperatures cause spontaneous abortion of flowers and the retention of pods in the plant [38]. Thus, in places where the average temperature varies between 26 and 27°C, an increase of 4.8°C [8] could change the development of the plants, harming their production.

Some studies based on climatic zoning of crops have also shown that climate change may have an impact on semiarid agricultural production, negatively interfering with the yield of some traditional crops of family agriculture, such as cassava [39]. This is because, climate change changes the hydrographic cycle, generating changes in hydric availability. And in the cassava case, the plants can be grown in temperatures ranging between 16 and 38°C; however, due to the scenarios of the dry season increase, this cultivation may have an increase in the risk area for its production. Thus, the amount of soil water available for cassava may be a negative factor if the hydric deficit occurs during the first 5 months after planting, needing adaptation measures to avoid possible losses [39].

Within the production systems existing in the Brazilian semiarid region, livestock farming plays an important role both for income generation and for the maintenance of families in the countryside. For the goats and sheep, about 80% of the properties use the Caatinga as a source of forage. In drought years, other practices such as the consumption of grains/pods, hay, fodder palm in the trough, and buffel grass are adopted for food management. However, irregular use and insufficient offer are the major bottlenecks of the current production system [40]. With climate change scenarios, hydric deficiency can directly affect the yield of forage species, thus increasing pressure on the Caatinga and intensifying also the lack of water for animal consumption.

A study carried out in the state of Pernambuco, in the Brazilian semiarid region, verifying the impact of land-use change on the carbon stock in different ones, showed that the carbon stock is higher in soils with higher clay content and these are more sensitive to use changes in

the first layer (0–0,1 m). However, in the layer of 0–60 cm, land-use change has a significantly greater impact on sandy soils when compared to clayey soils (**Table 2**) [41].

In the Brazilian semiarid region, sandy and low carbon soils predominate [30, 41] (**Table 3**). Thus, facing climate change scenarios, primary productivity would be compromised and carbon stocks would drastically reduce because of the predominant soil characteristics, aggravating both emissions and carbon storage capacity.

The impacts of climate change are not only restricted to agricultural production. The reduction in soil water availability may promote the vegetation replacement from semiarid regions by arid vegetation regions [20]. In this sense, some studies indicate biodiversity losses and increase of vulnerable areas to desertification. For the population that uses native plants as a source of animal feed and medicinal use and that even explores the diversity of fruit species for human consumption and to increase family income, the advent of climate change may be more of a challenge that needs to be understood to avoid the process of environmental degradation. This is because the climatic variability in semiarid regions coupled with human activities has led to the loss of biological and economic productivity of agricultural lands, pastures, and native forest areas, losing the ability to recover. Thus, understanding how changes in climate can influence the distribution of species, as well as establishment and regeneration, is a challenge that needs to be investigated to maintain the sustainability of this ecosystem.

The negative impact of a fall in agricultural production, with a consequent decrease in income, may apply a reduction of jobs, as well as a rural exodus. In this way, the rainwater harvesting and storage technologies implantation, the use of genetic materials resistant to drought and high temperatures, the integration of technologies, and the use of polycultures will be extremely important to achieve sustainable development of the region against the climate change, reducing risks and promoting the maintenance of family farming.

The main reasons responsible for the low productivity in the Brazilian semiarid region are water, thermal, and saline stresses in dryland, the impact of the land-use change associated with climate change, as well as few technological resources available for use in agricultural systems. The use of integrated technologies is important to increase the carbon stock and to mitigate climate change, increasing the productivity of agroecosystems in Brazilian's drylands.

Land use	Carbon (Mg ha ⁻¹)			
	Acrisol	Ferralsols	Leptosol	Planosol
Dense Caatinga	63.8 (5.5*)	47.2 (6.8)	54.5 (11.8)	26.2 (4.2)
Open Caatinga	45.9 (4.6)	39.7 (6.7)	39.1 (4.5)	26.2 (3.1)
Pasture	51.3 (10.4)	39.4 (4.6)	51.4 (0.7)	17.6 (2.8)
Agriculture	56.0 (5.7)	34.4 (5.6)	22.2 (1.5)	13.3 (0.7)

*Mean standard error.

Pernambuco, Brazil, 2014. Adapted from [41].

Table 2. Carbon stocks (mg ha⁻¹) in the top 0–60 cm soil layer under different land uses and soil types.

Soil type		ON*	Organic carbon	Clay g kg ⁻¹	Silt	Sand	Area	
FAO-UNESCO	USDA						km ²	%
Ferralsols	Oxisols	41	9.7	250	130	620	203.614	21
Leptosols	Lithic ...Orthents	45	10.4	132	250	618	184.222	19
—	Lithic...Psamments						—	—
Acrisols	Ultisols	90	8.9	147	157	696	145.438	15
Luvisols	Ultisols	47	11.8	176	258	566	126.047	13
Planosol	Albic suborder	68	7.4	105	188	707	38.784	4
Regosols	Orthents, Psamments	20	4.9	37	105	858	38.784	4
Cambisols	Inceptisols	13	12.2	295	212	493	38.784	4
Vertisols	Vertisols	16	12.3	374	238	388	9.696	1
Others							184.222	19
Total							969.589	100

Adapted from [27].

*ON, observation number.

Table 3. Soil types according to two different soil classification systems and relationship between carbon content and particle in surface horizons of the main types of soils in Brazilian semiarid region.

We will describe in this chapter some low-cost agricultural practices that can contribute to build healthy and sustainable agroecosystems. Among these, we will focus on the selection of plant species tolerant to the saline, water, and thermal stress, use of rhizobial inoculants to benefit economic and environmental impacts for leguminous crops, adoption of no-tillage systems, sowing of different species of green manure called plant mixture or plant cocktail, and technologies to stock water to improve its efficiency and productivity.

4. Low-cost agricultural practices that can contribute to build healthy and sustainable agroecosystems

4.1. Plant species tolerant to the saline, water, and thermal stresses in drylands

The plant species of the Caatinga present adaptations to face the low hydric availability, high temperatures, and salinity. The occurrence of abiotic stresses provokes biochemical and physiological responses in plants, to promote tolerance or increase their survival under adverse conditions. The plants adapted to drought, high temperatures, and salinity usually present some strategies such as succulence, dormancy, and leaves with serous layers or with capacity to store water and nutrients in specific structures of roots [42]. In this context, plant genetic resources, associated with biodiversity and biotechnology, are essential to explore new materials that make agriculture more competitive, secure, and sustainable. The value of genetic resources is enormous, and their conservation, characterization, and use are fundamental for

improvement programs that aim to identify species adapted to adverse conditions, such as the semiarid climate [42]. However, the strategy of identifying the mechanisms of adaptation to the stresses in native species and the incorporation to the cultivated species is quite complex and are currently linked with the association of genes, proteins, and others.

Genetic improvement of cultivated species is another important strategy aiming at tolerance to hydric deficit, temperature increases, and salt stress to guarantee the sustainability of agricultural production.

For these strategies, viability, the use of tools such as bioinformatics, systems biology, interaction ratio among them, the association of data deposited in databases, laboratory data, and field are essential. These studies require network projects, with complementary and interdisciplinary approaches, which need significant investments. To face this challenge, plant improvement programs are expanding the genetic base of prospecting and accelerating the search for novel phenotypic traits [42, 43].

In the semiarid region, some initiatives have contributed to the search for resistance genes to abiotic stresses. An example is the evaluation of cassava varieties resistant to dehydration in genetic improvement programs, searching for more productive varieties under conditions of water deficiency [44, 45]. The cultivars of guandu beans (Guandu Petrolina and Guandu Taipeiro) developed to adapt to the irregular regime of semiarid rains [46] are also noteworthy. The onion cultivar “Alfa São Francisco” was launched to resist to high temperature and it is a good option to family agriculture [47]. Through the transcriptome and proteome analysis, associated with physiological studies, we seek to understand the genetic mechanisms of *Tripogon spicatus* adaptation to drought. The results of this research may contribute to the generation of biotechnological alternatives for the improvement of cultivated plants, through the identification of genes associated with stress tolerance [48].

Soil salinization can occur by natural processes, named primary salinization, or by induced processes, named secondary salinization or anthropic. In the semiarid region, this process is accentuated due to the negative water balance most of the year with potential evapotranspiration of 2000 mm/year. Secondary salinity is a problem that affects the semiarid region of Brazil, especially in the irrigated perimeters. Studies investigating the evolution of salinity in an Argissol under irrigation in Petrolina—PE—observed that the indiscriminate use of salts in the fertilization and the excessive use of water contributed to a process of anthropic salinization in irrigated area. However, it is possible to consider that the salinization process, being in its initial phase, could be reversible, and among some measures suggested are the correction of the excess water applied, as well as avoiding the use of fertilizers with high saline indices, and the use of organic fertilization and/or green manure as a management practice [49]. Thus, in order to maintain a sustainable agriculture in the semiarid region, it is necessary to follow the chemical evolution of the soils in order to characterize the salinization process, the adoption of management practices for mitigation, and the selection of tolerant species strategies to increase productivity.

Several plants are able to grow under salinity conditions. The species *Atriplex nummularia* is a halophyte forage that shows high tolerance to salinity (>25 dS/m) [50]. In the semiarid region, this species is produced under irrigated conditions with desalination waste, producing a total of 55 t ha⁻¹ an⁻¹ of dry matter [50]. The good productive performance of this species allows the mobilization of soil salts and the production of firewood and forage material [51].

4.2. Economic and environmental impacts of the use of bacteria and mycorrhizal fungi

The use of efficient bacteria in the biological fixation of nitrogen and mycorrhizal fungi is a recent initiative used in the Brazilian semiarid regions, which aims to contribute to the reduction of the climate change impacts. In a scenario of climate change, the selection of efficient bacteria in the biological fixation of nitrogen and mycorrhizal fungi that increase the absorption of water and soil nutrients may contribute as important tools to help plant species and to reduce the impacts of adverse climatic conditions, such as high temperatures and low water availability [52–54].

In biological nitrogen fixation (BNF), the bacteria fix the atmospheric nitrogen in organic compounds that are used by plants, reducing the necessity to use nitrogenous fertilizers and improving the absorption of water and nutrients. The BNF, on the other hand, does not have specificity regarding the host plants; however, there are studies that indicate that BNF has ecological specificity. Species isolated from certain plant communities are more adapted to plants and to prevailing edaphoclimatic conditions, and they are therefore more adapted and able to colonize the root system and favor the development of the plant species that occur in these places [55].

Thus, the use of these techniques allows a greater production of the plants and an increase in the capacity to support environmental stresses, being able to be an additional tool in the integration of technologies for the family farming. Some published works indicate the potential use of these tools for leguminous crops [56, 57]. For cowpea, four strains of *Bradyrhizobium* sp. are currently authorized to produce inoculants in Brazil, the most widespread being the BR 3267 strain originating from Petrolina soils [58], demonstrating the potential of the region as a source of microorganisms. In addition, plant genotypes growing in the semiarid region show responsiveness to the inoculation of the bacteria used in commercial inoculants [59], which reinforces the necessity for constant prospecting of new rhizobia isolates.

4.3. No-tillage systems and the plant mixture

The no-tillage system is one of the main technologies encouraged by the ABC Plan. In the Brazilian agricultural soils, no-tillage system favors carbon sequestration, with increases of 5.2–8.5 MgC ha⁻¹, higher than the soil under conventional tillage [60]. However, the Brazilian semiarid region is the most difficult place for technology to be implemented for low-carbon agriculture. The difficulty of implementing the no-tillage system in the Brazilian semiarid region is due to climatic restrictions and cultural remains traditionally used to feed the herds [60, 61].

The use of green manures can be a viable low carbon emission technology for irrigated agriculture in the Brazilian semiarid region. The simultaneous cultivation of different green manure species is an alternative to take benefits promoted by different species [62–64]. In that way, studies in long-term experiments, using as a model for fruit the mango tree and for horticultural the melon (**Figure 5b–d**). In both systems, mango tree and melon, the simultaneous cultivation of 14 different species of green fertilizers, called plant mixture, was carried out, contemplating differentiated proportions of grasses, oilseeds, and legumes [61, 62]. The selected species were legumes (*Calopogonium mucunoides*), velvet bean (*Stizolobium aterrimum* L.),



Figure 5. Plant mixture preceding melon crop (a), t melon seedlings in plant mixture residues (b), no-tillage system of melon crop (c), and detail of the harvest phase with residues still on the soil (d). Source: Embrapa image bank.

gray-seeded mucuna (*Stizolobium cinereum* Piper and Tracy), crotalaria (*Crotalaria juncea*), rattlebox (*Crotalaria spectabilis*), jack beans ensiformis), lab-lab bean (*Dolichos lablab* L.); grasses: sesame (*Sesamum indicum* L.), corn (*Zea mays*), pearl millet (*Pennisetum americanum* L.), and milo (*Sorghum vulgare* Pers.); oil seed: pigeon pea (*Cajanus cajan* L.), sunflower (*Helianthus annuus*), castor oil plant (*Ricinus communis* L.) (**Figure 5a**). The spontaneous vegetation was composed by the predominant species: Benghal dayflower (*Commelina benghalensis* L.), purple bush-bean (*Macroptilium atropurpureum*), Florida beggarweed (*Desmodium tortuosum*), and goat's head (*Acanthospermum hispidum* DC).

Oilseeds, such as sunflower and castor oil, produce large amounts of biomass and cycling nutrients, especially nitrogen. Grasses generally contribute with relatively high amounts of phytomass, characterized by high C:N ratio, which increases the persistence of soil cover over time. On the other hand, the leguminous crops, because they fix the atmospheric N, have high levels of N in the vegetal matter, and the vegetal remains generally have a low C:N ratio, with relatively fast decomposition, promoting small soil cover [65, 66], but provide significant amounts of N to the next crops. Simultaneous cultivation of leguminous, grassy, and oleaginous species has the potential to double the rate of addition of biomass to the soil, addition of nitrogen, and cycling of nutrients such as phosphorus, potassium, magnesium, and sulfur (**Table 4**) [61]. The studies have shown that the simultaneous cultivation of green manures in the Brazilian semiarid region can add a large amount of carbon and nutrients to the soil in agricultural systems, in a short period of time, not exceeding 70 days, during which period most species are in full bloom stage and are managed.

CC	DM	N	P	K	Mg	S
	Mg ha ⁻¹			kg ha ⁻¹		
PM 1	8.73 a	300.24 a	28.81 a	203.68 a	30.30 a	27.60 a
PM 2	8.51 a	268.11 b	30.32 a	214.55 a	31.25 a	30.90 a
EV	4.09 b	103.66 c	15.15 b	111.27 b	16.70 b	9.70 b
VC (%)	6.09	9.96	8.90	12.99	6.90	14.92

Adapted from [61]. The means followed by the same letter do not differ statistically from each other by Tukey test at the 5% probability level. CC—cover crop; M—Management; PM 1—plant mixture 1 (75% leguminous +25% grasses and oilseeds); PM 2—plant mixture 2 (25% leguminous +75% grasses and oilseeds); SV—spontaneous vegetation; NT—not tillage; T—tillage.

Table 4. Means of dry matter phytomass (DM), potassium (K), and sulfur (S) contents and nitrogen (N), phosphorus (P), potassium (K), magnesium (mg), and sulfur (S) accumulation of five cycles of plant mixtures crop and maintenance of spontaneous vegetation between rows of mango orchard.

Emphasizing on the importance of no-tillage and green manuring on soil protection mechanisms and residence time of carbon in the soil containing clay, studies have shown that protection mechanisms involving organo-mineral interactions are more important in carbon accumulation than occlusion within aggregates. However, in the Brazilian semiarid region, where most soils predominate sand fraction, both the interaction with minerals (organo-mineral) and physical protection are limited. In this case, carbon storage in the soil may depend on a fragile and continuous equilibrium of addition rate and decomposition that occurs naturally in these environments [67]. However, once the equilibrium has been broken down by means of crops and irrigation systems, there is a need to develop soil and crop management systems that allow the balance between rates of addition and decomposition that, at a minimum, maintain the levels similar to those found in soils under Caatinga. Therefore, the use of systems with a higher degree of complexity/diversity for both rainfed agriculture and irrigated agriculture can be an important strategy to promote low carbon agriculture, including the efficient management of water resources and salinization process and carbon and water footprints.

4.4. Water in the semiarid region

Only 3% of the total water in Brazil is in the semiarid region, with 78% located in the São Francisco and Parnaíba River basins. The temporal variability of the precipitations and the dominant geological characteristics, where there is predominance of shallow soils based on crystalline rocks and, consequently, low water changes between the river and the adjacent soil, results in the predominance of intermittent rivers and few perennial rivers. The semiarid region is a low volume region of river water flow [68]. The exploitation of groundwater is limited and presents problems due to the water that presents high content of salts and low flow wells ($\sim 1 \text{ m}^3 \text{ h}^{-1}$), since over 80% of the crystalline region is about rocks [69]. However, the absence of rainfall is responsible for the insufficient supply of water in the region, but its poor distribution, associated with a high rate of evapotranspiration results in the phenomenon of drought and directly affects the population of the region. For this reason, the delimitation of the Brazilian semiarid zone is based on three technical criteria: average annual rainfall of less

than 800 mm; index of aridity less than 0.5, calculated by the water balance that relates rainfall and potential evapotranspiration ($I = P/ETP$), between 1961 and 1990; drought risk (days with hydro citric acid/year greater than 60% per year), based on the period between 1970 and 1990.

Most of the population and rural properties of the Brazilian semiarid region depend on rainwater for human consumption and for agricultural and livestock production. Rain-dependent environments occupy the largest area. The capture and management of rainwater have been a popular technique developed by different peoples in different parts of the world, and there are thousands of people, especially in arid and semiarid regions [70]. The population throughout the history of coexistence with drought was developing different strategies to deal with human, animal, and primary food, fiber, and energy production [71].

In relation to rainwater harvesting in the Brazilian semiarid region, two main problems are highlighted: first, low rainfall utilization, mainly due to the use of large reservoirs, large reservoirs that concentrate water in large water mirrors that facilitate evaporation; second, storage and use of water by processes of higher points of drainage for the accumulation at lower points of the land. In its displacement to the storage site, water transports particles, contaminating it [72]. To handle the issues of capitation, storage, and water productivity, several techniques for harvesting rainwater were developed by Brazilian semiarid inhabitants to increase the availability of water for crop and livestock production. Among them, we highlight the reservoirs (Cisternas), surface dams (Barragens Subterrâneas), tank trench, water storage pits, small dam (Barraginha), and techniques for capturing rainwater in situ [73–75].

However, the irregularity of rainfall in the Brazilian semiarid region does not allow a production planning model dependent on precipitation during the crop development cycle. However, the integrated use of geotechnology, forecasting models, genetic improvement of plants, use of biotechnologies, and soil and water management strategies can boost water productivity. Thus, the efficient management of the water resource assumes great importance to mediate soil-plant-environment relations in a favorable way to compose a productive and sustainable system in the semiarid region, both for rain-dependent and irrigated environments.

4.5. Integrated crop-livestock-forest system

The Caatinga is rich in forage species in its three strata: herbaceous, shrub, and arboreal. Approximately 70% of the botanical species of the Caatinga take part significantly in the diet composition of the herds in the Brazilian semiarid region [76]. Facing the rational management of the Caatinga, agroecosystem models were developed so that farmers could have native or cultivated fodder throughout the year for their herds, increasing drought resilience and now the impacts of climate change.

The first researches identified the forage potential of native and exotic species. Among the native species are manicoba (*Manihot pseudoglaziovii* Pax & Hofman), manioc (*Manihot sculenta* Crantz), porcupine (*Manihot* sp), venom papaya (*Jakarta corumbensis* O. Kuntz), postumeira (*Gomphrena elegans* Mart. elegans), mandacaru without thorn (*Cereus hildemaniaus* K Schum), camaratuba (*Cratylia argentea* desv. Kuntze), umbuzeiro (*Spondias tuberosa* Arr. Cam.), mororo (*Bauhinia* sp), and sage (*Mimosa caesalpinifolia* Benth). Among these exotic species, the most

widely studied species are Buffel grass (*Cenchrus* spp.), Urochloa (*Urochloa mosambicensis*), forage palms (*Opuntia cus-indica* (L.) Mill., *Nopalea cochenillifera* Salm-Dick), *Leucaena leucocephala* (Lam), gliricidia (*Gliricidia sepium* (Jacq), and algaroba (*Prosopis juli ora* (SW) DC) [77, 78]. The agroecosystem design basis for the Brazilian semiarid region is the integration of adapted native or exotic elements, giving rise to models capable of increasing the resilience of the productive systems both in relation to the current edaphic climatic codes and in relation to the different scenarios of climate change.

One of the first agroecosystems developed for the semiarid region was called CBL, because it contemplates Caatinga, Buffel, and *Leucaena* subsystems. The Caatinga is grazed for 2–4 months. Buffel, as a water stress tolerant grass, is used during dry periods, and finally, *Leucaena* is a leguminous that complements feeding as a protein source, in the form of hay or silage. A second system developed, called Sistema Glória, proposes that in the rainy season, the herd be maintained under alternating grazing conditions in areas of cultivated grasses (Buffel, urochloa, pangolão, and aridus grass), as well as native annual cycle pastures; with predominance of marmalade grass (*Brachiaria plantaginea*) and several species of annual herbaceous leguminous, mainly of *Phaseolus* genera, *Centrosema*, and *Stylosanthes*. Both systems, in the periods of extreme drought, provide as a forage support the Indian Fig (*Opuntia ficus-indica* (L) P.Will) or native species as the xique-xique (*Pilosocereus gounellei*) and mandacaru (*Cereus jamacaru* DC) [79–83]. In general, the agroecosystem most used for semiarid region is composed of perennial woody species, associated with crops and pastures [79–81] denominated agrosilvopastoril system. The species composition may vary depending on the type of soil and rainfall regime. The implantation of complex, stable, sustainable models integrating elements of local biodiversity, arboreal, shrub, and herbaceous stratum is still a challenge for models of crop-livestock-forest integration adapted to semiarid conditions, to climate change scenarios, needing further research.

Agriculture and livestock are very important activities in the dryland economy. The typical agricultural and livestock systems are characterized by high grazing density, slash and burn practices, and irrigated monocultures. Consequently, soil degradation occurs due to unsustainable soil management, decreasing soil carbon stock and biodiversity. The soil carbon depletion is also associated with saline, water, and thermal stresses, typical in dryland regions. Climate change must be considered as a potentializer of stress and degradation factors. The environmental impacts of a warming climate in the semiarid region create challenges as well as opportunities.

The physical, chemical, and biological degradation process can be avoided and climatic resilience increased by improving science and technologies for low carbon agriculture, building sustainable agroecosystems. The challenge is to develop state policies, internalized by the population, that promote the sustainable and socially just development of Brazil, incorporating definitively science, technology, and innovation structures that guarantee the supply of water, energy, food, health, and culture through actions to mitigate and adapt to climate change. Adaptation and mitigation actions to climate change will be fundamental to guarantee human well-being and the continuity of life in its diversity on the planet, as we know it. Science and technologies for dryland are important to intelligent design and organic and adapted agroecosystems. Plant species tolerant to the saline, water, and thermal stress, no-tillage system

associated with green manure, agroforestry, and water management are alternatives that can reduce GHG emissions, increase soil carbon sequestration, and mitigate the impact of climate change in the dryland, as well as to improve overall food security while making farmers more profitable and farms more profitable in Brazilian semiarid region. The physical, chemical, and biological degradation process can be avoided and climatic resilience increased by improving science and technologies to build sustainable agroecosystems.

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