Charis M. Galanakis *Editor*

Environment and Climate-smart Food Production

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Preface

Climate change is one of the biggest global challenges, affecting agriculture, food systems, forestry, and the marine and bio-based sectors. Among these sectors, climate change will affect farming first in line through changes such as rising temperatures, occurrence of droughts, rainfall regimes, heat waves, storms, and floods. Subsequently, farmers will need to adapt to climate change and develop farming systems resilient to fluctuating environmental and socio-economic conditions. Moreover, the well-being of citizens is directly affected by the way cities and rural regions are shaping food production. To this line, the challenge of providing consumers with safe, nutritious, and affordable food is more urgent than ever. Subsequently, there is a need for a new reference covering all these issues.

Food Waste Recovery Group (www.foodwasterecovery.group) has developed a portfolio of numerous activities, including consultation reports, e-courses, webinars, workshops, reference modules, publications, and multiple books in the broad fields of food, nutrition, bioresources, and environment. Following this trend, the current book aspires to fill this gap in the existing literature by providing specific solutions for industrial sustainability in terms of fish processing, production, and waste management and discussing current trends. The present book addresses climate change and resilience in the food sector, contributing to the transition towards a circular bioeconomy, as well as fostering functional and sustainable food systems, boosting major innovations in agriculture, and finally developing smart and connected value chains in rural areas.

The book consists of 11 chapters. Chapter 1 exemplifies climate-smart management schemes that can be applied in tropical production systems. Microclimate plays a determining role in the development of biotic and abiotic interactions within agriculture and livestock systems and the physiological and productive performance of plants and animals. Climate-smart agriculture can develop agroforestry-based production systems that contribute to soil water retention, soil and air temperature reduction, nutrient fixation, weed control, soil stabilization, and protection against wind and runoff in the improved physiological performance of crops and, therefore, higher productivity. Chapter 2 discusses sustainable, climate-smart, and agroecological farming systems in the face of adverse climatic variations and changes.

Particular emphasis is given to the agroforestry systems of smallholder farmers. Chapter 3 presents the telecoupling model to map out the causes and effects of each system and its relationship with others. The telecoupling model is applied in the Brazilian agri-food exportation to China case. It indicates implications of the high rate of meat production and export to long distances vis-à-vis the need to supply the increased demand for meat consumption due to economic prosperity.

Chapter 4 discusses genetic resources that play a crucial role in fulfilling the five basic needs of human beings (food, feed, fodder, fiber, and fuel). The need for systematic conservation and sustainable utilization of plant genetic diversity is highlighted to ensure food and nutrition security. Chapter 5 aims to advance the understanding of the ability of plants to adapt to extreme conditions or to react to sudden changes in their environment. The chapter outlines the mechanisms used by plants to sense and signal abiotic stresses, morphological and physiological changes that take place in plants as they adapt to stressful conditions, and the associated alterations in metabolic and biological reactions. Chapter 6 provides innovations in plant variety testing and insights on crop-specific characters that support resource efficiency and resilience to challenging environments. The technical issues addressed and new features (entomology and statistics) are expected to mitigate climate change effects, enhance performance, and significantly improve existing criteria and methods.

Chapter 7 discusses the global resource flows of agriculture and food production in the worldwide system that is now the focus of new circular economies and carbon-neutral programs. Long-term data are revised together with existing applications that assess how nutrients flow through food supply chains to their eventual consumption as the food and beverage products that make up our diets. This analysis defines how applications, technologies, and models can be used to identify systemic interventions in the global marketplace so that they can deliver environmentally climate-smart food production. Chapter 8 introduces vertical farming by discussing energy and water consumption, yield, and scalability criteria under climate effects. Cultivation methods such as hydroponic, aeroponic, and aquaponic systems are discussed together with novel technologies like artificial intelligence. Chapter 9 discusses the challenges and opportunities of digital technologies in ensuring soil quality and optimizing land management. The "whole to part" mapping strategy to guide sustainable land management is revisited, and scientific techniques discussed include multi-criteria analysis intended to: (i) screen-out sensitive variables to any complex problem, (ii) hierarchically rank significant variables, (iii) investigate the interrelationships of the facets, and (iv) synthesize information at various scales to explore viable solutions. Chapter 10 presents the production of high-quality fertilizers from biogas digestion. Biogas, one of the most important renewable energy sources, is obtained by anaerobic fermentation of organic wastes. While energy is received at the end of biogas production processes, in addition to this, biogas digestates generated as a result of production can be considered as a quality fertilizer source due to their chemical content.

Chapter 11 describes the impact of global food production and ultra-processed foods on sustainability and the importance of eating a plant-based diet. Food system transformation and the importance of citizen science as a catalyst for change are thoroughly discussed. Using the frame of Citizenshift, four examples of food-related approaches and engagement in cities to promote the food system's sustainability are explored. Today, despite increased information demand from consumers and food chain players alike, Europe's food businesses and farmers are slow at adopting digital technologies such as the Internet of Things, artificial intelligence, big data technologies, and remote and localized sensing. Chapter 12 engages the agri-food community in supporting the development of solutions to remove the barriers to adopting digital technologies, taking a multi-actor approach across different supply chains (conventional and organic) from farm to fork.

Conclusively, the current book is assisting food scientists and technologists; environmental, agricultural, and chemical engineers; as well as researchers working in the edge of the food and ecological field. It also concerns agricultural or food engineers seeking to improve the efficiency of production systems and professionals and strategy developers working in the agro-food industry, from farm to fork. Moreover, university libraries and institutes could use it as a textbook in undergraduate and postgraduate level multi-discipline courses dealing with sustainable food systems and agricultural and environmental science.

At this point, I would like to thank all authors for their fruitful collaboration and dedication to the editorial guidelines and timeline. I would also like to acknowledge the book' manager Arjun Narayanan and the acquisition editor Daniel Falatko, and all colleagues at Springer's production team for their assistance during this book's preparation. Finally, I have a message for all the readers: those collaborative efforts contain hundreds of thousands of words and may contain errors. Subsequently, constructive comments and even criticism are always welcome, so please contact me to suggest any changes.

Chania, Greece Charis M. Galanakis

Contents

Chapter 1
Microclimate Management: From Traditional Agriculture to Livestock Systems in Tropical Environments

Manuel Jesús Cach-Pérez, Gilberto Villanueva López, José Armando Alayón Gamboa, José Nahed Toral, and Fernando Casanova Lugo

Abstract Microclimate plays a determining role in the development of biotic and abiotic interactions within agriculture and livestock systems and the physiological and productive performance of plants and animals. Given that management practices determine the degree of microclimate modification within production areas, different agriculture and livestock management strategies can contribute to reducing the effects of climate change, a phenomenon that puts food sustainability at risk. Climate-smart agriculture can develop agroforestry-based production systems that contribute to soil water retention, soil and air temperature reduction, nutrient fixation, weed control, soil stabilization, and protection against wind and runoff in the improved physiological performance of crops and, therefore, higher productivity. Moreover, the implementation of silvopastoral systems contributes to the efficient use of water and space and forage production in livestock systems, making them

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more productive, profitable, durable, and resistant to climate change. This chapter exemplifies climate-smart management schemes that can be applied in tropical production systems.

Keywords Climate-smart agriculture · Climate change · Milpa · Agroforestry systems · Silvopastoral systems · Sustainability

1.1 Introduction

Since the discovery of agriculture little more than 12,000 years ago and the beginning of the domestication of plants and animals some 10,000 years ago, humankind has modified the environment to provide the ideal microclimatic conditions for the development of species that provide food, clothing, building materials, and other consumables (Vasey 2002). This has resulted in a constant increase in the productivity of crops and animals under management—a product both of natural selection and human selection—and the biotic and abiotic interaction within the spaces destined for food crops or livestock (FAO 1996).

However, population increase brings with it a greater demand for food to satisfy this need. It has been necessary to develop different cultivation and management techniques, new varieties of plants and animals and allocate more space and supplies ever to agriculture and livestock, in turn creating huge environmental problems such as loss of biodiversity, soil loss and contamination, and water and air pollution (Keenan et al. 2015; FAOSTAT 2020b).

Between 1997 and 2017, approximately 1.12% of the world's forest area lost, while agricultural land use increased by an average of 0.54%, the only exceptions being some countries in Europe and Oceania (Table 1.1; FAOSTAT 2020a). Latin America has one of the highest annual deforestation rates, associated with global food demand. Between 1990 and 2015, around 200 million hectares of tropical forest were lost due to anthropogenic activities such as fires and the transformation of land for agriculture and livestock use (Keenan et al. 2015). Recent estimates suggest that around one million square kilometers of dry forest persist in the tropical regions of South America (54.2%), North and Central America (12.5%), Africa (13.1%), Eurasia (16.4%), and Australasia and insular Southeast Asia (3.8%) are seriously threatened, mainly by conversion to cropland and grasslands (Miles et al. 2006). Pasture for global livestock production occupies 3315 billion hectares of land and uses approximately 33% of surface area to raise grazing animals (Herrero et al. 2013; FAOSTAT 2020a; Lorenz and Lal 2018). In Latin America, land use is mainly for pasture reaching between 60% and 80% of total land area in some countries, including Brazil, Nicaragua, Colombia, and Mexico.

In Mexico, the change in land use associated with agriculture and livestock has caused the fragmentation of ecosystems, creating complex landscapes with patches of transformed and non-transformed areas and causing the loss of more than 50% of vegetation cover. In some states of southeastern Mexico, land use for

Table 1.1 Forest and agricultural land use and emissions volume change between 1997 and 2017 per region in the world

Region/indicator	Forest land area (% of total land area)	Agricultural land area (% of total land area)	Emissions in agriculture (CO_2 eq. Gg)
Africa	−2.1	1.03	340,083
America	−1.6	0.4	194,064
Asia	−0.8	0.2	412,738
Europe	−0.7	−1.2	−101,030
Oceania	−0.4	−11.2	7618

Source: FAOSTAT (2020a)

agriculture and livestock takes up between 60% and 90% of total land area, as is the case with the humid tropics, including Veracruz, Tabasco, Campeche, and part of Chiapas (Ochoa-Gaona et al. 2004; Flamenco-Sandoval et al. 2007; Nahed-Toral et al. 2013a; Villanueva-López et al. 2019).

Food production is one of the primary sources of greenhouse gas emissions into the atmosphere and has accelerated global climate change, in turn, harming agriculture and livestock. Changes in rainfall patterns, extreme drought and atypical rains, higher temperatures, and lower air humidity, as well as more robust and more frequent hydrometeorological phenomena, are a severe threat to food sustainability in regions around the world (IPCC 2014).

Rural and family agriculture are particularly vulnerable since they lack the technical and economic means to confront environmental changes that significantly affect small scale food production. However, while up to 85% of global food production is estimated to come from small scale producers, recent years have seen a systematic decrease in their production compared to big producers, accentuating the problem of food production for self-consumption (FAOSTAT 2020b).

A search is needed for production alternatives that contribute to reducing climate variations caused by phenomena such as land-use change and climate change. These production schemes should be sustainable and accessible in technical, economic, and social terms for small-scale (family) producers, thereby benefiting food sustainability.

One alternative is undoubtedly the search or rescue of practices that modify the microclimate in a way that is beneficial to plant and animal development, many of which were widely practiced before the green revolution. For this, it is necessary to evaluate the advantages such practices can offer, for example, water retention capacity, soil cover as protection against erosion, and excessive soil temperature, shade, and quality food source for animals, among other benefits.

In this context, the dimension of the microclimate can be variable. Microclimate can be defined as the particular climatic conditions measured around an organism and includes factors such as air temperature and humidity, wind speed, light, precipitation, dew formation, soil temperature, and water content. An important fact about microclimate is that change in any of these factors has an effect on the others and on the organism itself. The delimitation of the microclimate depends on the capacity for mobility or dispersion of the organism it affects ((Jones 1985; Naiman et al. 2005; Mislan and Helmuth 2008).

For a plant, for instance, the microclimate may be the climatic conditions in an area measured in centimeters or meters around it, while for an animal, the microclimate may be much broader and more variable, given its capacity for movement and its location at any given time. The microclimate, therefore, plays a vital role in the development of processes such as growth, reproduction, productivity, and even mortality of organisms (Naiman et al. 2005).

This chapter addresses some practical examples of management strategies, firstly in agricultural systems that exemplify the advantages of positive impacts of microclimate modification on the physiology and productivity of maize and cocoa (as study cases), and secondly in livestock production management with a view to the development of climate-smart livestock. The aim is to identify practices that help to improve production processes through the more efficient use of resources and the potential reduction of possible effects of climate variation as a result of climate change and land-use change.

1.2 Microclimate Management in Agricultural Systems

1.2.1 Microclimate and Crops

Cultivated plants, like any other group of plants, interact with different biotic and abiotic elements of their surroundings, provoking a response in physiological, biochemical, morphological, and molecular performance (Fig. 1.1; Qaderi and Reid 2009). Any variation in the behavior pattern of these factors will cause the plant to respond as a means to acclimatize to the new conditions, as long as the variation in biotic and abiotic elements remains within the plant's tolerance threshold.

In this way, crop areas undergo continuous biotic and abiotic changes that depend on the crop type and management strategies and the environment, determining factors in the ecological dynamics within the crop area (Hoy 2015). Crop production is, therefore, highly vulnerable to climate variation; for example, rainfall patterns, increased air temperature and CO_2 concentration, drought, flooding, and interannual climate variation bring a considerable reduction in crop productivity (IPCC 2014; Mall et al. 2017; Siebert et al. 2017).

The above is derived from the physiological stress that crops suffer as a consequence of climate variability. In general, high temperatures reduce photosynthesis, increase respiration and transpiration, and affect hormonal regulation and secondary metabolism of the cultivated plants. This leads to lower growth and production rates: in tomatoes, temperatures higher than 34 °C reduce the formation of flowers, while in celery, lettuce, and spinach, temperatures above 35 °C inhibit seed germination; wheat production can drop by up to 6% per degree Celsius of air temperature

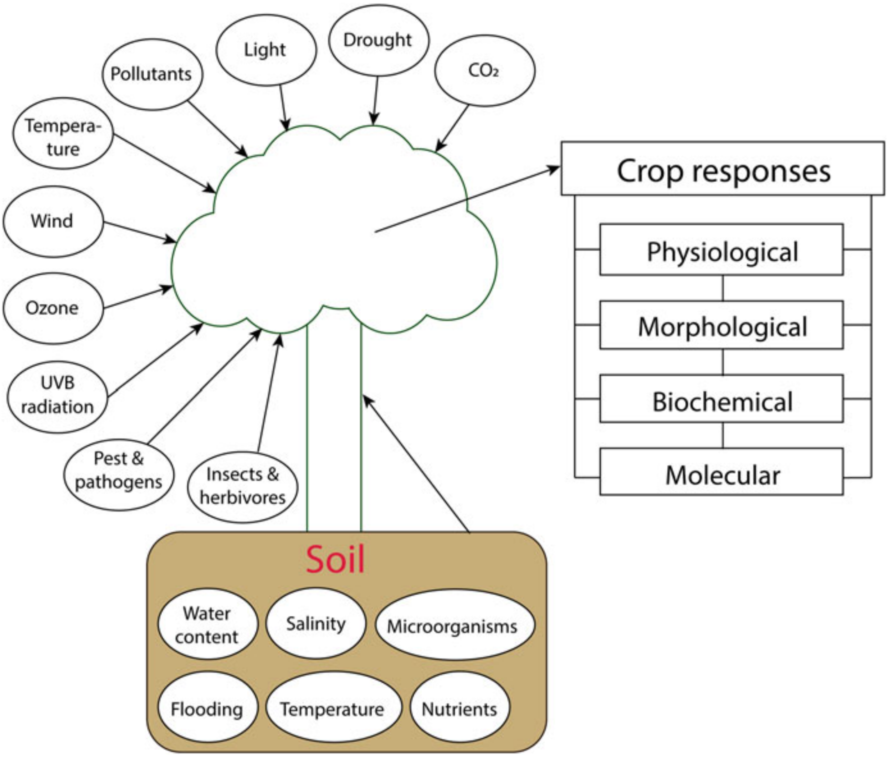

Fig. 1.1 Illustration of plant response to different biotic and abiotic factors. (Elaborated and modified from Qaderi and Reid (2009))

increase (Nascimento et al. 2000; Timsina and Humphreys 2006; Restrepo-Diaz et al. 2010; Jarma-Orozco et al. 2012; IPCC 2014).

The combined effect of high temperatures and low water availability causes an increase in atmospheric evaporative demand, as well as a reduction in soil humidity. This, in turn leads crops to suffer from hydric stress and reduced photosynthetic efficiency due to damage to the photosynthetic apparatus (Oliver et al. 2010; Sunkar 2010). For example, high temperatures and hydric pressure could minimize wheat production by up to 61% in some regions of India by 2050 (Vashisht et al. 2013).

Given the above, microclimate management within the crop area using different agricultural management practices can contribute to reducing or mitigating the possible effects of climate change, initially on a local scale, but which as a whole can mean the continuity of food production to meet growing demand worldwide.

1.2.2 Monoculture Vs. Polyculture: The Case of Maize

Rainfed agriculture represents around 75% of the world's cropped land (Reddy and Syme 2014). The practice is carried out by small producers in reduced areas making it highly vulnerable to climate variability. The management practices used in rainfed agriculture, therefore, can play a determining role in the economy of natural resources within these systems. Cropped areas, small-holdings or any other production system on any scale can be considered a mini-ecosystem, in which interactions established between all its components are, in no small degree, influenced by the microclimate evolving from the various production and management practices put into use (Hoy 2015). In this way, water retention, soil and air temperature, among other factors, will not be the same in a monoculture system (which also implies more significant demand for resources such as water, nutrients, fertilizers, and pesticides) as in a polyculture system (Pino et al. 2000; Pérez-Hernández et al. 2020).

Maize is an excellent example of this, cultivated in Mexico under a wide variety of highly contrasting environments in terms of altitude, rainfall, humidity, soil, and temperature, leading to the development of different management practices and, as a result, the development of 64 breeds (CONABIO 2011; Mariaca 2011; González-Merino and Ávila-Castañeda 2014; Weerarathne et al. 2017). One of the primary crop practices developed in rural agriculture is a polyculture system called "milpa". In the milpa system, maize is grown in combination with beans (*Phaseolus* spp.) and squash (*Cucurbita* spp.), although these last two components may vary depending on the particular geographical region (Aguilar et al. 2003; Mariaca 2011). It is well known that this combination provides a varied and balanced diet for farmers; however, it also brings ecological advantages to the system. These advantages include: the fixation of atmospheric nitrogen through a symbiosis between *Rhizobium* spp. and the bean plant roots, as well as soil water retention and weed control by the squash. The maize, in turn, provides support for the beans, acts as a physical barrier that prevents the spread of some diseases, and promotes the conservation of local agrobiodiversity (Nigh and Diemont 2013; Wang et al. 2017). Despite this, little is known about the microclimatic modifications involved or their potential advantages for the physiological performance of maize and, ultimately, its productivity. Also, the practice has been losing ground to public policies that prefer and encourage the implementation of monoculture systems.

Pérez-Hernández et al. (2020) tested microclimate variation in maize cultivation in the southeast of Mexico. They compared a monoculture system to the milpa system, which combined maize, bean, and squash (Fig. 1.2) and looked at the effect of microclimate variation on the physiological performance of the maize. Ninety-nine days after sowing the maize (close to harvest) when the bean and squash plants were fully developed, they found that the microclimate conditions were more suitable for the physiological development of maize in the milpa system. The milpa registered lower air temperature and vapor pressure deficit than monoculture. The most significant difference was that in the milpa system, water in the soil was close to saturation with a volumetric water content approximately 45% higher than in the

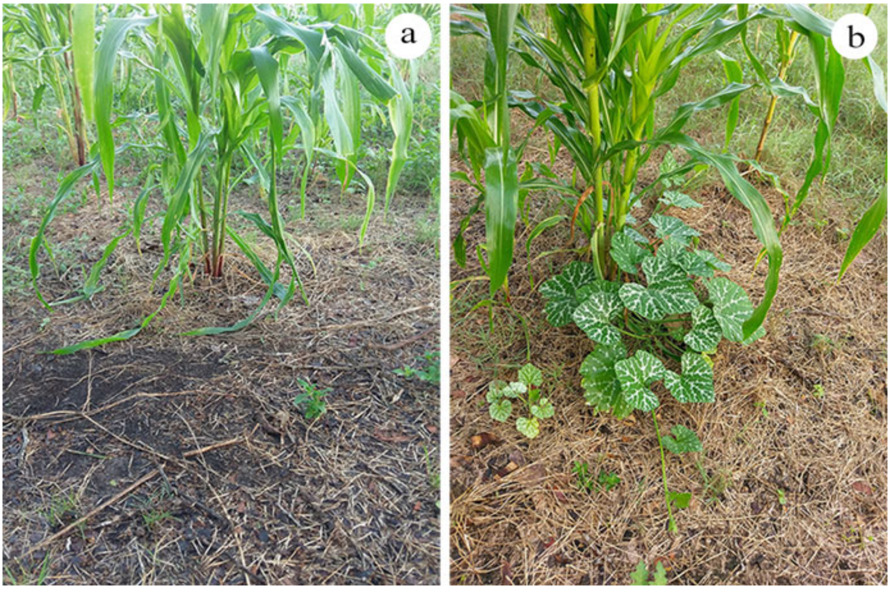

Fig. 1.2 Images that show (**a**), maize plants under monoculture treatment, and (**b**) under milpa treatment, which combines maize with bean and squash

Table 1.2 Maximum microclimate conditions recorded at 14:00 inside the maize crop area under two management schemes

Variable/management	Monoculture	Milpa	Difference in the milpa
Air temperature (°C)	38.8	37.5	−1.3
Soil temperature (°C)	35.3	30.9	−4.6
Soil volumetric water content (m^3/m^3)	0.18	0.33	+0.15
Vapor pressure deficit (kPa)	3.4	3.0	−0.4

Pérez-Hernández et al. (2020)

monoculture system. Air and soil temperatures were also close to 14% lower in the milpa system compared to monoculture (Table 1.2).

It should be noted that the rainfall in the experiment zone was 135.1 mm over 4 months; however, the high humidity (100% for more than 12 h during the afternoon and night) allowed water condensation to form on the leaves, which drained off and moistened the soil. The cover provided by the squash leaves helped to reduce the direct impact of solar radiation on the ground, lowering its temperature and, consequently, water evaporation.

The above is reflected in a 25% increase in total daily CO_2 assimilated through photosynthesis in the maize plants under the milpa system compared to the monoculture. This may have been possible due to the milpa plants having sufficient water in the soil to compensate for the loss by transpiration, thereby maximizing stomatal opening time. Although transpiration in the milpa plants was 21.7% higher than in the monoculture, water use efficiency was the same in both cases; that is, maize plants under both management systems lost the same amount of water per CO_2 molecule assimilated; however, higher assimilation of CO_2 in the plants under the milpa system may represent a higher production of maize grain compared to the monoculture.

Given the degree of microclimate modification produced by the milpa management system, this practice may be an excellent alternative to help mitigate the possible effects of climate change in rural agriculture. The milpa system contributes to the incorporation of nutrients, water retention even without rain, and lower soil temperature, which are more favorable conditions for the physiological performance of maize in comparison with the monoculture system. In addition, the wide variety of possible combinations of species grown with maize in the milpa system helps to promote the conservation of local biodiversity as well as enabling small producers to reach food sustainability by obtaining a balanced diet from the same plot.

1.2.3 Agroforestry in Maize and Cocoa Production Systems

Although the milpa system for the cultivation of maize in combination with other vegetable species offers microclimatic advantages that enhance the physiological performance of the crop, for it to become established, small portions of the forest must first be leveled and in some cases burned. These areas are used for up to 5 years, after which period the land is abandoned for a varying length of time to encourage its natural regeneration before the next clearing and use, known in some areas as lying fallow (Nigh and Diemont 2013; Rodríguez et al. 2016). Under a good management scheme, contrary to what might be thought, the milpa can favor nutrient dynamics, natural regeneration, and increased biodiversity (Rodríguez et al. 2016).

In this sense, agroforestry can contribute to the design of management schemes associated with the milpa and other maize and vegetable production systems and, in general, any surface destined for food production. Agroforestry systems are considered one of the most essential practices in the tropical regions of the world (Montagnini et al. 2015). The presence of trees can significantly and beneficially modify the microclimate within the growing area for the cultivated species. In addition to restoring and improving soil fertility through the incorporation of tree species with the capacity to fix atmospheric nitrogen, optimize water uptake and retention in soil, reduce air temperature and wind speed, and provide a habitat for organisms that contribute to biological control (such as birds and insects), among other benefits (Murgueitio et al. 2015; FAO 2017).

Under a simple scheme of living fences or the delimitation of cropland (Fig. 1.3), tree species can be established in tropical regions that contribute not only to the aforementioned gains but also help to generate biomass with higher nutrient content for (1) human and animal nutrition, (2) incorporation into the soil by direct application or through composting processes, and (3) wood production. Depending on geographical location, fruit species such as *Mangifera indica* L.,

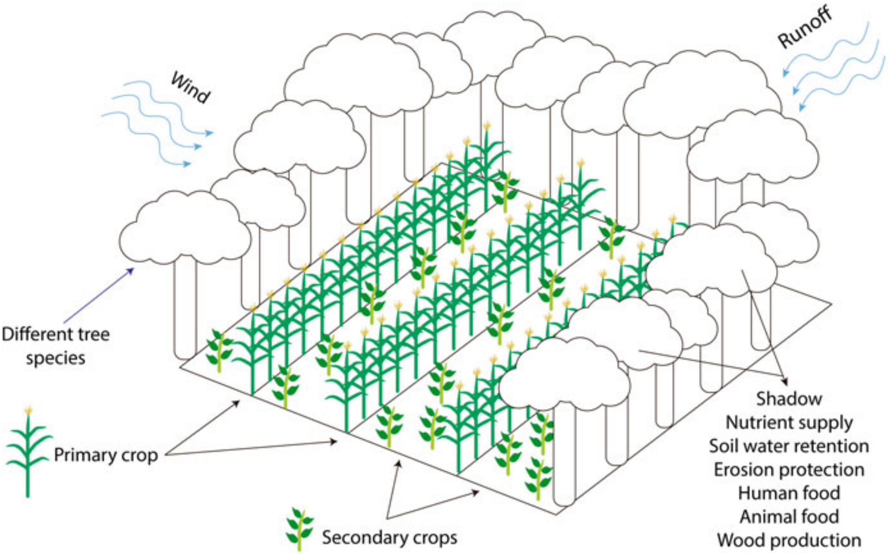

Fig. 1.3 Illustration of an agroforestry system showing how growing space is leveraged through the establishment and combination of different tree species that contribute to the production of food for human (fruits) and animal (foliage, seeds) consumption, wood, as well as provide shade for the animals. Foliage obtained by pruning can be incorporated into soil to provide nutrients within the growing area; the simple presence of trees helps protect crops against wind, runoff, pests and diseases, stabilizes and helps retain water in the soil. The main growing area can be used for the establishment of different species, as in the milpa system, which combines maize, beans and squash

Psidium guajava L., and *Tamarindus indica* L. can be incorporated into the first and second group, while species such as *Samanea saman* (Jacq.) Merr., *Enterolobium cyclocarpum* (Jacq.) Griseb., *Crescentia cujete* L., *Gliricidia sepium* (Jacq.) Kunth ex Walp., *Leucaena leucocephala* (Lam.) de Wit or *Guazuma ulmifolia* Lam., *Brosimum alicastrum* Sw. can be incorporated for animal consumption. In all cases, these species offer shade and edible fruits for people and animals, forage with high nutrient content for livestock feeding or incorporation into the soil within the farming area, and in some cases, fruits of traditional use in different regions. Within the third group, species such as *Swietenia macrophylla* King, *Cedrela odorata* L., *Tabebuia rosea* (Bertol.) DC. can be found (Hiwale 2015a, b; Murgueitio et al. 2015).

However, perhaps one of the best examples of agroforestry systems in the world is related to the production of cocoa (*Theobroma cacao* L.), a species commonly grown under the shade of other trees, mainly timber or fruit trees (Soto et al. 2008). Poor shade management of these trees, through the pruning (or absence of it), can lead to various problems such as the presence of fungal diseases; if the canopy is very closed (due to a combination of lack of pruning of shade trees and excess density of both cocoa and shade trees), less light will enter the growing area, causing poor air circulation, high humidity, and lower temperature than on the outside, conditions that create an extremely favorable habitat for the growth of fungi such as *Moniliophthora roreri*, one of the leading causes of depleted cocoa production.

With this in mind, Jiménez-Pérez et al. (2019) tested the effect of canopy management variation on the microclimate within shaded cocoa plantations and how this is related to hydric status and cocoa productivity. The authors' selected open canopy cocoa plantations (Leaf Area Index = 1.6) and closed canopy cocoa plantations (Leaf Area Index = 4.2) and characterized the microclimate inside the cultivation area, as well as the hydric state of the cocoa during two seasons (dry and rainy) in one year. They found that the amount of light received inside the canopy was up to 93.7% and 92.3% lower under closed canopy conditions during the dry and rainy seasons, respectively. This implies a decrease of up to 11% in vapor pressure deficit in the closed canopy cocoa plantations compared to open canopy (Fig. 1.4a), while air humidity increased by up to 8.6% in both seasons (Fig. 1.4b). Although the air temperature was similar under both canopy conditions (Fig. 1.4c), soil temperature was up to 2.9 °C lower under closed canopy conditions (Fig. 1.4d).

Despite the above, sap flow was higher throughout the day in cocoa trees under closed canopy conditions than open canopy, suggesting a higher water demand in closed-canopy conditions. Furthermore, it implies that cocoa trees under extreme shade keep stomata open for more extended periods in an attempt to assimilate

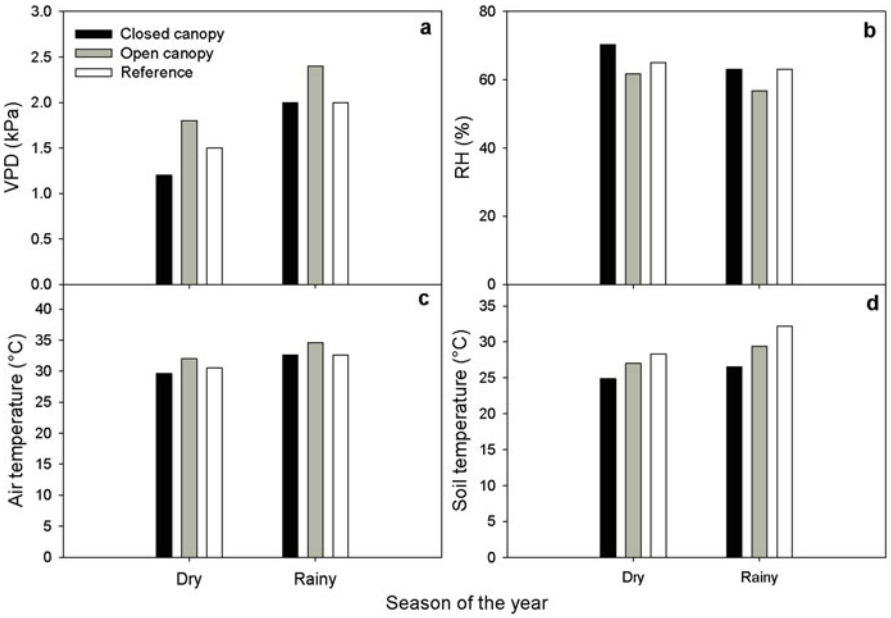

Fig. 1.4 Average microclimatic variables recorded between 11:00 and 16:00 in open canopy and closed canopy cocoa plantations and open space (reference). (**a**) vapor pressure deficit (VPD, kPa), (**b**) relative air humidity (%), (**c**) air temperature (°C), (**d**) soil temperature (°C)

more CO_2, however, without sufficient light the photosynthetic process is less than optimal. This is evident in the production reported for each system, which was up to 56% lower in shaded cocoa plantations (2633 kg/ha/year^{-1} vs. 1133 kg/ha/year^{-1} for open and closed canopy plantations, respectively).

The study by Jiménez-Pérez et al. (2019) demonstrates that proper management of canopy shade through pruning and thinning contributes to the development of microenvironmental conditions favorable for cocoa production, as observed by other authors who compared the physiological performance of cocoa under contrasting light conditions. Gómez (2002), for example, reported better photosynthetic performance of cocoa plants when they received between 40% and 60% of total incidental light, similar to the results recorded under open canopy conditions in the previous experiment.

1.3 Climate-Smart Livestock

1.3.1 Impact of Livestock on Climate Change

The ecosystem diversity that once characterized Latin America has been replaced by vast expanses of monoculture pasture. This represents a threat to numerous species of wild animals and plants, prompting the invasion of generalist species and interrupting pollination and seed dispersal, as well as raising the threat of new zoonotic diseases and the reemergence of tropical diseases. Nevertheless, it is possible to reverse these effects through improvements to the sustainable management of grazing, incorporating variables aimed at organic livestock production (Nahed-Toral et al. 2013a). Such measures can increase the diversity of flora and fauna species, improve the quantity and quality of forage, wildlife habitat, and lessen forest fires' risk by reducing the amount of fire-susceptible biomass. For example, the browsing of ruminants over shrubs and tree species acts as biological control of undesirable species. It stimulates the maintenance of grasslands by reducing the shade from trees and scrubs (Bermejo et al. 2012). Moreover, ruminants function as seed dispersers through the deposition of feces on the land, which modifies the presence and distribution of certain plant species. In humid and sub-humid tropical conditions and under low to moderate grazing intensities—which predominate in the south-southeast of Mexico—it is possible to encourage greater plant species diversity in grasslands, as shown by the intermediate disturbance hypothesis (Gao and Carmel 2020).

Furthermore, the transformation of natural vegetation into large areas of pasture for the development of extensive livestock farming, in addition to modifying the microbiological properties and macrofauna of the soil, reduces the content of organic matter (OM), nitrogen (N), phosphorus (P) and potassium (K), accelerates erosion and promotes compaction, and it is considered a significant cause of the depletion of soil organic carbon (SOC) reserves (Pulido et al. 2017; Angst et al.

2018; Poulton et al. 2018; Fornara et al. 2020). In the tropics, 25% to 27% of SOC can be lost by transforming forests to cropland (McSherry and Ritchie 2013; Kopittke et al. 2017). It is also known that affecting the composition of biotic communities and microbial activity reduces soil organic matter (SOM) storage and the cycling of nutrients (N, P, K, sulfur (S)), affecting plant growth and productivity. These changes are exacerbated by the effects of climate change (CC). For example, higher environmental temperature reduced precipitation, and a decrease in soil moisture affects the efficiency of microorganisms to incorporate OM into the soil and store carbon (C) (Tardy et al. 2015; Geyer et al. 2016 Villanueva-López et al. 2019).

The demand for water in livestock farming varies according to the production system, its productivity, and geographical region. The amount of water required to produce one kilogram of meat varies depending on the production system. Intensive systems (IS) have a higher demand than extensive systems (ES) due to the use of water for the intensive production of grain used in animal feed. In the humid and sub-humid tropics of Mexico, IS for calf rearing (cow-calf) and fattening demand more significant quantities of water compared to ES, due to the high impact (75%) caused by irrigation of the maize crop, the manufacture of fertilizers (14%) and the drying and transportation of maize (11%). Meanwhile, in ES, the highest impact on water depletion is the greater demand to generate electricity for water cooling (31%) and maize production (29%) (Rivera-Huerta et al. 2016).

Extensive livestock farming based on monoculture pasture also contributes to water pollution due to the indiscriminate use of synthetic fertilizers on grasslands. Less than half of the N and P applied as fertilizers is absorbed and used by the grasses; the rest is removed through surface runoff or leaching into the subsoil, thus contaminating water sources. Also, water runoff from agricultural fields can result in excess sediments, nutrients, and pesticides in surface water bodies, making it a significant contributor to eutrophication. This is common throughout Latin America, where only 20% of the water used for cleaning excreta undergoes treatment for reuse (Rivera-Huerta et al. 2016). Adaptation and mitigation strategies are needed, therefore, to make rational and efficient use of water for the development of climate-smart livestock farming, not only to help farmers adapt to a changing climate but also to provide fresh water for human consumption. For example, organic livestock farming can be adapted to allow cattle to deposit 170 kg of N per hectare per year, which is achieved with no more than two dairy cows per hectare, or their equivalent, to avoid contamination of the soil and surface and groundwaters with N, which becomes nitrate, and with diverse microorganisms contained in manure (IFOAM 2009).

The unprecedented transformation of forest cover into pasture since the mid-twentieth century has contributed to a global rise in greenhouse gases (GHG) emissions from the livestock sector of 51% and 117% in developing countries (Herrero et al. 2013; Chang et al. 2015). The primary GHG from livestock are CO_2, methane (CH_4), and nitrous oxide (N_2O); these gases are responsible for between 12% and 18% of total atmospheric emissions (Rosenzweig et al. 2016; Hu et al. 2019). The CH_4 produced by enteric fermentation in ruminants is an estimated emission of 1.6 Pg CO_2 eq, while manure management is 0.25 Pg CO_2 eq (Herrero et al., 2013). In the case of N_2O, the highest contribution is from agricultural land, with around 65% of current emissions due to synthetic nitrogen fertilizers (Wagner-Riddle et al. 2017). While there is little information about the effect of climatic conditions on N_2O emissions, it appears that the more humid the environment, the more N_2O is emitted.

1.3.2 Impacts of Climate Change on Livestock

Climate variability has a direct and indirect impact on livestock. In Mexico, particularly in the south-southeast region, the existence of fragile ecosystems, high poverty levels, and development strategies in discord with local conditions, among other factors, have made the region one of the most susceptible to severe damage from the adverse effects of climate change. Large expanses of pasture in these regions have been affected and degraded by the impact of drought and flooding, causing an increase in animal mortality, a higher rate of disease, loss of pasture, forest fires, loss of production infrastructure, and diminished assets for farmers (Schroth et al. 2009).

The Intergovernmental Panel on Climate Change (IPCC) warns that, if action is not taken to reduce GHG emissions, by 2100, a temperature increase of 1.8 °C to 4 °C (0.1 °C per decade) can be expected, which will strongly affect current precipitation patterns. Similarly, sea levels are foreseen to rise by 10 cm to 80 cm, increasing the risk of flooding in low-lying areas, along with more frequent and prolonged droughts. Together, all of these changes can limit crop growth and yield and, at the same time, render the majority of living species unable to adapt to CC. Water scarcity exacerbates soil degradation and delays the establishment and development of grass species, contributing to desertification and biological diversity loss (Smith et al. 2016). On the other hand, the root biomass of grass species responds differently to the impacts of CC. While some grass species such as *Brachiaria brizantha* are unable to survive prolonged periods of drought, others (e.g., *Cynodon nlemfuensis*) succumb to floods caused by tropical storms and hurricanes, which are becoming more intense and frequent. In animals, lack of water decreases productivity (milk, meat) and increases their susceptibility to disease.

CC is expected to increase the ambient temperature by 2 °C to 4 °C, depending on the biome; rainfall will decrease by 5% to 15%. The interaction of these conditions with ambient CO_2 concentrations will cause, in tropical regions, an increase in pasture biomass production (aerial and underground) by up to 15%, due mainly to an increase (10%) in OM decomposition, C cycling, and storage (5%) and a reduction in N mineralization (10%) (Parton et al., 1995). This change in pasture production represents the availability of forage that could be used efficiently for animal production. Care must be taken to optimize the use of metabolizable energy (ME), which may eventually be available to the animals and which is high in the tropics (9.5–12.5 MJ ME/Kg dry matter) (Herrero et al. 2013). In production units,

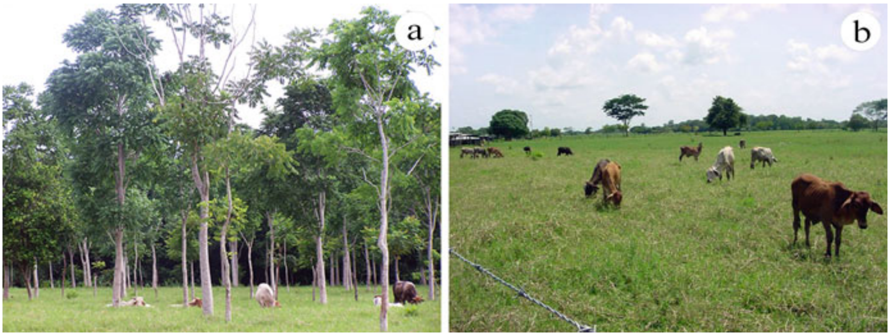

Fig. 1.5 (**a**) Livestock grazing system under the influence of shade from *Cedrella odorata* trees; (**b**) monoculture pasture livestock system (unshaded) in the tropical south-southeast region of Mexico

adaptation measures must be taken that allow changes and adjustments to pasture resting time and management of grazing intensity to avoid harvesting mature forage of low nutritional quality. One strategy is to strengthen hybrid (crop-livestock) production systems by implementing trees and scrubs in combination with the grass and which are used as food supplements. These systems generally allow higher productivity and forage quality than monoculture forage crops (Valladares and Niinemets 2008; Pang et al. 2019).

Furthermore, to achieve better animal welfare conditions in the face of CC, it will be necessary to change the management of shadeless pasture, under which conditions animals are susceptible to heat stress, while pasture with tree cover improves animal welfare by reducing heat stress; besides, the cattle spend more time ruminating and resting, which has a positive effect on productive and reproductive indicators (Valladares and Niinemets 2008; Calle et al. 2012; Pang et al. 2019) (Fig. 1.5).

1.3.3 Climate-Smart Livestock: Opportunities to Increase Productivity and Sustainability

Climate-smart livestock (CSL) is part of climate-smart agriculture (CSA). CSA is neither a new agricultural system nor a new set of practices. CSA is an approach to address the challenges implied by the interconnection of three areas: a) ensuring food security through productivity and income of the rural population; b) adapting to CC, and c) contributing to the mitigation of CC (FAO 2010). CSL faces the challenge of interconnecting these areas as a means of dealing with food security in a changing climate, with the aim of improving food security for the population, helping communities to adapt to CC and contributing to the mitigation of CC by adopting reasonable practices, developing policies, and mobilizing the necessary finances to build resilient systems (Nahed-Toral et al. 2013b). To that end, CSL shares principles and objectives with the concepts of sustainable development and a green economy. Its objective of food security and contributing to the conservation of natural resources also links it to the concept of sustainable intensification and with the agri-food chain approach (FAO 2010).

1.3.3.1 Principal Strategies for Achieving Climate-Smart and Resilient Livestock in the Tropical Region of Mexico

Farmers have already developed some local strategies to adapt to various environmental and climatic changes. However, the high demand for animal food products, population increase, and the substantial environmental impacts caused by agriculture and livestock have meant that such strategies are not always successful. For this reason, actions and mechanisms must be implemented to mitigate and adapt to CC and help to reverse the environmental impacts and reduce GHG emissions resulting from livestock activities, as well as restore the functionality of ecosystems in the medium and long term. Such actions must use natural resources more efficiently, prioritize biodiversity conservation and the preservation of native forest habitat within livestock landscapes, ensuring the goods and services they provide in the long term, maintaining or restoring tree diversity within the livestock systems, and retaining other types of tree cover in those systems to improve environmental sustainability, landscape connectivity and habitat availability (Balvanera et al. 2002; Barlow et al. 2016). Agroforestry Systems, which comprise a wide range of management strategies—including silvopastoral systems, the use, and management of *acahuales* and good livestock practices—are resilient and sustainable alternatives for agriculture and livestock production—understanding resilience in an ecological sense as the capacity of a system to respond to disturbances and recover through its processes and feedback mechanisms, which interact with decision-making and environmental processes (Holling 1973).

In this context, silvopastoral systems (SPS) allow the production of food in a sustainable way. SPS effectively buffers the yield and quality of grasslands against the impacts of CC, especially in the reduction of water availability, since they integrate woody perennials (trees and shrubs) with grazing pasture under a comprehensive management system. They also provide more nutritious and easily accessible food sources to the livestock (branches, flowers, fruits, and shoots of native species), which helps to reduce excessive grazing and slow down soil degradation. These systems encourage the efficient use of water, electricity, and space, making them more productive, profitable, durable, and CC resistant, capable of guaranteeing food security and attenuating heat waves and the effects of hurricanes (Calle et al. 2012). This has caused silvopastoral systems to receive more attention from farmers and public policies in recent years (Murgueitio et al. 2011; Portela Lima et al. 2017). The most common SPS in the tropical regions of south-southeastern Mexico is, in order of importance: Living fences (LF), scattered trees in the pasture (STP), grazing

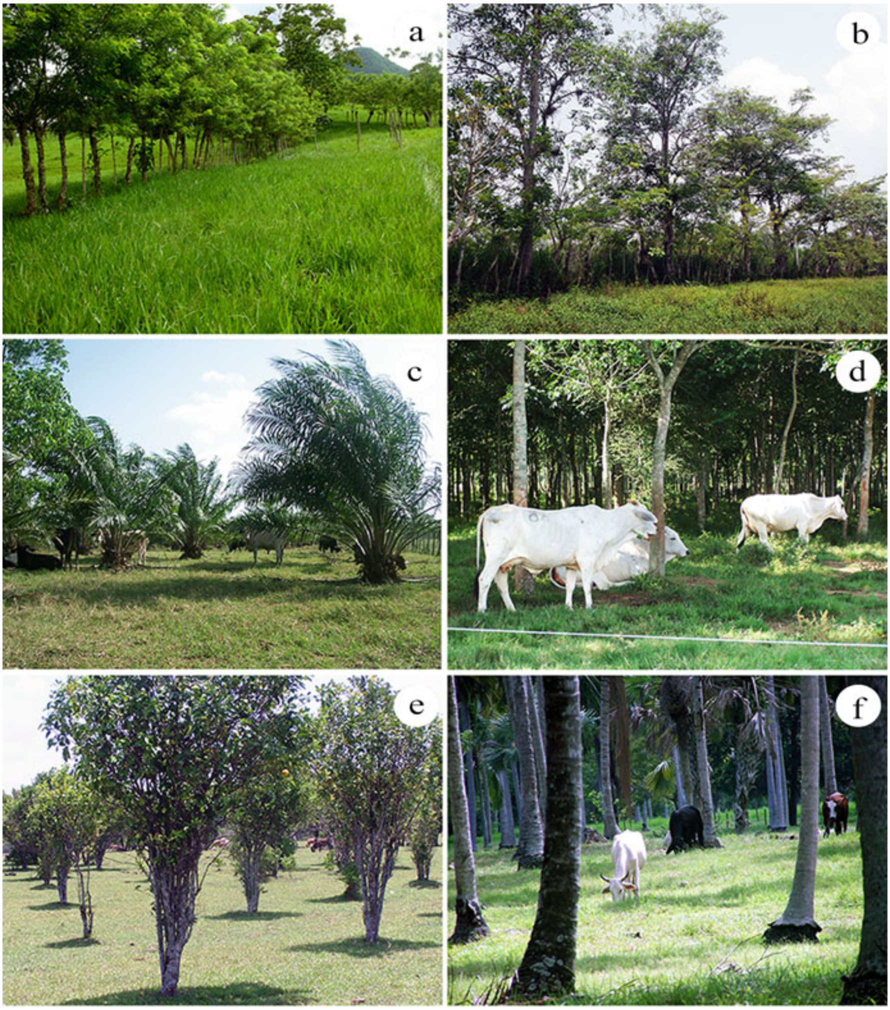

Fig. 1.6 Most common silvopastoral systems in tropical regions of Mexico. (**a**) monospecific living fences with *Gliricidia sepium*; (**b**) multistrata living fences with *G. sepium* (lower stratum) *Tabebuia rosea* (upper stratum); (**c**) *Elaeis guineensis*; (**d**) grazing in forest plantations (*Cedrela odorata, Swietenia macrophylla and Tabebuia rosea*)*;* (**e**) grazing in fruit plantations (*Citrus limon, Citrus sinensis*); (**f**) grazing in oilseed plantations (*Cocus nucifera*)

in plantations of forest species, fruit trees and oilseed species, alley cropping and protein banks (Figs. 1.6 and 1.7).

From the point of view of CC mitigation, trees in SPS have the potential to improve the physical, chemical, and biological properties of soil due to atmospheric N fixation through symbiotic associations and the input of plant litter (fallen leaves, branches, stems, roots, and their exudates). Over time, the deposition of fallen

Fig. 1.7 Most common silvopastoral systems in tropical regions of Mexico (continuation). (**a**) scattered trees in pasture; (**b**) alley cropping; (**c**) protein bank of *Morus alba*; (**d**) protein bank of *Gliricidia sepium*; (**e**) protein bank of *Tithonia diversifolia*; (**f**) protein bank of *Hibiscus rosa-sinenis*

material increases the surface and ground OM content, cation exchange capacity, and the availability and recycling of nutrients such as N, P, and K, among others, which help to decrease the rate of soil degradation (Angst et al. 2018; Poulton et al. 2018; Aryal et al. 2019). In that regard, Villanueva-López et al. (2015)—in a study carried out in SPS with live fences of *G. sepium* and in livestock systems in monoculture pasture (MP) in the humid tropics of southeastern Mexico—found that the soil of SPS had higher contents of OM (5.7% vs. 4.9%) and N (0.29% vs.

0.25%), and lower pH (7.23 vs. 7.53) and apparent soil density (1.3 vs. 1.5 g cm^{-3}) values compared to the MP livestock systems. In SPS with STP in the same tropical region, Aryal et al. (2019) also reported that soils had higher organic carbon content (5.7% vs. 3.7%) and electrical conductivity (72.7 vs. 48.9 ms m^{-1}), and lower pH values (6.2 vs. 6.9) and apparent soil density (0.9 vs. 1.1 g cm^{-3}) compared to MP livestock systems. Both studies indicate that live roots contribute with approximately 11% of C uptake by plants.

SPS has also been recognized for its potential to mitigate CC, given that they can store large quantities of C compared to MP livestock systems. This is because the tree component plays a vital role in atmospheric CO_2 absorption through photosynthesis and C storage in aerial biomass, plant litter, and soil reservoirs and functioning as CO_2 sinks. In the humid and sub-humid tropics of Mexico, many examples demonstrate the advantage of SPS over MP livestock systems to mitigate the effects of CC by C capture. Along these lines, Morales et al. (2020) reported for the sub-humid tropics of southeastern Mexico changes in C storage above and below ground and its relationship with the production of fine roots in SPS with LF, STP, and MP livestock systems. The SOC content was significantly higher in SPS (LF: 2.4%, STP: 3.1%) than the MP livestock systems (1.6%). The fine roots production differed between the SPS (LF: 27.8, STP: 45.4, and MP livestock systems: 9.4 g m^{-2} $year^{-1}$) and was positively correlated with SOC content.

Similarly, Aryal et al. (2019), in the same tropical region, also quantified C storage above and below ground in SPS with STP and in MP livestock systems. They found that SPS with STP stored 104.82 Mg C ha^{-1}, compared to MP livestock systems (58.63 Mg C ha^{-1}). C in aerial biomass in the SPS with STP varied from 11.53 Mg C ha^{-1} to 14.63 Mg C ha^{-1}. SOC concentrations were higher in SPS, while apparent soil density was higher in MP livestock systems.

In a study under dry tropical conditions in the Yucatán Peninsula, Casanova-Lugo et al. (2018) evaluated C concentration and storage in tree biomass above and below ground and in the soil in forage banks of *Leucaena leucocephala* (Lam.) de Wit, *Guazuma ulmifolia* (Lam.) and a combination of both species (Fig. 1.8). They found that C concentration was higher in stems (45.1%) and roots (44.9%) compared to foliage (43.4%); in addition, total C storage in soil was higher in the forage banks with only legumes than in the mixed-species banks (35.7 vs. 30.8 t C/ha). They concluded that, in tropical regions, forage banks are an essential option for improving C capture in plant biomass and in soil, thereby reducing CO_2 emissions from the soil into the atmosphere and providing a high-quality diet that enhances the efficiency of the animal production system.

A study by López-Santiago (2018) in the humid tropical region of the state of Tabasco in southeastern Mexico evaluated C storage in biomass in STP consisting of *Brachiaria brizantha* grasses and in a livestock system in a MP of *Brachiaria decumbens* (Fig. 1.9). It found that SPS with STP stored a total of 130.8 Mg C ha^{-1}, while the livestock system in MP stored a total of 96.9 Mg C ha^{-1}. In a parallel study in the same systems, the author found that the CO_2 fluxes from the soil were different, with the MP showing higher values (36.01%) compared to the STP

Fig. 1.8 Protein banks in dry tropical conditions in southeastern Mexico: (**a**) *Leucaena leucocephala*; (**b**) *Guazuma ulmifolia*

Fig. 1.9 (**a**) Silvopastoral system with trees scattered in pasture; (**b**) livestock system in monoculture grass (unshaded) in the humid tropics of southeastern Mexico

system. The highest releases presented in the rainy season with 36.98% and 38.84% for STP and MP concerning the early dry season. In the same region, Villanueva-López et al. (2015) also quantified the existence of C in the biomass of trees above and below ground and the soil in SPS with LF of *G. sepium* and MP livestock systems. The authors found that SPS with LF stored a more significant amount of C in the soil than MP livestock systems (119.82 vs. 113.34 Mg C ha^{-1}, respectively). This means that the presence of *G. sepium* trees in the LF contributed 6.48 Mg C ha^{-1} (5.7%) of the total C stored. In addition, they found no variations in CO_2 between systems. However, fluxes were higher in the rainy season compared to the dry season. Similarly, Adame-Castro et al. (2020) also evaluated CO_2 fluxes from the soil in two SPS: one with *L. leucocephala* and *C. plectostachyus*, and another with *L. leucocephala* and *P. maximum*, under sub-humid tropical conditions in the south of Quintana Roo, in southeastern Mexico. They found that CO_2 fluxes from soil were similar in both systems with values of 6.0 ± 0.14 and 6.1 ± 0.12 μmol $CO_2/m^{-2}/s$, respectively. However, fluxes in the *L. leucocephala* and *P. maximum* system were 12.5% higher in the rainy season compared to the dry season.

Table 1.3 Nutritional composition (%) of *Leucaena leucocephala* and grasses in two silvopastoral systems in the sub-humid tropics of southern Quintana Roo, Mexico

	L. leucocephala + *P. maximum* cv. Mombasa		*L. leucocephala* + *C. plectostachyus*	
Parameters (%)	Legumes	Grass	Legumes	Grass
Crude protein	19.5	7.4	22.4	9.2
Neutral detergent fiber	66.6	74.2	68.5	75.6
Organic matter	89.9	87.0	89.9	89.2
Ash	7.0	11.3	6.5	8.0

Table 1.4 Biomass yield (g DM/m^{-2}) of *Leucaena leucocephala* (Ll), *Panicum maximum* cv. Tanzania (Pm) and *Brachiaria brizantha* (Bb), in pure and mixed crop systems

Treatments	Ll	Pm	Bb	Total
Ll (pure)	691.4			691.4 b
Pm (pure)		368.4 a		368.4 c
Bb (pure)			557.0 a	557 bc
Ll + pm (mixed)	596.6	115.7 b		712.3 b
Ll + bb (mixed)	520.7		115.8 b	636.5 b
Ll + pm + bb (mixed)	684.1	152.0 b	191.4 b	1027.5 a
SE	81.3	32.2	29.7	143.2

Means followed by different literals in the row indicate significant statistical differences ($P \leq 0.05$). SE, standard error

Another alternative for the development of resilient livestock is to increase forage yield and quality by including tree species with potential forage in pastures, which in turn can help reduce overgrazing and slow down soil degradation. In this context, in the sub-humid tropics of southern Quintana Roo, Mexico, it was found that SPS of *L. leucocephala* with grasses such as *P. maximum* cv Mombasa and *C. plectostachyus* reported forage yields that fluctuate between 10 and 12 t DM/ha/year, under rainfed conditions and gleysol soil. The nutritional quality of these forage species varies based on the frequency of use by the animals, which is from 3 to 5 days of grazing in each paddock with rest periods ranging from 30 to 50 days (Montejo-Martínez et al. 2020) (Table 1.3).

Another study carried out in this same tropical region by Aldava-Navarro et al. (2017) in a SPS of *L. leucocephala* with *P. maximum* cv Tanzania and *B. brizantha* grasses found that the various associations of *L. leucocephala* with the evaluated grasses had dissimilar agronomic behaviors (Table 1.4). However, the crude protein content of the grasses increased significantly in all cases (Table 1.5). It should be noted that the biomass yield and crude protein content of L. *leucocephala* remained uniform during the evaluation period (Tables 1.4 and 1.5).

Table 1.5 Crude protein content (%) of *Leucaena leucocephala* (Ll), *Panicum maximum* cv. Tanzania (Pm) and *Brachiaria brizantha* (Bb), in pure and mixed crop systems

Treatments	Ll	Pm	Bb	Mean
Ll (pure)	21.6 a			21.6 a
Pm (pure)		11.7 c		11.7 d
Bb (pure)			10.5 c	10.5 d
Ll + pm (mixed)	22.0 a	15.0 a		18.5 b
Ll + bb (mixed)	22.1 a		13.0 a	17.6 b
Ll + pm + bb (mixed)	22.7 a	14.1 b	12.0 b	16.3 c
SE	0.4	0.2	0.3	0.3

Means followed by different literals in the row indicate significant statistical differences ($P \leq 0.05$). SE, standard error

Another alternative for climate-smart livestock is the use of *acahuales*. In Mexico, Mayan livestock farmers living in sub-humid tropical conditions, with a dominance of deciduous forest, designate areas of secondary vegetation known as *acahuales* as reserve and grazing zones for multiple purposes. These *acahuales* provide enough protein for the diet of the animals during the dry season, and despite being subjected to foraging, they preserve a diversity of plant species, similar to the vegetation of the deciduous forest (Albores-Moreno et al. 2020). Furthermore, the menu of forage species consumed by the animals provides them with enough condensable tannins to reduce the emission of enteric methane (31%), thereby contributing to the mitigation of GHG (Albores-Moreno et al. 2018; Albores-Moreno et al., 2019). Furthermore, the use of *acahuales* influences animal health and welfare, providing shade during foraging, and some plant species consumed can potentially remove rumen protozoa (defaunation). In contrast, others have anthelmintic activity, such as *Gymnopodium floribundum*, *Mimosa bahamensis* (Castañeda-Ramírez et al. 2018), and *Diospyros anisandra* (Flota-Burgos et al. 2020). The decision to maintain *acahuales* avoids the transformation of larger areas used for pasture cultivation and with that the emission of CO_2 due to changes in land use. Farmers also benefit from multiple ecosystem services: wood for the home, bushmeat for self-consumption, honey for commercialization, and conservation of water bodies for their animals (Ortiz-Colín et al. personal communication).

Grazing management is another strategy for CSL in tropical regions. However, due to inefficient management practices and the complex interactions of variables such as temperature, rainfall, and soil pH, many pastures are degraded and instead of acting as C sinks become a source of CO_2 emissions (McSherry and Ritchie 2013; Poulton et al. 2018; Wiesmeier et al. 2019). These issues can be addressed by managing the intensity and frequency of grazing, animal load, grass species, soil, and climate conditions (Smith et al. 2016). From a mitigation point of view, one of the more apparent benefits is soil C sequestration, which results from reducing grazing pressure as a means of stopping land degradation or rehabilitating degraded land. Similarly, with less grazing, animals tend to choose forage more nutritious and easily digestible, thereby reducing enteric emissions. Restoring degraded grasslands improves soil health and water retention, increasing the resilience of the grazing