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Preface

Silvopastoral systems are a form of agroforestry that intentionally integrates trees, shrubs, grasses and livestock on the same unit of land to provide mutual benefits to each component. They can vary from relatively simple systems where livestock graze under native canopy such as the Dehesa systems in the Iberian Peninsula to more complex arrangements with trees, forage shrubs and grasses with more intensive management as those practiced in Colombia, Mexico and Brazil.

Silvopastoral systems have recently gained significant attention as a sustainable alternative to traditional agriculture and livestock production systems in regions such as North America, Europe, Asia and Oceania.

In Latin America and the Caribbean, these systems have been used for decades either as organized arrangements planted in pastureland areas for timber or fruit production or as a result of adaptation measures to cope with climate change, or to manage vegetative succession.

This region is an essential player in the global livestock and cattle industry as it contributes with more than 26% of the beef production and 38% of the beef exports globally, and with 10% of dairy production. This has grown steadily during the last decade and will continue to grow further due to the increasing demand and the region's geographical position, experience, and human and natural resources. The greater participation of this subcontinent in beef exports has also resulted in a higher awareness of the co-responsibility for protecting natural resources and mitigating climate change. This is particularly important as Latin American countries contribute with 30% of the GHG emissions of the global cattle sector.

In recent years, the use of silvopastoral systems has gained prominence in the region thanks to the work of research institutions, and the interest of cooperation agencies, private companies and governmental institutions to promote sustainable cattle production. Silvopastoral systems are becoming increasingly popular as a way to address the challenges of climate change and biodiversity loss, and to improve animal welfare and food security. They can help satisfy the growing demand of agricultural products worldwide, while simultaneously providing a range of products and services to local rural communities.

The silvopastoral systems practiced in different countries of the region are the result of the promotion of several institutions and adaptations made by farmers and local communities to respond to their respective agricultural, environmental and socioeconomic challenges.

Argentina, Brazil, Colombia, Panama, Cuba, Costa Rica and Mexico are among the countries in the region that have embraced this approach mainly for cattle production to obtain environmental and economic benefits. Peri et al. (2016) covered the experiences on silvopastoral systems of the south of the continent in Argentina, Chile and the south of Brazil.

This book explores the different silvopastoral systems that exist in the northern part of South America and Mesoamerica including examples from the tropical part of Brazil, and from Paraguay, Peru, Colombia, Venezuela, Panama, Nicaragua, Mexico and Cuba. It presents an overview of the most important research results and developments in silvopastoral systems of this part of the continent including the most common silvopastoral arrangements in each country and their production aspects, environmental characteristics and socioeconomic attributes. Overall, the book provides a summary of the state-of-the-art knowledge on different aspects of silvopastoral systems in this region.

Cali, Colombia — Julián Chará
Columbia, MO, USA — Shibu Jose

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Without their dedication and involvement, this accomplishment would not have been possible.

Contents

About the Editors

Julián Chará is the research coordinator of CIPAV (Centre for Research on Sustainable Agriculture) in Cali, Colombia. With over 30 years of experience in the field of sustainable cattle ranching, watershed protection and climate change mitigation, he is the coordinator of the Global Network of Silvopastoral Systems and leads several projects related to sustainable cattle ranching, climate change mitigation and silvopastoral systems in Colombia and other countries. He coordinated the preparation of the project "Mainstreaming biodiversity in sustainable cattle ranching" that established over 30,000 ha of silvopastoral systems in Colombia. He has published over 30 articles, book chapters and books, and is the coordinator of Editorial CIPAV and Associate Editor of the *Agroforestry Systems* Journal.

Shibu Jose is currently the Associate Dean for Research in the College of Agriculture, Food and Natural Resources at the University of Missouri. Previously he served as the Director of the School of Natural Resources and also led the Center for Agroforestry at the University of Missouri. He also served as the Editor-in-Chief of *Agroforestry Systems*, the premier journal in the field of agroforestry, published by Springer-Nature for 14 years. He has led major interdisciplinary research projects involving agronomists, plant breeders, soil scientists, animal scientists, natural resource scientists and socio-economists. He uses ecological information in designing agroforestry systems and restoring degraded and damaged ecosystems. Over the past 25 years, Dr. Jose and his research team have conducted studies in the United States, Australia, Costa Rica, Belize, Panama, Bangladesh, Indonesia and India.

Chapter 1
Sustainable Silvopastoral Systems: Basic Design and Management Considerations

Shibu Jose, Dusty Walter, and B. Mohan Kumar

Abstract Silvopastoral systems are sustainable production systems characterized by greater biodiversity and multifunctionality, compared with other livestock production methods. Although silvopastoral systems are analogs of savanna ecosystems for the most part, complex functional dynamics make silvopastoralism a difficult construct to design and manage. The key design criterion is to optimize the use of spatial, temporal, and physical resources, by maximizing positive (facilitation) and minimizing negative (competition) interactions among the components, for which the principles of complex natural ecosystems are relevant. In this paper, we address the cardinal questions, how do the general ecological principles common to natural systems apply to the design and management of silvopastoral systems, and how sound management might be identified with the notion of sustained yield? In particular, we explore (1) spatial and temporal heterogeneity for maximizing resource use efficiency, (2) competitive interactions in perennial systems, (3) structural and functional diversity for resource conservation, and (4) integration of the principles of disturbance ecology in silvopastoral system management.

Keywords Silvopastoralism · Design and management · Spatial and temporal heterogeneity · Perennialism · Resource conservation · Disturbance regimes

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1.1 Introduction

Silvopasture intentionally combines livestock (cattle, sheep, goats, poultry, hogs, etc.) with trees or other woody perennials and forages on the same unit of land such that it is mutually beneficial to each component. Although integration of livestock into forestlands is not always done by following the silvopastoral principles, it is a dominant land use system in both the tropical and temperate regions of the world alike (e.g., Payne 1985; Sharrow 2007; Orefice et al. 2019). Precise estimates of the global area under silvopastoralism are not available, yet its potential is great (Jose et al. 2019).

Properly designed and managed, silvopasture practices and grazing systems have the potential to improve livestock productivity and provide environmental services. The global demand for meat and milk is expected to increase in the foreseeable future (Mottet et al. 2017). Land-based production of livestock and poultry provides an important source of protein and associated amino acids that are critical to human health and development (Wu et al. 2014; Elmadfa and Meyer 2017). At the same time, the growth of worldwide populations and the demand for better quality food means increased pressure on lands (Flachowsky et al. 2017). Additionally, concerns over the impact of livestock on climate issues are very relevant. Both productivity of livestock and climate change are interconnected and of significant importance to our environment and healthy populations (Mottet et al. 2017; Cheng et al. 2022). When silvopasture design takes into account appropriate ecological considerations, positive climate change can potentially be realized (Udawatta et al. 2022) while increasing overall animal productivity (Kallenbach et al. 2006; Gomes da Silva et al. 2021).

Silvopastoralism aims to achieve both environmental services (soil enrichment, efficient nutrient cycling, carbon storage, provision of shelter, shade, and food for livestock and poultry) (Jose 2009; Lin 2010; Udawatta and Jose 2011; Orefice et al. 2017) and economic benefits (income generation, expansion, and diversification, greater potential return on land investment) in an integrated fashion. It is often regarded as a compromise between conservation objectives and livelihood needs (Le Houerou 1987; Broom et al. 2013). There are many variants of the system in the tropics and temperate regions (Vandermeulen et al. 2018; Cubbage et al. 2012), but only a few of its forms are documented in the literature and even fewer are understood by the general public.

Of all agroforestry practices, silvopastoralism is the most commonly practiced in developed countries (Sharrow 1999). According to Steinfeld et al. (2006), of the world's total land surface, 33% is used for livestock production; presumably, a significant proportion of that is grazed forestlands. In the USA alone, there are about 70 million ha of land where forests are accessed by livestock and could therefore be enhanced if placed under silvopasture management (Clason and Sharrow 2000; Montagnini and Nair 2004).

The silvopastoral systems practiced in various regions of the world offer a wealth of information on the various methods by which innovative landholders have attempted to realize ecological and economic benefits. The practice of mixing trees, crops, and livestock has been in existence for millennia, including such examples as the Dehesa system in Spain, Iberia, and Morocco (Blondel 2006) and the Montados in Portugal (Ferraz-de-Oliveira et al. 2016). Similarly, research from Brazil seeks to enhance animal performance by designing silvopasture systems with the correct combination of legume trees and grasses in ways that enhance ecosystem services (Gomes da Silva et al. 2021). Silvopastoralism will thus take on many forms depending on the objectives of the individual landholder, the climate, culture, and other factors. Unlike temperate-region practices, where silvopasture implies grazing systems, silvopastoral practices in the tropics tend to be more complex and site-specific, and are not easily separated from the larger agroforestry practices of which they may be a part (i.e., grazing, cropping systems, and tree crops, may all be combined on a land parcel) (Payne 1985). Thus, to describe silvopasture as an independent land-use feature separate from other agroforestry practices will be a distinction that does not usually exist in most tropical farm settings. Likewise, fodder systems—in which fodder (usually from fast-growing multipurpose woody perennials) is fed to nearby animals— are also a common practice in the tropics. Thus, in a broader context, silvopasture involves both grazing systems and tree-fodder systems (Payne 1985; Nair et al. 2005, 2021).

As an association of woody and herbaceous plant communities with domesticated or semi-wild animals, silvopastoral systems are intentionally designed to optimize the use of spatial, temporal, and physical resources, by maximizing positive interactions (facilitation) and minimizing negative ones (competition) among the components (Jose et al. 2004). Although land use systems of this kind are thought to be highly productive owing to the vertical stratification of the above- and belowground components, they are extremely dynamic with available resources and environmental conditions changing over time. While silvopastoral concepts and paradigms may reflect the complexity expressed in natural mixtures like the savannah and their natural disturbance regimes, many of the modern silvopastoral systems that are seen today throughout the world are much simpler than their natural analogs (Fig. 1.1). Yet, the design and management remain challenging because of a lack of understanding of the nature of interactions among components that ultimately drive system productivity and sustainability. An understanding of the biophysical processes and mechanisms involved in allocating site resources is essential for developing ecologically sound systems that are economically viable and socially acceptable (Ong et al. 1996; Rao et al. 1998). This brief review will focus on the principles of designing sustainable silvopastoral systems.

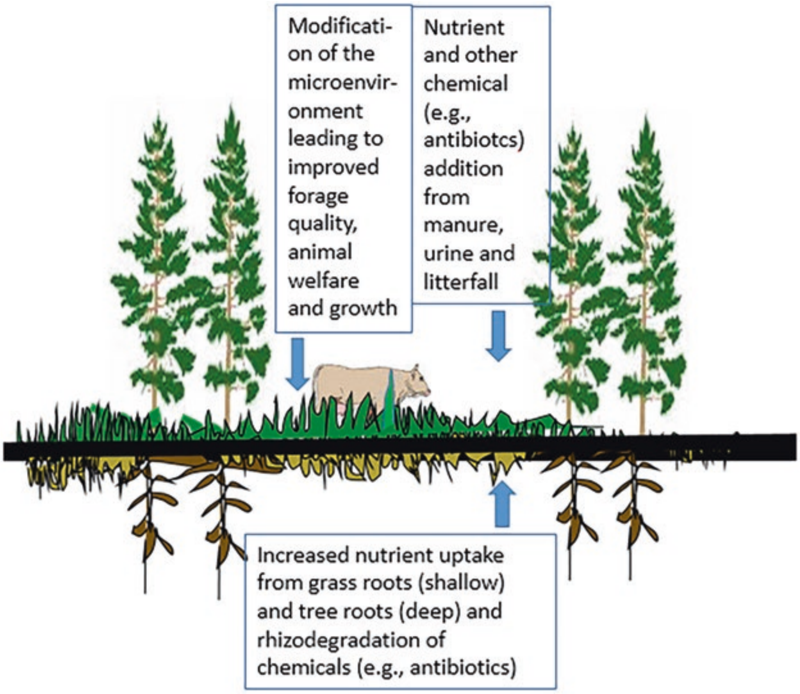


Fig. 1.1 Diagrammatic representation of components of a silvopastoral system

1.2 The Basics of Silvopastoral Design

The four "I" criteria developed by Gold and Garrett (2009) for temperate agroforestry apply to silvopastoral design. These four criteria distinguish silvopasture from livestock grazing in general, and specifically, from current practices that place cattle in unmanaged woods:

1. *Intentional:* combinations of trees, crops, and/or livestock are intentionally designed, established, and/or managed to work together and yield multiple products and benefits
2. *Intensive:* agroforestry systems are intensively managed to maintain their productive and protective functions and interactions and often involve cultural operations such as cultivation, fertilization, irrigation, pruning, and thinning
3. *Integrated:* components are structurally and functionally combined into a single integrated management unit so that the productive capacity of the land is fully utilized.
4. *Interactive:* agroforestry systems actively manipulate and utilize the biophysical interactions among component species for an optimal yield of multiple products, including ecosystem services.

Among the biophysical interactions, competition for light drives many design and management considerations as it is often the most obvious for practitioners. Although belowground interactions can also impact the productivity of the overall system, it is often difficult to quantify or observe until there is severe resource limitation such as a prolonged drought limiting soil water availability. As a result, the design of a silvopastoral system is often dependent on how much light should be available for forage growth. The available light will influence how tree species, tree spacing, and forage species are combined, as well as then shape how the broader management of the practice impacts overall resource availability.

The four general ecological principles common to complex natural systems (Olson et al. 2000) are also of particular interest in designing agroforestry systems such as silvopasture. They are: (1) *Ecosystems are distinguished by spatial and temporal heterogeneity*, (2) *Perennialism is the most common condition in natural ecosystems*, (3) *Structural and functional diversity are important to ecosystem performance*, and (4) *Disturbance is a primary determinant of ecosystem structure and function*. The rest of the review will focus on these general ecological principles and their application in silvopastoral design and management.

1.3 Exploiting Spatial and Temporal Heterogeneity to Enhance System Performance

An ecosystem or landscape consists of a mosaic of patches and linear components. The boundaries or edges between patches, or the interface of different habitats, are often the sites of increased rates of processes such as nutrient and energy exchange, competition, facilitation, and movement of organisms. In silvopastoral design, structural and phenological heterogeneity that can occur both spatially and temporally needs to be exploited. For example, tree species should be selected carefully with characteristics such as open crowns, good self-pruning ability, nitrogen-fixing ability, and ease of regeneration. The spatial arrangement of the tree component is yet another critical determinant of light availability and understory forage production (Dibala et al. 2021). It would also be ideal if their root systems possessed the morphological plasticity (Zamora et al. 2007; Kumar and Jose 2018) to accommodate the root systems of the associated forage species without competing for belowground resources (see the ensuing Sect. 1.4 for a discussion on root interactions also). These characteristics are not only important for tree and forage production, but also for the long-term ecological sustainability of the system. Selection of tree species for the silvopastoral practice should, therefore, recognize both the need for long-term system viability and desirable outcomes associated with, and facilitated by, the tree-forage-livestock component interactions. Consequently, tree adaptability to the site and climate should be a major driving factor in the selection of tree species. If options are available, then considerations of forage and livestock interaction should come to bear.

The sustainability of the perennial trees or shrubs in silvopastoral systems, particularly when it involves natural forest manipulations, is a concern. Most of the negative competitive dynamics described earlier could limit the regeneration of the overstory species. Similar to rotational grazing with multiple paddocks, any forest regeneration method can also be applied in strips or small compartments of the stand that progress across the entire stand over time. Excluding cattle, or browsers such as goats, from that portion of the forest where a regeneration method has been applied for a period to enhance natural regeneration is an option in such circumstances. Once regeneration is established and the threat of damage by livestock is no longer a concern, livestock can be reintroduced. Protection of individual seedlings or saplings can encourage early growth and survival (Bendfeldt et al. 2001; Sharrow 2001). By not applying the regeneration method uniformly over the entire stand at the same time, livestock can be a part of the system with minimal or no damage to regeneration.

Apart from the tree attributes mentioned earlier, characteristics of the understory species are other important design parameters of sustainable silvopastoral systems. The dependence of understory herbage production in silvopastoral systems on the shade tolerance of the species involved is a case in point. Tolerant grasses are likely to maintain higher understory productivity levels under increasing levels of canopy closure (Mathew et al. 1992; Kumar et al. 2001; Pang et al. 2019a, b). Similarly, palatable shade-tolerant shrubs that can be browsed directly as a mid-story component may be another way to diversify resources and mitigate losses in forage productivity under partial shade (Dibala et al. 2021). Therefore, information on the relative shade tolerance of understory species is particularly valuable in the design and management of silvopastoral systems. If fire is applied as a management tool, fire-adapted trees and forage species must be chosen.

Compared to open pastures, silvopastoral systems offer many benefits in terms of microclimate modifications. For example, in temperate regions, forage crops remain near dormant during the early and late part of the growing season due to episodic radiation frost. A well-designed silvopasture can potentially extend the grazing period on both ends of the growing season (Feldhake 2002; Kallenbach 2009). For example, Kallenbach (2009) showed that cool-season forage growth started early in the spring and lasted longer in the fall in silvopasture compared to open pasture (Fig. 1.2). Forage growth in the silvopasture was also higher in the hottest time of the summer (mid-July through mid-August) compared to open pasture. Tree canopies can reduce the temperature during summer months so that heat stress on forage can be alleviated. For example, measurements in the semi-arid zone of Botswana (25° S, 25° 50′ E; 550 mm; 1000 m altitude) showed that under the canopy of *Peltophorum africana*, *Acacia tortilis* and *Grewia flava*, solar radiation and wind speed were reduced by about 50% as compared to a nearby open test area (c.f. Le Houerou 1987). As a consequence, potential evapotranspiration was reduced by 70% under the canopy and the grass remained greener for a longer period. Consistent with this, in a study in the southeastern USA, Karki and Goodman (2015) reported lower average values for all the measured microclimatic variables in silvopasture compared to open pasture (Table 1.1). The average air temperature in the

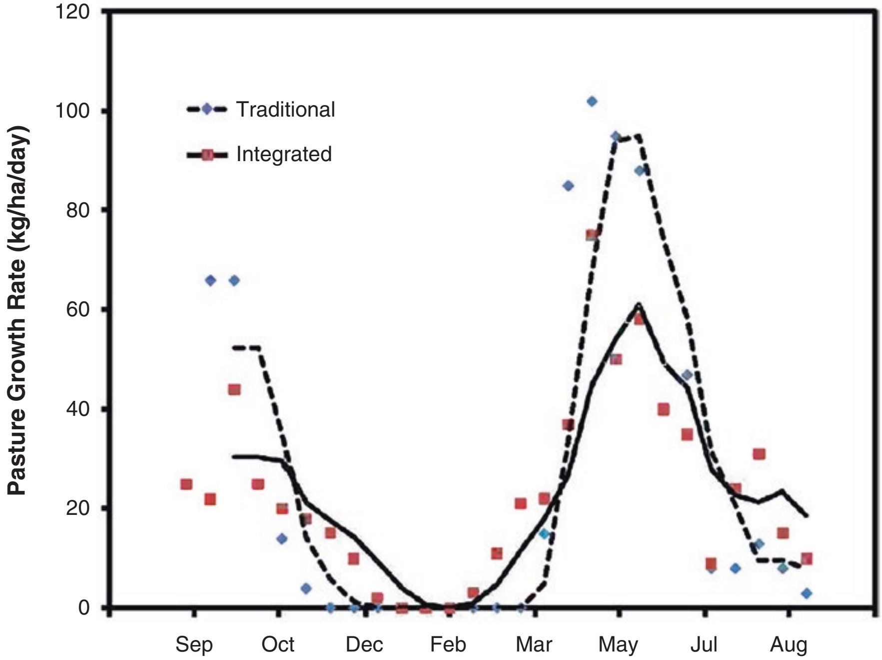


Fig. 1.2 Pasture growth rates in the traditional and integrated pasture systems at New Franklin, MO. Data are averaged over 2 years. Trend lines are the 3-week moving average. Traditional "open" pastures and in the integrated forage-livestock system with approximately 25% of the land area under silvopasture practice. (Adapted from Kallenbach (2009))

Table 1.1 Average values of different weather variables (LS mean ± SE) from silvopasture and open pasture, Nov. 2005–Jan. 2008, Chipley, FL, USA

Weather variables	Silvopasture	Open-pasture	P value
Air temperature (°C)	19.2 ± 0.05[§, b]	21.5 ± 0.05[a]	<0.0001
Dew point (°C)	12.8 ± 0.05[b]	15.7 ± 0.04[a]	<0.0001
Relative humidity (%)	72.4 ± 0.11[b]	73.5 ± 0.10[a]	<0.0001
Soil temperature at 5-cm depth (°C)	20.3 ± 0.02b	22.4 ± 0.02[a]	<0.0001
Soil temperature at 10-cm depth (°C)	20.3 ± 0.02[b]	22.1 ± 0.01[a]	<0.0001
Total solar radiation (W m^{-2})	212 ± 1.7[b]	394 ± 1.3[a]	<0.0001
Photosynthetically active radiation (μE m^{-2} s^{-1})	355 ± 3.3[b]	899 ± 2.6[a]	<0.0001
Rainfall (mm)	0.006 ± 0.0007 [b]	0.008 ± 0.0006[a]	<0.0001
Wind speed (m s^{-1})	0.51 ± 0.00[b]	1.02 ± 0.00[a]	<0.0001
Gust speed (m s^{-1})	1.07 ± 0.01[b]	2.28 ± 0.01[a]	<0.0001
Wind direction (ø)	179 ± 0.5[a]	171 ± 0.4[b]	<0.0001
Soil-moisture content (m^3 m^{-3})	0.053 ± 0.0001[b]	0.064 ± 0.0001[a]	<0.0001
Evapotranspiration (mm day^{-1})	1.79 ± 0.021[b]	2.63 ± 0.021[a]	<0.0001

Source: Karki and Goodman (2015)

[§, a, b]Values in a row with different superscripts are different ($P < 0.0001$)

silvopasture, for example, was 2.3 °C lower and the average soil temperature (at 5 cm) was 2.1 °C lower than in open pasture.

Heat stress has been identified as a major constraint to cattle production in the tropical and temperate regions of the world (Payne 1990; Mitlohner et al. 2001; St-Pierre et al. 2003). Providing appropriate levels of shade with the right tree species, however, can reduce the energy expended for thermoregulation, which in turn can lead to higher feed conversion and weight gain, as well as improved milk yields (Blackshaw and Blackshaw 1994; Kallenbach 2009). In a study in Texas, USA, Mitlohner et al. (2001) found that cattle provided with shade reached their target body weight 20 days earlier than those not afforded shade. These authors concluded that cattle without shade had a physiological (i.e., higher respiration rate) and behavioral (i.e., less active) stress response to heat that negatively affected productivity.

1.4 Perennialism: Managing Resource Competition and Maximizing Complementarity

Natural systems feature perennials in mixtures rather than annuals in monoculture. Annual plants tend to dominate early in the successional process but are often replaced by perennials. In silvopastoral systems, either annual or perennial forage grasses can be mixed with early or late successional tree species, shrubs, and livestock depending on the objectives of the landowner. When two perennials share the same resource base, however, competition can be expected (Jose et al. 2007). Competition between trees and forage crops for resources such as light, water, and nutrients is often reported in silvopastoral systems. An excellent review of this topic is given in Sharrow (1999). Aboveground competition for light is the most commonly studied of all the competitive vectors. Tree canopies are known to impact both the quality and quantity of light received beneath them. Since many of the warm season forage plants (C_4 photosynthetic pathway) have their light saturation points at about 85% of the full sun, shading could negatively impact their yield (Gardner et al. 1985). However, cool season forage plants (C_3 photosynthetic pathway) reach light-saturated photosynthesis at about 50% of the full sun (Gardner et al. 1985). As a result, shading up to 50% may not negatively impact their growth and yield.

In a comparative study of both cool-season and warm-season forage crops, Lin et al. (1999) examined the effects of light on forage yield. Thirty forages, including eight introduced cool-season grasses, four native warm-season grasses, one introduced warm-season grass, eight introduced cool-season legumes, five native warm-season legumes, and four introduced warm-season legumes, were grown in full sun, 50%, and 80% inanimate shade created by shade-cloth over a greenhouse frame. Warm-season grasses displayed significant reductions in forage dry weight under shade regardless of the growing season. All cool-season forages grown during spring-early summer showed a decrease in dry weight under shade; the reductions in dry weights of some of them such as *Desmodium canescens* and *D. paniculatum* were not significant under 50% shade.

Comparison between open pasture and tree-shaded pasture, however, has demonstrated that tree shade can improve forage quality (Kallenbach et al. 2006). When annual ryegrass and cereal rye were established in the understorey of a 6 to 7-year-old stand of pitch pine (*Pinus rigida*) × loblolly pine (*Pinus taeda*) and black walnut (*Juglans nigra*), and the performance compared against pastures without trees, crude protein content was increased (Fig. 1.3). Other forage quality measures, Acid Detergent Fiber and Neutral Detergent Fiber were not significantly different between treatments. As stated earlier, in a companion study, Kallenbach (2009) also showed that cool-season forage growth started early in the spring and lasted longer in the fall in silvopasture compared to open pasture. His work highlighted the potential of silvopasture through the incorporation of trees in 25% of the land area (Kallenbach 2009) of the rotational paddocks.

Furthermore, from tropical to the Mediterranean, savanna research highlights a pattern of increased herbaceous productivity under trees. In California's oak woodland, research comparing soil under an oak canopy with that of open grasslands identified that many soil properties, such as bulk density, pH, organic carbon, and others, were improved and low grazing pressure had little effect on these properties (Dahlgren et al. 1997). Similar results were identified in association with tropical savannas. The drier the site, the greater the difference in herbaceous productivity under trees as compared to open grassland (Belsky et al. 1993). This was attributed, in part, to higher soil N and reduced evapotranspiration. Other studies have also identified that forage or herbaceous productivity improvements were more likely under trees growing on poorer sites. Moreno et al. (2005) identified that microclimate and fertility improved significantly in the vicinity of trees grown in Dehesa. The reduction in solar radiation and localized temperature under tree canopies can result in similar soil moisture adjacent to trees as is found in open grasslands (Belsky et al. 1993).

Belowground competition is most likely to occur when two or more species develop a specialized root system that directs them to explore the same soil strata for growth resources (van Noordwijk et al. 1996; Allen et al. 2004b; Jose et al. 2006). This can be problematic even in silvopastoral systems and highlights how critical our understanding of natural systems, such as savannas, and species selection, can be to silvopasture productivity. Researchers in the temperate zone, humid tropics, and semiarid tropics have reported observing the greatest concentration of tree root density within the top 30 cm of soil, the region predominantly explored by crop root systems (e.g., George et al. 1996; Itimu 1997; Imo and Timmer 2000; Jose et al. 2000; Kumar and Jose 2018). Although there could potentially be niche separation between roots of forage species and trees, competition has often been reported, with resultant reductions in both tree and pasture growth. George et al. (1996) evaluated root competition in polyculture systems involving combinations of four tree species and four grass species based on ^{32}P recovery by each species in mixed and sole crop situations. They reported that while the grass species grown in

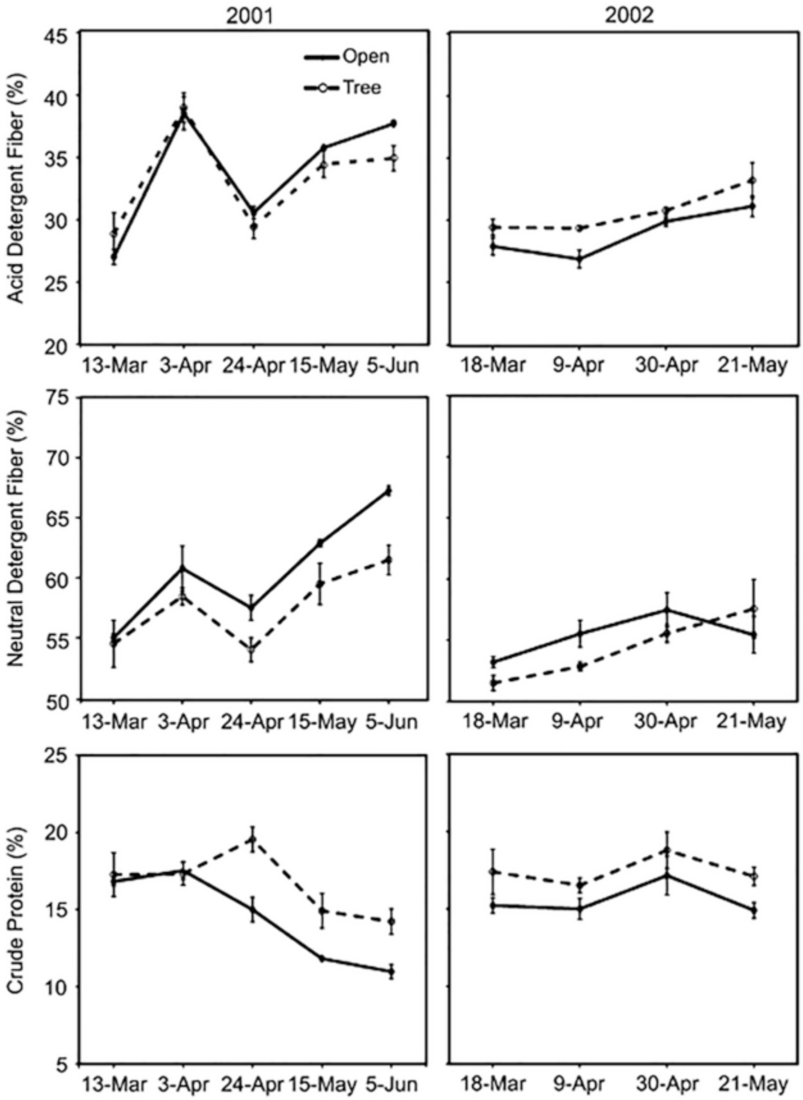


Fig. 1.3 Acid detergent fiber, neutral detergent fiber, and crude protein of annual ryegrass/cereal rye in OPEN and TREE pastures at the Horticulture and Agroforestry Research Center near New Franklin, MO. Bars indicate standard errors at each sampling. (Adapted from Kallenbach et al. (2006))

association with tree components in polyculture systems did not adversely affect the absorption of ^{32}P by trees, the trees exerted either a competitive or complementary influence in polyculture systems, depending on the nature of the species involved, implying the need for proper choice of species mixes to alleviate root competition in such mixed-species production systems. With proper choice of species, managing tree density and canopy cover, appropriate soil fertility amendments, and proper stocking of livestock, competitive interactions can be managed to a large extent. Then, when interactions are accounted for and kept in balance, yield reductions can be minimized while taking advantage of complementary interactions, such as quality improvements to select forages.

Competition between forage and trees, especially when the trees are young, however, can result in reduced tree growth. Additionally, livestock may interact negatively to slow down tree growth. Continuous, or unregulated, grazing practices of natural forests increase compaction, and runoff, and decrease soil moisture available for growing plants (Hawley and Stickel 1948; Den Uyl et al. 1938). Compaction of soil also inhibits the movement of oxygen throughout the soil and may reduce tree growth (Kozlowski and Pallardy 1997; Kozlowski 1986). However, rotational grazing has less of a negative effect on the soil environment. Under rotational grazing, soil compaction and porosity changes are minimized and the soils will return to forest-level conditions after 2 years of non-grazing (Sharrow 2007). Additionally, a comparison of the effect of continuous versus rotational grazing in a black walnut plantation in Missouri, USA, revealed no significant differences in the diameter or height growth of trees (Lehmkuhler et al. 1999). The practice of rotational grazing helps reduce the likelihood of soil compaction and, at the same time, minimizes potential growth reductions of silvopasture trees.

Management interventions such as thinning to establish forage crops underneath tree canopies can also have positive effects on residual tree growth. Walter (2011) observed much-improved growth of black and white oak (*Quercus velutina* and *Q. alba* respectively) following the conversion of a north-facing upland oak forest in Missouri to silvopasture. Forest trees were thinned to a residual basal area of 10.3 m^2 ha^{-1} and 165 trees ha^{-1} (mean residual diameter at breast height, dbh, was 25.4 cm). These areas were then seeded to Kentucky 31 Tall Fescue. The growth response of thinned trees when rotationally grazed, coupled with fertility management associated with proper forage recommendations, was compared for 6 years before silvopasture and 6 years post-silvopasture implementation. Under silvopasture management, black and white oak basal area increment improved by 45.9% and 121.9%, respectively (Walter 2011). When all that is required for proper silvopasture implementation (spacing of trees to allow light for forage production, proper selection of forages, proper soil amendments for forage production, and proper rotational grazing) is practiced, then interactions can be positive for each component.

1.5 Structural and Functional Diversity Leading to Improved Resource Utilization

When ecosystems consist of species that create structural and functional diversity, resource use efficiency and system productivity are often enhanced. The competitive exclusion principle (Gause's principle) has been central to explaining the co-existence of species in mixtures for decades (Grime 1973). It states that different species having identical ecological niches cannot exist for long in the same habitat. In other words, stable coexistence of two species is only possible where intraspecific competition is greater than the interspecific competition for both species.

Structural and functional diversity can result in improved resource utilization and enhanced ecosystem benefits. One such benefit is the reduction in nutrient leaching to groundwater in silvopastoral systems as a result of the deep tree roots. Most pastures will have shallow-rooted pasture grasses as a result of repeated grazing by animals. For example, in a northern mixed-grass prairie in North Dakota, USA, Rogers et al. (2005) showed that heavy and moderate grazing reduced belowground root biomass of prairie grasses compared to no grazing in a long-term experiment (Fig. 1.4). The increased use of N fertilizer to intensify pasture production has exacerbated water quality concerns worldwide. Planting trees, particularly with deep roots, on pastures can take up the nutrients that are leached down below the rooting zone of the associated pasture grass. This 'safety net' hypothesis of nutrient capture assumes that the nutrients captured will be eventually recycled as tree litterfall and root turnover in the cropping system (Allen et al. 2004a) (Fig. 1.1). Research conducted on a silvopastoral system in Florida on flatwood soils (Spodosols) suggests that silvopastoral sites are less likely to experience phosphorus loss compared to an open treeless pasture (Nair et al. 2007; Fig. 1.5). This supports the hypothesis that the silvopastoral system minimizes the leaching of nutrients from the soil because of enhanced uptake by deeper tree roots and shallower grassroots, compared to more localized and shallow rooting depths of the regular pasture.

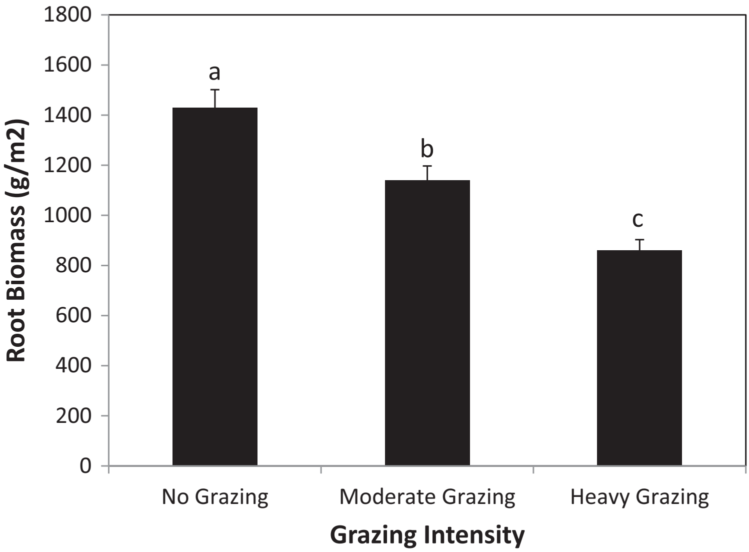


Fig. 1.4 Root biomass of mixed-grass prairie for three grazing intensity treatments in North Dakota. Different letters within a depth denote differences at alpha = 0.05. (Based on data from Rogers et al. (2005))

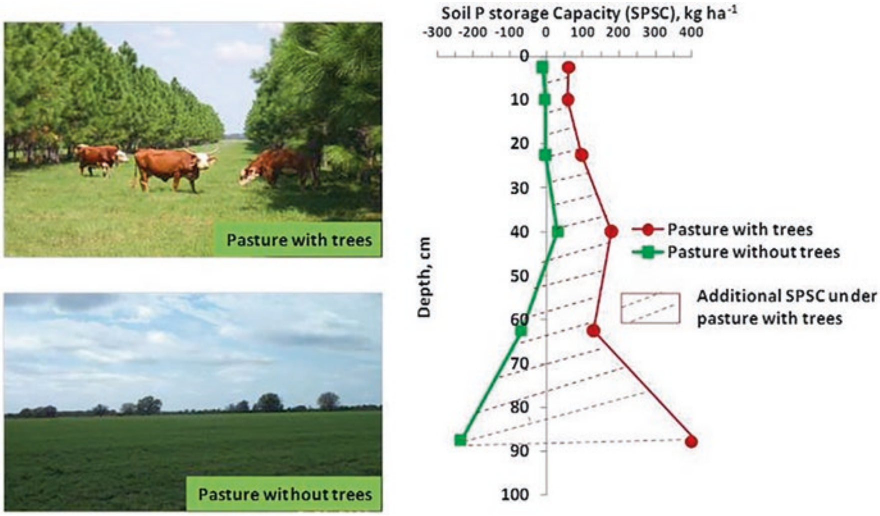


Fig. 1.5 Comparison of the SPSC of soil profiles to a meter depth in a silvopasture vs. a bahiagrass pasture without trees. The profiles depicted are representative of the two conditions (with and without trees) based on random sampling within each pasture type. (Adapted from Chakraborty et al. (2011))

The belowground niche separation leads to increased uptake and cycling of nutrients. In silvopasture systems, structural and functional diversity are increased by mixing the component species (McEvoy and McAdam 2005; McAdam and McEvoy 2009). As a result, they can co-exist and increase the overall resource use efficiency of the system.

Complementary resource utilization can also lead to increased environmental sustainability. For example, the presence of trees in silvopastoral systems has been shown to reduce antibiotic loss from pasture soil. The use of veterinary antibiotics in animal agriculture to treat infectious diseases, prevent animal illness, and improve animal growth is a common practice. A significant proportion (30–80%) of the administered antibiotics is excreted and deposited on the soil surface and poses a serious risk to water quality. Chu et al. (2010) demonstrated that the presence of Eastern cottonwood trees (*Populus deltoides*) in pasture resulted in enhanced sorption of two commonly used veterinary antibiotics compared to regular pasture or agriculture soil. In a companion study, Lin et al. (2010) showed that increased microbial enzymatic activity associated with the root system of Eastern cottonwood was directly correlated with enhanced antibiotics dissipation, suggesting that increased enzymatic activity stimulated by the tree rhizosphere increased antibiotics dissipation in silvopastoral soils.

1.6 Disturbance: The Fundamentals of Management

Ecosystems are in a state of constant flux, in ways that are only partially predictable. Natural systems are dynamic systems, forever changing in response to successional forces, long-term fluctuations in climate, and the more immediate effects of natural disturbance from disease, drought, fire, insects, storms, and the movements of the earth, wind, and water. Managed ecosystems such as silvopasture are also subject to an array of disturbance regimes. However, integrating the principles of disturbance ecology into sustainable silvopastoral management practices has not received much attention.

Using silvicultural treatments that mimic natural disturbance can create an environment favorable to the development of silvopastoral systems. For example, in northeastern North America, stand renewal was identified with both natural canopy gaps, and severe fire and wind (Seymour and White 2002). However, while canopy gaps occurred more frequently, they impacted a smaller contiguous land area than severe fire and wind, which, renewed a much larger land area, but occurred more rarely. The importance of such disturbance events ties directly to forest renewal and seedling requirements (Zhang and Yi 2021). In the managed silvopastoral system, managing gaps, or space between trees, is tied directly to providing adequate light for forage production and replacement seedling development (Feldhake et al. 2005)

A silvopasture practice seeks to create an even dispersal of canopy openness to allow pseudo-uniform light to reach the forest floor. However, the role of gap size has little effect on available light when openings are smaller than 0.04 ha and larger than 0.4 ha in size (Dey and MacDonald 2001). Additionally, there exists a direct relationship between the degree of slope and the percentage of direct solar radiation reaching the forest floor. Forest gaps up to two times the height of adjacent trees on south-facing slopes of 30° have a greater percent direct solar radiation than similar gaps on slopes of 15° (Fischer 1979). To evenly distribute forage growth across a forested area, adequate light levels must be ensured.

Silvicultural treatments applied across a broad area, a forest stand, can have this impact. For example, the shelterwood harvest can effectively increase the available light on the forest floor as evidenced in its application to promote oak regeneration. Dey and Parker (1996) identified that the removal of 43% and 77% of the basal area within a shelterwood harvest increased light intensities to 35% and 65%, respectively. Most herbaceous plants need only about 10% of full sunlight to reach a state of growth where daily photosynthesis exceeds daily respiration, and these plants will reach a light saturation point at approximately 50% and 85% of full sunlight (cool-season (C_3) and warm-season (C_4), respectively) (Gardner et al. 1985). In practice, the shelterwood harvest supports residual tree densities such that a more evenly dispersed light is created at the forest floor and can be manipulated to a level adequate for forage growth.

Disturbance may also be detrimental to system productivity. For example, physical damage to trees during the early years of silvopasture establishment is commonly reported in the literature. Lehmkuhler et al. (2003) examined cattle damage to tree seedlings for four species (*J. nigra, Gleditsia triacanthos, Q. rubra,* and *Carya illinoensis*). Likewise, grazers, such as goats, require special consideration to minimize damage to trees (Karki et al. 2019). Cattle damage to young trees was prominent during the 2 years for trees without protection. *Q. rubra* suffered the highest degree of damage from livestock. They recommended the use of an electrified fencing system to prevent cattle damage to young seedlings and saplings. Likewise, Bendfeldt et al. (2001) observed that establishment of bare-root seedlings of black walnut (*J. nigra*) and honeylocust (*G. triacanthos*) in a silvopastoral study with tree shelters (60 cm-tall poultry wire cage and 1.2 m-tall plastic Tubex) resulted in a significant reduction of deer damage, leading to better tree growth and a significant increase in stem volume; although tree survival was comparable (Table 1.2).

McEvoy et al. (2006) reported significant differences in tree form as a function of grazing and browsing, with unbrowsed saplings of *Q. robur* having the greatest height-to-canopy width ratio and those in the continuously browsed plots having the smallest. The bottom line is that irrespective of livestock selection, grazing or browsing should not be allowed until terminal buds on trees have reached heights beyond the reach of livestock. Haying is recommended until the trees are old enough to better withstand pressure from livestock. While browsing animals such as goats, sheep or deer will eat young trees, large ruminants such as cattle are more likely to trample them.

Grazing is another example of disturbance with potential to impact productivity. Although the Grazing Optimization hypothesis (Dyer et al. 1993; McNaughton 1993; Noy-Meir 1993) implies that moderate grazing resulted in greater aboveground biomass in grasslands, there is no consensus in this respect. For instance, Biondini et al. (1998) and Rogers et al. (2005) did not support the hypothesis that aboveground productivity was maximized at a moderate grazing intensity. Conversely, Patton et al. (2007) noted that light grazing produced the most herbage and production decreased as the grazing intensity increased further in a prairie

Table 1.2 Results of tree protection study, Kentland Farm, Blacksburg, Virginia 1996–1998

Treatment	Survival (%)	Damage (%)	Diameter (cm)	Height (m)	Stem volume (cm^3)
Black walnut:					
Control	100 ns	47 a*	3.1 b	0.9 c	879 c
Poultry wire (0.6 m)	100	7 b	3.9 a	1.2 b	1873 b
Tubex (1.2 m)	97	2 b	4.2 a	1.8 a	3208 a
Honeylocust:					
Control	100 ns	36 a	1.9 b	1.2 c	527 b
Poultry wire (0.6 m)	100	24 b	2.0 b	1.3 b	594 b
Tubex (1.2 m)	100	0 c	2.2 a	2.3 a	1175 a

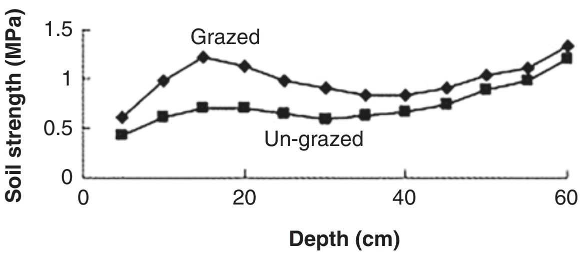
Source: Bendfeldt et al. (2001)

*Means within columns followed by the same letter were not significantly different (Duncan's Multiple Range Test, alpha = 0.05) dominated by Kentucky bluegrass (*Poa pratensis*) in south-central North Dakota. Wenhaui et al. (2021) noted that select grazing by livestock results in patches of vegetation, but that with management, the disturbance induced by grazing can produce a more sustainable long-term grassland. As with other silvopasture elements, management ties directly to function.

Disturbance from livestock can also damage the soil. For example, soil compaction from grazing can occur in a wide range of soils and climates. It is exacerbated by low soil organic matter content and high soil moisture content. Soil compaction increases soil strength (Fig. 1.6) and decreases soil physical fertility through decreasing storage and supply of water and nutrients, which leads to additional fertilizer requirements and increasing production costs. Additionally, changes in soil physical properties alter the composition of the invertebrate community. Proesmans et al. (2022) identified that grazing-associated changes consistently reduced the richness and abundance of soil microarthropods. A detrimental consequence of reduced plant growth, leading to lower inputs of fresh organic matter to the soil, reduced nutrient recycling and mineralization, and reduced activities of microorganisms, follows (Hamza and Anderson 2005).

Improper stocking of livestock could also have negative effects on soil chemical properties. Northup et al. (2005) examined the effects of different levels of applied grazing pressures on herbaceous vegetation and soil properties around grass tussocks of a dry eucalypt woodland in northern Australia. Applied grazing pressures significantly affected all soil properties except total P. Concentrations of N and C were highest at locations close to plants, which declined under sustained heavy grazing. Paddocks receiving heavier grazing pressures also produced less standing crops and tussocks were smaller and more widely dispersed. However, a summary of grazing research in Australia noted that woodland rotational grazing resulted in improved soil porosity as compared to *set stocked grazing* (the practice of putting livestock in a large pasture and allowing them to graze year-round; Fig. 1.7; Southorn and Cattle 2004). Of note, the Australian study highlights results from under-managed grazing scenarios. In a different study reporting the impact of cattle on forest soils, long-term grazing led to a four-fold increase in available soil phosphorous (Proesmans et al. 2022). The same study also reported that the C:N ratio was significantly lower in grazed sites. Matching grazing seasons to soil conditions and forage availability is crucial to mitigating the detrimental impact on soil properties associated with land-use by livestock.

Fig. 1.6 Average soil strength for grazed and un-grazed sandy soil. (Adapted from Ballenger (2001))



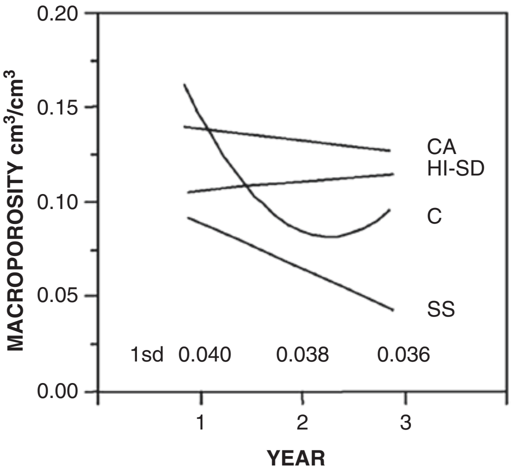


Fig. 1.7 Average topsoil (0–100 mm depth) macroporosity under alternative grazing tactics with sheep over 3 years. The least significant difference is within any year at 5% (SS = set stocked, HI-SD = high-intensity short duration rotational grazing, C = ungrazed control, CA ≡ grazed over pasture cages). (Adapted from Southorn and Cattle (2004))

Fire, if used properly as a management tool, may benefit certain silvopastoral systems (Mosquera-Losada et al. 2006). The benefit will, however, depend on the species chosen for the system. For example, prescribed fire can be used in silvopastoral systems to stimulate forage productivity. Annual grasses and broadleaf plants will be damaged if burned during the active growing season whereas perennial grasses may tolerate the fire. Many tree species can be killed by fire, but some can resprout. However, fire may assist in the control of invasive species (Huebner 2006) and diseases (Holzmueller et al. 2006; Holzmueller et al. 2007). If properly applied, fire may be used to kill unwanted vegetation, favor the desired understory, increase nutrient availability in the soil, and enhance forage quality (Gruell et al. 1986; Huebner 2006).

Overall, it is essential to understand that a silvopasture is a disturbance-maintained ecosystem. Depending on the animals used, grazing or browsing, or both, may be the predominant forces shaping the structure of the silvopastoral system. Other management interventions as explained earlier (silviculture, grazing, fire) will also play a major role in deciding the successional trajectory of such a production system. Whether a landowner is transitioning from a pasture to silvopasture or from a forest to silvopasture, the key role of disturbance should not be overlooked.

1.7 Conclusions

While the principles that govern the ecological sustainability of silvopastoral systems have been well documented, the management challenges remain elusive. In no small way, this is due to the integrated nature of the components and, as identified throughout this paper, how the management of each component may result in facilitation (complementary) or competitive outcomes within the system.

However, the future needs of society for productive agricultural livestock systems and meat and milk products place challenges on land use. Regardless of the changing climate and weather patterns or population dynamics, productive use of agricultural lands and food security are strongly inter-linked (Fitton et al. 2019). While models and predictions highlight the uncertainties, the understanding of ecological interactions in silvopasture design and management has a role to play in creating sustainably productive animal-based systems.

Properly managed silvopasture can provide many environmental benefits such as enhanced water quality and improved small farm profitability by providing multiple income sources. However, "proper management" is an ambiguous term, since managing a silvopastoral system involves managing complex interactions among its tree, forage, and animal components. While combinations of trees, grasses, and livestock may exist, if the four "I" requirements (intentional, integration, interactions, and intensive management) are not met, they do not qualify as silvopastoral systems. Management interventions that can influence the components and their spatial and temporal configuration are critical in determining resource availability and system performance.

The foundational principles of silvopastoral design are a sound beginning to enhance complementary interactions and promote sustainable system management. This paper has highlighted the need for a few such management choices, including canopy management. Whether through tree spacing or species selection, canopy management will influence light availability for forage production. The selected forages will also have to be adapted to the light environment existing in a specific system. The forages will need to be utilitarian in terms of their availability and grazability to the livestock of choice. Also, identified in this paper is the role that fire can play in maintaining forage quality and composition. Finally, a sustainable silvopastoral system is rooted in the best management principles of livestock grazing. Using rotational grazing principles is necessary to minimize damage to trees and maintain sustainable forage productivity levels and acceptable livestock performance.

Silvopasture is complex, yet the potential for livestock to benefit from living shade is expressed around the world by the general integration of livestock into wooded lands. However intentional these systems might be, they are not removed from the ecological principles that guide and direct interactions between trees, forages, and livestock. We must therefore seek the positive outcomes associated with management to facilitate complementary interactions and minimize competitive interactions. Continued research is needed to fully define the "proper management" needed to make silvopastoral systems sustainable in both tropical and temperate regions of the world.

Acknowledgments This manuscript is an updated version of Jose et al. (2019) cited in the references.

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Chapter 2
Silvopastoral Systems and Their Role in Climate Change Mitigation and Nationally Determined Contributions in Latin America

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Abstract Cattle ranching is a productive activity that generates high amounts of greenhouse gases (GHG) such as methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), but can also provide effective alternatives to mitigate and adapt to climate change. Within the livestock sector, silvopastoral systems (SPS) have the capacity to reduce GHG emissions, increase carbon stocks, adapt to climate change, improve animal welfare and increase production of milk, beef and timber under different conditions. This chapter seeks to identify relevant elements related to the capacity of SPSs and livestock in general to meet the Nationally Determined Contributions (NDCs) of Latin American countries, and how nations are incorporating these systems into their mitigation policies. Different research and experiences demonstrating the mitigation potential of SPSs are presented, as well as those elements that must be considered for a successful upscale of these technologies. It also demonstrates the versatility of SPSs and the need for these systems to be incorporated into the NDCs and contribute to their achievement. Countries such as Argentina, Brazil, Chile, Colombia, Costa Rica, Mexico, Paraguay, Uruguay, highlight the need to have mitigation options in livestock activities in order to achieve

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the objectives proposed in their NDCs, which aim at reductions above 30% of the inertial scenarios.

Keywords Adaptation · Carbon sequestration · Climate change mitigation · Livestock sustainable systems · NDC

2.1 Introduction

In Latin America, cattle production, is an important economic activity that contributes to rural livelihoods, and provides essential nutrients to the population. Cattle ranching is well rooted in the culture of many regions and is an important source of employment and exports. However, it is also an activity considered as a significant source of greenhouse gas (GHG) emissions and with high vulnerability to climate change (Gerber et al. 2013; Coppock et al. 2017; Arango et al. 2020). Cattle production contributes significant amounts of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), as it is estimated that approximately 14.1% of GHG emissions in Latin America are generated by this activity (Gerber et al. 2013; Aynekulu et al. 2019; Arango et al. 2020). In recent years several initiatives have advanced in the identification and characterization of technologies that contribute to climate change mitigation and to the fulfillment of the objectives established in the countries' Intended Nationally Determined Contributions (iNDC) (Molina et al. 2016; Piñeiro-Vázquez et al. 2018; Tapasco et al. 2019; González-Quintero et al. 2020).

According to the United Nations Framework Convention on Climate Change (UNFCCC), the iNDCs are framed in the Paris Agreement, where the parties seek to transform their trajectories of progress in order to put the world on the path to sustainable development and limit global warming to 1.5–2 °C above pre-industrial levels, in addition, the Glasgow agreement of 2021 established adaptation and funding objectives that must also be addressed in order to achieve the proposed climate change goals.

One of the alternatives with high aptitude for mitigation and adaptation to climate change within livestock are Silvopastoral Systems (SPS). These are arrangements that purposely combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees for animal nutrition and complementary uses including timber, nuts, fruit production (Chará et al. 2019). Thanks to the integration of different biological components and appropriate technical management, these systems have the ability to mitigate GHG emissions, increase the amount and quality of animal products, and improve carbon reservoirs in agricultural systems (Harrison et al. 2015; Murgueitio et al. 2015; Rivera-Herrera et al. 2017; Chará et al. 2017; Aynekulu et al. 2020).

This chapter seeks to explore the capacity of SPSs to be included in the proposed iNDCs of countries in Latin America, based on their ability to decrease CH_4

emissions from enteric fermentation and other gases from manure and soil, increase the quality and quantity of animal products, increase the resilience to climate change, and increase carbon reservoirs. It also explores how these systems can be incorporated into the NDCs of Latin American countries.

2.2 Silvopastoral Systems and Mitigation of Climate Change

2.2.1 Reduction in the Emissions of Greenhouse Gases

Different researchers have agreed that properly managed pastures associated with shrub and tree species under rotational management, such as that given in SPSs, have the capacity to mitigate GHG emissions (CH_4, N_2O and CO_2) in different livestock systems (Nahed-Toral et al. 2013; Montagnini et al. 2013; Harrison et al. 2015; Rivera et al. 2016; Molina et al. 2016; Molina-Botero et al. 2019; González-Quintero et al. 2020; Rivera et al. 2022).

Most of the research has been oriented to identify the mitigation of CH_4 by enteric fermentation of ruminants, probably due to its greater reduction potential, since this gas is the most important in bovine systems (>70% of the total) (Gerber et al. 2013; Rivera et al. 2016; González-Quintero et al. 2020), and because of the multiple existing alternatives for its reduction (Molina et al. 2016; Rivera-Herrera et al. 2017; Valencia-Salazar et al. 2018; Molina-Botero et al. 2019; Ku-Vera et al. 2020; Montoya-Flores et al. 2020; Rivera et al. 2022). At the beginning of the century, some research in the region focused on evaluating the effect of reducing ruminal protozoa due to the role they play in methane production, for which foliage of creeping and shrub legumes (*Arachis pintoi, Cratylia argentea, Calliandra calothyrsus*) as well as fruits of tropical trees rich in saponins (*Sapindus Saponaria*) were used. However, the results between experiments were contradictory (Abreu et al. 2003; Galindo et al. 2016; Hess et al. 2003).

According to more recent measurements carried out in this region, the introduction of shrubs in livestock systems can decrease CH_4 by 25 ± 13.4% depending on the system implemented, the species used, and the amount consumed Arango et al. (2020). Species such as *Leucaena Leucocephala* (Lam.) de Wit, *Samanea saman* (Jacq.) Merr., *Gliricidia sepium* (Jacq.) Walp., *Tithonia diversifolia* (Hemsl.) A. Gray and *Enterolobium cyclocarpum* (Jacq.) Griseb are perhaps the most studied species by their potential to contribute to mitigation in SPS. Aspects such as a low fiber content that improves the rate of passage, voluntary consumption and dry matter degradation; the amount of crude protein that favors the fermentative efficiency at rumen level and the over-passing contents of nitrogen; and phytochemical compounds such as tannins, saponins, essential oils and flavonoids that modify the fermentation dynamics and modulate the population of microorganisms in the rumen, are the main properties that favor the reduction in CH_4 emissions in enteric fermentation in ruminants (Valencia-Salazar et al. 2018; Molina-Botero et al. 2019;

Ku-Vera et al. 2020; Beauchemin et al. 2020). Table 2.1 presents the mitigation potentials found in different studies with shrub species in different Latin American countries.

2.2.2 Modification of Manure and Soil Gas Fluxes

In cattle production systems, manure (feces and urine) managed and deposited on pastures is the second largest source of GHG emissions after enteric methane and is responsible for approximately 7% of agricultural CH_4 and N_2O emissions around the world (Aguirre-Villegas and Larson 2017). Excessive manure application or improper manure management, in addition to increasing GHG emissions with high warming potentials, can lead to water pollution through leaching or runoff (Burkholder et al. 2007).

Within the mitigation alternatives for soil GHG emissions, especially for N_2O fluxes, the use of pasture species with nitrification inhibition (BNI) is an option to reduce the production of this gas (Byrnes et al. 2017; Nuñez et al. 2018). Species such as *Brachiaria humidicola* (Byrnes et al. 2017), *Sorghum bicolor, Oryza sativa* and *Triticum aestivum* have demonstrated their ability to reduce N_2O fluxes (Tanaka et al. 2010). Byrnes et al. (2017) reported that in urine patches with *B. humidicola* cv. Tully N_2O emissions were 60% lower than in areas with *B. humidicola* cv. Mulato (32 *vs.* 80 mg N_2O-N m^2, respectively).

Other studies have shown that maintaining a more diverse environment with well-maintained soils and good pasture cover can contribute to reduced emissions. Regarding the effect of soil cover on N_2O emissions, a study by Chirinda et al. (2019) in seven locations in South America found that the emission factors of this gas in urine patches were reduced in grasslands with higher vegetation cover when compared with pastures with lower vegetation cover (0.42% *vs.* 0.18%). According to these authors, poor soil cover and pasture degradation may stimulate or restrict N losses thus generating higher emissions. For example, low vegetation cover may reduce nitrogen sinks for deposited excreta and thus increase N loss through soil microbial processes and leaching (Chirinda et al. 2019). Reduced soil vegetation cover could also generate fewer plant root exudates which in turn decreases microbial activity and changes N_2O emissions (Henry et al. 2008).

SPSs favor a better and greater soil cover due to the use of different strata formed by forage, shrubs, and trees in the grazing areas, in addition to allowing the modification of microorganism populations in the soil that can regulate nitrification and oxidation processes. In a study in Colombia, Cubillos et al. (2016) found that SPS of different ages have a significantly lower potential for ammonia nitrification (between 15% and 20%) when compared with adjacent pasture monocultures. The ammonia nitrification potential of SPSs was similar to that observed in forested areas, which is why it is expected that under these systems N_2O fluxes can be reduced (Cubillos et al. 2016). Rivera et al. (2019) in a research in Colombia found emission factors for SPS and conventional systems of 1.37% and 1.77% for feces,

Table 2.1 Mitigation options for enteric methane evaluated in Latin America

Country	Region	Mitigation action	Reduction potential	References
Colombia	Cauca Valley	Silvopastoral systems	23.4% less methane production compared to traditional grazing systems	Molina et al. (2015)
	Cauca Valley	Improvement in the management of pastures – Silvopastoral systems	50.1% less methane production than degraded pastures	Gaviria-Uribe et al. (2019)
	Amazonian Piedmont	Silvopastoral systems with *T. diversifolia*	12.3% less methane production compared to traditional grazing systems	Rivera et al. (2022)
Argentina	Buenos Aires-Southeast	Improving reproductive efficiency	The estimated methane emissions intensity of growing weaned calves decreased by 40–60% based on weaning rates, calf distribution and feed quality data.	Ricci and Aello (2018)
	Buenos Aires-Southeast	Improved grazing with supplementation	The emission intensity of beef production is 26% lower than that of those without supplementation.	Ricci et al. (2018)
Costa Rica	Atenas, Costa Rica	Improving forage quality	Steers fed high-quality hay during the summer months had 30% less methane production than those fed low-quality hay.	Montenegro et al. (2016)
Brazil	Rio Grande do Sul	Grazing supplementation and crop diversification – Silvopastoralism	Cattle fed natural pasture plus commercial soybean crops had 7 and 5% lower emissions intensity than cattle fed natural pasture only and low supplementation, respectively.	Pereira et al. (2018)
Uruguay	Colony	Improved grazing management	Cattle fed high-quality pasture had 12% lower methane emissions than those fed low-quality pasture.	Dini et al. (2018)
Mexico	Yucatan Peninsula	Silvopastoral systems	Inclusion of 40% *L. leucocephala* in a low-quality grass diet reduced enteric methane emissions by 36% in cattle.	Piñeiro-Vázquez et al. (2018)
	Yucatan Peninsula	Silvopastoral systems	Including 30% of *Samanea saman* ground pods decreased enteric methane emissions from a low-quality grass-based diet by 51% in cattle.	Valencia-Salazar et al. (2018)
Peru	Central Andes	Improving forage quality	Lactating cows fed on pasture grown during the rainy season had 79% lower methane emission intensity than those fed on native pasture.	Alvarado et al. (2019)

Adapted from Arango et al. (2020)

and 0.3% and 3.47% for urine of excreted N, respectively. As in intensive monoculture grazing systems the use chemical nitrogen fertilization (especially urea) generates an important amount of N_2O emissions, the conversion to intensive silvopastoral systems (ISPS) with high atmospheric nitrogen fixation reduces this emission source as fertilizer application is completely eliminated (Murgueitio et al. 2015).

2.2.3 Increase in Carbon Reservoirs and Carbon Stocks

While forage inputs and their technical management favor the reduction of GHG emissions, SPSs also increase carbon stocks due to higher biomass productivity and the possibility of intensifying production and releasing areas for conservation purposes or for other agricultural activities. According to Chará et al. (2017); Rivera-Herrera et al. (2017) and Lerner et al. (2017), higher production obtained in SPSs has the potential of increasing carrying capacity up to four times compared to conventional systems and thus use less land to achieve the same amount of animal products.

Several studies have shown that incorporating trees into cropland and pasture results in greater net C storage (Haile et al. 2010). Estimates of the carbon sequestration potential of agroforestry systems are highly variable, ranging between 0.29 and 15.21 Mg ha^{-1} $year^{-1}$ aboveground and between 30 and 300 Mg C ha^{-1} down to 1 m soil depth (Nair et al. 2010). For SPSs, the aboveground carbon sequestration potential varies from 1.5 Mg ha^{-1} $year^{-1}$ (Ibrahim et al. 2010) to 6.55 Mg ha^{-1} $year^{-1}$ (Kumar et al. 1998). In general, the values found in C storage are a direct manifestation of the biomass production of the system, that is influenced by site and soil characteristics, species involved, stand age plant density and management practices (Nair et al. 2010). The amount of soil organic carbon – SOC can be increased by 20–100% when N_2-fixing tree legumes are incorporated as they promote higher plant productivity (Resh et al. 2002). According to Radrizzani et al. (2011) Leucaena in SPS in Queensland (Australia) accumulated between 79 and 267 kg ha^{-1} $year^{-1}$ of N more than adjacent plots based on monoculture. In a study in Colombia, Arias et al. (2015) found that on average the aboveground carbon stock was 13.42 Mg CO_2 eq ha^{-1} in iSPS and 7.55 Mg CO_2 eq ha^{-1} in control sites with conventional pasture monoculture.

Just as different SPSs have the potential to increase carbon sequestration in livestock systems, proper pasture management also has the capacity to sequester carbon in soil and aboveground biomass. Authors such as Maia et al. (2009) and Soussan et al. (2010) have reported that, according to soil type, pasture species and type of management, traditional pastures can achieve carbon sequestration rates between 0.11 and 3.01 Mg C ha^{-1} $year^{-1}$, thanks to activities such as improved rotations, inclusion of leguminous species, renovation of pastures and inclusion of fertilization activities.

According to Aynekulu et al. (2020) in an analysis done in Colombia C stocks in pastures increased from 34 to 39 Mg ha^{-1} in a period of 17 years thanks to the incorporation of trees. These same authors also found that pastures in Colombia contained on average 34 Mg ha^{-1} of C, while other arable land showed 36% less. These significant levels of carbon in SPS systems suggest a great opportunity for climate change mitigation, especially when considering the existing and projected area of silvopastoral systems in different Latin American countries.

In other study, Feliciano et al. (2018) found that systems using controlled grazing practices and appropriate grass species can increase the average aboveground carbon sequestration between 2.29 and 6.54 Mg ha^{-1} year^{-1}. Likewise, López-Santiago et al. (2018) reported that systems with *L. leucocephala* associated with *Megathyrsus maximus* contained higher aboveground C (19.6 ± 1.6 Mg ha^{-1}) and belowground biomass (7.7 ± 0.90 Mg ha^{-1}) compared to tropical deciduous forest and monoculture pastures in Mexico.

2.2.4 Increased Animal Productivity and the Possibility of Higher Economic Income

The chemical composition of shrub species offered in SPS allows diets with lower fiber content (FDA and FDN), higher crude protein (CP) and minerals, and higher dry matter (DM) degradability than tropical pastures. In addition, due to their ruminal behavior, diets offered in SPS have the ability to overcome degradation at the rumen level and pass to the posterior tract without undergoing major transformations, so that nutrients can be used directly by the animals (Rivera-Herrera et al. 2017; Chará et al. 2017).

Cuartas et al. (2015) mention that forage consumption in SPS can be up to 30% higher compared to conventional systems and, with a better chemical quality, the production of meat and milk is higher both per animal and per unit area (Tables 2.2 and 2.3).

On the other hand, the intake of *T. diversifolia* has also been associated with increases in animal productivity and carrying capacity in the systems. Rivera et al. (2015) evaluated the effect of this shrub under grazing conditions on the production

Table 2.2 Productive response in traditional and silvopastoral systems for beef production in Colombia

Productive response	CP	IP	iSPS1	iSPS2	iSPS3
Plant Productivity; tons DM ha^{-1} year^{-1}		19.2	19.2	15.6	15.4
Stocking rate AU ha^{-1} (1 UGG = 450 kg)	0.85	2.34		2.71	3.5
Weight gain per animal, kg day^{-1}	0.25	0.4	0.42	0.84	0.69
Animal Productivity; kg meat ha^{-1} year^{-1}	77.6	341.6	609	827	864

Adapted from Rivera-Herrera et al. (2017)
CP conventional pasture with native and degraded species, *IP* improved or introduced pasture based on *C. plectostachyus* and *M. maximus*, **iSPS* intensive silvopastoral system with *L. leucocephala* (>10,000 plants ha^{-1}) and *C. plectostachyus*, *DM* dry matter, *AU* Animal Unit (450 kg)

Table 2.3 Plant and animal productivity in dairy production systems in different regions of Colombia

Productive response	DP	iSPS1	iSPS2	iSPS3	iSPS4
Plant Productivity; Mg DM ha^{-1} $year^{-1}$	7.0	15.4	13.9	12.4	17.9
Stocking rate AU/ha (1 AU = 450 kg)	0.80	2.90	3.30	3.34	3.80
Production per animal; l day^{-1}	3.3	11.6	3.9	11.4	11.8
Animal Productivity; l ha^{-1} $year^{-1}$	1150	13,462	5551	15,725	18,412

Adapted from Rivera-Herrera et al. (2017)

DM dry matter, *AU* Animal unit, *DP* traditional pasture with native and degraded species, *iSPS* intensive silvopastoral system with leucaena (>10,000 plants ha^{-1}) and *C. plectostachyus*

and quality of milk in a dual-purpose system of Caquetá, Colombia and found significant effects on liters of milk ha^{-1} day^{-1} (9.70 vs 15.4 kg for the control and *T. diversifolia* systems respectively). In addition, protein, fat, and total solids production were also higher when animals consumed *T. diversifolia* ($p < 0.05$). Carrying capacity was increased by 15% and economic income by 25%. In another study in the same region, Rivera et al. (2022) found an 12% increase in milk production per animal per day and a 20% increase in stocking rate.

Increasing production not only per animal but also per unit area will allow the possibility of offering better conditions to producers in social and economic terms, objectives also included in the iNDCs.

2.3 iNDCs in Latin America

At the Conference of the Parties of the UNFCCC in Paris in December 2015 (COP21), countries around the world adopted a historic international agreement to mitigate climate change through GHG abatement. In this agreement, the Intended Nationally Determined Contributions are the means by which each country puts on the table the national efforts it will undertake from 2020 to meet the Agreement's two most ambitious goals: (i) keeping global temperature increase well below 2 °C compared to the pre-industrial era, with efforts to limit it to 1.5 °C; and (II) strengthening adaptive capacity to the adverse effects of climate change and building resilience.

The iNDC acronym emerged at COP19 in Warsaw, where countries were initially invited to independently determine what their contribution to the global GHG emissions reduction effort would be. The initiative was so well received that shortly before the start of the Paris Conference, more than 180 countries representing more than 90% of global emissions had submitted their contributions, detailing GHG reduction targets, action plans (mitigation and adaptation), as well as financing measures (European Commission 2019).

Despite the above, current climate change studies suggest that, if the average global temperature increase is to be kept below 2 °C, the ambition of the commitments (iNDC) needs to be significantly increased, and efforts must be even greater if the condition is not to exceed a 1.5 °C increase. The UN Environment's Emissions Gap Report (United Nations Environment Programme 2018) explains that to reach that target by 2030, with a trajectory of lower costs, it is necessary to reduce by 25% the figure of global emissions consigned in 2017; while, to limit warming to 1.5 °C, the reduction must be 55%. The gap to meet this challenge is about 29%, i.e., emissions in 2030 would need to be 29% lower than projected today with the unconditional and conditional targets stipulated in the NDCs reported to the UNFCCC.

Particularly in Latin America, according to the European Commission (2019), 18 countries show different stages of implementation of their iNDCs, and at the same time, evidence heterogeneous levels of ambition, in which it is possible to identify and characterize progress and challenges (Table 2.4). Currently all 33 countries in Latin America and the Caribbean have made some progress on their mitigation targets under the UNFCCC. According to the information reviewed, Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Uruguay, and Venezuela are the countries that present clear initiatives to define their iNDCs. Each of these countries has a different number of regulations or policies related to climate change management. According to information from the London School of Economics – Graham Research Institute *in Climate Change and the Environment and Sabin Center on Climate Change Law (Columbia Law School)* and updated information from the national files, it is identified that, for the 18 Latin American countries, there are 213 policies or regulations that address it (European Commission 2019). These show that the sectors with the highest number of related laws and policies are Energy (58.8%) and Forestry (25.36%). Table 2.4 presents some relevant aspects of the national files of each of the main Latin American countries and their iNDCs associated with the agricultural sector.

According to Table 2.4, 12 of the 18 countries explicitly express the need to include livestock activities in their NDCs, mainly because the AFOLU sector contributes a large part of GHG emissions. Most Latin American countries have large areas devoted to agricultural use. On average it is estimated that 26% of the area is under land uses associated with the agricultural sector (Willaarts et al. 2014), within which livestock is the predominant activity occupying approximately 16% of the territory (Willaarts et al. 2014), and it is estimated that more than 20% of national emissions come from it (Arango et al. 2020). For this reason, technologies such as SPSs would be of great importance as mitigation and adaptation strategies contributing to the achievement of the proposed NDCs. Table 2.5 shows the areas dedicated to livestock farming and their GHG contribution in the main Latin American countries.

Table 2.5 shows the high GHG contributions of livestock in the different countries, reinforcing the need to establish viable and effective mitigation and adaptation alternatives, adjusted to the specific conditions of each country and oriented to livestock and agricultural activities in general; under this scenario, the SPSs have shown their capacity to contribute significantly to both mitigation and adaptation.

On the other hand, a new pact was recently established at COP26, mainly oriented towards adaptation, financing, and collaboration, which means that not only

Table 2.4 Relevant aspects in the iNDCs of Latin American countries and relationship with livestock systems objectives

Country	Aspects to highlight
Argentina	Argentina aims not to exceed net emissions of 349 million tons of CO_2 by 2030. The goal will be achieved through the implementation of economic measures, focusing on the energy, agriculture, forestry, transport, industry, and waste sectors. Unconditional mitigation measures are planned that lower the 2030 target from 570 to 349 million tCO_2eq. Argentina has adaptation measures focused on forests, water, crop management, health, biodiversity conservation and extreme events. The National Forest and Climate Change Action Plan proposes to avoid 27 $MtCO_2eq$ of net emissions by 2030 unconditionally, and another 81 $MtCO_2eq$ less, conditional on financing and technology. It focuses on conservation, sustainable use (forest harvesting and forest management with integrated livestock), restoration and recovery, forest fire prevention and avoiding deforestation. In October 2021 Argentina announced an increase in mitigation ambition of 2 percentage points. This represents a reduction in emissions limitation to 2030 of 27.7% compared to the first NDC presented in 2016. In the case of cattle farming, an increase in production efficiency was contemplated. The decrease in emissions from the Forestry and Other Land Use sub-sector stems from a strong boost to forestry plantations and a drastic reduction in deforestation.
Bolivia	Bolivia has an integrated approach to climate change adaptation and mitigation aligned with its policy of Living Well, prioritizing three areas: water, energy, and forests/agriculture. The contribution establishes goals for 2030, in a base scenario with national effort, and another more ambitious scenario with international cooperation. As for the Bolivian NDCs, they include the areas of water, energy, forests, and agriculture with the following objectives: Water. To comprehensively increase adaptive capacity and systematically reduce the country's water vulnerability. Energy. To increase the capacity of electricity generation through renewable energies for local and regional development. Forests and agriculture. Increase joint mitigation and adaptation capacity through integrated and sustainable forest management. Bolivia's NDCs do not set sectoral GHG emissions targets, as it focuses on developing structural changes. However, sectoral targets are set, such as tripling water storage capacity by 2030, increasing the share of renewable energy to 79% by 2030, and increasing the area of forests under integrated and sustainable management with a community approach to 16.9 million hectares by 2030. In April 2022, the country's NDC update focused on four areas: (i) water; (ii) forests; (iii) energy; (iv) agriculture and livestock. In the forestry axis, the reduction of deforestation by 80%, doubling the areas under integrated soil management and increasing forest areas by one million ha are highlighted. In addition, in the agricultural sector, the goal is to recover 0.75 million hectares of degraded soils and increase production of strategic crops by 70%.

(continued)

Table 2.4 (continued)

Country	Aspects to highlight
Brazil	Reduction of emissions by 37% from 2005 levels by 2025. Prioritized sectors include land use change, energy (including biofuels), agriculture, industry, and transport. The contribution is unconditional. Additionally, Brazil commits to reduce its emissions in 2030 by 50%, compared with 2005. Brazil's commitments also include a long-term objective to achieve climate neutrality by 2050. Brazil's updated NDC is broad in scope and includes a consideration of means of implementation and the implementation of mitigation and adaptation actions in all economic sectors. In the agricultural sector, the aim is to strengthen the Low Carbon Agriculture Plan (ABC Plan) as the main strategy for sustainable development. This includes the additional restoration of 15 million hectares of degraded pastures by 2030 and the increase of five million hectares of integrated rural-livestock-forestry (iLPF) systems by 2030. The plan aims to reduce GHG emissions from agricultural activities; reduce deforestation; increase agricultural production on a sustainable basis; adapt rural properties to environmental legislation; expand the area of cultivated forests; stimulate the recovery of degraded areas.
Chile	Chile has a carbon intensity target, not including the land use, land-use change and forestry (LULUCF) sector, in which it proposes to reduce CO_2 emissions per unit of GDP by 30%, with respect to the level reached in 2007. It also proposes to increase the reduction between 35% and 45% by 2030, conditional on international financing. The prioritized sectors include energy, industrial processes, use of solvents and other products, and agriculture (including the livestock sector and waste). Additionally, it presents a specific contribution for the LULUCF sector, focused on the sustainable management and recovery of 100,000 hectares of forest, mainly native; and the afforestation of 100,000 hectares, mostly with native species. Of the nine prioritized sectors, the agricultural sector presented the Adaptation Plan for the Forestry and Livestock Sector in Chile in 2013. It involves 12 institutions of the Ministry of Agriculture and presents 21 territorial adaptation measures in the agricultural and forestry sectors. The forestry sector has implemented the REDD+ initiative through the National Forestry Corporation (CONAF), which contributes to Chile's voluntary commitment to the UNFCCC to reduce GHG emissions by 20%. This initiative is complemented by the Forest Nationally Appropriate Mitigation Action (NAMA). In addition, plans for forestry and agriculture (2013), biodiversity (2014), fisheries and aquaculture (2015), health (2016), infrastructure (2017), cities (2018) and energy (2018) are already in the implementation phase.
Colombia	Colombia's NDC has a relative target that proposes a 51% reduction in projected emissions by 2030 under a BAU scenario. Twenty percent is unconditional, while 51% is conditional to the provision of international support. Prioritized sectors include transport, energy, agriculture, livestock, housing, health, trade, tourism, industry, and natural protected areas. Adaptation and building resilience to climate change are priorities for Colombia and constitute a national security issue. The country will focus on socio-ecosystem based adaptation, risk management and institutional capacity building. Additionally, there is a commitment to advance in the means of implementation that will allow the effectiveness of the actions proposed in the NDC. Colombia, at the date of submission of its NDC, has two comprehensive sectoral climate change management plans – PIGCCS sector mines and energy and transport (primary road network). Since 2018, progress has been made in the formulation of the PIGCCS of the Water and basic sanitation, housing, industry (manufacturing subsector), agriculture and livestock, and health sectors. Within the livestock sector Colombia formulated the NAMA of Bovine Livestock that include a strong component of silvopastoral systems to reduce between 15.2% and 33.9% of GHG emissions from this sector by 2030.

(continued)

Table 2.4 (continued)

Country	Aspects to highlight
Costa Rica	Costa Rica's NDC covers the whole economy and sets an absolute maximum emissions target of 9,374,000 tons of carbon equivalent (tCO_2eq) by 2030. The target is consistent with the global trajectory needed to meet the 2 °C target. The contribution is unconditional and includes 41 actions, both in mitigation and adaptation. The NDC establishes a target of 60% of the territory with forest cover by 2030, specifically in land use change, and other actions within the framework of the REDD+ Strategy. At the beginning of 2018, the Sectoral Agreement for the reduction of emissions in the agricultural sector was signed, and there are plans to sign the Sectoral Agreement for the reduction of emissions in the transport sector. Costa Rica commits to an absolute maximum net emissions budget for the period 2021–2030 of 106.53 million tons of carbon dioxide equivalent (CO_2eq) including all emissions and all sectors covered by the corresponding National Greenhouse Gas Emissions Inventory.
Cuba	Cuba's NDC is based on mitigation and adaptation policies and actions, which are advanced through foreign investment (in the case of mitigation) and domestic support, but whose comprehensive and effective completion is conditional on the receipt of international funding. Cuba's NDC prioritizes actions on coastal vulnerability reduction, mangrove and coral reef recovery, food production, integrated water management, land use planning, forestry production, fisheries, tourism, and health.
Ecuador	The NDC of Ecuador is composed of the aggregate inputs for the energy, agriculture, industrial processes, and waste sectors. The land use and land use change sector (LUCLUCF) was analyzed separately. In the case of the aggregate sectors, the estimated GHG emission reduction potential corresponds to 9% compared to the baseline scenario (with base year 2010) for 2025. Likewise, for the same period, the NDC identifies a reduction potential of 20.9%, conditioned to the support of international cooperation. In the case of the LUCLUCF sector, the NDC identifies a 4% reduction compared to the baseline (with reference year 2008) by 2025. Under a conditional scenario, a 20% reduction would be achieved. Ecuador's NDC establishes a set of conditional and unconditional adaptation measures for six priority sectors: human settlements; water heritage; natural heritage; productive and strategic sectors; health; and food sovereignty, agriculture, livestock, aquaculture, and fisheries. On the other hand, in the agriculture sector, there is the Climate-Smart Livestock Project. Its objective is to reduce land degradation and increase the capacity to adapt to climate change and reduce GHG emissions through the implementation of intersectoral policies and sustainable livestock farming techniques.

(continued)

Table 2.4 (continued)

Country	Aspects to highlight
El Salvador	El Salvador has presented a NDC based on actions and policies for mitigation and adaptation to climate change. In both cases, the following issues have been prioritized: strengthening the institutional and legal framework for the formulation and sustained implementation of national contributions; Law on Climate Change, Law on Land Management and Development; infrastructure; water resources; agriculture, livestock, and forestry; ecosystem restoration, energy; health, environmental sanitation, labor and social prevention and transportation. El Salvador commits to have an annual emissions reduction (by 2030 and with respect to a baseline scenario (BAU) from 2019) of 640 Kton CO_2eq. In addition, El Salvador commits to have a cumulative emissions reduction, for the period between 2035 and 2040, counted from 2015, of 50,857 Kton CO_2eq from emission reductions and activities to increase carbon sinks and reservoirs in the agricultural landscape of its AFOLU Sector, provided that large-scale financing is obtained from international and national sources with the participation of the private sector. In the livestock sector, it proposes a Low Carbon Resilient Livestock (NAMA Livestock) plan. According to the Ministry of Agriculture estimates, the required support has an indicative amount of USD$57 million to implement the various strategic lines of the project. This required support is based on the NAMA roadmap for the cattle sector, developed through pilot technical assistance actions on mitigation and adaptation, capacity building, development of a MRV system for GHG measurement, among others.
Guatemala	Guatemala has a relative target that proposes to reduce 11.2% of its total GHG emissions from the base year 2005 projected to 2030, in a BAU scenario as an unconditional target. And as a conditional target, to reduce 22.6% of its total GHG emissions from the base year 2005 projected to 2030, in a BAU scenario. Prioritized sectors include forestry, agriculture, and transport. It has an NDC focused on cross-cutting vulnerability reduction and improvement of adaptation processes in key sectors such as human health, marine-coastal zones, agriculture, livestock and food security, forest resources, protected areas, conservation and management of strategic ecosystems, infrastructure, integrated management of water resources, quality of productive infrastructure, soil protection and integrated management of disaster risk reduction. The Guatemala NDC Update 2021, considers 34 targets for the Adaptation component in the sectors of: Agriculture and food security; Marine-coastal zones; Forest resources, ecosystems, and protected areas; Integrated water resources management; Human health; and Infrastructure; and 10 targets for the Mitigation component in the sectors of: Land use, land use change and forestry; Energy; Agriculture; and Waste. The sectoral targets have institutional implementation officers and the support and follow-up of the Ministry of Environment and Natural Resources as the national focal point.

(continued)

Table 2.4 (continued)

Country	Aspects to highlight
Honduras	This country has a conditional relative target of a 15% reduction in emissions by 2030 compared to the BAU scenario. Its unconditional contribution proposes the afforestation/reforestation of one million hectares by 2030 and a 39% reduction in household fuelwood consumption. The NDC considers adaptation to climate change as a priority to reduce the country's vulnerability. The prioritized sectors are water resources, risk management, agriculture and food security, forests and biodiversity, coastal marine systems, human health, and infrastructure. The main national actors are the Presidential Office for Climate Change (Clima+), the Secretariat of Natural Resources and Environment/MiAmbiente, the Institute of Forest Conservation (ICF), the Secretariat of Agriculture and Livestock (SAG), and the National Electricity Company.
Mexico	Mexico has an unconditional target to reduce 35% of its GHG emissions, considering a baseline of emissions in 2030, and 51% of its black carbon emissions with respect to its BAU by 2030. In addition, it conditionally considers reducing 40% of GHG emissions and 70% of black carbon emissions with respect to its BAU by 2030. The forestry and agricultural sector hope to achieve zero deforestation by 2030, recover pastures and promote biodigesters on agricultural farms. The Mexico REDD+ Alliance, with the support and collaboration of local partners, has implemented the project *Strengthening capacities for the identification and implementation of silvopastoral technologies and good livestock practices*. The Mexican Carbon Platform is implementing the first pilot program for a carbon market in Latin America.
Nicaragua	In terms of its unconditional target, Nicaragua proposes that 60% of the installed capacity of the electricity matrix should come from renewable energy sources by 2030; and promotes the conservation of the absorption capacity of carbon sinks with respect to the Reference Scenario to 2030. Its conditional target represents an increase in carbon absorption capacity by 20% with respect to the Reference Scenario to 2030. The country requires financial support to develop priority adaptation measures around infrastructure, health, forests, agriculture, water and sanitation, disaster risk management, early warning systems, resilient ecosystem management and sustainable use and management of protected areas.
Panama	The forestry sector proposes to increase the GHG absorption capacity by 10%, with respect to the BAU scenario to 2050, through reforestation and restoration activities in protected areas. Its conditional contribution in the forestry sector proposes to increase the GHG absorption capacity by 80%, with respect to the BAU scenario to 2050, through international support sources. With respect to the LULUCF sector of the NDC, there is the Alliance for a Million Hectares (Alianza por el millón de hectáreas) initiative. This is promoted through public-private management to increase the country's forest cover by one million hectares in 20 years, under different modalities (reforestation, conservation and enrichment of early secondary forests, restoration of degraded areas and agrosilvopastoral systems). Currently, more than 50 public and private institutions and NGOs have joined this initiative which, since its launch in 2014, has managed to reforest 7451 hectares.

(continued)

Table 2.4 (continued)

Country	Aspects to highlight
Paraguay	Paraguay has a relative reduction target of 20% of projected emissions by 2030 in a BAU scenario, which is broken down into 10% unconditional and 10% conditional. In its adaptation contribution, priority is given to the sectors of water resources, forests, agricultural and livestock production, energy, infrastructure, health and sanitation, risk management and natural disasters, and early warning systems. The country has 16 policies or regulations related to climate management, which are mainly related to the energy sector, institutional arrangements, and the forest sector (including REDD+ and land use change). At the sectoral level, there is a national plan for risk management and adaptation to climate change in the agricultural sector and a vulnerability analysis and action plans for agriculture, livestock, health, and water resources with the following strategies: (1) Facilitate access to technology for sustainable agricultural-livestock-forestry production, prioritizing strategies for the inclusion of women and young people from rural and indigenous communities. (2) Encourage research on agricultural-livestock production systems on the impact of climate change on vulnerable sectors, and (3) Promote the use of nature-based solutions to increase the resilience of the sector to the negative impacts of climate change.
Peru	Peru has a relative reduction target of 20% of projected emissions by 2030 in a BAU scenario. An additional 10% reduction would be conditional on access to international finance. In its adaptation contribution, Peru indicates that priority is given to the water, agriculture, fisheries, forestry, and health sectors to reduce vulnerability to climate change. With the support of international cooperation, NAMAs have also been developed for the transport, solid waste, energy, bioenergy and agricultural sectors. Ninety-one adaptation measures corresponding to 46 products have been identified for the NDC. The measures are distributed among the thematic areas of agriculture, 17; forests, 12; fisheries and aquaculture, 18; health, 14; and water, 30. Sixty two mitigation measures have also been identified. The measures are distributed among the sectors as follows: stationary combustion for energy, 23; mobile energy combustion, 14; industrial processes and product use, 2; agriculture, 6; LULUCF, 8; and, waste, 9. The NDC proposes a GHG emissions level for 2030 of 298.3 $MtCO_2eq$ and a reduction of 89.4 $MtCO_2eq$, which represents a 30% reduction target (MINAM 2019).
Uruguay	Uruguay has set an unconditional target of 19.1% reduction of GHG emissions from the energy sectors, including transport and industrial processes (22.2% of emissions in 2012), and a conditional target of 29% with additional means of implementation. For CH_4 from energy, agriculture (including livestock), waste, and industrial processes (43.2% of emissions) – the unconditional target is 57%, and 61% conditional. For N_2O from energy, agriculture, waste, and industrial processes (34% of emissions) the reduction target is 48% unconditional and 52% conditional. They also have specific intensity targets for food production (51.1% of emissions): 32% reduction of CH_4 emissions per kilogram of live weight of beef and 37% conditional; and unconditional reduction of 34% of N_2O emissions per kilogram, and 38% conditional. In the LULUCF sector, which had net removals in 1998–2012, there are unconditional mitigation targets for CO_2: for the category of living biomass in forest land, it is proposed to maintain 100% of the area of native forest in 2012 (and increase by 5% conditional); at least maintain 100% of the amount of effective area under forest plantation management in 2015; and maintain 100% of the area of forest plantations for shade and shelter in 2012 (and increase by 25% conditional). In the category of organic carbon in soil (SOC) it is proposed to avoid emissions in 10% of the grassland area (30% conditional), avoid SOC emissions in 50% of peatland areas in 2016 (100% conditional) and avoid emissions in 75% of the area of crops under land use and management plans in 2016, as well as sequester CO_2 in 25% of the remaining area.

(continued)

Table 2.4 (continued)

Country	Aspects to highlight
Venezuela	Venezuela has a GHG emissions mitigation target set out in its current NDC of 20% by 2030, relative to the baseline scenario, most of it conditional on the provision of means of implementation (Article 4.7 of the Convention). This country reserves the right to revise the provisions of the NDC based on national priorities. Venezuela considers adaptation to the adverse effects of climate change a national priority, which is why it plans measures and actions in the areas of electricity, industry, housing, transport, health, popular organization and participation, biological diversity, food sovereignty and sustainable agriculture, water conservation and management, conservation and sustainable management of forests, research, monitoring and systematic observation, education and culture, waste management, land use planning, risk management, emergencies and disasters. In addition, the development of municipal and local adaptation plans is encouraged for risk management scenarios that directly involve co-responsibility between the State and the People's Power.

will mitigation efforts in the NDCs of the countries be important, but also that the alternatives to be implemented must have the capacity to adapt to climate change. In addition, some countries have increased their mitigation ambition. According to COP 26 records, 80 countries now have Adaptation Communications or National Adaptation Plans to prepare for climate risks. The Glasgow-Sharm el-Sheikh Work Program on the Global Goal on Adaptation, which will drive action on adaptation, was also agreed. Unprecedented amounts of adaptation funding were pledged, including a commitment to double by 2025 the levels of adaptation funding recorded in 2019. According to records this is the first time a funding target specifically targeted for adaptation has been agreed at the global level. Several nations announced new partnerships to improve access to finance (UNFCCC 2021).

In terms of financing, technologies such as SPS could achieve economic support for their implementation due to cooperation agreements and their potential. Following COP 26, industrialized countries made progress towards achieving the $100.000 millions climate finance target, a goal they will reach by 2023. Private financial institutions and central banks are on track to realign trillions of dollars towards the goal of global net zero. In Glasgow, several countries agreed on a course of action to achieve the new post-2025 funding target. Several industrialized nations pledged significantly higher amounts for essential funds such as the Least Developed Countries Fund.

According to reports, the Glasgow Breakthroughs will accelerate collaboration between governments, business, and civil society to achieve climate goals more quickly. COP26 established the "Paris Rulebook", agreeing on the "enhanced transparency framework" (countries must report progress on emissions and support), a new mechanism and new standards for international carbon markets as well as common deadlines for emissions reduction targets.

Table 2.5 Areas devoted to cattle production and mitigation objectives in the cattle sector of seven Latin American countries

Country	Livestock area (million ha)	Domestic GHG emissions ($MtCO_2$ eq)	Livestock emissions relative to domestic emissions (%)	Mitigation objective	References
Argentina	110.1	364.4	17	Limit increase to 35% above 2010 levels by 2030	UNFCCC (2016), Piquer-Rodríguez et al. (2018), and Secretaría de Ambiente y Desarrollo Sustentable (SGAyDS) (2019)
Brazil	168	1465	19.2	Limit increase to 5% above 2010 levels by 2025	MCTIC (2016), UNFCCC (2016), ApexBrasil (2018), and MRE et al. (2019)
Colombia	37	236.97	9.6	20% below business as usual (BAU) in 2030	IDEAM et al. (2018)
Costa Rica	1.04	11.25	19.4	25% below 2012 levels by 2030	Chacón-Navarro et al. (2015) and Ministry of Environment and Energy (2015)
Mexico	109.8	534.61	13.2	22% below the BAU scenario by 2030	Servicio de Información Agroalimentaria y Pesquera (SIAP) (2019)
Peru	18.7	169.71	6.3	20% below 2010 levels by 2030	Multisectoral Working Group of a temporary nature tasked with generating technical information to guide the implementation of the NDCs (GTF-NDC) (2018)
Uruguay	13.3	32.36	72	42% below BAU scenario by 2025	Ministry of Livestock, Agriculture and Fisheries (MGAP) (2019) and National System of Response to Climate Change and Variability (SNRCC) (2018)

Adapted from Arango et al. (2020)

2.3.1 Current Status of the SPSs Within the GHG Inventories

Currently, the biennial update reports, submitted by the signatory countries to the United Nations Framework Convention on Climate Change, began to quantify the absorptions attributed to silvopastoral systems represent for the national carbon balance. Brazil and Colombia report between −3 and −2 million tons (Mt) for the last years of official reporting; Although other countries such as Peru, Uruguay, Mexico and Argentina report removals between −0.14 and −0.55 Mt year^{-1}; this demonstrates the need to have an established improvement plan in order to continue incorporating the largest number of areas in national GHG inventories.

Table 2.6 summarizes all the official information reported for the grassland category in some Latin American countries and the most recent measurement year for each report.

In recent years great efforts have been directed to mitigate CH_4 emissions as this gas has a global warming power up to 80 times greater than CO_2 in a period of 15–20 years (Pathak et al. 2022). It is currently estimated that CH_4 is responsible for 30% of the increase in global temperature, and due to processes, such as enteric fermentation, livestock systems account for 39.1% of the sector's emissions and 6% of global emissions according to Beauchemin et al. (2020). For all these reasons, production alternatives must should have the capacity to reduce CH_4 emissions and, at the same time, favor its cycling so that concentrations in the atmosphere do not increase. SPSs can contribute in both directions as they can reduce CH_4 emissions per animal and per Kg of product and, at the same time, improve carbon cycling and enhance CH_4 sinks with the improvement of soil conditions (Dunfield 2007; Rivera et al. 2019).

2.3.2 Use of SPSs as Tools to Achieve NDCs and Constraints to Their Scaling Up

According to Aynekulu et al. (2020), in Latin America, nine countries include SPSs as an alternative to achieve their iNDCs. The importance of SPSs for achieving the NDCs is based on their potential for GHG mitigation, carbon sequestration,

Table 2.6 Current status of carbon sequestration by SPS in some countries of the LAC region

Country	Measurement year	Carbon emissions ($MtCO_2$ eq)	UNFCCC Report	References
Colombia	2018	−2.04	BUR 3	IDEAM et al. (2021)
Argentina	2018	−0.15	BUR 4	MAyDS (2021)
Costa Rica	2015	–	BUR 2	MINAE et al. (2019)
Brazil	2016	−3.43	NC 4	De Araújo et al. (2020)
Uruguay	2019	−0.38	BUR 4	MA & SNRCC (2021)
Mexico	2019	−0.55	BUR 3	SEMARNAT (2022)

increased production, and their applicability to different contexts thanks to their versatility (Suber et al. 2019). It is estimated that in Latin America there are approximately 560 million ha in pastures, where different SPSs could be implemented as mitigation and adaptation alternatives having an important impact due to the potential area of application (FAOSTAT 2017).

In Colombia, for example, according to the MADR (2018), four low-emission alternatives with high mitigation capacity are proposed. Table 2.7 presents their characteristics, highlighting SPSs as an alternative with high mitigation potential.

However, it is important to highlight that large-scale experiences with SPS-based initiatives are scarce. Tapasco et al. (2019), for example, analyzed the experiences in Colombia and highlighted the importance of identifying and overcoming the different scaling constraints in order to achieve the true potential of efficient technologies such as SPS within the NDCs of the countries.

Particularly in the scaling up of technologies such as SPSs, the implementation of improved pastures or the use of strategic supplementation, among others, have traditionally been limited by different factors even though they have demonstrated

Table 2.7 Low GHG emission alternatives in the livestock sector, their reduction contributions, and economic characteristics in Colombia

Alternative	Implementation potential (M ha)	Proposed mitigation contribution to 2030 (Mt CO_2 eq/year)	Contribution to NDC target of agriculture sector (%)	Investment required (US$ Millions)	Cost/benefit ratio	Cost-effectiveness (US$/ton of CO_2eq.)
Pasture management[a]	2.2	1.94	15	1.84	2.3	−247
Non-intensive SPSs[b]	1.25		31	1.100	4.3	−102
Intensive SPS (iSPS)[c]	0.37	3.99	35	618	3.7	−67
Conversion of pastures to crops	0.554	5	38	808	1.5	−13.2
Total	4.374	14.93		4.366		

Adapted from Tapasco et al. (2019)

[a]It includes both good and bad pasture management. Good management consists of renewing pastures according to soil conditions, use of fertilizer, and implementing fencing for rotational management. Poorly managed pastures are those that are not renewed and not fertilized, and grazing is continuous or alternate. The grasses are *Brachiaria decumbens, B. humidicola, B. braquipara, Panicum maximum* and *Cynodon plectostachyus*. The reference baseline is the established native grassland

[b]These are well-managed paddocks under rotation with trees in the grazing areas and with densities of 100–600 trees/ha and can be accompanied by forage shrubs with densities of less than 1000 shrubs/ha

[c]Intensive systems with fodder trees and shrubs with densities above 5000 shrubs/ha, managed in rotation

their ability to mitigate GHG emissions, increase carbon stock and improve the productivity of cattle production (Calle et al. 2013; Enciso et al. 2018; Charry et al. 2018; Tapasco et al. 2019). According to different studies, to achieve the necessary scale that allows a significant impact of technologies such as SPSs, it is necessary to ensure access to the necessary inputs, capital, and knowledge for their implementation (Tapasco et al. 2019; Arango et al. 2020). According to Arango et al. (2020), one of the basic constraints is that formal seed sales systems for grasses and legumes are underdeveloped in most Latin American countries, which restricts the purchase of planting material needed to implement large areas in the short term. Also, because the establishment of slightly more complex technologies such as SPSs require high initial investments when compared to extensive grazing- -although lower than forestry systems or intensive agriculture-., official credit systems become essential. However, in most Latin American countries there are few specific credit options for these purposes, leaving many producers (especially small- and medium-scale producers) with scarce financial resources and no opportunities to implement mitigation options. Another aspect that requires significant changes is to reduce the limitations of the banking systems to the to provide credit access for small and medium-sized producers, such as excessive procedures, guarantees against risks, short or inexistent grace periods and high interest rates.

To address the economic constraint, differentiation of meat and dairy products derived from environmentally friendly production systems (Charry et al. 2019) or payments for ecosystem services could help raise capital to invest in mitigation options, but efforts in this direction remain scarce and have not yet been shown to be applicable on a large scale. Although the scientific community is generating valuable information on different mitigation options, there is no guarantee that this information will reach end-users (livestock producers), especially if it is not disseminated in a way that is understandable to them. Furthermore, while extension services and technical assistance have been improving, they are still insufficient to meet high demand under variable production conditions (Arango et al. 2020).

On the other hand, when looking at cultural and behavioral factors, many livestock producers in Latin America prefer traditional production systems to more technical and sustainable ones for reasons of simplicity and risk avoidance. To overcome this barrier and find entry points with these producers, the dissemination of information on the economic, social, and environmental benefits of mitigation options becomes even more critical (Arango et al. 2020).

On the political aspect, Tapasco et al. (2019) highlight that most of the projects that have been developed in the Latin American context have a high potential to scale up mitigation technologies, but these were completely isolated from national policymakers and implementers. This shows that national policy does not consider local initiatives, which is an obstacle to scaling up any success. An analysis of 16 case studies concluded that large-scale implementation of adaptation and mitigation in agriculture requires strong government support to achieve it (Cooper et al. 2013). Success requires support at the policy level and through the establishment of frameworks that build on the comparative advantages of the local partners involved.

Finally, Tapasco et al. (2019) found that land tenure is often a key barrier to land use intensification. It is a structural issue that makes it difficult for producers without clear land titles to access credit from government programs or to be beneficiaries of internationally funded projects. Three types of policies are needed to address this problem following actions at policy level (Balcázar and Rodríguez 2013): (i) Promote the regularization Regularize and formalize land ownership rights, (ii) implement policies and instruments to trade land markets and democratize access, (iii) Promote sustainable intensification of land use with specific planning, regulation and control policies and instruments.

Regarding economic constraints, these limit the application of viable technical mitigation options to <10% of the potential (Herrero et al. 2016). In the three projects studied by Tapasco et al. (2019), international and national technical cooperation had a short-term impact. However, it is also an obstacle to longer-term progress because producers expect more non-reimbursable aid to finance new technologies. Financing agricultural technology by public institutions is very attractive to producers but making agricultural credit available to them can be difficult. In many areas of Latin America, producers, especially smallholders, lack land titles. Without a title to serve as insurance for any debt, financial institutions are unwilling to provide them with finance (Perfetti et al. 2013). Inefficient livestock production is not very profitable, so many producers have few resources. In addition, the agricultural sector faces high climatic risk, which often leads to credit defaults and poor credit histories. Public entities can offer loans at low-interest rates and other incentives, but the amounts allocated are often insufficient and run out quickly (DNP 2014).

Other mechanisms such as microcredit, financial cooperatives and financing by agricultural supply houses try to overcome some of these limitations (Mission for the Transformation of the Countryside 2015). However, in most cases, microcredit for agriculture charges interest rates close to the formal usury level (55% in 2018, SFC 2018). Microcredit user's cite high-interest rates and low amounts available as main problems (Banco de la República 2018), in addition, small loan caps are a major problem for technologies that require high investments, such as SPSs, which can cost up to USD 2330 per hectare (FEDEGAN 2017). It often means that larger areas of medium- and large-scale livestock producers are excluded.

Despite this panorama, there are reasons to be optimistic with the scaling of SPS because their benefits go beyond improving productivity, income and climate change mitigation. A broader analysis shows that the additional benefits contribute to several of the Sustainable Development Goals agreed by the United Nations that all the countries of Latin America ratified within their commitments (Chará et al. 2019).

2.4 Final Considerations

Latin American countries have ambitious objectives within their NDCs and for this reason, effective and viable alternatives must be identified to achieve the objectives of mitigation and adaptation to climate change. Since these are countries with large areas under livestock and other agricultural systems, these productive activities generate large amounts of GHGs and therefore agriculture sector is key to achieve the goals proposed in the different NDCs. Silvopastoral systems, due to their great versatility, GHG mitigation potential, capacity to improve and increase carbon stocks, ability to increase animal productivity and capacity to adapt to climate change, can contribute to the ambitions of the NDCs in different contexts. Although these systems technically demonstrate their potential for mitigation and adaptation supported by diverse experiences and research, efforts should still be focused on their massification and scaling up based on their inclusion in public policies. They can also be part of the initiatives developed by private investment funds and international resources aimed at combating climate change, improving climate resilience and achieving Sustainable Development Goals.

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Chapter 3
Silvopastoral Systems: A Pathway to Scale-Up Restoration in Colombia

Alicia Calle

Abstract In Colombia, vast areas of rich natural ecosystems have been transformed for extensive cattle grazing, a production system whose ecological footprint exceeds its productive and socio-economic benefits. With multiple degradation drivers on the rise, large scale forest landscape restoration (FLR) is more relevant and urgent than ever. Silvopastoral systems (SPS) have the potential to work synergistically with other restoration approaches to transform landscapes within relatively short timeframes. At the farm scale, SPS help restore productivity; at the landscape scale, they help protect critical areas and increase connectivity; at the regional scale they contribute to optimize land use and reduce the pressure to clear more land. Mainstreaming SPS into the national restoration toolkit is therefore an important step towards scaling up FLR while creating economic, social, and environmental co-benefits. Better coordination between the environmental and agricultural sectors, innovative financial mechanisms, and stronger monitoring efforts are still needed, but the country's accumulated experiences in SPS research and implementation provide strong foundations on which to build the process.

Keywords Forest landscape restoration · Agroecology · Agroforestry · Intensification · Scaling-up

3.1 Introduction

Two things became evident in 2005, when the Millennium Ecosystem Assessment identified anthropogenic activities as the driving force behind a 60% global decline in ecosystem services. First, the current input-based agricultural model is unsustainable, more so in the face of a changing climate, and alternatives for sustainable intensification are needed that maximize food production while minimizing the

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environmental and social footprints (Foley et al. 2011; Garnett et al. 2013). And second, a global effort to restore ecosystems capable of providing important services is necessary. But far from being independent, landscape restoration and agricultural intensification are inevitably intertwined and should be addressed jointly.

Ecosystems across the globe have been transformed and damaged like never before. One fourth of the earth's ecosystems and agricultural lands (FAO 2011a, b) are now degraded and their capacity to provide vital services is hindered. Most affected are people whose livelihoods directly depend on forests and agricultural lands, the majority in the global south. Given that annual degradation costs are estimated at US$6.3 trillion globally, ecosystem restoration has become a smart investment and governments around the world have pledged to restore more than 160 million hectares (Ding et al. 2017).

Globally there are 1500 million hectares of mosaic landscapes where natural ecosystems are interspersed with small-scale agriculture and human settlements (WRI 2014). In these multifunctional landscapes, stewardship can be improved by jointly managing remaining fragments, restoration areas, connective elements, and agricultural lands. This approach, known as forest landscape restoration (FLR), combines different methods to fulfill a variety of goals, from delivering ecosystem services and conserving biodiversity, to enhancing food production and supporting livelihoods (IUCN and WRI 2014). FLR recognizes the value of agricultural systems that contribute to rehabilitate lands degraded by unsustainable production, thereby strengthening human livelihoods, and protecting the natural capital (Chazdon et al. 2017; Holl 2017b; Meli et al. 2019).

Livestock is an important source of food, fuel and income, and provides employment for 1.3 billion people worldwide (Herrero et al. 2009). However, this sector is known for its environmental impacts as it uses 45% of the global surface and contributes 18% of anthropogenic greenhouse gasses (Gerber et al. 2013; Herrero et al. 2009). These impacts will intensify as demand for livestock products continues to grow (Godfray and Garnett 2014). Sustainable intensification is therefore a priority for a sector whose ecological footprint already exceeds its productive and socioeconomic benefits (Havlík et al. 2014; Herrero et al. 2009; Strassburg et al. 2014). The challenge is double: to improve food security by producing more food at a reasonable cost and to reduce environmental impact by using less land and fewer resources. Given their large scale, high emissions intensity, and suboptimal productivity, extensive cattle systems in the developing world present one of the most interesting opportunities for sustainable intensification (Gerber et al. 2013; Herrero et al. 2010).

This chapter illustrates the synergies between FLR and sustainable intensification using cattle production in Colombia as an example. I briefly introduce Colombia's restoration challenges and highlight the role of agricultural landscapes in advancing restoration goals. I provide an overview of the country's cattle sector and explain how the sustainable intensification goals can be met using silvopastoral systems. I use examples to illustrate how scaling up SPS on previously degraded lands contributes to strengthen livelihoods, recover ecosystem services and prevent further deforestation. I close with some reflections on other implications of mainstreaming SPS into the country's restoration strategy.

3.2 Colombia's Restoration Challenges

In Colombia, 25% of the territory is degraded (MADS 2012b) and 40% of the soils show signs of erosion (IDEAM and UDCA 2015). More than 42 million hectares of natural ecosystems have been transformed at a high cost for the country's megadiversity (Etter et al. 2008). Important ecosystem services have been lost largely as the result of habitat transformation and resource overexploitation. Despite modest forest cover gains in the first decade of the 2000s (Sánchez-Cuervo et al. 2012), deforestation spiked by 44% in 2016 relative to the previous year and the country lost nearly 200,000 ha of forest in 2018 (IDEAM 2017, 2019). With deforestation, mining, inadequate agricultural use, and other degradation drivers on the rise (IDEAM and UDCA 2015), restoration is more relevant than ever.

Since the launch in 1998 of its first restoration plan (MMA 1998), Colombia has been increasingly committed to restoration. In 2012 the government issued the current National Restoration Plan (NRP) (MADS 2012c) followed by a Manual for Biodiversity Offsets through ecological restoration (MADS 2012b). Restoration goals have been included in the last three government plans, the most recent aiming for 300,000 restored hectares by 2022 (Gobierno de Colombia 2018). Colombia has also made international commitments, pledging to restore one million hectares under the Bonn Challenge and the 20 × 20 Initiative.

The lack of an official national registry of restoration projects makes it difficult to assess progress towards these targets. Nevertheless, a recent study of 119 projects in Colombia provides some idea of the challenges for scaling-up restoration. According to this study, most restoration projects in the country are funded and implemented by the government on public lands, with marginal participation of local communities; they are small-scale projects (i.e. less than 100 hectares) that focus on ecological goals; monitoring is usually short-term and rarely includes socioeconomic indicators; and only a small portion of projects work to recover privately-owned agricultural lands (Murcia et al. 2015). Meanwhile, most lands suitable for restoration in Colombia are private agricultural lands located in densely populated areas (MADS 2016). This clear gap between restoration projects and available lands creates an unprecedented opportunity to scale-up FLR on degraded agricultural landscapes.

Colombia's NRP recognizes the central role of agricultural landscapes in its overall strategy by including different restoration approaches. Aside from strict ecological restoration aimed at recovering function, structure, and composition in damaged ecosystems, the plan also contemplates rehabilitation and reclamation. Rehabilitation is particularly relevant in degraded agricultural lands where the goal is to regain productivity and/or ecosystem services related to specific functional or structural attributes. The plan also explicitly highlights the need to address the social dimension by improving the livelihoods of human populations (MADS 2012b). Scaling-up initiatives that help private landowners and communities rehabilitate their agricultural lands would therefore complement existing government-led ecological restoration projects.

3.3 Colombia's Need for Sustainable Intensification

Across many tropical regions, the expansion of grazing has driven ecosystem transformation affecting native forests, natural savannas and grasslands (McAlpine et al. 2009). In Latin America alone there are approximately 600 million hectares of extensive grazing pastures, most of them for cattle (FAO 2009). Habitat loss has affected native plant and animal species, many of them endemic, at a high cost for biodiversity. Grazing pressure, the use of fire, and the introduction of exotic grasses have altered the structure and composition of these systems, resulting in soil and water degradation, desertification, and the depletion of key ecosystem services (Herrero et al. 2009; McAlpine et al. 2009; Steinfeld et al. 2006).

In Colombia, pastures occupy 84% of the country's agricultural land or 24.6 million hectares, of which only 18 million are suitable for grazing. Meanwhile, lands with cropping potential are underutilized with only 6 million hectares currently in that use (IDEAM 2013; IGAC et al. 2012). Historically, pasture expansion has driven the transformation of different ecosystems, from high Andean to lowland dry forests (Etter et al. 2008). Cattle production directly contributes 9% of the country's gas emissions, and forest clearing for pastures an additional 12% (IDEAM 2016). With an average 0.6 heads per hectare, productivity per animal and per unit area are disappointing at best (Fedegan 2006).

Nevertheless, the cattle sector is a key player in the national economy, contributing 21.8% of the agricultural GDP or 1.4% of the national GDP, and directly employing 810,000 people or 6% of the country's workforce (Fedegan 2017). Of the estimated 500,000 families that derive their livelihoods from cattle, 82% are small farmers owning 50 heads or less and only 3% are large landowners with over 250 animals (Fedegan 2017). For those trying to make a living on lands too degraded or too remote for other uses, cattle ranching serves an important social role by providing a last economic alternative. Cattle production is therefore a complex issue, and addressing it requires consideration for the variety of ecological, economic and social factors at play.

In recent decades perceptions about the livestock sector have shifted, from a main driver of environmental degradation to a critical player in addressing a variety of global challenges ranging from sustainable development to deforestation, and especially climate change (Gerber et al. 2013; Steinfeld and Gerber 2010). One approach to intensification that delivers on all three axes of sustainability —economic viability, environmental responsibility and socially equitability— is the widescale adoption of silvopastoral systems (SPS) (Herrero et al. 2010; Montagnini et al. 2015; Murgueitio et al. 2011).

3.4 Silvopastoral Systems

SPS are diverse agroforestry arrangements that combine fodder plants, shrubs and trees to improve animal nutrition and provide diverse goods and services (Dagang and Nair 2003). Plants are intentionally combined for structural and functional complementarity above and below ground. Trees, shrubs and grasses are arranged in vertical strata to maximize biomass productivity, and the sun's energy is harnessed as the basic input (Montagnini et al. 2015). Short rotations and long resting periods facilitate the physical and biological recovery of soil health (Young 1997), and mixed perennial vegetation supports biological processes such as photosynthesis, nitrogen fixation, and nutrient cycling. Thus, practices like burning or the application of most agrochemicals become unnecessary (Montagnini et al. 2015, Murgueitio et al. 2011). SPS also sequester more carbon and provide improved diets that reduce methane emissions from enteric fermentation (Aynekulu et al. 2019; López-Santiago et al. 2019; Peters et al. 2012). These complex systems support significant increases in per hectare productivity and carrying capacity, allowing farmers to release lands from production and reducing the need to clear additional lands (Latawiec et al. 2015; Murgueitio et al. 2011).

SPS rely on the application of agroecological principles, not on the use of prescribed technological packages (Nicholls et al. 2016). Therefore, they are adaptable to most farm conditions and especially well-suited for smallholders in the developing world who need affordable, low-input options for a diversified and resilient cattle production (Pagiola et al. 2010; Herrero et al. 2010; Harvey et al. 2014). SPS respect a long cultural heritage of cattle production and contribute to improve this traditional productive activity by engaging farmers in the protection of their natural capital (Calle 2019; Garen et al. 2009; Lazos-Chavero et al. 2016). Additionally, silvopastoral products can meet society's growing demand for cleaner and healthier foods, and products from animals raised under improved welfare conditions (Broom et al. 2013; Godfray and Garnett 2014).

3.4.1 Silvopastoral Systems for Landscape Restoration at Multiple Scales

The transition from conventional pastures to SPS has effects at different scales, and at each scale serves different goals that contribute to FLR. At the farm scale, the goal is to improve productivity on the best lands so the farmer perceives direct benefits, some of which are visible in the short term while others will accrue over time. Addressing the landowners' priorities first helps set the foundations for farmers to willingly engage in further restoration actions (Calle 2019).

At the local scale, the goal is to rehabilitate degraded lands to recover critical ecosystem services. SPS increase perennial vegetation cover through the addition of fodder shrubs, scattered trees, live fences and other elements, and by improving soil and water management. Over time, this enhances the ecological functions that underpin services such as connectivity, erosion control, soil fertility, water provision, biological pest control or carbon sequestration (Montagnini et al. 2015). In addition, because complex agroforestry systems recover into forests more rapidly than other uses, SPS can eventually facilitate a transition towards ecological restoration (Latawiec et al. 2016).

At the landscape scale, the goal is to protect critical areas and increase landscape connectivity. Using SPS to increase productivity on the best lands can facilitate the decision to remove grazing animals from areas that are challenging to farm and marginally productive, such as steep slopes and riparian buffers. When immerse in a friendly landscape matrix, these areas often provide good conditions for forest regrowth (Chazdon and Guariguata 2016) and once recovered, they are less likely to be re-cleared for farming (Reid et al. 2017). SPS also improve the quality of the pasture matrix by adding tree cover in grazing areas, and connecting live fences and riparian buffers to remnant and recovering forests (Murgueitio et al. 2011; Calle and Holl 2020). All of these elements support biodiversity by complementing existing conservation areas and build climate resiliency (McAlpine et al. 2009). With adequate planning, an aggregation of sustainable land uses across a region can improve ecosystem services, facilitate species persistence, reduce pressure on remaining ecosystems, and support livelihoods (Calle et al. 2013).

At the regional scale, the goal is to optimize land use. This is especially relevant in Latin America given the sheer scale of low-productivity grazing lands. Scaling-up SPS and concentrating production on less land can help spare larger areas for ecological restoration and reduce the pressure to clear new ones (Strassburg et al. 2014; Murgueitio et al. 2011). According to one estimate, through agroecological intensification Brazil could increase cattle productivity by 30–70%, releasing enough land to support the country's entire agricultural needs, and still have an extra 36 million hectares for ecological restoration (Strassburg et al. 2014; Latawiec et al. 2015). Colombia's Strategic Plan for the Livestock Sector 2019 envisioned doubling the herd from 24 to 48 million heads, reducing the total grazing area by 20 million hectares, and freeing up to 10 million more for agriculture and restoration using SPS as one of its key strategies (Fedegan 2006). This is not unreasonable according to one study that estimates the same amount of meat can be produced on 14.8 hectares of extensive pastures as on 1.2 hectares of SPS (Murgueitio et al. 2012).

3.4.2 SPS Projects in Colombia

The need for changes in global livestock production has led to renewed interest in SPS. Latin America, and Colombia in particular, have made important advances through research collaborations, knowledge-sharing networks, and the implementation of several small-scale projects. However, broader SPS adoption is still hindered by two main barriers: capital and knowledge. When access to capital is limited, even modest establishment costs and time lags before investment recovery put SPS beyond reach for many farmers. Similarly, implementing management-intensive systems can be too risky in the absence of adequate information or technical assistance (Calle et al. 2009; Pagiola et al. 2010). Here I describe the two largest SPS projects in Colombia and some important lessons they have generated.

3.4.2.1 The Regional Integrated Silvopastoral Ecosystem Management (RISEM) Project

Funded by the Global Environmental Facility (GEF) and the World Bank, the RISEM project took place from 2002 to 2007 in three regions of Colombia, Costa Rica and Nicaragua. In Colombia it was implemented by the Center for Research on Sustainable Agricultural Production Systems (CIPAV) on 104 farms comprising 2947 hectares in the La Vieja river watershed. Participants were introduced to better management practices, received assistance in implementing the SPS of their choice (i.e. fodder banks, live fences, trees on pastures, intensive SPS), and encouraged to release marginal lands for riparian buffers and forest regrowth. Farmers were initially paid for their baseline vegetation cover, and subsequently for land use changes that favored biodiversity and carbon sequestration based on annual monitoring. Nevertheless, implementation required a deeper cultural change as payments compensated farmers for less than 20% of incurred costs (Pagiola et al. 2010).

By the end of the project, 70% of tree-less pastures had been converted to fodder banks, pastures with high tree-density and other SPS; 354 km of live fences and 23 hectares of new riparian corridors had been established, and 210 hectares of forests were protected (Pagiola and Rios 2013). In protected streams, biological indicators of water quality improved as suspended solids and mean coliform counts declined (Chará et al. 2007). Bird abundance and diversity in SPS with high tree density increased relative to all other land uses, including remnant forests (Fajardo et al. 2009), and were second only to forests for ants and dung beetles (Giraldo et al. 2011; Rivera et al. 2013). Increased perennial vegetation and better management practices resulted in higher carbon storage and reduced soil erosion, and enhanced animal diets led to lower methane emissions (World Bank 2008). Meanwhile stocking rates increased by 40%, milk production became more stable, and agrochemical use dropped by 43% (World Bank 2008). Overall, the RISEM project demonstrated that SPS effectively contribute to increase farm productivity, enhance the agricultural matrix, deliver ecosystem services and conserve remaining forests.

3.4.2.2 Case Study: Permanence of Land Cover Changes in Four RISEM Farms

As a restoration strategy, SPS are only effective if they can trigger long-term changes in perennial vegetation cover. In the context of the RISEM, this means that satisfied farmers should have maintained or expanded their SPS after the project ended in 2007. A 2011 ex-post study showed that 4 years after its conclusion, and despite the absence of payments or technical assistance, 95% of the positive land use changes were still in place (Zapata et al. 2015).

To test for permanence in the new land covers, I conducted a detailed analysis of land use change on four RISEM farms. These farms differed in size, location, topography, baseline land use covers and SPS implemented, but all had reported productivity improvements and earned the maximum $6500 USD incentive during the *project. I used high-resolution satellite images from 2003 and 2016 to visually classify land cover types and produce detailed before/after farm maps* (Figs. 3.1 and 3.2). *I identified 12 land cover types which I then grouped into four categories:* (1) *unsustainable production*, (2) *sustainable production*, (3) *conservation uses, and* (4) *infrastructure. I obtained aggregated land cover changes over the 13-year period across the total 256 hectares* (Table 3.1).

The results show important land cover changes on all farms during the study period. In 2003, 83% of the farmland was under unsustainable productive uses, mostly degraded pastures, while only 4% was in sustainable production and 13% was being conserved. By 2016, 18% of productive lands had shifted from unsustainable to environmentally friendlier production, the majority (*17%*) *to SPS and the rest* (*1%*) *to forestry plantations. During the same time, 11% of the land had been*

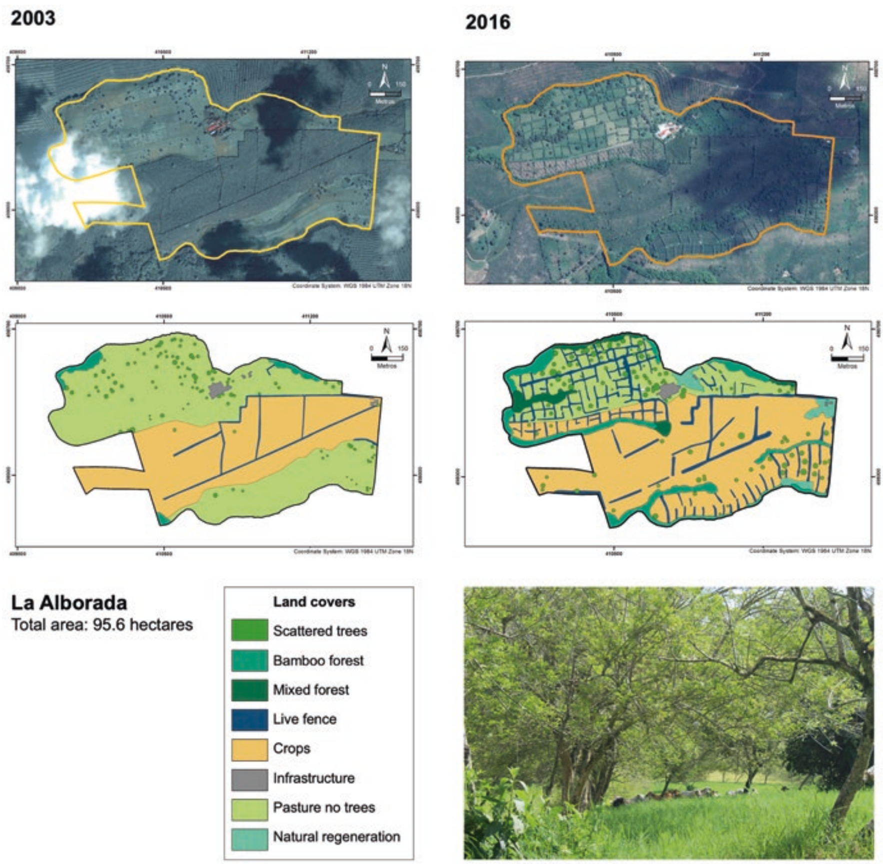

Fig. 3.1 Land cover changes in Finca La Alborada, Quindío, Colombia. Land cover at baseline of the RISEM project in 2003 (left) and 9 years later in 2016 (right). Treeless pastures were transformed into silvopastoral systems pictured here in 2017 (bottom right)

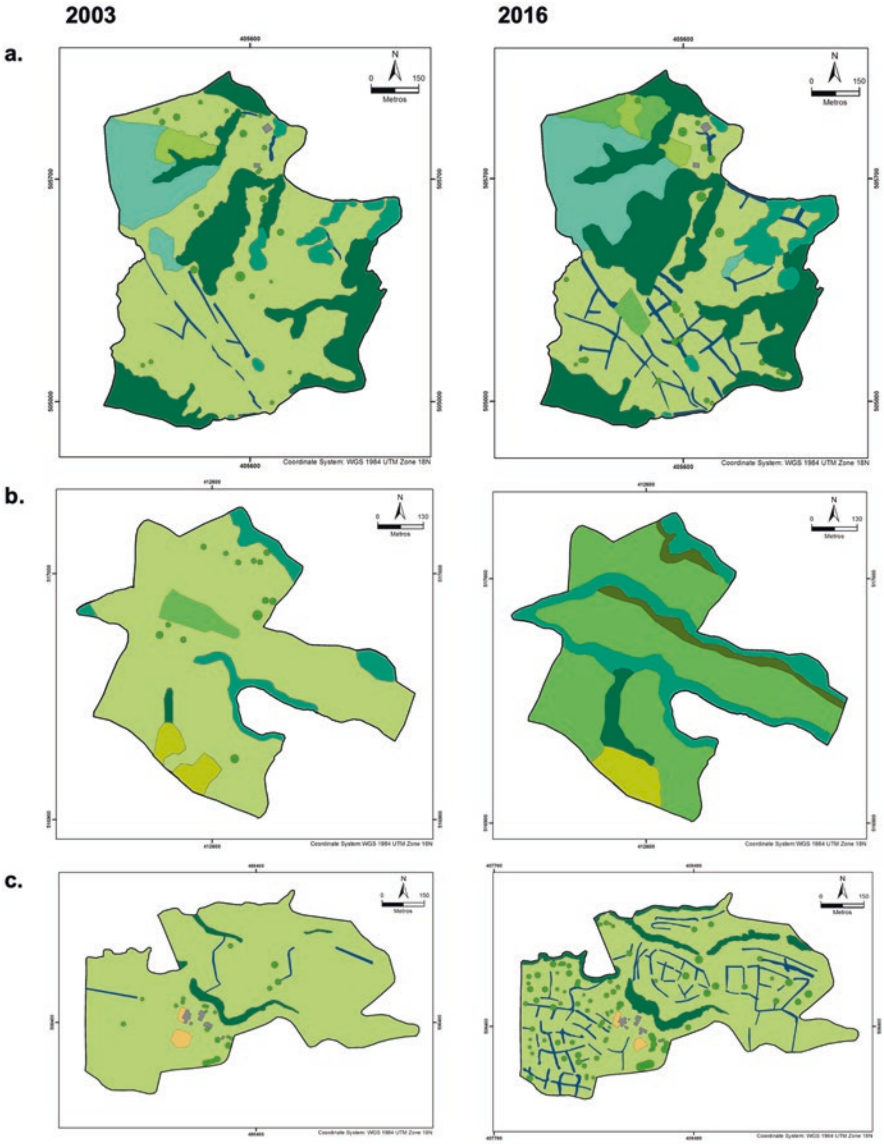

Fig. 3.2 Land cover changes in three farms in between 2003 and 2016, Quindío, Colombia: (**a**) Finca Veraguas, (**b**) Finca Pinzacuá, and (**c**) Finca La Ramada

Table 3.1 Changes in land cover on four farms of the RISEM Project from 2003 to 2016

Land use category	Type of cover	2003 area		2016 area		Total change		Change by category
		Hectares	%	Hectares	%	Hectares	%	
Unsustainable productive uses: Monocrop systems that rely on external inputs: provide few ES, low biodiversity, contribute to degradation	Crops	38.2	15	51.2	20	13	5	−29
	Pasture without trees	172.8	68	87.3	34	−86.5	−34	
	Pasture low tree density	1.3	1	1.2	0	−0.1	0	
Sustainable productive uses: Systems that intentionally incorporate more vegetation cover to promote biological processes that enhance productivity, improve the landscape matrix, and provide key ES	Live fences	3.5	1	16.0	6	12.5	5	18
	Scattered trees	3.3	1	6.0	2	2.7	1	
	Agroforestry systems	1.6	1	1.9	1	0.3	0	
	Pasture with high tree density	1.4	1	28.5	11	27.1	11	
	Forestry plantation	0.0	0	2.4	1	2.4	1	
Conservation uses: Forest cover at some stage of succession	Mixed riparian forest	17.7	7	29.1	11	11.4	4	11
	Bamboo forest	7.8	3	19.6	8	11.8	5	
	Natural regeneration	7.1	3	12.0	5	4.9	2	
Infrastructure: Roads and buildings	Infrastructure	1.0	0	0.9	0	−0.1	0	0
Total		256.7	100	256.1	100	−0.6	0	0

released from production and left alone for young forests to recover. Nine years later the impact of RISEM is still visible: unsustainable production areas decreased by 29%, and were replaced by sustainable agriculture and forests.

Furthermore, a comparison of 20 RISEM farms to the surrounding lands confirms important differences in tree cover change during the same 13-year period (Calle 2020). *While an increase in pasture tree cover* (*i.e., live fences plus scattered trees*) *and total tree cover* (*i.e., pasture tree cover plus forest cover*) *and a decrease in low tree cover* (*i.e., treeless pastures plus croplands*) *were the general trend across the entire landscape, the magnitude of those changes differed. Overall, silvopastoral farms had a significantly greater increase in pasture tree cover and total tree cover* (*5% and 8% more, respectively*) *and a greater reduction in uses with low tree cover* (*7% more*)*, although the latter difference was not significant.*

Although the results of this case study cannot be generalized, they do suggest that relatively modest investments in SPS adoption can trigger long-term positive changes in tree cover making them a cost-effective restoration strategy. On these farms, productivity and tree cover increased in tandem during the project (World Bank 2008; Pagiola and Rios 2013) and the adopted land uses have been maintained over time (Zapata et al. 2015), supporting the claim that SPS and restoration are compatible. The permanence of areas voluntarily ceded to forest uses is particularly encouraging as it hints to a cultural change in cattle farmers, who did not have an obligation to maintain these restoration areas.

3.4.2.3 The Mainstreaming Sustainable Cattle Ranching (MSCR) Project

Building on lessons from RISEM and other smaller initiatives, MSCR was a first attempt to scale-up SPS nationwide. The project was designed with dual goals: to sustainably increase cattle productivity and to protect forests, enhance the agricultural matrix, and facilitate connectivity. MSCR helped farmers re-design their farms as units where production and environmental protection work together for their benefit. Implementation began in 2010 across five regions selected for their potential to improve grazing landscapes in the vicinity of protected areas (World Bank 2009). By its conclusion in 2019, MSCR had directly benefitted 4100 farmer families, mostly small and medium holders, to promote SPS adoption, and used technical assistance and PES to overcome knowledge and capital barriers. The GEF, the UK Department for Business, Energy and Industrial Strategy, and the Colombian Government provided the funding, and CIPAV, the National Cattle Association, The Nature Conservancy and Fondo Acción were tasked with implementation (Proyecto GCS 2020).

During the project, 160,000 hectares formerly under extensive production were transformed into sustainable production systems, including 38,390 hectares of live fences, trees in pastures and other types of SPS. Additionally, 18,000 hectares of mature and secondary forests were protected on project farms. More than 600 people were trained as extension agents to provide SPS technical assistance, over 24,000 people including farmers, practitioners and policy makers were sensitized to better alternatives for cattle production, and a network of over 50 demonstration farms was established across the country to facilitate dissemination and adoption (Proyecto GCS 2020). MSCR's monitoring and research teams recorded changes in production, land use, and biodiversity indicators gathering critical data. Perhaps most importantly, by convening regional open fora and broadly disseminating its results the project brought sustainable cattle ranching to the national spotlight.

3.5 Mainstreaming SPS into National Restoration Efforts: The Way Forward

Agriculture has transformed Colombia's rich natural ecosystems through a process that almost inevitably results in vast extensions of cattle pastures. Confronted with this challenge, the country has opted to advance restoration using a multipronged approach. SPS have already proven their potential for social and environmental change in the livestock sector. Mainstreaming SPS into the national restoration toolkit is therefore an important step forward that could allow the country to meet its national and international commitments to restoration, climate mitigation and adaptation, and sustainable development. Fortunately, accumulated experiences in SPS research and implementation provide the foundations on which to build this process.

Mainstreaming SPS into national restoration efforts entails, first and foremost, a change of mentality. For too long Colombia's livestock and conservation establishments have been at odds, precluding any collaboration. But this is changing as the cattle sector seeks a more sustainable growth alternative and restoration practitioners realize the need to engage with agriculturalists. The MSCR project raised the visibility of SPS among a traditional-minded livestock sector and put them on the government's radar. Colombia's ministries of agriculture and environment are now considering SPS to advance their goals, including those established in the country's National Development Plan 2018–2022 and low-carbon development strategy (MADS 2012a). SPS also figure in the intended Nationally Determined Contribution as a tool for mitigation and adaptation (Gobierno de Colombia 2015), in the biodiversity offset program as an alternative to compensate for losses from infrastructure development under certain conditions (MADS 2012b), and in the "green-growth" strategy for the agricultural sector. Sustainable livestock systems are also visible in more recent initiatives such as the Tropical Forest Alliance and the Food and Land Use Coalition. Despite their increased visibility, better legal and financial instruments, and more direct government involvement in and support for SPS projects are still needed to achieve a relevant scale.

Whereas governments are increasingly recognizing restoration as a smart investment, restoration financing is still inadequate (Ding et al. 2017). Strengthening a SPS component within FLR could help overcome some of these challenges. For example, SPS can provide common grounds for collaboration between government bodies that traditionally work towards apparently diverging goals, such as environmental protection or rural development (Ding et al. 2017). Because they render direct social benefits in rural areas, SPS can make restoration projects more attractive to a broader range of funders with different interests, including poverty alleviation, climate change adaptation, avoided deforestation, or even Colombia's post conflict process. Funds leveraged and pooled through the government could then be allocated to specific but complementary components depending on the funder's objectives. SPS can also facilitate the scaling-up of restoration across larger landscapes and can deliver early returns on forestry or carbon investment, which can attract private investors who often overlook smaller projects with long-term investment horizons (Ding et al. 2017). Emerging markets for sustainable, organic or zero-deforestation animal products present additional opportunities for greater engagement by the private sector and environmentally-minded urban consumers. Finally, the long-term financial information generated by SPS farmers over time can help fill gaps in the business model, strengthening the case for the economic value of restoration.

In Colombia cattle have long been a part of the national identity, and SPS could help introduce the general public to the benefits of restoration in a tangible way. Livestock already contributes one fifth of the agricultural GDP and there is room for significant growth (Fedegan 2015). Using SPS to scale-up restoration could create jobs that support sustainable growth in the cattle sector, fueling demand for restoration-based labor and technical expertise. In Colombia's post-conflict era, the importance of creating rural jobs should not be understated. Strategies to ensure the economic viability of this production-restoration model are still needed, but there are promising initiatives. One example is the Zero-Deforestation Pact in Caquetá, the state with the highest recent deforestation rates (IDEAM 2019). The Pact helps farmers design farm-zoning plans designating some areas for improved sustainable production and others for nature reserves. In return, farmers are linked to green supply chains that ensure purchase of their products regardless of market fluctuations, and benefit from the branding of their products as zero-deforestation (R. Torrijos, 2017 Aug 29, "personal communication"). The Pact is inclusive of both small and large cattle farmers, as they all contribute to landscape restoration. This approach helps farmers overcome their natural resistance and become actively engaged in restoration.

Like in other parts of the world, restoration projects in Colombia often suffer from deficient monitoring and evaluation, including the lack of baseline information and long-term assessments (Murcia et al. 2015). Integrating SPS with national restoration efforts can contribute to overcome some of these weaknesses. For example, MSCR has collected ecological, productive and land use data from farms across different ecological regions, with emphasis on biodiversity sampling in remnant ecosystems, mostly on demonstration farms where landowners are committed to future re-sampling. These data can provide a solid baseline for comparison in future restoration assessments. Monitoring data from previous SPS projects can also shed light on the evolution of decade-long restoration processes on working landscapes. Replicated experiments testing a variety of restoration techniques and their applicability could also be set up on SPS farms (Holl 2017a), reducing both implementation costs for farmers and monitoring costs for researchers.

I advocate SPS as an agroecological strategy for livestock intensification in Colombia and across Latin America, where cattle are at the heart of both agricultural production and land degradation. I argue that integrating SPS into national and regional restoration efforts can effectively contribute to scale-up FLR and meet restoration targets while creating multiple economic, social and environmental co-benefits. Previous projects have shown that SPS work synergistically with other restoration approaches to transform landscapes within relatively short timeframes. MSCR has left a legacy of installed technical capacity, demonstration farms, and a wealth of information and lessons that serve as a springboard to scale-up. The key lesson, however, is that vast pasture-dominate landscapes all across Latin America may in fact be a huge restoration opportunity hidden in plain sight.

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Chapter 4
Could Biomass Revolution Be Achieved with Silvopastoral Systems?

Rogerio M. Mauricio, Adibe L. Abdalla, Simon Perez, and Domingos S. Paciullo

Abstract According to the theory of Ignacy Sachs, a Polish naturalized French ecosocial economist, several world contemporaneous problems could be solved by the process called by him “Biomass revolution”. Livestock products are part of the needs of the world’s growing population, and the adopted production system to meet this demand, should be sustainable. Therefore, we considered Sachs’ thinking extremely appropriate as biomass is the primary source of nutrients for cattle production in the world. However, biomass is much more than forage. Why? Because biomass is feed and food, organic fertilizer, carbon sink, energy, fuel, promoter of biodiversity and animal welfare, part of the landscape scenario, an important component to regulate the water cycle, and the main component of agroforestry systems and agroecology science. In addition, as the negative effects of global warming are putting at risk the world’s food security, the reduction of biomass could potentiate this risk in pasture monocultures and the increase of biomass could also be part of the solution to enrich the agropastoral ecosystem (e.g. grasses, bushes and trees in the silvopastoral system – SPS). Thinking in a broader perspective, biomass could also be considered an important part of the linkages of the global livestock sector to the sustainable development goals (SDGs) of the UN Agenda 2030: no poverty, zero hunger, good health and well-being, gender equality, decent work and economic growth, responsible consumption and production, climate action, life on land and

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partnerships for the goals. These SDGs also constitute an important framework for the Global Agenda for Sustainable Livestock, which has several actions to analyze and promote sustainable cattle production. SPS is defined as an agroforestry arrangement that aims to combine fodder plants (grass and leguminous forages) with shrubs and trees for animal nutrition and other uses (Murgueitio et al., Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. For Ecol Manag 261:1654–1663, 2011). The present chapter will establish a link between the necessity of the world to generate the "*biomass revolution*", and the potential of silvopastoral systems studies developed in Brazil and South America, as a possible mechanism to increase biomass, cattle/livestock production and environmental services in a sustainable way.

Keywords Circular food systems · Food security · Nutrient cycling

4.1 Introduction

Following the *Cambridge Dictionary*, the definitions of the term biomass are related to two main areas, engineering, and biology. For the *Engineering sector*, biomass is defined as dead plant and animal material suitable for use as fuel. For the *Biology* sector biomass is composed of dead plant and animal material suitable for use as fuel or energy. However, the *Biology sector* also defines biomass as the total amount of living things (animals and plants) in a particular area. In this chapter, when using the term "biomass" we refer to vegetation biomass which is used to feed humans and animals. Our main focus is the role of biomass as a source of energy and organic matter for soil, which also plays a key role as an ecological variable in different ecosystems.

Regarding carbon stocks in the world, vegetation biomass has a higher capacity to maintain carbon compared to the atmosphere. Therefore, any change in land uses with high vegetation biomass, such as grasslands, pastures, tree plantations, or forests can increase the biomass as a carbon sink or reduce it generating a net source of carbon to the atmosphere (FAO 2009). This impact could in turn disturb the local, regional, or global climate and consequently affect the availability of biomass for livestock production. On the other hand, the use of biomass around the world can directly affect the climate; an example of this is the growing use of biomass as fuel that could lead to increasing greenhouse gas (GHG) emissions when it is burned or capturing carbon when a forest is preserved, and land degradation is avoided (FAO 2009). In this context, pasture biomass availability is one key point to consider in livestock systems as a measure of sequestration or emission of carbon.

4.2 Biomass Is the Primary Source of Nutrients for Cattle Production in the World

The livestock sector has a critical role to feed the global population, which has 768 million people considered undernourished (FAO et al. 2021), and could contribute to reversing this scenario by acting in a sustainable way. In terms of nutritional composition, food from animal origin is an important source of protein and nutrients (long-chain fatty acids, minerals, vitamins – e.g., D and B12) that are highly bioavailable compared to plant foods (Leroy et al. 2022). It is also important to mention that ruminants can consume feeds that are not edible for humans and convert them into high-quality protein (Smith et al. 2013) and can also be raised in marginal areas that are not suitable for other agricultural activities (Gerber et al. 2013).

In 2020 the global cattle sector produced 883 million tons of milk, 72 million tons of meat (cattle and buffalo), and 16 million tons of small ruminant meat (FAOSTAT 2021). Around 69% of the milk and 61% of the meat globally produced is obtained in mixed crop-livestock systems (where more than 10% of the diet comes from crop by-products, stubble or more than 10% of the total value of production comes from non-livestock farming activities) the rest is produced in solely livestock systems where 90% of feed comes from rangelands, pastures, annual forages and purchased feeds (Herrero et al. 2013). Around 4.8 billion tons of feed are consumed by ruminants globally (Mottet et al. 2017), 89% are fresh grasses, hay, silage and crop residues, 4% comes from cereal grains (grains from wheat, maize, barley, millet, rice, sorghum, oat and buckwheat), 4% comes from grain by-products of the brewer and biofuel industry, 0.5% comes from soybean cakes, 1% from rape, canola, cotton and palm kernel oil seed cakes and 1% comes from other non-edible materials such as corn gluten, pulp, molasses, fish meal, synthetic amino acids and lime (Mottet et al. 2017). Of the total amount of feed consumed by ruminants, only 242 million tons (5%) is considered to be human edible (Mottet et al. 2017).

4.3 Biomass Is Feed and Food

Actually, the key question is whether we can generate enough biomass to produce all the food, animal feed and bioenergy needed for our future population. The capacity of the planet to produce biomass is limited by its biophysical boundaries (Erb et al. 2016) and by socio-economic and policy constraints (European Environmental Agency (EEA) 2017). The challenge is, therefore, the competition between food, feed and fuel for biomass. About 40% of all global cropland is currently used to produce high-quality feeds, some of which are cereals that humans could also consume (Mottet et al. 2017) resulting in feed-food competition. Around 30% of the global cropland dedicated to cereals is used to grow livestock feed. Direct consumption of these cereals by humans is more resource-efficient than consumption of animal-source food produced by animals fed with these cereals (Garnett 2009; Goodland 1997). The use of biomass edible for humans or farm animals for bioenergy production further complicates the competition for resources. Currently, about 13% of global cropland is used to produce biofuels and textiles (Poore and Nemecek 2018). The use of human-edible ingredients to feed animals has been increased to improve livestock productivity and efficiency, increasing the competition between humans, the animal sector, which also creates pressure on natural resources (Muscat et al. 2020a; Van Zanten et al. 2018). Livestock has an important role in food security when the feed or biomass comes with low opportunity costs and does not compete with food and feed (Muscat et al. 2020a). Following this conception, we consider that livestock production based on SPS could fulfill these gaps related to competition as the animals are mostly fed by biomass (e.g., grasses, legumes, trees, leaves and shrubs).

4.4 Biomass Production and Circular Food Systems

The definition of circular economy for the food system is well defined by Jurgilevich et al. (2016) and it is the fundamental point for this topic: "The concept of circularity originates from industrial ecology, which aims to reduce resource consumption and emissions to the environment by closing the loop of materials and substances. Under this paradigm, losses of materials and substances should be prevented, and otherwise be recovered for reuse, remanufacturing, and recycling. In line with these principles, moving towards a circular food system implies searching for practices and technology that minimize the input of finite resources, encourage the use of regenerative ones, and prevent the leakage of natural resources (e.g. carbon (C), nitrogen (N), phosphorus (P), water) from the food system, and stimulate the reuse and recycling of inevitable resource losses in a way that adds the highest possible value to the food system (Jurgilevich et al. 2016)."

The management of biomass varies according to its different uses, however, one positive strategy to manage is based on the use of circular agriculture that minimizes the intense use of natural resources and increases the use of regenerative ones in the food system chain (de Boer and van Ittersum 2018; Jurgilevich et al. 2016). The objective of this concept is to reduce food losses and food waste, using biomass primarily for human consumption and then recycling any by-products back into the system. In this context, livestock plays an important role as converter of biomass not suitable for human consumption into milk or beef (Van Zanten et al. 2016). In addition, when the crop residue, co-product or by-product originated from the biomass process is not used for human consumption, it could be used to produce food or livestock (including field, industrial, food losses and human and animal excreta) and it can be recycled as organic fertilizer to produce crops, forage or even to feed animals (Muscat et al. 2020b).

The negative effects of cattle production are enormous not only in Latin America but in several parts of the world due to unsustainable extractive practices – deforestation, GHG emissions, etc. (Gerber et al. 2013). The SPS has been developed in Latin America as a sustainable land-use alternative that improves soil properties and microbial metabolic functions, which are directly linked to the increment of plant biomass (Vallejo et al. 2012), and restores the ecosystem services provided by soil microbial communities by restoring physical, chemical, and biological properties of soils (Cubillos et al. 2016). The use of legume plants or nitrogen-fixing trees (e.g. *Gliricidia sepium* or *Leucaena leucocephala*) in SPS not only contributes to increase biomass production but it also has demonstrated the ability to increase N content in the grass by 21% as a consequence of biologically fixed nitrogen (Jayasundara et al. 1997). This reduces the need for N fertilizers that are costly and of reduced availability to farmers.

In addition, a study conducted in Australia comparing Leucaena-grass pastures (LGP) to native pasture demonstrated that LGP have higher soil organic carbon and total nitrogen accumulated and the capacity to offset methane and nitrous oxide from beef cattle by the amount of CO_2-e accumulated on the topsoil given a positive GHG balance (Radrizzani et al. 2011). In Brazil, similar results were obtained when *Gliricidia sepium* (Jacq.) Kunth ex Walp and *Mimosa caesalpiniifolia* Benth were associated with pasture in low-input systems. The litterfall and nitrogen cycled throughout the litter and symbiotic fixation, which were associated with lignin concentration, behaved differently for both trees species but a slower decomposition rate demonstrated that trees increased the soil cover protection (High C/N ratio) and N concentration in the tropical SPS (Apolinario et al. 2016). According to Calle et al. (2014), with the rehabilitation of cattle ranching after the implementation of SPS landholders can achieve better productivity and profitability, increase the provision of environmental goods/services, and have the opportunity to promote restoration of marginal lands of the farm (riparian forest, etc.). All these benefits are maximized by natural biological processes like photosynthesis, nitrogen fixation, and phosphorus solubilization which increase organic matter in the soil, plant biomass, resilience of the system, animal welfare and environmental services. Therefore, the principles of circularity are embedded in the SPS which have high biomass production (not only from the pastures forages but also from trees and shrubs) and could be considered as a sustainable option to increase biomass and animal production, recycling nutrients (litter, manure, urine), reduce inputs of external resources (fertilizers) and strengthen the regenerative grazing system (Mauricio et al. 2019).

4.5 The Use of Biomass as Organic Fertilizer

Biomass in the form or fresh or composted vegetal material or animal manure is the primary source of organic fertilization which has an enormous potential to replace chemical sources of nitrogen, phosphorus and potassium. The use of biomass as organic fertilizer has positive impacts on the soil due to the provision of organic matter and micronutrients that, after the mineralization process transfer the phosphorus and nitrogen to the plant's roots gradually, thus reducing losses. In addition, when pastures are well managed, that is, with high biomass production, part of it returns to the soil as organic matter, favoring soil fertility (de Boer and van Ittersum 2018).

A study developed in China demonstrated that the amount of N available in the biomass originated from only 12 resources (Maize, wheat, rice, beans, tubers, cotton, oil crops, sugar crops and hemp crop, municipal sludge, garbage, wastes from vegetables, orchards, and gardens; vinasse, etc.) contains 4.12 times the amount of synthetic N required by the agriculture sector (Cui et al. 2021). This result emphasizes the potential of the plant resources as a source of nutrients that could be returned to the soil. It is also possible to explore the biological fixation of nitrogen by leguminous plants, that may reach 100–300 kg of N/ha per year according to the availability of other nutrients in the soil including phosphorus (Giller 2001; Herridge et al. 2008). Phosphorus is an essential nutrient for plants with limited reserves (phosphate rocks) in the world (Sattari 2014). One possibility to avoid the use of scarce phosphorus resources is to use mycorrhizas, an association between fungi and plant roots that could contribute up to 10% of the P required by the plants (Kuyper and Giller 2011). However, as animal manure contains a high amount of phosphorus, (Schoumans et al. 2015) when well managed and associated with the circularity principles in pasture management, could potentialize biomass production. The use of organic instead of chemical fertilizers is an important agricultural practice, that directly affects crop yields, soil properties, bacterial community structure and diversity, and the biogeochemical cycling.

In this context, SPSs that include multi-strata structure (forages, shrubs, and trees), in association with animals (manure and urine) maximize biological processes such as photosynthesis, nitrogen fixation, and phosphorus solubilization by mycorrhizas and other soil microorganisms (Calle et al. 2014). Biomass nutrient recycling based on the efficiency of the SPS recovers nutrients by closing the nutrient cycles on-site without the necessity of external inputs (fertilizer or irrigation) and improves the sustainability of animal production.

4.6 Biomass & Energy

Biorefinery produces energy and useful chemicals based on the transformation of biomass, but for the supply chain management to be competitive, it should be based on sustainable biomass production (Blair et al. 2021). Biomass production has the potential to contribute not only to food security but also to C sequestration and to reduce the emissions caused by the combustion of fossil fuels for energy production (Blair et al. 2021). It is a promising strategy not only to mitigate climate change but also to improve rural economy and livelihoods. However, bioenergy production from first generation energy crops competes with food production for land and other resources and is limited because to meet food and bioenergy demands for global population the croplands expansion will exceed the planetary boundaries (Henry et al. 2018). According to Lewandowski (2015), for the supply of biomass for energy production to be sustainable, it should meet the following criteria: (i) it is not obtained from food crops, (ii) it does not affect the environment, (iii) it is not cultivated in lands suitable for food crops, (iv) it is produced close to the processing plants to reduce transport costs and emissions. In addition, the carbon efficiency of biomass production needs to use carbon-neutral power and organic fertilizer, to be transported by rail or by sea and to be based on carbon-negative fuels (Jones and Albanito 2020). Silvopastoral systems offer the possibility of generating biomass for animal production, for soil protection and for biorefineries reducing the competition for land and taking advantage of the integration with the livestock sector and contribute to the SDGs (sustainable development goals) of the UN Agenda 2030. Recent work of Blair et al. (2021) has concluded that sustainably sourced biomass for bioenergy generation will be essential to support sustainable development.

4.7 Biomass and Silvopastoral Systems

In Latin America, cattle production systems have been historically considered the main driver of deforestation, with around 70% of the cleared land devoted to this activity (Mauricio et al. 2019). After deforestation, cattle production has traditionally been conducted based on monoculture pastures (mainly *Brachiaria* and *Panicum* species).

Sustainable intensification has been described as one of the most promising strategies (Herrero et al. 2016) to increase the efficiency of livestock systems and reduce their negative environmental impacts without threatening food security or changing cultural patterns. In this context, agroforestry arrangements (e.g., SPS), and the use of leguminous and/or shrub forages to complement pasture feeding systems are considered sustainable alternatives for productive intensification (Mauricio et al. 2019; Murgueitio et al. 2015). In Latin America, the conversion of treeless pasture lands to silvopastoral systems has contributed to enhance productivity and provide environmental services (Rivera et al. 2013).

The use of native species that produce palatable fruits or leaves of high nutritional value may represent an important strategy to overcome the challenges of low nutritional quality of pastures in specific yearly weather conditions. At the same time, as the nutritional condition of the herd is improved, the biomass from shrubs and trees contributes to other agroecological functions, such as the provision of shade for the animals, the supply of nutrients and organic matter to the soil in the form of litter, and the improved quality of grass. In addition, this biomass contributes to biodiversity conservation, especially by the provision of habitats and greater permeability of the landscape matrix to the movements of the native fauna, acting as "ecological trampolines" or "stepping stones" and thus increasing the gene flow between forest fragments (Olival et al. 2021).

Silvopastoral systems increase the amount of biomass per unit of area and provide other ecosystem and biological services (Chará et al. 2017; Murgueitio et al. 2011). They are also recognized as a sustainable alternative to reduce the environmental impact of animal production (GASL 2018). According to Murgueitio et al.

(2011), some of the most common silvopastoral systems worldwide are: trees dispersed in paddocks, managed plant successions, living fences, windbreaks, fodder tree banks, forestry plantations with cattle grazing, and pastures between tree alleys. In addition, systems with shrubs in high densities (Intensive silvopastoral systems) are agroforestry arrangements where highly productive trees and pastures are combined with forage shrubs at high densities (>10,000 plants/ha) for direct grazing (Murgueitio et al. 2011; Chará et al. 2017) and are one of the most productive examples of silvopastoral systems, present in countries such as Colombia, Mexico, Cuba, Panama and Australia (Calle et al. 2013), and *Tithonia diversifolia* and *Leucaena leucocephala* are the most common species used in this type of systems (Chará et al. 2017).

Globally there are several initiatives on this topic, and one is The Global Agenda for Sustainable Livestock (GASL) (www.livestockdialogue.org), which has several actions networks to promote the importance of pastures and a specific one denominated the Global Network on Silvopastoral Systems. This international platform aims to facilitate dialogue, knowledge, and practices on livestock with pastures and trees and information on the impact of silvopastoral systems on economy, production, and livelihoods of farmers around the world.

4.8 Conclusions

The world is facing the negative effects of climate change, the present and future crises related to the use of fossil fuels and the impacts of both on food security. The "biomass revolution" could be one sustainable approach to overcome the problems faced by the agriculture and livestock sectors around the world.

For the livestock sector, the "biomass revolution" is already in process when the silvopastoral systems are adopted by farmers. In this system, biomass means low dependence on fertilizers and concentrates, protection of ecosystems, reduction of deforestation and GHG emissions, and a positive contribution to the economy and livelihoods of many countries in the world.

Finally, the "biomass revolution" is an instrument to potentialize the Sustainable Development Goals, mainly those related to responsible production and consumption, climate action, life on earth, and zero hunger.

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Chapter 5
Effect of Silvopastoral Systems on Biodiversity and the Provision of Environmental Services in Tropical Agro-Landscapes

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Abstract A number of studies have highlighted the potential of silvopastoral systems as conservation tools in highly intervened agricultural landscapes in the tropics. However, to date there has not been a synthesis of the scientific evidence on the effects of different types of silvopastoral systems on biodiversity and the supply of ecosystem services. This chapter aims to synthesize the scientific information on biodiversity and ecosystem services associated with some of the most widely used silvopastoral arrangements in tropical landscapes. From this synthesis, the mechanisms by which silvopastoral systems affect biodiversity are discussed and areas requiring further research are identified.

Keywords Conservation · Sustainable livestock · Biological resources · Birds · Live fences · Scattered trees in paddocks

5.1 Introduction

Tropical forests harbor at least 50% of the planet's biodiversity and provide critical ecosystem services to the global population (Bradshaw et al. 2009; Gardner et al. 2009; Giam 2017). However, these ecosystems currently face threats of unprecedented scale, including deforestation, overexploitation of resources, invasive species, and climate change (Bradshaw et al. 2009; Alroy 2017). In addition, only 9.8% of the tropical biome lies within strictly protected areas (Gardner et al. 2009), which reduces the effectiveness of conventional conservation practices. Given these challenges and the increasing state of intervention of tropical forests, it is a priority to seek management alternatives that allow the conservation of the species and

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ecosystem services that persist in intervened landscapes (Mendenhall et al. 2016). An example of these alternatives is the implementation of agricultural production systems that conserve part of the ecosystem functions and provide complementary habitats for some of the species that originally inhabit the forests (Perfecto and Vandermeer 2008; Gardner et al. 2009; Defries and Rosenzweig 2010).

Conversion from conventional livestock systems to silvopastoral systems has been identified as a promising management strategy in this context (Chará et al. 2019a). Silvopastoral systems are a type of agroforestry intervention that complements the conservation of forest patches with the introduction of tree species into livestock production systems. In this way, livestock, crops, trees, pastures, and shrubs are combined on the same land unit to optimize animal feed and take advantage of beneficial interactions between components (Murgueitio and Ibrahim 2008; Giraldo et al. 2011). There are different types of silvopastoral arrangements that vary in the type of plant species used and the distribution and density of woody vegetation. These include live fences, dispersed trees in paddocks, mixed forage banks, forage hedges, and intensive silvopastoral systems.

In many tropical regions, the popularization of silvopastoral systems arose out of concerns about the negative environmental effects and low productivity of conventional livestock systems with monoculture pastures (Murgueitio and Ibrahim 2008). Conventional pastures generally represent an extensive production system, characterized by low animal density in pastures that degrade few years after establishment and encourage more deforestation to incorporate new areas into the production process (Murgueitio and Ibrahim 2008; Murgueitio et al. 2011). In addition, in many regions, this type of cattle ranching is practiced on inappropriate land, which accelerates soil degradation and further reduces the carrying capacity of the systems (Murgueitio and Ibrahim 2008; Murgueitio et al. 2011). Through these processes, conventional cattle ranching causes significant environmental impacts such as fragmentation of natural ecosystems, soil erosion and compaction, loss of biodiversity, contamination of water sources, loss of water regulation, and emission of greenhouse gases due to deforestation and enteric fermentation (Ibrahim et al. 2007; Murgueitio et al. 2011).

Since the 1990s, several studies have shown that different types of silvopastoral arrangements can increase connectivity in the landscape for forest-dependent wildlife species and serve as permanent habitat for generalist species (e.g., Söderström et al. 2003; Giraldo et al. 2011; Sekercioglu et al. 2012; Garcia-Morales et al. 2013; Guerra-Alonso et al. 2019). Other lines of research have demonstrated that these systems are able to sequester carbon, improve soil conditions, regulate microclimatic conditions, decrease erosion, and provide other ecosystem services (e.g., Ríos et al. 2006; Rueda et al. 2011; Broom et al. 2013; Polanía-Hincapié et al. 2021; Ramakrishna et al. 2021). However, evidence on the effects of silvopastoral systems on wildlife and ecological processes is fragmented according to different types of silvopastoral arrangements, and there are no syntheses that allow inferences to be made about the characteristics of the systems that promote these ecological effects. This chapter aims to synthesize scientific information on the effects on biodiversity and ecosystem services associated with some of the most widely used silvopastoral arrangements in tropical landscapes. From this synthesis, the mechanisms by which silvopastoral systems affect biodiversity are discussed and areas requiring further research are identified. The first part of the review examines the evidence associated with different types of silvopastoral arrangements commonly implemented in the tropics and the second part presents a synthesis of emerging patterns and areas requiring further research to advance the understanding of these systems as potential conservation tools.

5.2 Effects on Biodiversity and Ecosystem Services Associated with Different Silvopastoral Arrangements

5.2.1 Live Fences

Live fences are strips of trees or shrubs used to delimit boundaries, paddocks, or corrals, with the purpose of controlling the movement of animals or people. (Schroth et al. 2004; Zuluaga et al. 2011). Live fences are usually composed of a row of trees or shrubs planted at close spacing and can support barbed or electrified wire, thus replacing dead posts made of wood, cement or other materials commonly used in cattle farms (Schroth et al. 2004; Zuluaga et al. 2011). A good variety of species are employed for this purpose in different regions and altitudes, but it is worth mentioning *Castilla elastica, Erythrina poeppigiana, Ficus wreckleana, Spondias mombin*, and *Cordia alliodora*, commonly used in Costa Rica (Greenler and Ebersole 2015) *Gliricidia sepium, Montanoa quadrangularis, Euphorbia spp., Trichanthera gigantea, and Mimosa trianae* in Colombia (Calle 2011; Giraldo et al. 2018).

- ***Effects on biodiversity***

In fragmented landscapes, live fences increase the area covered by trees and create linear networks that can connect forest fragments, reducing isolation between patches of good-quality habitat and allowing wildlife movement across the landscape (Schroth et al. 2004; Harvey et al. 2005; Chacón and Harvey 2006; Pulido-Santacruz and Renjifo 2011; Atangana et al. 2014). When not severely pruned, live fences can provide perching, shelter, breeding, and foraging sites for animal species (Schroth et al. 2004; Pulido-Santacruz and Renjifo 2011). These positive effects have been widely documented in birds (Schroth et al. 2004; Saenz et al. 2006; Pulido-Santacruz and Renjifo 2011; González-Valdivia et al. 2014). For example, in Veracruz, Mexico, live fences of *Bursera simaruba* and *Gliricidia sepium* were found to provide habitat for 98 bird species, which constituted 54% of the species detected in surrounding forests (Estrada et al. 1997). Similarly, in Colombia Molano et al. (2003) reported 105 bird species in live fences resulting from natural regeneration in the Orinoco piedmont, and Pulido-Santacruz and Renjifo (2011) reported 98 bird species, of which 26 were forest species, in live fences in agricultural landscapes in the Andean region. In the Esparza region of Costa Rica, live fences are consistently among the land uses with the highest diversity and abundance of avifauna in cattle-ranching landscapes (Saenz et al. 2006; Enriquez-Lenis et al. 2007). Other studies in Costa Rica have found that live fences can also be of great importance for Neotropical migratory bird species, which may even have a preference for live fences over secondary forests in the area (Sáenz and Menacho 2005; Greenler and Ebersole 2015).

Live fences can also provide significant benefits to other wildlife in agricultural landscapes; Estrada and Coates-Estrada (2001) observed 12 bat species (37% of the species detected in surrounding forests) in live fences of *Bursera simaruba* and *Gliricidia sepium* in Mexico. In this same system of live fences, 14 species of dung beetles (47% of the species detected in the forest samples) and 11 species of non-flying mammals (29% of the species detected in surrounding forests) were reported (Estrada et al. 1994; Estrada and Coates-Estrada 2001). In the Central Pacific region of Costa Rica, Tobar and Ibrahim (2010) found that live fences played an important role in sustaining butterfly diversity, providing food sources and niches in agricultural landscapes. They observed a total of 76 butterfly species in both simple live fences and those with complex plant structures, also known as Multistrata. Multistrata fences registered a higher diversity of butterfly species, most of them forest dependent. In Nicaragua, Harvey et al. (2006) reported that live fences harbored 15 species of bats, constituting the second land use with the highest richness of bats in an agricultural landscape after riparian forests.

In addition, several studies have explored the characteristics (i.e., structural complexity of vegetation, plant species richness, landscape connectivity, etc.) of live fences that increase their conservation value (Lang et al. 2003; Molano et al. 2003; Harvey et al. 2005; Pulido-Santacruz and Renjifo 2011). Although there is variation in the response of different taxonomic groups, in general these studies have observed that fences of greater structural complexity (i.e., greater canopy cover, greater basal area, greater crown width) tend to harbor greater diversity of animal species (Lang et al. 2003; Molano et al. 2003; Harvey et al. 2005; Pulido-Santacruz and Renjifo 2011).

- ***Provision of ecosystem services***

Live fences can regulate microclimatic conditions, improve surrounding soil characteristics, and contribute to above- and below-ground carbon storage (Zuluaga et al. 2011; Villanueva-Lopez et al. 2015). In Mexico, the soil around live fences of *G. sepium* presented 3% lower temperatures and 16% higher relative humidity than the soil in paddocks without trees (Villanueva-Lopez et al. 2016). In these same systems, Villanueva-Lopez et al. (2015) demonstrated that paddocks with live fences were able to store up to 120 Mg C/ha, of which 5.7% was stored by trees. In the Chiapas region of Mexico, the concentration of soil organic carbon reached the highest values in systems with live fences compared to other land uses (Aryal et al. 2022). Additionally, live fences can serve as nuclei of natural regeneration, as they attract seed-dispersing animals such as bats and fruit-eating birds (Harvey et al. 2006; Pulido-Santacruz and Renjifo 2011) and provide protection for seedlings in the midst of paddocks, increasing their chances of survival and growth (Love et al. 2009).

5.2.2 Scattered Trees in Paddocks

Scattered trees in paddocks are silvopastoral arrangements that integrate trees (30–50 trees per hectare) to natural, naturalized or improved pastures (Giraldo et al. 2018). Trees can be remnants of the original forests, planted by producers, or the product of natural plant succession (Zapata and Silva 2020; Harvey et al. 2011b).

- ***Effects on biodiversity***

Scattered trees in pastures constitute small patches of habitat for wildlife (Murgueitio and Ibrahim 2008). At the local scale, trees provide food and nesting sites for animals (Harvey et al. 2011a). At the landscape scale, increased tree cover improves connectivity, functioning as "stepping stones" that facilitate the mobility of species between forest patches surrounded by pasture (DeMars et al. 2010; Gillies and Clair 2010; Harvey et al. 2011a; Siqueira et al. 2017). For example, Harvey et al. (2006) and Vilchez et al. (2004) observed that scattered trees in paddocks had similar levels of bird diversity to secondary and riparian forests in rural landscapes in Nicaragua. Similarly, Sáenz et al. (2006) reported that natural pastures with high tree density were the land use with the highest avifauna richness in livestock landscapes in Nicaragua (Matiguás Region) and Colombia (La Vieja river catchment). In Costa Rica, pastures with high tree density presented similar richness and higher abundance of birds than riparian forests in the study of Cárdenas et al. (2003) and were among the uses with the highest abundance and diversity of birds in the cattle landscapes studied by Enríquez-Lenis et al. (2007).

Another factor worth mentioning is the use of these trees by neotropical migratory birds; Mcdermott et al. (2015) found that in western Colombia 20% of the species recorded in live fences and scattered trees were migratory, with species such as the orange-throated warbler (*Setophaga fusca*) present in 80% of the silvopastoral plots studied. Another example was reported by Greenberg et al. (1997) who observed that pastures with *Acacia pennatula* trees had the highest density and diversity of migratory birds detected in land uses of mid-elevation valleys in southern Mexico.

The positive effects of introducing trees into pastures have also been reported for other faunal component groups. For example, a comparative study in northern India reported that pasture systems with trees had 5 to 150 times higher density of edaphic macrofauna than surrounding treeless pastures, depending on the tree species used (Tripathi et al. 2005). In a global meta-analysis, Prevedello et al. (2018) reported 50–100% higher richness of arthropods, vertebrates and woody plants in areas with scattered trees than in open areas. In agricultural landscapes of Chiapas, Mexico, Arellano et al. (2013) observed that pastures with *Acacia* sp. had five times more abundance and 50% more dung beetle species than surrounding pastures without trees. In this study, pastures with high shrub density (1500–2000 shrubs per hectare) harbored several species typical of more mature forests in the same area. Similarly, a study by Ballesteros-Correa and Pérez-Torres (2022) in Córdoba, Colombia, found that silvopastoral systems had more bat species and foraging guilds than conventional pastures in the region.

- ***Provision of ecosystem services***

The presence of trees in the paddocks offers protection and food resources for livestock and wildlife. For example, in Costa Rica, Nicaragua, Colombia and Venezuela, trees such as *Samanea saman*, *Enterolobium cyclocarpum*, *Ceiba pentandra*, *Guazuma ulmifolia*, *Gliricidia sepium*, *Acacia pennatula*, *Mangifera indica* and *Psidium guajava* are commonly used in pastures to provide shade and fruits for people, livestock and wildlife (Murgueitio and Ibrahim 2008; Calle 2011; Harvey et al. 2011a).

Some bat and bird species that use scattered trees for foraging are crucial agents for seed dispersal. In modified tropical landscapes, frugivorous bats play an important role in the dispersal of both primary and secondary rainforest plants (Manning et al. 2006). According to Duncan and Chapman (1999) seed dispersal by bats tends to occur more frequently in degraded areas lacking trees, while bird seed dispersal becomes increasingly important as trees stablish. The presence and survival of bats and birds in these landscapes therefore is considered crucial to habitat restoration.

Additionally, several studies have found that trees significantly improve microclimate and soil characteristics in their area of influence (Ibrahim et al. 2007; Atangana et al. 2014; Siqueira et al. 2017). For example, Casals et al. (2014) observed higher concentrations of organic carbon, nitrogen, assimilable phosphorus, as well as higher exchangeable potassium and calcium in paddock soils under tree canopy than in adjacent pastures. A study by Guerra Alonso et al. (2019) in the Chaco region of Argentina, found that canopy cover in livestock systems benefits dung beetle communities through regulation of temperature and humidity. The introduction of trees in pastures can also improve the water regulation capacity of watersheds. For example, in Nicaragua and Costa Rica, Ríos et al. (2006) observed that pastures with scattered trees had 27 times more infiltration and three times less runoff than pastures without trees. Finally, trees in paddocks are also considered nuclei of plant regeneration for forest recovery in abandoned pastures, as they attract seed-dispersing species and generate microclimatic conditions conducive to seedling growth under their canopy (Siqueira et al. 2017; Esquivel and Calle 2002; Esquivel et al. this volume).

5.2.3 Intensive Silvopastoral Systems

Intensive silvopastoral systems (iSPS) are characterized by the combination of high densities of forage shrubs (4000–40,000 plants/ha) with improved pastures and tree species (approximately 100–600 trees/ha) (Calle et al. 2012; Chará et al. 2019b).

These systems are managed following the intensive rotational grazing model that is characterized by high animal density, short periods of occupation (12–24 hours) and long periods (40–50 days) of rest in which the vegetation cover is recovered (Calle et al. 2012; Chará et al. 2019a). These systems are suitable for the production of meat, milk, dual-purpose cattle, as well as for buffalo, sheep and goats (Calle et al. 2012).

- ***Effects on biodiversity***

The establishment of trees and shrubs in iSPS increases the vertical and horizontal complexity of habitat available to wildlife and plants and increases connectivity between forest fragments (Chará et al. 2019a). In agricultural regions, this means that iSPS complement the conservation value of forest fragments at the landscape level by providing temporary habitat for forest-dependent species and permanent habitat for generalist species (Tarbox et al. 2018). A summary of the effect of intensive silvopastures on the diversity of different taxonomic groups is presented below.

- ***Avifauna***

Intensive silvopastoral systems are capable of providing food and shelter for avifauna, fulfilling the role of biological corridors in agricultural landscapes (Murgueitio et al. 2011; Chará et al. 2019a). Several studies in Cuba have documented that bird richness in leucaena iSPS tends to increase with age of the system, indicating that systems with more developed trees and shrubs have the capacity to host greater numbers of avifauna species (Alonso et al. 2004; Iraola et al. 2018). In La Vieja river basin (Quindío, Colombia), Fajardo et al. (2010) observed intensive silvopastoral systems had some of the highest bird abundance values among the agricultural uses studied, and tripled the species richness compared to pastures without trees. In addition, studies in several countries have documented intensive silvopastoral lands can harbor a unique assemblage of birds, which is not only a subset of the species found in local forests, but also includes open-area and migratory species (Schroth et al. 2004; Mcadam et al. 2007; Calle et al. 2012). An example of this trend was reported by Fajardo et al. et al. (2008) in Colombia, where intensive silvopastoral systems showed intermediate diversity values and assemblages between pastures and forest fragments. As with the other silvopastoral systems reviewed, the contribution of iSPS to bird conservation is not only limited to local or resident species, but also contributes to the conservation of migratory species. For example, Alonso et al. (2004) observed that in times of low rainfall, migratory birds constituted 42% of the bird species documented in leucaena SSPi with 6 years of exploitation in Cuba.

- ***Dung beetles***

In tropical agricultural landscapes, the presence of trees in intensive silvopastoral systems has a positive effect on the diversity and abundance of dung beetles (Giraldo et al. 2011). In a comparative study in the Colombian Andean region, Giraldo et al. (2011) found that intensive silvopastoral systems with improved pastures and

L. leucocephala shrubs had higher abundance of dung beetles compared to pastures without trees. Similar results were reported in the Cesar River Valley (Colombia), where iSPS had 36% more dung beetle species than pastures without trees (Montoya-Molina et al. 2016). The latter study also reported iSPS harbored 61% of the species found in the forest, highlighting the value of this land use as a biodiversity reservoir. In addition to the benefits in terms of biodiversity, the increased abundance and diversity of coprophagous beetles in productive livestock systems has been related to the provision of ecosystem services of interest to ranchers. For example, Giraldo et al. (2011) reported that as a consequence of the higher number of dung beetles in iSPS, these systems had higher rates of soil and seed removal, as well as significantly lower numbers of adult flies than pastures without trees.

- ***Edaphic fauna***

Intensive silvopastoral systems harbor higher abundance and diversity of ants than do treeless pastures (Rivera 2009; Rivera et al. 2013; Ramírez-Barajas et al. 2019). In the La Vieja river basin (Quindío, Colombia), Rivera (2009) reported that intensive silvopastures harbored 72% of the ant species present in adjacent forest fragments. Another study in the same region reported that ant species richness was 62% higher in intensive silvopastures than in treeless pastures, and that intensive silvopastures harbored 55% of the species present in surrounding forests (Rivera et al. 2013).

Several investigations have shown that intensive silvopastoral systems have a positive effect on the integrity of soil-associated micro- and macro-organism communities. In a comparative study carried out in Valle del Cauca (Colombia), Vallejo et al. (2012) found the microbial community in intensive silvopastoral soils was more similar to that of forests than that of degraded pastures. This study also reported that the microbial community in intensive silvopastures presented markers indicating lower metabolic stress, higher enzymatic activity and higher biomass than the microfauna associated with pastures. In a parallel study conducted in the same system, Cubillos et al. (2016) observed that once pastures were converted to intensive silvopastoral, soil physicochemical conditions gradually changed until they became more forest-like, which was reflected in the composition and function of bacterial communities. On the other hand, a comparative study in Cuba reported that intensive silvopastoral systems with leucaena had 1.7 times more biomass of edaphic macrofauna than native pastures (Rodrigues and Gaston 2002). The researchers attributed these differences to the presence of greater plant diversity, greater quantity and better quality of leaf litter and more favorable microenvironmental conditions for macrofauna in intensive silvopastures.

- ***Conservation and improvement of soil quality***

Various studies have shown intensive silvopastoral systems have positive effects on soil physical, chemical and microbiological characteristics (Broom et al. 2013; Chará et al. 2019a). These effects are attributed to improved nutrient recycling, increased soil formation, prevention of erosion, and improved microclimatic conditions that increase the diversity of beneficial organisms associated with the soil (Giraldo et al. 2011; Broom et al. 2013; Chará et al. 2019a).

Due to the structural complexity and diversity of plant species, soil in intensive silvopastoral systems receives heterogeneous plant material, including dry leaves, branches, fruits, resins and exudates that have beneficial effects on organic matter, nutrients and edaphic organisms (Vallejo et al. 2012; Martínez et al. 2014). These benefits are reflected in the improvement of chemical parameters such as pH and the availability of phosphorus, potassium and calcium (Martínez et al. 2014). Complementarily, the use of nitrogen-fixing trees and shrubs in silvopastoral arrangements increases nutrient availability. For example, Sierra et al. (2002) observed that the rate of nitrogen mineralization was 20% higher in silvopastures with *Gliricidia sepium* than in adjacent treeless pastures in the French West Indies. Similarly, Vallejo et al. (2012) reported higher concentrations of organic carbon, total nitrogen, nitrate and available phosphorus under the canopy of carob (*Prosopis juliflora*) in intensive silvopastures in the Colombian Cauca Valley and Radrizzani and Shelton (2011) reported higher concentrations of organic carbon and total nitrogen in intensive leucaena (*L. leucocephala*) silvopastures in Queensland, Australia. It has been shown that these changes in soil quality can be of such magnitude that some intensive silvopastoral arrangements, such as systems with high density of leucaena inoculated with *Rhizobium* strains, do not require the application of synthetic fertilizers to sustain long-term forage production because they promote greater nutrient recycling (Bacab et al. 2013; Broom et al. 2013; Chará et al. 2019a).

The establishment of intensive silvopastoral systems also produces measurable improvements in soil physical parameters and other characteristics. For example, Giraldo and Chará (2022) observed that intensive silvopastoral systems decrease soil loss rate up to 35.3%, and improve infiltration and hydraulic conductivity compared to conventional pastures. Trees and shrubs have deep roots that allow the extraction of nutrients and water from deeper soil layers and provide structural complexity (Broom et al. 2013). Mature intensive silvopastures generally have better values of porosity, bulk density and resistance to soil penetration than conventional pastures (Vallejo et al. 2010; Polanía-Hincapié et al. 2021).

- ***Conservation of water resources***

As previously mentioned, the adoption of intensive silvopastoral systems improves soil porosity, bulk density and penetration resistance, parameters that increase water retention capacity and reduce runoff, improving watershed regulation capacity. The coverage of trees and different strata of vegetation in intensive silvopastoral prevents moisture loss, as it reduces direct solar radiation on the soil (Cuartas et al. 2014). On the other hand, practices such as the establishment of drinking troughs for livestock reduce or prevent the entry of livestock into stream channels, which can cause significant improvements in the channel condition and water quality of these ecosystems (Cuartas et al. 2014).

- ***Biological pest control***

Appropriate rotation practices and improved microclimatic conditions in intensive silvopastoral systems favor the recovery of the ecological functions of insects, birds, ants and entomopathogenic fungi, which reinforces biological pest control. For example, Giraldo et al. (2011) found greater numbers of coprophagous beetles in intensive silvopastures than in the surrounding pastures, which significantly reduced the presence of hematophagous flies and their larvae. Similarly, increased abundance and diversity of birds and other insectivorous organisms can reduce the incidence of ticks (Cuartas et al. 2014; Salazar et al. 2016). Salazar et al. (2016) observed that cattle in intensive silvopastoral systems had 56% less *Rhipicephalus (Boophilus) microplus* tick load than cattle in monoculture pasture systems in southwestern Colombia. The same authors found similar results in farms in the Ibagué plateau (Tolima, Colombia), where *R. (B.) microplus tick* loads were significantly lower in intensive silvopastoral systems than in rice chaff pastures and traditional pastures (Salazar et al. 2015).

The presence of natural enemies in silvopastoral systems has enhanced the control and reduction of different pest species. An example of this is the reduction of *Atta cephalotes* leaf-cutter ants reported by Castaño-Quintana et al. (2019) in the Valle del Cauca, Colombia, thanks to the predation by insectivorous birds during the breeding season, which prevents the formation of new nests. The same study reported a wide variety of natural enemies in silvopastoral systems that prey on leafcutter ants. Among them are different species of birds (*Theristicus caudatus*, *Vanellus chilensis*, *Crotophaga ani*, *Milvago chimachima*), ants (*Dolichoderus* sp., *Azteca* sp., *Crematogaster* sp., *Ectatomma ruidum*, *Nylanderia fulva*), and wasps (*Polistes* sp.). Ochoa-Londoño et al. (2019) found that monocultures with kikuyo grass *Cenchrus clandestinus* harbor a higher density of grass-sucking insects than silvopastoral systems with the suflower *Tithonia diversifolia* and *Alnus acuminata* trees. Results of this study suggested the presence of natural enemies in silvopastoral systems may be influencing the reduction of populations of the sucking insect complex.

On the other hand, animals in rotation in intensive Leucaena silvopastures can have 40% fewer intestinal parasites than animals in conventional pastures, due to the effects of secondary metabolites present in Leucaena and the interruption of parasite life cycles due to rotations (Cuartas et al. 2014).

5.3 Emerging Patterns

5.3.1 Structural Complexity as an Important Mechanism of the Effects

One of the patterns that emerge from this synthesis is the tendency for greater biodiversity and ecosystem service supply as the structural complexity and diversity of vegetation associated with different land uses increases. In general, despite some variation in the response of specific taxonomic groups, most studies that evaluated land uses along a gradient of vegetation structural complexity (in which primary and secondary forests are located at one end of the gradient and treeless monocultures of grasses at the other end) found that more complex land uses had higher rates of biodiversity and greater supply of ecosystem services (Philpott et al. 2008; Vallejo et al. 2012; Arellano et al. 2013; Montoya-Molina et al. 2016; Guerra-Alonso et al. 2020). This pattern is also clear in studies that explicitly evaluated the effect of variation in structural complexity within the same productive system, variables reflecting greater vertical and horizontal complexity (basal width of trees, canopy cover, vegetation volume, etc.) were generally positively correlated with animal species richness and abundance within productive systems (Lang et al. 2003; Molano et al. 2003; Sáenz and Menacho 2005; Colorado Zuluaga and Rodewald 2015; Mcdermott et al. 2015). In this sense, the evidence collected here coincides with other research suggesting that vegetation structural complexity can be used as a proxy indicator of the value of a land use in terms of biological resource conservation (Philpott et al. 2008; Gardner et al. 2009).

At the landscape scale, by increasing tree cover, silvopastoral arrangements provide habitats of greater structural complexity than monocultures. For example, two investigations, one in the La Vieja river basin (Quindío, Colombia) and the other in the Cesar River Valley, Colombia, found that pastures with trees had vegetation with higher stem density (number of plants with more than 2.5 cm diameter at breast height), greater basal area, and more complex vertical structure than conventional pastures (Calle and Méndez 2009; Giraldo et al. 2022). This increased complexity improves the quality of the landscape matrix for species present in forest remnants (Tarbox et al. 2018; Chará et al. 2019a). In this way, silvopastoral arrangements increase connectivity between forest patches, acting as stepping stones (e.g., scattered trees in paddocks) or corridors (e.g., live fences) for species that depend on trees for dispersal (Schroth et al. 2004; Harvey et al. 2005; Atangana et al. 2014). Additionally, the presence of trees on productive land uses increases the area of habitat available for generalist species and forest edge species (Fajardo et al. 2008). In addition to the positive effects at the landscape scale, silvopastoral systems have local benefits that are also related to the increase in the structural and compositional complexity of the vegetation. Examples of this are their action as nuclei of vegetation regeneration, their action as windbreaks and their capacity to regulate microclimatic conditions (Fajardo et al. 2008; Siqueira et al. 2017).

5.3.2 The Importance of Management Practices at the Farm Level

The second emerging pattern is closely related to the first; the effectiveness of silvopastoral land uses as conservation features depends to a large extent on the practices employed for their management. Management patterns, determined by the frequency and intensity of pruning, rotation periods, agrochemical application regime and spatial distribution of woody vegetation, among other factors, directly affect the structural and compositional complexity of these systems, and thus have a great impact on their capacity to host biodiversity and sustain levels of ecological functioning. To cite an example, several studies showed that the value of live fences as biodiversity corridors correlated with tree crown size and distance between trees (Lang et al. 2003; Molano et al. 2003). This is determined by the planting and mowing strategies employed by the growers. For this reason, it is important to study in greater detail how specific management strategies for each silvopastoral arrangement affect their effectiveness as conservation elements. This information will allow management strategies to be adjusted to enhance the provision of ecological services in the long term.

Another example of the importance of management practices is the handling of regeneration and planting of trees, which may strongly influence plant diversity in the different silvopastoral models. For example, in the Cesar River Valley (Colombia), Giraldo et al. (2022) found that although silvopastoral systems can conserve a significant number of shrub and tree species, they only shared about 7% of the species present in adjacent forests.

5.3.3 Silvopastoral Systems as Novel Ecosystems

Overall, the research consulted in this review suggests that silvopastoral systems can be considered novel ecosystems. The term "novel ecosystems" has been used to denote emergent ecological systems with assemblages of species occurring in combinations and relative abundances not previously observed in a given biome (Hobbs et al. 2006). In these systems, selective loss and gain of taxonomic groups occurs due to the creation of dispersal barriers, or changes in productivity that alter the relative abundance and composition of the local biota (Hobbs et al. 2006; Gardner et al. 2009). In silvopastoral systems this pattern has been particularly documented in birds, with research showing that they are capable of harboring unique species assemblages, combining forest-associated species with open-field and migratory species (Schroth et al. 2004; Mcadam et al. 2007; Fajardo et al. 2008; Greenler and Ebersole 2015). However, this pattern has also been observed in other taxonomic groups, including coprophagous beetles and edaphic microorganisms (Vallejo et al. 2012; Montoya-Molina et al. 2016).

5.3.4 The Importance of Forest Remnants

The studies reviewed in this synthesis also provide evidence of the irreplaceable role of forest patches for conservation at the landscape and regional levels. Despite the growing recognition of silvopastoral systems as emerging ecosystems capable of sustaining a significant portion of biodiversity in agricultural landscapes, their conservation value is inextricably linked to the availability of forest patches in good conservation status (Schroth et al. 2004; Gardner et al. 2009; Atangana et al. 2014; Arroyo-Rodríguez et al. 2022). Forests provide shelter and food for unique species of plants and animals (Giraldo et al. 2011; Zuluaga et al. 2011). For this reason, many of the biodiversity benefits that originate with the establishment of the previously described silvopastoral arrangements depend on the existence of forests that serve as a source of species in the landscape mosaic (Schroth et al. 2004; Atangana et al. 2014). Likewise, forest patches increase connectivity in the landscape, facilitating migratory and dispersal movements for mammals, birds, amphibians, and other organisms (Schroth et al. 2004). Therefore, the successful use of silvopastoral systems as a conservation strategy depends to a large extent on ensuring the protection of forest patches at the landscape level.

5.4 Strategies for Assessing the Conservation Value of Agroforestry Systems

This synthesis exercise also provides an overview of the type of studies used to understand the ecological effects of silvopastoral and other agroforestry land uses. Approaches used include descriptive studies at the land-use level, experimental trials, comparisons between different land uses within a landscape or region, and the collection of anecdotal information on changes perceived by producers or researchers. Although all of these approaches are potentially valuable depending on the research objectives, we conclude from our results that one of the most effective strategies for assessing silvopastoral implementation in terms of conservation is the quantitative comparison of between silvopastoral arrangements and other land uses within the same landscape unit. In particular, we believe that comparisons between silvopastoral, conventional pasture and forest land uses are especially useful for understanding the contribution of silvopastoral systems to biodiversity at the regional level. Comparisons with traditional livestock systems allow us to determine whether silvopastoral systems represent effective improvements over conventional production systems of less structural complexity. On the other hand, comparisons with forest patches within the same landscape unit allow estimating the percentage of species usually associated with forests that are able to use silvopastoral systems as temporary or permanent habitat.

In this same vein, we believe that it is of great importance that in biodiversity studies such comparisons are not limited to species richness indices, as is the case in many of the articles included in this review. Biodiversity indices should be complemented with information on species identity (i.e. relative abundance at the specific level, the percentage of unique species and species shared with other land uses) and their functional role in the ecosystems (i.e. classification of functional guilds or trophic guilds), since these data are fundamental to understand the level of ecological integrity that is conserved within silvopastoral systems.

We also propose that it is extremely important to systematically characterize the land uses studied. In the specific case of silvopastoral systems, part of the challenge in achieving a global vision of their potential value as conservation tools is that their definition can change between regions or organizations. For example, there is wide variation among arrangements that can be classified as live fences or tree strips, as different regions use different tree species for the arrangements and establishment and management practices may vary (Schroth et al. 2004). As a consequence, responses in terms of biodiversity and ecosystem services can vary widely and make it difficult to discern patterns or trends. To address this difficulty, we recommend that studies start from the basis of a quantitative description of the system under study. Table 5.1 lists some recommended parameters for describing silvopastoral systems in this type of research. The recommended parameters cover measures of the structural complexity of the system, the spatial distribution of the arrangements, the classification of the plant species introduced as part of the production system, the management practices, the age of the system, and the edaphic and climatic characteristics of the study region.

Table 5.1 Recommended parameters for the characterization of silvopastoral systems

Parameter	Measure
Characteristics of the production system Spatial description of the system	Woody and shrub vegetation density
Structural complexity of vegetation	Vertical vegetation structure Total volume of vegetation Leaf density index Canopy cover Number of shade layers Height of woody vegetation
Composition of plant species used in the productive system	Species inventory Species richness
Management practices	Frequency and intensity of pruning Application of agrochemicals Animal rotation plan
Age	Years since establishment
System size	Area covered by the studied land use
Type of soil	Soil type classification
Topographic conditions of the terrain	Average slope
Characteristics of the study region Climatic regime	Maximum, minimum and average annual temperature Rainfall regime Season and weather conditions at the time of sampling

5.5 Conclusions

The compendium of studies presented in this review provides significant evidence of the value of silvopastoral systems as conservation strategies in disturbed tropical landscapes. In these rural landscapes, silvopastoral systems can complement the role of forest fragments by increasing the structural complexity and diversity of woody vegetation. This increase not only improves the supply of provisioning and regulating ecosystem services, but also increases the habitat available for biodiversity. To continue to encourage the adoption of silvopastoral systems and enhance their contributions to regional conservation, it is necessary to understand in greater depth how the practices associated with these production systems affect their ecological functioning.

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Chapter 6
Silvopastoral Systems as an Alternative of Dairy Cattle Production in Tropical Pastures

Domingos Sávio Campos Paciullo, Maria de Fátima Ávila Pires, Marcelo Dias Müller, and Rogério Martins Maurício

Abstract Silvopastoral systems can be an important strategy for increasing sustainability of animal production in tropical regions. Among the benefits of utilizing such systems are improved thermal comfort and performance of animals, increased forage quality, and the possibility of diversifying the incomes in the farm. However, these benefits depend on the balance between components, as competition for growth can render the system's sustainability unfeasible. Some of the challenges to developing these systems are related to shade tolerance of grass and economic investments.

Keywords Animal comfort · Forage production · Forage quality · Shading tolerance · Sustainability

6.1 Introduction

The tropical region has privileged conditions for animal production on pasture, considering some factors, such as the high potential for forage production, the great diversity of forage species, the extensive area available for agriculture, and the relatively favorable climate in most of the year. The milk production chain, present in a large part of the tropical region, is responsible for generating employment and income for thousands of families, which shows its economic and social importance.

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Despite the advances that livestock based on tropical pastures have shown, productivity levels are still low. Different factors contribute to this scenario, among them the degradation of pastures, the inadequate management practices, the low genetic potential of animals and the low level of adoption of effective technologies. As an example, in Brazil it is estimated that about 60 million hectares of pasture areas in the Cerrado and Atlantic Forest biomes are degraded or in degradation.

Among the alternatives for sustainable agricultural production, silvopastoral systems stand out. This type of system refers to the associated cultivation of trees and pastures, in addition to animals, in the same management unit, in which there must be both ecological and economic interactions. Some benefits have been attributed to the use of these systems, including the possibility of increasing fertility and soil conservation, improving thermal comfort for animals, increasing the quality of forage, diversifying and increasing income and gain from environmental services (Schoeneberger 2009; Müller et al. 2011; Paciullo et al. 2014; Chará et al. 2019).

In this chapter, we will discuss aspects related to the main components of silvopastoral systems, with information on the effects of tree shading on pasture characteristics and dairy cattle comfort. Issues related to production potential and forage quality in silvopastoral systems, and implications for animal performance will be also addressed.

6.2 Forage Species: Shade Tolerance and Technological Level of the System

The choice of forage grasses tolerant or moderately tolerant to shade is an essential condition in the associations of pastures with trees. Research on the shading tolerance of forage has advanced from studies carried out with different species of grass and forage legumes in various parts of the world (Wong et al. 1985; Andrade et al. 2003, 2004; Soares et al. 2009), which has allowed safe guidance for choosing the most suitable species to compose silvopastoral systems.

Among the grass species with medium shade tolerance some are widely used in the tropical region, such as *Brachiaria* spp. and *Megathyrsus maximus*. Grasses such as *B. decumbens* cv. Basilisk, *B. brizantha* cvs. Marandu, Xaraés and Piatã, *B. ruziziensis*, *M. maximus* cvs. Tanzania and Massai also showed relative tolerance to moderate shading, being potentially suitable for silvopastoral systems (Andrade et al. 2004; Guenni et al. 2008; Soares et al. 2009).

The tolerance of forage legumes to shade also varies between species. Among the moderately tolerant are *Calopogonium mucunoides*, *Centrosema pubescens* and *Pueraria phaseoloides*. The *Stylosanthes guianensis* and the Siratro (*Macroptilium atropurpureum*) were considered to have a low tolerance to shading (Wong 1991; Andrade et al. 2003). And Forage peanuts (*Arachis pintoi*) performed well in shade conditions, being considered by Andrade et al. (2004) as tolerant to shade.

Table 6.1 Grasses and legumes adapted to different technological levels or intensities of use

Technological level/ intensity of use	Forage Grass	Forage legume
High/intensity	*Pennisetum purpureum, Cynodon spp., Megathyrsus maximus, Brachiaria brizantha*	*Medicago sativa, Leucaena leucocephala*
Medium	*M. maximus, B. brizantha, B. decumbens, Setaria sphacelata*	*L. leucocephala, Neonotonia wightii, Arachis pintoi, Cajanus cajan*
Low/extensive	*B. decumbens, B. humidicola, Hyparrhenia rufa, Melinis minutiflora, Paspalum notatum*	*Stylosanthes guianensis, Calopogonium mucunoides*

Adapted from Cantarutti et al. (1999)

Another important aspect to guide the choice of forage species for production systems is their adaptation to the technological level intended for the management of the system. The information in Table 6.1, adapted from Cantarutti et al. (1999), summarizes the adaptability of forage grasses and legumes to systems of high technological or intensive, medium and low or extensive systems, according to the characteristics of the forage, such as productivity, nutritional value, and nutritional requirements. The systems of high technological level present rotational stocking, use of fertilizer and lime in large doses, and irrigation. In these systems, higher stocking rates, ranging from 4 to 7 Animal Units (AU)/ha are expected when pasture is the main food in the animals' diet. Systems with low technological level are characterized by stocking rates normally lower than 1 AU/ha, while medium-level systems have grazing intensity and stocking rates at intermediate level (Cantarutti et al. 1999).

Grasses adapted to the high technological level are more demanding in terms of soil fertility and other growth factors, although some are also suitable for the intermediate level, such as *B. brizantha* and *M. maximus*. The use of intensive systems, which require, in most cases, high doses of nitrogen fertilization, should be carefully analyzed in silvopastoral systems. In this case, there will be some degree of light reduction for the pasture, depending on the tree species, age of the trees and spacing, among others. When there is a nutritional limitation, moderate shade is no longer the limiting factor for plant growth. In other words, the productive response of pasture under moderate shade can be similar to that of full sun. However, high forage productivity, in soils fertilized with high doses of fertilizers, can be compromised by the limited Photosynthetically Active Radiation (PAR) available for the pasture, in silvopastoral systems. The use of intermediate technological systems may be a good option, especially since *B. brizantha* and *M. maximum* species are also moderately shade tolerant (Table 6.1), allowing pasture to accumulate forage at levels compatible with intermediate stocking rates (2–3 AU/ha).

Extensive animal production systems can also be a good alternative to silvopastoral systems, especially when implanted in conditions of poorer fertility soils, mountainous topography, and without the use of fertilization. Data obtained from pastures of *B. decumbens* implanted in silvopastoral systems demonstrated the potential of these systems for animal production, either in the heifer-rearing phase (Paciullo et al. 2011; Lima et al. 2019a) or in the milk production phase (Paciullo et al. 2014). In the study with dairy heifers, average body weight gains of 600 g/heifer were obtained, and in that with crossbred cows, average milk yields of 10.5 kg/cow/day, both with animals kept exclusively on pasture.

In countries such as Colombia, and Mexico, among others in South and Central America, an intensive silvopastoral system has been proposed, in which high shrub densities per hectare are recommended, especially the *Leucaena leucocephala* species (Chará et al. 2019).

6.3 Nutritional Value of Forage

Shade generally favors increased nitrogen availability in the soil and stimulates plant growth and, consequently, induces increases in nitrogen concentration in grasses (Samarakoon et al. 1990; Kephart and Buxton 1993).

In *B. decumbens* pastures the levels of shading influence the crude protein content. In leaf blades, the crude protein (CP) content was 29% higher in the grass under shade than in that exposed to the sun (Paciullo et al. 2007). The shade allows greater water retention in the soil, whose positive effect on microbial activity, results in greater decomposition of organic matter and nitrogen cycling (Wilson 1996).

Regarding the levels of neutral detergent fiber (NDF) and in vitro dry matter digestibility (IVDMD), the results, although contradictory, indicate a tendency to reduce NDF levels and increase IVDMD under shade conditions (Carvalho 2001). Kephart and Buxton (1993) found that by imposing 63% shade on five species of perennial grasses, the cell wall content decreased by only 3% and the lignin content by 4%, factors that contributed to an increase in digestibility of 5%. In the shade, grasses have a slight increase in digestibility (1–3%), due to their lower concentration of cell wall. However, an increase in lignin content has been reported in grasses grown under shade, compared to those kept in full sun (Samarakoon et al. 1990).

A significant effect of the luminosity condition was observed on the NDF content of *B. decumbens*, which was higher in unshaded areas than under the shade (Paciullo et al. 2007). A similar result was found for *B. brizantha* and *M. maximus*, cultivated in different levels of shade (Denium et al. 1996). According to these authors, the higher concentration of NDF in full sun, is a consequence of the greater availability of photoassimilates, resulting in an increase in the amount of sclerenchymatous tissue, with a greater number of cells and thicker cell walls.

The literature shows that the effect of shading on IVDMD varies with the species, level of shading and climatic conditions, mainly temperature and humidity. An example of a positive outcome is a study carried out by Carvalho et al. (1999), in which after four years of the introduction of nine tree legume species in a pasture, *B. decumbens* presented better quality in shaded than in unshaded areas. The CP content of the forage was higher in shaded conditions than in the full sun, in both seasons. During the rainy season, shading conditions did not have a significant effect on IVDMD. However, during the dry season, the forage produced in the shade showed higher IVDMD than that observed in the sun.

6.4 Shading and Animal Comfort

Environmental variables such as temperature, humidity, air movement and solar radiation, can have a negative influence on the performance of dairy cattle when they fall outside the range considered of thermal comfort, compromising milk production, weight gain and reproduction, as a result of a process known as heat stress. Some indexes have been developed and used to assess the impact of environmental variables on the performance of dairy cattle, seeking to predict the thermal comfort or discomfort of animals submitted to different climatic conditions. In general, four environmental parameters have been considered: the temperature of the dry bulb thermometer, the relative humidity of the air, the wind speed, and solar radiation. The most commonly used comfort index is the Temperature and Humidity Index (THI). When this index exceeds the value of 72, the animal is considered to be under heat stress, since this point represents the limit of the comfort zone for cows in production.

The animal's ability to withstand the rigors of heat stress has been physiologically assessed by changes in rectal temperature and respiratory rate and in animal behavior (Pires et al. 1998). Some management strategies can mitigate the effects of thermal stress and among them, the physical modification of the environment stands out, in order to reduce the incident radiation via the provision of shade, decreasing the caloric load received by the animals (Buffongton et al. 1983). In the silvopastoral system, the forest component contributes to the comfort of the animals, through the provision of shade, attenuating extreme temperatures, reducing the impact of rain and wind, and serving as a shelter for the animals (Salla 2005; Oliveira et al. 2018).

The effects of shading on the physiological variables and behavior of crossbred dairy heifers were evaluated in a silvopastoral system and in a monoculture of *B. decumbens* pasture (Pires et al. 2009). It was verified that in the afternoon shading provided an attenuation of 1 °C in air temperature in relation to those values measured in full sun (Table 6.2). The same trend was observed in the values of the Radiant Thermal Load, showing that the provision of shade in the pasture is an efficient method to reduce the radiation incident on the animal, improving its thermal comfort.

According to Morais (2002), the RTL represents the total thermal energy exchanged between the animal and the environment and should be as low as possible, to obtain thermal comfort. Thus, the author considered values between 666 and 801 to be high. Table 6.2 highlights that all RTL values obtained in the shade were lower than the lower limit mentioned by Morais (2002), while in full sun, the values below the limit established by the author, were only obtained in the morning. It is

Table 6.2 Ambient temperature (AT), radiant thermal load (RTL), and globe temperature and humidity index (GTHI) in a silvopastoral system and in a monoculture of *B. decumbens*

	Silvopastoral system		Monoculture of *Brachiaria decumbens*	
Variable	9 am	15 pm	9 am	15 pm
AT (°C)	21.5	27.4	21.9	28.5
RTL (W-m^2)	477	516	644	707
GTHI	71	76	80	85

Adapted from Pires et al. (2009)

also noteworthy that in the silvopastoral system, the microclimate in full sun, represented by the RTL values, was more adequate to the thermal comfort conditions than in the *Brachiaria* paddocks, under the same conditions of insolation, which highlights the importance of providing shade for grazing animals.

6.5 Dairy Cattle Performance in Silvopastoral Systems

The improved thermal comfort and the higher protein content of the forage in silvopastoral systems, correlate positively with the performance per animal, but the drop in the forage production can negatively interfere with the gain per area. In temperate conditions, some studies did not detect differences in animal performance in silvopastoral systems compared to monoculture (Neel and Belesky 2017). Nevertheless, given the high sensitivity of dairy cattle to heat stress, in regions of warmer temperatures, improvements in milk production of cows in silvopastoral systems are expected. However, the magnitude of the response is variable. In this case, the lack of response may be due to the low production capacity of the animals, an inadequate or insufficient observation period or favorable environmental conditions (especially in a subtropical climate).

The weight gain of Holstein x Zebu heifers in a silvopastoral system was compared to that obtained in a monoculture of *Brachiaria*, during 9 years (Paciullo et al. 2011; Lima et al. 2019a, b). The data from the first 4 years is presented in Table 6.3. In the second and fourth experimental years, greater weight gains were observed in the silvopastoral system than in the monoculture (Table 6.3). The authors considered that the higher CP content in the silvopastoral system may have contributed to improve the quality of the heifers' diet, favoring animal performance, as during the rainy season, the average consumption of crude protein in the silvopastoral system was 13% higher than that in the monoculture system.

The data from the same area, considering all experimental periods, from 2003 to 2016, was submitted to conjunct analyses (Fig. 6.1; Lima et al. 2019b). Considering the grouped analysis, the average daily gain remained similar between the systems most of the time, despite the lower forage mass observed in the SPS than in the monoculture from 2004 to 2016. The results showed a progressive decrease in

Table 6.3 Performance of dairy heifers in a monoculture of *B. decumbens* and in a silvopastoral system during four experimental years

	Average daily gain (kg/heifer/day)		Weight gain per area (kg/ha/year)	
Year	Monoculture	Silvopastoral	Monoculture	Silvopastoral
2003–04	0.612	0.637[a]	257	268[a]
2004–05	0.624	0.722[b]	256	298[b]
2005–06	0.563	0.647[a]	230	242[a]
2006–07	0.515	0.628[b]	211	258[b]

Adapted from Paciullo et al. (2009, 2011)
[a]= not significant
[b]Significant system effect ($P < 0.05$)

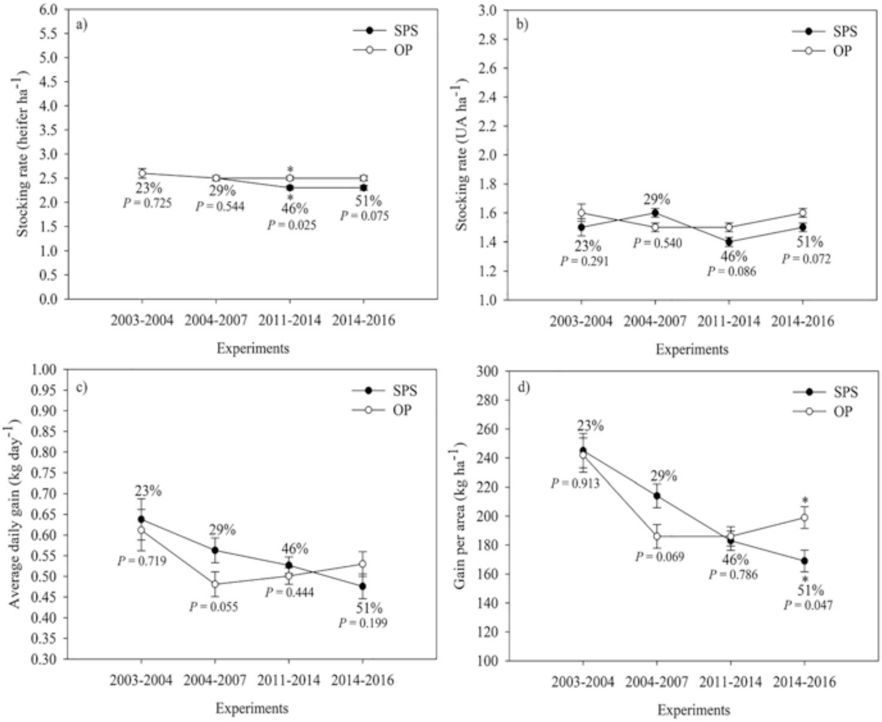

Fig. 6.1 Productivity of dairy heifers during rainy seasons from 2003 to 2016, in silvopastoral system (SPS) and monoculture (OP) of *B. decumbens*. "Experiments" represent each one of four experimental periods developed from 2003 to 2016. (Adapted from Lima et al. 2019b)

weight gain per area over time, culminating in lower values being observed in SPS in 2014–2016 (Fig. 6.1). The authors concluded that in a long-term silvopastoral system, strong light competition between the tree component and the pasture results in a decrease in forage productivity when compared to open pasture. However, to some extent, the higher protein content in the silvopastoral nutritionally compensated for the reduction in forage mass over time and the live weight gain of heifers was higher in SPS (2004–2007; P = 0,05) or similar (2003–2004, 2011–2014 and 2014–2016; P > 0,05) to *Brachiaria* monoculture. Nevertheless, the authors recommended that severe shading should be avoided with management practices such as thinning and pruning of trees in silvopastoral systems that focus on animal production, in order to stabilize forage yield, which would help maintaining the long-term overall performance of the system.

A study conducted with crossbred cows, for three years, showed greater milk production in the silvopastoral system, consisting of *B. decumbens,* trees (*Acacia mangium*, *Gliricidia sepium* and *Leucaena leucocephala*), and herbaceous legumes (*Stylosanthes* spp., *Pueraria phaseoloides* and *Calopogonium mucunoides*), than in the monoculture of *B. decumbens*, only during the first year. In the subsequent 2 years, there were no differences in milk production, which varied between 10.5 and 12.4 kg/cow/day, without concentrated supplementation (Paciullo et al. 2014).

Other studies carried out in tropical regions have shown positive results in milk production in SPS. In countries such as Colombia and Mexico, the use of forage shrubs in SPS improves the supply of nutrients, and enhances animal comfort, with positive impact on production per animal and per hectare and on milk. The proposed systems are considered intensive and recommend high densities of plants per hectare, especially of the species *Leucaena leucocephala*. Murgueitio et al. (2011) present results that demonstrate the potential of intensive silvopastoral systems, with a stocking rate of 4 AU/ha, milk production of more than 10,000 L/ha/year and system persistence potential of more than 20 years.

6.6 Product Diversification and Increased Dairy Farm Income

Trees in a silvopastoral system can remain for a long time, performing important functions, such as shading for animals, increased recycling of nutrients, carbon sequestration, among others. On the other hand, it is possible to foresee the removal of the tree component at different times of development of the system. In this case, there is the possibility of using the wood on the property and/or marketing with a view to obtaining financial profits.

Vale (2004) compared the economic performance of three production systems with trees in Minas Gerais (Brazil): (1) *Eucalyptus* reforestation (3 × 3 m); (2) conventional dairy farming and (3) silvopastoral system - eucalyptus (10 × 4 m) + dairy farming. Several economic indicators demonstrated the advantages of the silvopastoral system with *Eucalyptus* + dairy farming as a viable alternative for the sustainable development of the region.

At Embrapa Dairy Cattle, Brazil, a long-term experiment has been conducted to assess the environmental, productive, and economic aspects of a silvopastoral system model implanted in a mountainous area. A selective thinning of the eucalyptus

Table 6.4 Net Present Value (NPV) and Internal Rate of Return (IRR) of a silvopastoral system, considering the three market alternatives for the wood, with a discount rate of 6%

Economic characteristic	Alternative to selling Wood		
	Standing wood	Wood piled on the road	Wood placed in the consumer's yard
NPV	R$ 303.16	R$ 389.47	R$ 458.76
IRR	10%	11.00%	11.65%

Adapted from Muller et al. (2011)

trees was carried out 7 years after planting with the objective of increasing the incidence of PAR in the understory, reducing the time to reach the desired trunk size and quality of the remaining trees, and obtaining intermediate incomes before the final timber harvest. To evaluate the revenue obtained from the sale of wood, the following alternatives were considered: (1) sale of standing wood; (2) sale of wood piled on the road; and (3) sale of wood placed in the consumer's yard (the sale of posts on the property was also considered). By analyzing Table 6.4, it can be seen that at a discount rate of 6%, both NPV and IRR, indicated that all the alternatives for obtaining revenue from the sale of wood were feasible (Muller et al. 2011). These values also showed that adding value to the forest product (Alternative 3) and keeping all other products in the system constant provided an increase in revenues.

The authors concluded that the system is not very sensitive to changes in product prices and is moderately tolerant to increased costs. For meat, the price must fall by 25%, 33%, and 39%, when the timber is sold as standing wood, piled on the road, and delivered to the consumer's yard, respectively, to become economically unfeasible. For wood, the system supports an even greater drop in price and becomes unfeasible only if prices drop 56%, 57%, and 59%, respectively.

6.7 Final Remarks

One of the great challenges of agriculture is to maintain production at levels that support a growing population without contributing to increasing environmental degradation. The use of silvopastoral systems for the production of dairy cattle appears as a technically and economically viable option. These systems have several advantages from an agronomic, zootechnical, economic, and environmental point of view. Although it should be considered that shading should only be moderate over the cycle of plant and animal production, in order to avoid a reduction in forage production in the understory. Nevertheless, under proper management, it is possible to obtain higher production of dairy cattle or even maintain production when compared to the grass monoculture system, with the possibility of diversifying production and increasing income in silvopastoral systems, which may represent an incentive for the dairy farmers in the tropical region.

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Chapter 7
Silvopastoral Systems in Paraguay

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Abstract Cattle production is an important activity in Paraguay both in terms of its contribution to the Gross Domestic Product and the area occupied. During recent years the country has experienced an important growth in silvopastoral systems mainly devoted to the production of beef and timber with *Eucalyptus*. According to INFONA, the area under silvopastoral management in Paraguay is close to 20 thousand hectares distributed in seven departments of the Eastern Region. San Pedro is the department with the largest area with silvopastoral systems representing 54 % of the areas planted until 2021. For El Chaco or Western region, there are no official data regarding the area under silvopastoral systems that are mainly based on the management of white mesquite (*Prosopis alba*) and black mesquite (*Prosopis nigra*). Silvopastoral systems in Paraguay are a powerful tool for the sustainable management of natural resources, the recovery of the environment and the management of native and implanted forests. They can also contribute to increase forage and livestock production and improve animal welfare, and are suitable for small, medium and large-scale producers.

Keywords Dry Chaco · *Eucalyptus* · *Prosopis* · Timber production

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7.1 Introduction

Paraguay is a Mediterranean country in South America, with two distinct geographical and climatic regions: the Oriental (Eastern) and the Occidental (Western) or Chaco (Fig. 7.1). It is administratively divided into 17 departments and its capital is Asunción.

Paraguay is ranked 98 in the 2019 Human Development Index (HDI), among 189 registered countries. Currently, 59% of the population resides in urban areas and 41% in rural areas. Although it has decreased, rurality continues to be a characteristic of the country when compared with other countries in the region. The average population density is 14.5 inhabitants per km^2. Most of the population lives in the Central, Alto Paraná, and Itapúa departments that belong to the Eastern Region (DGEEC 2011).

From the perspective of production and according to official data from the Ministry of Agriculture and Livestock (MAG), agriculture has registered a growth of 3.5% compared to the same quarter of 2018 and has accumulated a variation of −10.3% in the third quarter of 2019. The favorable result observed in the quarter was mainly due to better levels of soybean production in the 2019/2020 season, accompanied by other agricultural items such as corn, rice, sesame, beans, and canola.

The agricultural sector is an important engine in the Paraguayan economy. According to data from the Inter-American Development Bank, it represented 24% of the Gross Domestic Product (GDP) in 2017 (18.9% agriculture and 5.2% livestock). The participation grows up to 25.3% of GDP if forest exploitation and fishing are added (1.2% forest exploitation and 0.04% fishing) (Cresta Arias et al. 2018), and up to 35% if the agro-industry is included. The primary agricultural and livestock sector generates around 15.2% of national exports and, according to data from the Permanent Household Survey of 2016, employs 21.7% of the country's workforce (26.1% of men and 15% of women) (DGEEC 2017).

Livestock, Forestry, Fishing and Mining activity has shown growth of 3.1% compared to the same quarter of the year 2018, thus accumulating a −2.7% reduction to the third quarter of 2019. The result for the quarter is mainly explained by a higher level of slaughter of cattle, poultry and production of other livestock products (BCP 2019).

Livestock, especially beef production, is another key economic activity in the agricultural sector. Livestock represents 5.2% of the country's GDP, without including the later stage of beef processing, which, according to data from the 2015 National Accounts, represented 3.05% of the GDP (Cresta Arias et al. 2018). According to data from the United States Department of Agriculture (USDA 2022), Paraguayan beef production in 2022 is forecast at 570,000 tons carcass weight equivalent (cwe), a 6.5% decrease from the previous year, as suboptimal weather and strong cattle prices are encouraging many producers to market fed cattle earlier than planned. The total slaughter for 2022 is projected down at 2.4 million head, as roughly 200,000–300,000 head which would have been slaughtered in 2022 are expected to be slaughtered in 2021.

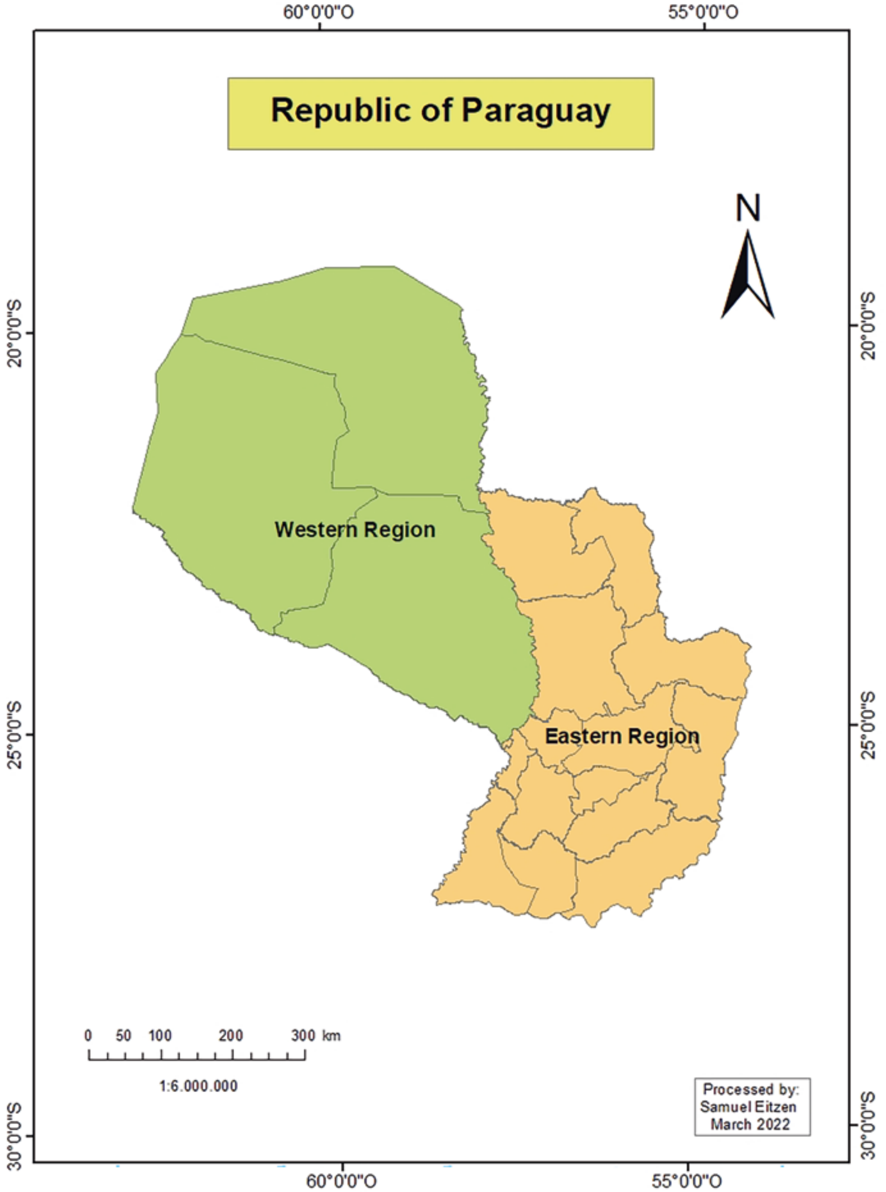

Fig. 7.1 Political division of the Republic of Paraguay

In 2022, roughly 2 million head are expected to be slaughtered in large export plants, 200,000 head in small to medium sized abattoirs and a similar number on-farm and in very small operations in the interior of the country. The average carcass weight in 2022 is forecast at 238 kilograms (kg), almost 3 kg more than in 2021, which is projected to be lighter due to a larger than normal slaughter and many cattle being marketed earlier than expected.

In relation to land use, the highest proportion of the area in the country is occupied by livestock and mechanized and non-mechanized agriculture (STP 2011). In recent years there has been an increase in the conversion of forest to agriculture with little consideration of the risks of causing soil and environmental degradation, nor the drastic changes caused by deforestation and its consequences (Mereles and Rodas 2009; Mahecha et al. 1998).

Paraguay has two of the most important and also most threatened forest ecosystems worldwide: The Atlantic Forest, a humid subtropical forest, rich in flora and fauna present in the Eastern Region and the Gran Chaco, the largest forested ecoregion in South America after the Amazon and the largest extension of dry forests on the continent. These two biogeographic zones or regions with totally different characteristics are very well differentiated in the country.

7.1.1 Eastern Region

The Eastern region of Paraguay has fourteen departments. Geographically it is located between the Paraguay and Paraná rivers. The climate of the Eastern Region is hot and very sunny with about 310 sunny days per year. In general, the warm winds from the North and East are stronger than the cold ones from the South. The hottest months of the year are December, January, and February, and the annual average temperature is 24 °C. The time of least precipitation is winter and the one with highest rainfall is summer (DGEEC 2005).

With altitudes as high as 600 m in the extreme northeast and as low as 55 m in the southwest, Eastern Paraguay is a wet region of rolling hills covered in ferralitic and largely acidic soils located on ancient crystalline rocks. A recent evaluation of Eastern Paraguay shows that agriculture and pastures cover more than 80% of the region; cattle production occupies about 8 million hectares, the majority of which is not used at its full capacity. However, much of the traditional beef production in this vast area occurs in lowlands that are unsuitable for forestry production. Agriculture is also crucial; It covers 5 million hectares, and soybean production is predominant (FCPF 2014).

7.1.2 Western Region

The Western Region of Paraguay, also known as Chaco has an approximate extension of 245,945 km^2. Two hundred thousand people, which is roughly 2% of the Paraguayan population, live in this part of the country.

The region is characterized by soils of recent alluvial origin and a bush forest called the Chaco Dry Forest. In this region, surface water is scarce or absent depending on rainfall, that ranges from 800 mm in the east to 400 mm per year to the west. Average temperatures of 24–28 °C create evapotranspiration conditions of between 1300 and 1500 mm per year on average. With this characteristic of permanent water deficit, Dry Chaco is classified as a semi-arid zone (Kruck et al. 1998).

The Western region of Paraguay is currently the area with the greatest expansion of agricultural activity, with the largest increases in the national livestock herd in recent years.

Considering the current biophysical conditions and land use patterns in Eastern Paraguay, an area of approximately 5.8 million hectares is ideal to start silvopastoral systems without affecting natural forests or agriculture. About 1.9 million hectares in this area are already covered with implanted pastures (ARP 2010).

7.1.3 Regulatory Framework

The establishment of silvopastoral systems in Paraguay is regulated by laws and their respective regulatory decrees, in addition to resolutions of the enforcement authorities: the National Forestry Institute (INFONA), and the Ministry of the Environment and Sustainable Development (MADES).

In this context, the Forestry Law 422/73 in its Article 23 prohibits the destruction of forests and forest lands, as well as the irrational use of forest resources, and Article 42 establishes that all properties greater than 20 ha. must have 25% of its area as forest reserve. Likewise, Art 1 of Res. INFONA No 1915/13 establishes that the land use changes that are made for agro-livestock activities should be carried out under silvopastoral models.

In addition, the Resolution 1136/11 of INFONA establishes the reference parameters for the annual authorization of forest cover areas in the western region, and defines that the conversion of forest to pastures for livestock activities must be carried out using silvopastoral systems in which the number of standing trees per hectare should be at least 30% of the trees inventoried in the original forest.

7.2 Main Silvopastoral Arrangements by Region

Livestock can be boosted and does not need to be an activity with destructive effects. The implementation of silvopastoral systems is an alternative that allows a more centralized use of each of the resources, provides animal welfare, improves soil conditions, and improves the quality of meat and milk in an economically and environmentally more sustainable way (Calle et al. 2012; Crespo 2008; FAO 2015).

According to INFONA (2019), the area under silvopastoral management in Paraguay is 19,475.44 hectares distributed in seven departments of the Eastern Region, with San Pedro being the department with the largest area with silvopastoral management representing 54% of all the systems installed in the country until 2021. To date, there are no official data regarding the area under silvopastoral systems in the Chaco. Table 7.1 presents the distribution of this area per department in the Eastern region.

The description of silvopastoral systems in terms of forest species, pastures and cattle is presented in Table 7.2. This table was prepared based on interviews with producers and managers of livestock establishments.

The National Platform for Sustainable Commodities, established within the framework of the United Nations Development Program (UNDP), works with an emphasis on the production and marketing of soy and meat as an instrument of dialogue between the sectors of production and marketing of these. It is made up of social and indigenous groups interested in the best use of natural resources and the conservation of biodiversity. Among the main achievements of this project led by MADES, the implementation of 200 hectares of silvopastoral systems with partners of the Rural Association of Paraguay in Caazapá can be cited (ARP 2019).

In order to evaluate and compare the economic, environmental and social performance of silvopastoral systems and traditional livestock or forestry production systems, a large-scale Paraguayan agro-industrial company has been used as a reference case for the analysis and modeling of scenarios.

Research carried out by Gamarra Lezcano et al. (2018) in the Paraguayan Central Chaco reveals that the arboreal component of silvopastoral systems consisted of *Prosopis alba* (white carob tree) and *Prosopis nigra* (black carob tree), in association with cultivated grassland composed mostly by *Megathyrsus maximus* cv *Gatton panic* (Gatton Panic), *Digitaria decumbens* (Pangola grass), and *Cenchrus ciliaris* (Buffel grass). On the other hand, Díaz Lezcano et al. (2019) found on average 31 trees per hectare of Prosopis in silvopastoral systems of the Paraguayan Central.

In plant inventories in silvopastoral systems of the Chaco, Díaz Lezcano et al. (2021) reported species of the families Fabaceae, Apocynaceae, Bignonaceae, Capparaceae, Rhamnaceae, Sapotaceae and Zhygophyllacea. The most abundant genus was *Prosopis* (carob) found associated with grasses of the species of *Megathyrsus maximus*, *Digitaria decumbens* and *Cenchrus ciliaris* (Fig. 7.2).

Table 7.1 Area under silvopastoral coverage by department

Department	Area (ha)
San Pedro	10,534.6
Caazapá	3913.9
Paraguarí	2289.5
Concepción	951.9
Caaguazú	753.3
Cordillera	517.3
Alto Paraná	514.9
Total	**19,475.4**

Source: INFONA (2021)

Table 7.2 Description of silvopastoral systems by region

Silvopastoral system, trees and pasture	**Region**	**Livestock**
Eucalyptus sp. with megathermic pastures (*Brachiaria* sp.) or natural grassland.	Oriental.	Breeding and fattening cattle with Brahman and Nelore herds, mainly. Animal load of 1.5 to 2.0Animal Units (AU) ha^{-1}.
Eucalyptus sp. and management of the genus *Prosopis* as white mesquite (*P. alba*), black mesquite (*P. nigra*) and Karandá (*P. kuntzei*) with the presence of tropical pastures such as Gatton panic (*Panicum maximum* cv Gatton panic), pangola (*Digitaria decumbens*), elephant grass (*Cenchrus ciliaris*), urochloa (*Urochloa panicoides*), star grass (*Cynodon nlemfuensis).*	Occidental or Chaco.	The livestock component is made up of the Brangus, Holstein, Zebu and Jersey breeds. Animal load of 1,0 to 2,0 AU ha^{-1}.
Silvopastoral system, trees and pasture	**Location**	**Livestock**
Eucalyptus urograndis from seeds, combined *Jesuit grass Axonopus catharinensis*. *Pinus taeda* from seeds combined *Jesuit grass Axonopus catharinensis*. The objective of the system is forest production for roundwood.	Obligado, Itapúa (Associate of the Cooperativa Colonias Unidas).	Brangus, Angus, rotational grazing system with a total of 50 cows for beef production.
Eucalyptus grandis from seeds combined with *Brachiaria brizantha*. The objective of the system is forest production for roundwood.	Obligado, Itapúa (Associate of the Cooperativa Colonias Unidas).	Brangus, Angus, rotational grazing system with a total of 50 cows for beef production.
Eucalyptus urogrand is from seeds, combined *Jesuit grass Axonopus compressus*.	Encarnación and Capitán Miranda, Itapúa within the framework of the Green Commodities Project.	Project started in December 2019, without an instant animal load.
Eucalyptus urograndis, E. grancam, E. urocam, E. grandis combined with *Brachiaria brizantha* and *B. humidicola*.	San Rosa del Mbutuy and Carayao, Caaguazu Juan de Mena, Cordillera in the framework of the projects led by (Kofpi) Korea Forestry Promotion Institute; Korean Forest Promotion Institute through an agreement with INFONA.	Brangus, Brahman and Senepol.
Eucalyptus urograndis from clones in single and double lines with a density of 8 × 2 combined with *Brachiaria brizantha*.	Owned by Asismed S.A. San Juan Nepomuceno, Caazapa.	Brangus and Brahman.

(continued)

Table 7.2 (continued)

Eucalyptus urograndis and *E. grandis* from clones combined with implanted pasture *Brachiaria brizantha, B. humidicola*, oats (*Avena sativa*).	Fundación Nikkei CETAPAR Yguazu District, Alto Paraná, (Technological and Agricultural Center of Paraguay).	They will be loaded in divided paddocks, average of 6 animals of the Brangus, Brahman and Holstein breeds.
Eucalyptus grandis and its hybrids, *Eucalyptus grandis* x *Eucalyptus urophylla, Eucalyptus camaldulensis* and their hybrids, in addition to *Eucalyptus grandis* x *Eucalyptus camaldulensis*.	PAYCO S.A. Agricultural Corporation S.A., San Pedro and Caazapa Paraguay.	Livestock is a very prominent economic activity in the project region. Through an innovative leasing concept in Paraguay, PAYCO cooperates with landowners who are engaged in ranching. Ranchers lease part of their land for the reforestation project, change their livestock system to a silvopastoral system and participate in the economic benefit of the project.
Eucalyptus urograndis from clones in single lines with a density of 8 × 2 combined with *Brachiaria brizantha* variety MG4.	Estancia Santa Silvia, Horqueta, San Pedro, belonging to the Agroganadera San Luis S.A.	Nelore.
Eucalyptus spp. combined with *Brachiaria* spp. and approximately 200 hectares with native forest species consisting of *Anadenanthera colubrina* (kurupa'y), *Cordia trichotoma* (petereby) and *Handroanthus heptaphyllus* (lapacho).	Most of the established plots are in Ybycui, Paraguarí, and others are distributed in Forestal SYLVIS S.A. Caaguazu, Caazapa and Benjamín Aceval.	The activities for the empowerment of silvopastoral land are framed under Law 4890/13 of Real Forest Area Law, taking over forest management, leaving livestock activities in charge of the landowners.
Eucalyptus spp. combined with *Brachiaria* spp. The afforestation with eucalyptus of Silvopastoral in Coronel Maciel are from clones of *Eucalyptus*, Pines and native forest species.	Estancia Curuzu and Estancia San Pablo, Coronel Maciel and Caazapa, Group Ferbel Forestal.	The company is in charge of forest management and the owners manage livestock production.
Eucalyptus urophylla x *Eucalyptus camaldulensis* combined in a high area with *Brachiaria brizantha* and *Brahiaria humidicola.*	Estancia Guavirá, Moisés Bertoni, Caazapá.	Brangus Loading broods and heifers.

(continued)

Table 7.2 (continued)

Clones of *Eucalyptus grandis* combined with *Brachiaria brizantha.*	Owned by Juan Pablo Lobo, Paraguarí.	Intensive rotation. Average Animal Load: MG5: 0.8–1 AU/ha. in winter, 2.5–3 AU/ ha. In summer; Marandu: 0.5–0.6 AU/ha. in winter and 2 AU/ha. in summer.
Clones of *Eucalyptus grandis* combined with *Brachiaria brizantha* variety MG5 and *Brachiaria brizantha* variety Marandu.	CIGESA Inversiones Generales Company S.A. Paraguarí.	It raised 150 kg, output 300 kg/ha.
Clones of *Eucalyptus urograndis* combined with *Brachiaria brizantha* variety MG4 and *Panicum maximum* cv. Mombasa.	Ganadera and Forestal Herrera, Caazapá.	Average animal load: 1.2 AU/ha. Intensive rotation System.
Clones of *Eucalyptus urograndis* combined with *Brachiaria brizantha* variety Marandu.	Family Martínez, Caaguazú.	Nelore and Braford. Rotational system, management based on the height of the grass.
Eucalyptus grandis, E. grandis x *urophylla* and *Corimbia* sp. from seeds combined with *Brachiaria brizantha* variety Marandu.	Family Albertini, Caaguazú.	Hybrid breeds. Rotational System.
Brachiaria brizantha cv. Piata, *Brachiaria brizantha* cv. MG5. *Eucalyptus urograndis* and *E. saligna* combined with *Brachiaria brizantha* variety Marandu, *Brachiaria brizantha* cv. Piata, *Brachiaria brizantha* cv. MG5.	Silvipar Coronel Bogado, Itapúa.	Hybrid breeds for fattening.
Clones of *Eucalyptus grandis, E. grandis* x *urophylla* and *Corimbia* sp. from seeds combined with *Brachiaria brizantha* variety Marandu*Panicum maximum* cv. Tanzania, *Panicum maximum* cv. Colonial.	Ganadera Vista Alegre, San Pedro.	Nelore, Brahman, Brangus Rotational system, management based on grass height.

7.2.1 PAYCO (Paraguay Agricultural Corporation)

According to Solymosi et al. (2016), the Paraguay Agricultural Corporation (PAYCO) is a company that invest in agriculture, beef production, and forestry. The company began investing in forestry plantations in Eastern Paraguay in 2011 and since that year, it has combined forestry and beef production in silvopastoral systems that include *Brachiaria spp.* and *Megathyrsus maximus*. The company is planning to expand the area under silvopastoral systems to 9000 ha with fast-growing plantations, composed mostly of *Eucalyptus* varieties. By 2020 7697 ha, had already been established.

Fig. 7.2 Silvopastoral systems of the Paraguayan Chaco

The strategy for project expansion is innovative in the Paraguayan landscape. PAYCO works closely with beef producers through land leasing on traditional cattle farms where silvopastoral systems are established and managed jointly with the farmer under a benefit-sharing agreement. Cooperation increases the income of farmers, allowing for a sustainable intensification and diversification of the beef sector.

The cooperation with the beef sector has also environmental implications. In eastern Paraguay, traditional beef production is losing its competitiveness vis-a-vis agriculture. This is causing the sector to migrate to other regions, such as Western Paraguay (Chaco). Silvopastoral systems can contribute to increase the value addition of beef production through sustainable intensification. This allows beef producer to increase their competitiveness in the region, with positive environmental and socio-economic impacts.

The project foresees the reforestation with *Eucalyptus grandis* and its hybrids in 11,500 ha to produce high-value wood and, with *Eucalyptus grandis* x *camaldulensis* in 2000 ha for the production of biomass, most of them in combination with livestock in silvopastoral systems. The plantations are established within a mosaic of natural ecosystems respecting local environmental conditions. In this way, native species are planted to establish bio-corridors and protect water courses and dense palm groves and the remaining native forests that are in different states of degradation will be conserved.

This project obtained a certification from the *Forest Stewarship Council* (FSC®) in 2014 and follows international practices, according to FSC® standards.

- **Silvopastoral Systems with emphasis on beef production**

Silvopastoral systems with a focus on beef production integrate timber trees and beef farming, with an emphasis on maintaining beef production as the primary business. In this system, *E. grandis* x *urophylla* plantations are established to produce high-quality timber in a 12-year cycle. Three hundred and twenty trees are planted per hectare in double rows, with a spacing of (5 × 2.5) × 20 meters (Solymosi et al. 2016). Pastures of *M. maximus* cover 90% of the land, while the remaining 10% is allocated for the tree planting strips. In the third year, a thinning process is carried

Fig. 7.3 Silvopastoral systems installed in the Department of San Pedro in the Oriental Region

out, in which 50% of the trees are removed. To prevent damage to the trees, grazing by cattle is not allowed in the pastures until the end of the second year. The average stocking rate throughout the production cycle is 0.68 heads per hectare due to the absence of cattle during the first 2 years and the presence of shade from the trees (Solymosi et al. 2016).

- **Silvopastoral Systems with emphasis on timber production**

In this situation the silvopastoral system is implemented with a primary focus on timber production. It is also based on *Eucalyptus* trees (*E. grandis* x *urophylla*), which are planted at a density of 714 trees per hectare in order to produce high-quality timber within a 12-year cycle. Two thinnings take place in years 3 and 6, to reduce tree density by 30% and 60% respectively, ultimately reaching a final density of 200 trees per hectare (Solymosi et al. 2016). The trees are planted in double rows with a spacing of (5 × 2) × 9 meters. To accommodate the timber trees, 80% of the area is dedicated to planting pastures of *M. maximus*, while the remaining 20% is reserved for the trees. Throughout the entire forestry production cycle, the average stocking rate is 0.51 heads per hectare. As in the previous scenario, cattle are not allowed to graze the pastures until the second year to ensure that planted trees are not damaged (Solymosi et al. 2016) (Figs. 7.3 and 7.4).

7.3 Silvopastoral Experiences of Livestock Production in the Dry Chaco of Paraguay

The Chaco Seco (Dry Chaco) area in the center of the region has been colonized with small towns since 1927 starting from a central core area. From family dairy cows with Creolized English genetics, beef cattle farming began, gradually going

Fig. 7.4 Silvopastoral systems installed in the Paraguarí Department of the Oriental Region

through phases of genetic improvement with Zebu breeds and improvement of forage areas. In the open forest bush areas, pastoral grass species adapted to the edapho-climatic conditions of the Chaco zone were planted. With this practice, the productivity index improved from 5 <– 10 to 154–190 Kg ha^{-1} $year^{-1}$.

With this production system, the process of clearing the Dry Chaco Forest and the strengthening of human settlements began by integrating its agricultural production into the national and international economy in the 1950s to 60s.

The Dry Chaco Forest changed from an "impenetrable forage area" for man to an area of management opportunity, especially in terms of planning of the productive units. Since the beginning of the 70s, farmers promoted the creation of windbreaks, also called firebreaks or simply protection stripes. These stripes, composed of pristine bush vegetation, are generally located on the edge of areas planted with pastures or forage crops (sorghum – for grain and for silage). However, in the area with the pastures planted between the protection strips, the dynamic of invasive shrubbery characteristic of the Chaco area continues, forcing the producer to implement a management system to maintain the high productivity achieved after the habilitation. The control of invasive shrubs represents on average 30% of the production cost in livestock, due to the inclusion of Zero Burning control practices in pasture areas.

The productive landscape in the Paraguayan Dry Chaco currently has a network of protection fringes made of native vegetation that play additional roles to those initially stipulated. The initial function, that was the forage value, stands out especially due to the high percentage of species of the Leguminosae family found in the scrubland. The productive units that have a percentage between 15% and 25% of their property with protection strips and some pasture plots with a shrub rate of between 10% and 20% cope better with the months and years of drought than those units with smaller areas of protection strips and pastures completely free of invading bushes (FECOPROD LTDA 2017).

The distribution of the protection strips in the perimeter and the pasture divisions provides easy access of cattle to that area for rumination and resting which contributes to animal welfare. The infrastructure for water provision is located in most cases at the crossing points of the protection strips providing access to shade near the water source.

In addition to the provision of shade, the persistence of pristine vegetation, both shrubs and trees, in the protection strips is considered by livestock producers as a source of forage in dry seasons. If this landscape matrix is accepted and recognized as a silvopastoral system for its components and the services they offer to livestock production, the system has a chance of persisting in the future. In other words, it will continue contributing to the sustainability of agricultural production.

The analyses of the distribution of protection strips have yielded a connectivity index of pristine vegetation greater than 90%, which also encourages the development of the Chaco Seco animal wildlife, which is also favored by the safe provision of water located at the points of the nodes. The analysis area has 51,583 ha, of which 7153 ha correspond to forest strips, that have an estimated length of 653 km.

7.4 Cases Studies

7.4.1 Silvopastoral Systems with a Community Approach

One of the most important examples of silvopastoral systems managed with a community approach in Paraguay is the *Cooperativa de Producción, Consumo y Servicios Volendam Ltda* (Cooperativa Volendam). It is located in the north of the Eastern Region of Paraguay, in the Department of San Pedro, in the Colonia of the same name. This rural community was founded in 1947 by a group of immigrants from Germany. The main economic activities of the cooperative from the beginning were forest exploitation, agriculture, and livestock, going through many difficulties in the first years that provoked the emigration of 70% of the total originally settled population.

Currently, agriculture is the most important economic activity, covering approximately 16,000 hectares, mainly with soy and corn. As for the number of producers involved, livestock is the most important activity, managing between 50,000 and 60,000 heads of cattle, according to the season. Within livestock, the main income comes from the sale of calves.

- ***Biodiversity***

In planning for the establishment of forest plantations, the farmers try to create large blocks, to connect plantations and native forests, in such a way as to create biological corridors. This has had positive effects on biodiversity, especially of native fauna. For example, it can be mentioned that certain birds such as toucans that were absent in the zone for many years, returned to the area. There has also been an increase in the number of certain species, such as the talking parrot. Within pure plantations or silvopastoral systems, many wild animals, especially birds, are observed. This is because there is more area with tree cover, many fruit orchards have been planted and efforts have been made to raise awareness in the communities. Silvopastoral systems, according to local experience, undoubtedly also favor wildlife.

No negative effects have been noted with *Eucalyptus* plantations. The Cooperative seeks to diversify *Eucalyptus* varieties, as well as working with other plant species including native trees.

- ***Silvopastoral systems***

The Volendam Cooperative is in a phase of change, where the density of the plantation is oriented towards the impregnated and laminated market, as far as possible not exceeding 500 trees per hectare as initial density, or in case it is higher, apply the first thinning as soon as possible. Furthermore, forest production today is practically only focused on silvopastoral systems, due to their perceived advantages. Previously, plantations began with 600–900 trees per hectare. The focus of both the producer and the technical assistance is shifting from pure forest to silvopastoral systems.

The main objective is the production of high-value wood and more intensive livestock production. Most of the installed systems are single-row, generally oriented from east to west. However, more recently double and triple rows plantations are also being implemented. Trials are currently being carried out on Nelder rings experiments, to find the right density for each forest variety.

Soil correction prior to planting is essential for the project to be successful. There are basically two planting seasons: autumn (March, April and May) and spring (August, September and October). However, the Cooperative is prioritizing autumn as a planting season, since during the early growth of trees, there are fewer problems with frost in winter than with very hot and dry summers.

Currently, many producers have adopted silvopastoral systems, using different *Eucalyptus* clones implanted in an average area of 5 hectares. In these practices, the combination with legumes has been included with good results. All these activities require continuous support for the producer.

What is being achieved are silvopastoral systems with trees of good genetics, well cared for, pruned, and with good spatial distribution. Silvicultural tasks are essential, especially pruning and thinning. Livestock activities are also being improved through the subdivision of pickets with electric fencing, the more intensive use of pickets, high rotation of paddocks, provision of good quality water, improvement of the grass component, correct mineralization of the Livestock, tick and fly control, daily rounds of pickets, tamer animals, etc. Silvopastoral systems are changing for the better and are beautifying the landscape of the area.

- ***Social component***

The Volendam Community has 550 people grouped in 177 families who are nucleated in the Cooperative. In addition, the Cooperative works with 200 more families, about 800 people, from neighboring communities linked to family farming, who are assisted by the Neighborhood Cooperation with Small Farmers (Covepa) program. These in turn have their own organization, be it a cooperative, an association of committees or producer committees.

One positive aspect of silvopastoral systems is that a very traditional activity, such as cattle ranching, is complemented by forestry. The producer does not need to change the use of the land, but complement it. Forestry activities generate a good source of employment for farmers, technical assistants, work teams, service providers, industry, logistics, etc. There are many people, from the cooperative or from neighboring communities, that can be trained. The Volendam Cooperative is located in an area where jobs need to be generated to avoid migration to the cities or social problems.

It is in a process of promoting the return to the use of wood, in all its forms and uses. When the pioneers founded the colony, many people lived on wood, knew how to transform it and use it. This was lost over time and the wood lost value as a material. The cooperative is working to reverse this trend by adding value to timber as it is a renewable resource generated locally.

In the Cooperative, the producers work at their own initiative, without incentives or external financing. Silvopastoral systems are a way of capitalizing the farm and generating adherence of the farmers to their land. The forestry industry contributes with additional income to the community. The purpose of Volendam is that the majority of services required in the industry could be provided by producers in the area, as a business option.

Parque Foresto - Industrial. A joint project with the German Cooperation Agency - GIZ is currently being developed, promoting silvopastoral systems and implementing a Forest-Industrial Park.

- ***Challenges***

Forest development must be planned in the long term, continue generating various silvopastoral production systems, also with higher value species. Corymbia and Australian cedar are just two good alternatives. It is necessary to continue with the training and the work of convincing the producers. Intervening in the wood value chain is something the Cooperative has set itself. The incorporation of legumes into silvopastoral systems is also something that is still very little spread.

Also in research, it is necessary to continue investing and aim to continue improving livestock. In terms of data collection, it is generally more linked to tree growth and much less to forage production or gain of kg of meat. A challenge is also to continue developing forest logistics, which is very early. There is still a lack of small or large undertakings that transform or industrialize wood.

The draft LAND USE PLAN: SILVOPASTORIL SYSTEM is a technical document that complies with the provisions of Law 294/93, in order to obtain the

Table 7.3 Lands subject to silvopastoral systems in the Paraguayan Chaco

District, Departament	Enabled surface (hectares)	Regulations in force MADES
Mariscal Estigarribia, Boquerón	2006	DGCCARN 016/2018
Carmelo Peralta, Alto Paraguay	1522	DGCCARN 798/2018
Mariscal Estigarribia, Boquerón	3900	DGCCARN 1446/2018
Mariscal Estigarribia, Boquerón	3187	DGCCARN 1031/2017
Pozo Colorado, Presidente Hayes	1900	DGCCARN 565/2019
Bahía Negra, Alto Paraguay	2133	DGCCARN 2182/2016
Mariscal Estigarribia, Boquerón	2000	DGCCARN 1059/2019
Fuerte Olimpo, Alto Paraguay	11,508	DGCCARN 0725/2017
Bahía Negra, Alto Paraguay	6060	DGCCARN 2209/2017
Villa Hayes, Presidente Hayes	833	DGCCARN 2010/2017
Bahía Negra, Alto Paraguay	6061	DGCCARN 2209/2017
Mariscal Estigarribia, Boquerón	513	DGCCARN 1951/2017
Teniente Martínez, Presidente Hayes	1127	DGCCARN 033/2019
Villa Hayes, Presidente Hayes	131	DGCCARN 0501/2016
Villa Hayes, Presidente Hayes	1516	DGCCARN 1986/2019
Villa Hayes, Presidente Hayes	902	DGCCARN 0724/2016
Mariscal Estigarribia, Boquerón	1121	DGCCARN 1835/2017

Environmental Impact Statement to be presented in MADES, and thus be able to present said Environmental Impact statement, to INFONA within the framework of Law 422/73 and its regulatory decree No. 11.681/75 (See Table 7.3).

7.5 Final Thoughts

Silvopastoral systems in Paraguay are a powerful tool for the sustainable management of natural resources, the recovery of the environment and the management of native and implanted forests. They can also contribute to increase forage and livestock production and improve animal welfare, and are suitable for small, medium and large producers.

In this sense, the experience that is being developed aims to have a correct management of the forest component seeking higher prices for the roundwood produced, and an integration with livestock production.

The implementation of silvopastoral systems is presented as highly promising due to the social, environmental and economic benefits, understanding that there is an intention to increase the surface area destined for their establishment, emerging as a challenge to face the management and administration of complexities that could arise in its harmonious and balanced handling of all its components.

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Chapter 8
Development of Silvopastoral Systems in the Peruvian Amazon

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Abstract Pasture-based livestock systems in the Peruvian Amazon region are characterized by degraded pastureland and their association with deforestation processes. Silvopastoral systems are an alternative to traditional tree-less pastures that has been recently developed and studied in this region of the country. This chapter provides information about the progress in the development of silvopastoral systems (SPS) in the Peruvian Amazon and the perspectives at national level for the next years. To accomplish these goals, we first review the experiences of establishing and evaluating SPS in five departments of the Peruvian Amazon. Then, we present a list of barriers for the implementation of SPS practices in the country and the current initiatives at the regional and national levels to promote and develop sustainable livestock production systems in the Peruvian Amazon region. We conclude that barriers such as available technology, capacity building, market access and associativity, financing and favorable environmental conditions need to be cleared first for the promotion and successful implementation of SPS in the Peruvian Amazon. Moreover, some of them need to be assumed by the producers, and others by the State at local, regional and national levels.

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8.1 Introduction

The Peruvian Amazon region represents 62% of the national territory. It concentrates 13.4% of the national population, with 27% of them living under poverty. The country faces significant deforestation problems recently with an annual deforestation of 160,000 hectares between 2012 and 2016, led mainly by agriculture (49–54% of total deforestation) and livestock activities (32–39%), followed by the exploitation of hydrocarbons, gold mining, hydraulic energy and road construction. Agriculture alone is responsible for approximately 70,000 ha $year^{-1}$ of forest loss, while livestock farming contributes to approximately 40,000 ha -$year^{-1}$.

Small-scale agriculture is the main driver of deforestation in Peru (ENBCC 2016). According to the ENBCC, between 2001 and 2014 around 1.6 million hectares were deforested for the expansion of coffee, cocoa, oil palm and cattle raising. Seventy nine percent (1,311,884 ha) of this loss occurred in San Martín, Loreto, Ucayali, Huánuco, and Madre de Dios departments. Deforestation caused by livestock activity is more permanent compared to agriculture, because grasslands are used for many years and even if they are abandoned, take longer to recover as secondary forests.

The total cattle population of Peru in 2012 was 5.2 million heads, 14.7% higher than that of 1994 (CENAGRO 2012). Cattle production is mainly practiced by small-scale farmers and only 21% of all agricultural producers belong to farmers' associations. Lack of a formal organization among farmers reduces their possibility to access credits from financial institutions and limits their ability to cover the expenses associated with technical support and new technologies for improving pasture management (CDP 2018).

Nearly 17% (887,299) of cattle population is concentrated in the Peruvian Amazon. Livestock activities in this region are developed in fragmented forest areas, as a result of early successional forests (locally called *purma*), or in abandoned land covered by native grasses such as *Axonopus, Paspalum* and *Homolepsis* after deforestation (Meza et al. 2007). According to CENAGRO (2012), 353,458 hectares of natural pastures (*Axonopus compressus*) are used for livestock in the Amazon region. In this regard, Rosenberg (2017) reported that around 80% of the pastures in the Peruvian Amazon are degraded or in the process of degradation.

Traditional animal production systems in the Peruvian Amazon are based on grass monocultures that, due to the lack of fertilization and inadequate grazing management, result in a high rate of land degradation and soil erosion. These cattle raising practices are characterized by low capital investment, and are viewed by farmers as a low-risk activity compared to crops that are subject to price fluctuations. However, the productivity is low and results in poor economic returns, contributing to rural poverty, vulnerability, and malnutrition, which in turn increases the need of farmers to continue deforesting. Loreto, Ucayali, Madre de Dios, San

Martín and Huánuco are the five departments located in the Amazon region that are most affected by deforestation, representing 86% of forest loss (355,555 ha) in the period 2010–2014. According to CENAGRO (2012) and the Ministry of Agriculture, cattle farms in the Amazon region of Peru have on average 25.4 hectares, and 10.6 animals, with milk production of 4.1 Kg per lactating cow per day and an average meat production per beef animal of 134.3 kg per year.

Peru plans to increase its per capita consumption of milk and beef by 16 and 28% respectively, and to reduce the imports of these goods by 2027. Such goal requires the increase in cattle production, that could increase deforestation in the Amazon region if a transformational change does not occur in the livestock sector. To prevent this situation, Peru launched in 2017 The National Livestock Farming Development Plan (MINAGRI 2017). This plan is focused on five key areas including: adequate management of natural resources, increasing competitiveness and value-added products, improving coverage of services to improve access to markets, and strengthening producers' technical capacity. This strategy generates space for improvement in the livestock sector through more sustainable production including silvopastoral systems (SPS). The SPS could increase productivity while increasing and diversifying farm income. This alternative is relevant environmentally, if we consider the 353,458 hectares of degraded pastures in the Amazonian region of Peru that could be improved, and the Peruvian Government commitment to implement 119,000 hectares of SPS by 2030 for reducing carbon emissions in the framework of The Nationally Determined Contributions (NDC). Although SPS have been used for decades and have shown the ability to increase land-sparing and to reduce deforestation (Loconto et al. 2019), their development and adoption in Peru is still limited when compared with other countries of Latin America. Hence, this chapter provides a review of SPS experiences in five significant departments of the Peruvian Amazon, the current constraints for the implementation of these practices in the country, and the initiatives at a regional and national level to promote and develop a more sustainable livestock production in the Peruvian Amazon region.

8.2 Characteristics of the Peruvian Amazon

The Peruvian Amazon covers an area of approximately 78,456,483 hectares. Geographically, this area is located between 0°2′20,76″ and 14°30′55″ south, and between 68°39′12″ and 79°29′01″ west (Fig. 8.1). The Peruvian Amazon consists of two distinct ecoregions: the lowland or thick jungle of the Amazon basin and the highland jungle or semi-tropical forest on the mountain slopes (Klarén 2017). The lowland jungle, is the largest ecoregion of Peru, standing between 80 and 1000 meters above sea level (masl). It has very warm weather with an average temperature of 27 °C, high relative humidity (over 75%) and yearly rainfall of approximately 1000 mm (MIDAGRI 2022). Because of high temperatures and high rainfall, soil fertility is generally low. The highland jungle is the ecoregion that extends into the eastern foothills of the Andes, between 1000 and 3800 masl with an average

Fig. 8.1 Map of the Peruvian Amazon (left) and the five most representative departments (right). (Source: MINAM (2015))

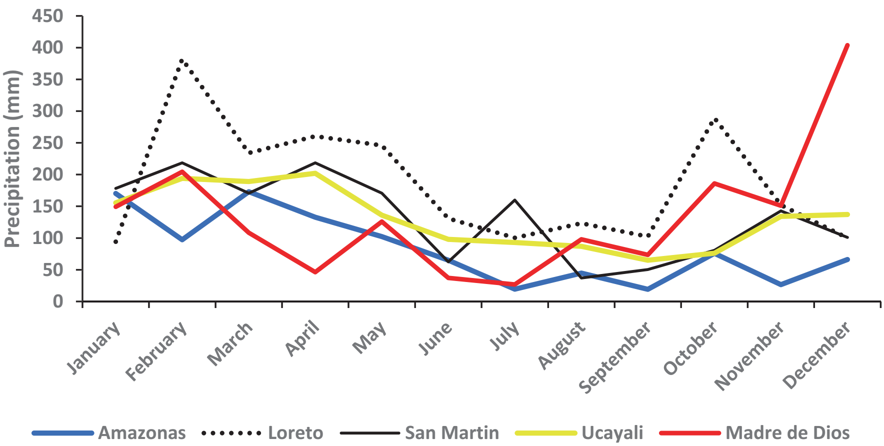

Fig. 8.2 Annual precipitation (2022) in five most representative departments of the Peruvian Amazon

temperature of 23 °C, average relative humidity of 75%, and yearly rainfall of approximately 2600 mm to 4000 mm. (see Figs. 8.2 and 8.3) (MINAGRI 2020).

These eastern slopes of the Andes are home to a diverse fauna and flora because of the different altitudes and climates (Pulgar Vidal 1979). In the Amazon region of Peru, the departments with more geographical extension are Loreto (47.8%), Ucayali (13.4%), Madre de Dios (10.8%), San Martín (6.2%) and Amazonas (4.7%) that together represent 83.0% of the region (MINAM 2015). Elevation, rainfall,

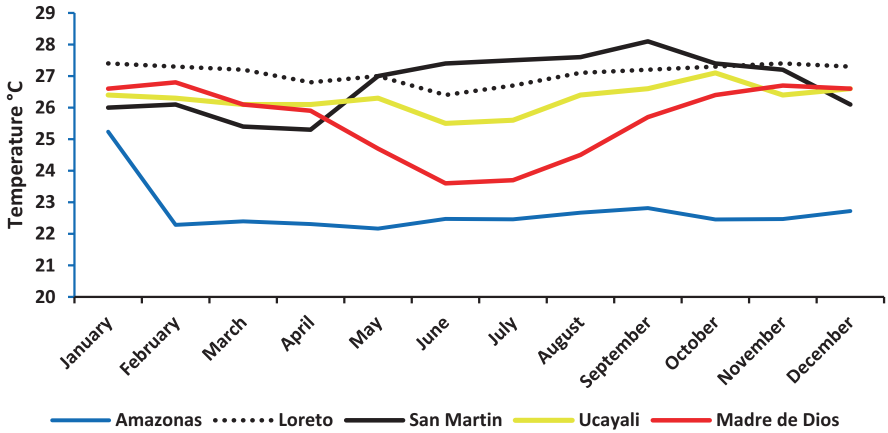

Fig. 8.3 Annual temperature (2022) in five most representative departments of the Peruvian Amazon (MIDAGRI 2022)

Holdridge's life zone and temperature affect the development of SPS in terms of trees species, pasture species and the type of spatial arrangements used.

8.3 SPS Technology Available in the Peruvian Amazon

In the last decades, various silvopastoral initiatives have been developed in the Peruvian Amazon at experimental stations and small-scale farms, but mainly for research purposes. The national government, through the Directorate General for Livestock Development, the National Institute of Agrarian Innovation (INIA) and regional governments have been conducting actions to promote and implement SPS in regions such as San Martín, Amazonas and Madre de Dios. Local and national universities have also been conducting research activities in the area, whereas non-governmental organizations (NGO) have been focused to provide training and assistance to farmers on technical issues.

Livestock production systems in the Peruvian Amazon are predominantly extensive and semi-extensive. However, production is limited due to inadequate grazing management. SPS consist mainly of live fences and scattered trees in pastures (Fig. 8.4).

8.3.1 Loreto

Loreto department is located in the lowland jungle and has a surface of 37,503,942 hectares. In this department, Agroforestry systems have been studied during the last 30 years in order to improve degraded soils, which are prevalently classified as Ultisols. In Yurimaguas province, SPS with grass-legume mixtures as the forage

Fig. 8.4 Silvopastoral system with trees arranged as live fences, and dispersed in the paddocks (left) and conventional system with trees arranged as live fences (right)

component of the system are some of the main alternatives evaluated to recover degraded lands (Arevalo et al. 1998). Livestockis predominantly oriented to beef production. Land degradation in this area has been induced mainly by overgrazing with long-term changes in soil physical properties and surface soil compaction (Alegre and Lara 1991). Alegre et al. (2012) evaluated a SPS with brachiaria (*Brachiaria sp.*), peach palms (*Bactris gasipaes*) planted at a 5 × 5 m distance, and a legume cover crop (*Centrosema macrocarpum*) for beef production. Cattle was managed in rotational grazing (14-days resting and 14-days grazing periods) with a stocking rate of 3 animals ha^{-1}. As a result, there was an improvement in soil fertility and a reduction of soil compaction in the grazing area. The average daily weight gain was 445 g – $animal^{-1}$ day^{-1} during the 4 years of the study. These results are substantially better than the values registered in traditional grazing systems. Current work in the area is focused on recovering degraded brachiaria (*Brachiaria brizantha*) pastures (Alegre et al. 2017). The approach consists of fertilizing with 40 kg ha^{-1} of P and then overseeding the legume *Centrosema*. After the full establishment of the pasture component, fast-growing trees are planted at a density of 3 × 3 m. The trees include capirona (*Calycophylum spruceanum*), bolaina (*Guazuma crinita*) and marupa (*Simarouba amara*). After 5 years of tree growth, the tree stand is thinned to a distance of 6 × 6 m. Cattle is managed under rotational grazing at a stocking rate of 3 animals ha^{-1}, based on previous experience. The carbon stocks for different land-use systems were also evaluated in Yurimaguas. The average carbon stock of a 10-year-old peach palm plantation with *Centrosema macrocarpum* was 55 t C ha^{-1} with a flux of 5.5 t C ha^{-1} y^{-1}; and in a 10-year multistrata system with *Centrosema* the carbon stock was 59 t C ha^{-1} with a flux of 5.9 t C ha^{-1} y^{-1} (Alegre et al. 2002; Palm et al. 2002).

8.3.2 Ucayali

Ucayali department is located in the lowland jungle and has a surface of 10,532,795 hectares. Livestock production systems in this department are predominantly extensive and semi-extensive and farming practices are characterized by low level of inputs and mainly oriented to beef production with a small proportion oriented to dairy production. However, production is limited due to inadequate grazing management which has led to soil erosion and the presence of invasive species. Vela et al. (2010) developed a baseline of silvopastoral initiatives in Ucayali, observing the different designs of SPS (trees in paddocks, forage banks, live fences and windbreaks), and identified that 50% of farmers implement SPS as a complement of cultivated pastures, 19% to improve the nutritional value of natural pastures, 13% to diversify production systems, 13% to recover degraded land used for pastures or crops, and 5% to improve the sustainability of the soil – plant – animal system. Farmers also indicated as main benefits for implementing SPS the improved management of their productive system (46% of farmers), the increased knowledge of livestock systems (34%), the improved value of the land (8%), the higher economic income (8%), and the introduction of new production systems (4%). Studies conducted by Riesco et al. (1995), Clavo et al. (2006) and Vela et al. (2019), identified livestock farms that incorporate primary forests trees such as *Amburana cearensis, Ceiba samauma, Swietenia macrophylla, Aspidosperma macrocarpon* and *Dipteryx odorata*; and secondary forest trees such as *Calycophyllum spruceanum, Simaruba amara, Guazuma crinita, Tabebuia serratifolia, Terminalia oblonga, Erythrina spp., Inga edulis, Ficus insipida, Inga* spp.*, Gmelina arborea, Jatropha curcas, Crescentia cujete, Schizolobium amazonicum* and *Vitex pseudolea;* for providing shade to cattle, firewood, timber, fruits and medicinal products. In this regard, Clavo and Fernandez-Baca (1999) suggested the importance of natural regeneration as an alternative to tree planting during the establishment of silvopastoral systems in Ucayali. They identified *Cordia ucayalensis, Ochroma pyramidale, Tabebuia serratifolia,* and *Trema micrantha* as potential natural tree species due to their frequency (42 plants ha^{-1}), survival rate (86%), noninterference with planted tree species and potential economic value.

Vela et al. (2019) reported the performance of a multistrata SPS prototype in Ucayali department based on pasture (*Brachiaria dictyoneura)*, shrubs and forage trees (*Crescentia cujete, Cratylia argentea, Erythrina berteroana* and *Leucaena leucocephala*), short-cycle tree (*Simarouba amara*) and long-cycle tree (*Dipteryx odorata),* compared with a monoculture plot of *Brachiaria dictyoneura* grazed by Holstein × Zebu Gyr cows. Results showed improved soil physical and chemical characteristics, increased macrofauna, lower luminosity (189.9 *vs*. 463.7 °lux before), decreased temperature (32.5 vs. 35.4 °C before), increased system relative humidity (63.6 *vs*. 50.8% before), average daily milk production of 5.0 kg cow^{-1} day^{-1}, stocking rates of 5 Livestock Units ha^{-1} and a potential of carbon sequestration equivalent to 133 t C ha^{-1}. These results suggest that there is a wide variety of shrubs and tree species that can be used as fodder, wood, and live fences among other purposes. Currently, the average carrying capacity of the improved grass is 2.5 mature cattle ha^{-1}; nevertheless, it has been commercially possible to increase the carrying capacity to 4–5 mature cattle ha^{-1} in intensively managed systems by supplementing forage using cut and carry, polishing rice or other supplements available in the department. Additionally, supplementation with brewery residue and palm oil byproducts promote increases in milk production up to 3400 kg of milk per lactation with F1 Holstein × Zebu Gyr cows. In terms of carbon sequestration, an evaluation of a SPS based on a 30-year rubber (*Hevea brasiliensis*) plantation with kudzu (*Pueraria phaseoloides*) produced an average carbon stock of above and below ground of 152.6 t C ha^{-1}. Similarly, legumes and grasses within the different tree species increased the carbon stocks by 2–5 t C ha^{-1} (Alegre et al. 2002; Palm et al. 2002). Concha et al. (2002) reported a difference of 22.5 t C ha^{-1} of carbon stock between a SPS based on scattered trees and pasture on degraded land in Ucayali; demonstrating the potential environmental contribution of SPS in this department.

8.3.3 Madre de Dios

Madre de Dios department is located in the lowland jungle and has a surface of 8,503,657 hectares. It is located in southeastern Peru, on the border with Bolivia and Brazil. This department is considered the capital of the Peruvian biodiversity since it hosts more than fifteen protected areas. Livestock production is mainly located in the provinces of Tambopata and Tahuamanu and is predominantly oriented to beef production. A baseline study conducted by The Ministry of Agriculture (MINAGRI 2019a) in the area, reported average livestock farms with 67 hectares of cultivated pasture and different crosses of Brown swiss cattle with Zebu breed. MINAGRI (2019b) also evaluated chemical characteristics of the soil in the department, determining low soil fertility and the need of fertilization using phosphoric rock and agricultural dolomite prior to the implementation of cultivated pastures. Silvopastoral systems present in the area are based on timber and fruit trees such as *Inga edulis, Guazuma crinita, Calycophyllum spruceanum, Guazuma ulmifolia, Gliricidia sepium, Bactris gasipaes, Dipteryx Micrantha, Gmelina arborea,* and *Cedrela odorata*, in association with different varieties of *Brachiaria*. MINAGRI is currently promoting the implementation of SPS in Madre de Dios, as an alternative of sustainable land use against illegal mining activities and deforestation. They are supporting the establishment of 600 hectares of trees (*Guazuma crinita* and *Dipteryx micrantha*) in live fences associated with cultivated grasses, using a pasture density of 4.0 Kg seed of *Brachiaria* sp. per hectare. Additionally, MINAGRI is also encouraging the implementation of high-density protein banks for improving livestock production, prioritizing the use of *Leucaena leucocephala* and *Centrosema macrocarpum*.

8.3.4 San Martin

San Martin department is located mainly in the high jungle and has a surface of 4,907,221 hectares. Out of 70 surveyed farms in this region, Pizarro et al. (2020) reported that more than 47% of farmers with SPS in this department have on average less than 10 ha of total land while 35% of landowners have between 10 and

30 ha. Livestock in the department is oriented to dairy and beef production mainly in dual purpose systems. In Moyobamba province, the predominant livestock breeds are Zebu x *Bos taurus* crossbreds (36%) followed by Brown Swiss (34%). Silvopastoral systems consist mainly of live fences and scattered trees in pastures. The tree species in SPS are mainly used as a source of firewood, timber or fruits. The most predominant species are *Inga edulis, Eucalyptus* sp*., Ormosia coccinea, Psidium* sp., *Cedrelinga catenaeformis, Colubrina glandulosa* and *Mangifera indica*. These trees were observed in associations with the following pastures: *Digitaria decumbens, Brachiaria brizantha, Arachis pintoi, Pueraria phaseoloides, Brachiaria decumbens, Axonopus compressus* and *Paspalum dilatatum.* Holmann & Lascano (2001) reported increased stocking rates in farms of San Martin compared with pasture on degraded land by the use of *Centrosema macrocarpum, Brachiaria decumbens* and *Brachiaria brizantha*. Similarly, SPS with *Eucalyptus torelliana* in live fences and *Brachiaria decumbens* supported a stocking rate of 1.8 livestock units (LU) ha^{-1} and a productivity of 2200 kg of milk per lactation (Pizarro et al. 2020). Alegre et al. (2019) reported chemical soil attributes in three types of SPS of Moyobamba province, showing acid pH (4.83), high organic matter (4.3%), low phosphorus (2.36 ppm) and low to medium potassium (114 ppm). In relation to environmental aspects of SPS in San Martin department, Ruiz-Llontop et al. (2022) determined the carbon footprint (CF) of milk production (in kg of CO_2 equivalents (CO_2e) per kg of fat and protein corrected milk (FPCM)) on eight representative dairy farms of Juan Guerra district based on cultivated grasses such as *Brachiaria brizantha*, and living fences with *Guazuma ulmifolia* as the predominant silvopastoral arrangement, and low level of external inputs, obtaining an average value of 2.26 ± 0.49 kg CO_2e per kg of FPCM, with enteric fermentation as the most important source (1.81 ± 0.51 kg CO_2e per kg of FPCM), followed by manure management, land use, and energy/transport (0.26 ± 0.06, 0.14 ± 0.04, and 0.05 ± 0.04 kg CO_2e per kg FPCM, respectively).

8.3.5 Amazonas

Amazonas department is located mainly in the high jungle region and has a surface of 3,724,462 hectares. Out of 219 surveyed farms in Molinopampa (n = 130) and Huayabamba (n = 89), Pizarro et al. (2020) reported that more than 80% of farmers located in the Amazonas have less than 30 ha of average total area. The SPS are predominant in the southern part of the department, and livestock is mainly oriented to dairy production. Alegre et al. (2019) reported SPS based on the associations of *Populus alba, Inga edulis* and *Eucalyptus torelliana* trees with *Brachiaria mutica* at 1200 masl and *Pinus patula, Cupressus sempervirens L., Ceroxylon peruvianum* and *Alnus acuminata* trees with *Dactylis glomerata* and *Lolium perenne* pastures at 2400 masl. Vasquez et al. (2020) evaluated the average carbon stock of above and below ground of four types of SPS: *Alnus acuminata* in alleys, *Pinus patula* in alleys, *Cupressus macrocarpa* in live fences and *Ceroxylon quindiuense* in scattered trees, associated in all the cases with *Dactylis glomerata, Lolium multiflorum* and *Trifolium repens.* In this study, researchers reported average biomass and soil carbon stock of 179.5 t C ha^{-1} for *Ceroxylon quindiuense*, 160.8 for *Pinus patula*, 150.1 for *Cupressus macrocarpa* and 108.2 for *Alnus acuminata*. They also observed high dry matter yields (0.3 kg m^{-2}) and nutritional quality (Crude Protein: 16.1% and IVDMD: 66.1%) in pastures of SPS associated with *Alnus acuminata*. Similarly, Oliva et al. (2018a) reported positive effects of *Erythrina edulis*, *Alnus acuminata* and *Salix babylonica* on yield and nutritional values of *Lolium multiflorum* and *Trifolium repens.* In terms of financial aspects, Chizmar (2018) evaluated a SPS model comparing with a typical cattle forage system at Amazonas department determining higher net present values (992.5 vs. 796.9 US Dollars ha^{-1}) and benefit-cost ratio (1.16 vs. 1.11) at a 4% discount rate. However, SPS showed higher establishment cost (1203.4 vs. 1197.5 \$ ha^{-1}) and payback period (4 vs 3 years).

8.4 Barriers for Implementation of SPS Practices

To achieve the required scale of SPS in Latin America there is a need to ensure that farmers have access to inputs, capital and information (Arango et al. 2020). There are 350,000 ha of degraded pastures in the Amazonian region of Peru that could be improved by implementing SPS aimed at enhancing carbon sinks as well as reducing the carbon emissions associated with deforestation and forest degradation. Here we present, based on an exchange of ideas with relevant actors in Peru associated with land use options, the main constraints to implement SPS practices in the Amazon region:

8.4.1 Technology

The technical knowledge required for pasture management, livestock management, and forest management are perceived to be major difficulties during SPS adoption (Frey et al. 2012). More specifically, new rotational grazing systems (Bussoni et al. 2015), planting, pruning, and harvesting of trees and shrubs (Dubeux Junior et al. 2017) are the main challenges of small-scale farmers for implementing SPS. We have described examples of SPS practices, validated with farmers, for certain areas in the Amazon region of Peru. In order to determine the appropriate species to include in SPS, it is necessary to conduct research activities and participatory workshops with farmers to recover indigenous and local knowledge and exchanging experiences with specialists of Latin America working in SPS. Indeed, successful SPS implementation requires compatibility with farmers' previous experience and knowledge, the priorities and objectives of the farm, and the ease of incorporation into current farming practices (Zabala 2015). Proper selection of species is critical to the success and sustainability of SPS, since the costs of introducing tree and shrub species and the time required for their development can be considerable. It is also important to consider that the technical and economic feasibility of establishing a specific technology will be decisive for its adoption. Oliva et al. (2018b) reported for example that the land size, the total number of cattle, the number of cows in production, the soil conservation, the trees inside the property, and the access to support in planting activities are some of the factors that determine the adoption of SPS technology in the Amazonas department. Experience is also needed in designing and testing silvopastoral innovations such as the rational use of adapted forages, new spatial and temporal arrangements of trees and pastures, improved feeding strategies, and more studies related to the beneficial effect of prevalent tree species in Peruvian SPS. In all cases, the presence of an efficient value chain for products derived from SPS should be considered. For example, lack of technology and supply providers (seeds, fertilizers, tree seedlings, electric fences, etc.) has been identified in most of the amazon region for the establishment of SPS. Furthermore, when markets are distant, the probability of selling value added products from the SPS is reduced, thus reducing the potential probability of adopting new systems. The physical infrastructure also reduces farmers' access to cheap seeds and seedlings, fertilizers, and other vegetal material critical for SPS implementation. This situation is similar for most Latin American countries where formal grass and legume seed sale systems are underdeveloped, limiting the purchase of planting material or the number of varieties available (Arango et al. 2020).

8.4.2 Training

Considering that silvopastoral practices are relatively new in the Amazon region of Peru, it is necessary to develop and implement technical extension activities that consider specific characteristics of the farmers in the region such as the size of the production unit and the farmer's level of education. Aspects of forestry management, crop and livestock practices, genetic improvement of cattle, farm economic management, environmental impacts of SPS measures, irrigation practices, and market access should be discussed with the farmers in order to ensure a full understanding of the potential of SPS. In this regard, technical assistance sustained beyond the timeframe of initial adoption and implementation is critical to ensure the continued adaption of specific SPS management practices to each farmer's needs (Chará et al. 2019; Frey et al. 2012; Zabala 2015). In addition, to assess land use options, it will also be necessary to define the impacts of sociocultural characteristics of farmers, as they could significantly affect the implementation of SPS. When looking at cultural and behavioral factors, many livestock producers in Latin America prefer traditional production systems over more technical and sustainable ones for reasons of simplicity and risk aversion. It is important to understand how livestock producers make decisions, regarding the adoption of technologies or the factors that influence those decisions. Certainly, this is, as indicated by Arango et al. (2020), a knowledge gap that needs to be addressed in order to assure a more widespread adoption of strategies such as SPS. Another important issue that Peruvian Government has to face for offering an adequate extension service to farmers, is related to the establishment of strategies oriented to ensure the availability of extension agents in the Amazon region and to cover their training needs related to the production of SPS. Barrantes et al. (2017) found that only 10.2% of Peruvian agricultural and livestock producers in the country had access to extension services. Limited road connectivity and rural road deterioration also prevent free movement of extension agents and inhibit service delivery to farms. Universities of the Amazon region may play a key role in this aspect by providing trained professionals in SPS management.

8.4.3 Incentives

It is frequently recognized that there is a need to provide farmers with incentives to adopt silvopastoral practices such as those that have already been defined in other countries. A financial mechanism to cover the initial investment and to alleviate farmers' negative cash flow during the first 5 years of operation is needed. A key element is the definition and valorization of the primary ecosystem services that SPS provides. These mechanisms are oriented to those benefits, direct and indirect, that people obtain from properly functioning ecosystems, such as water regulation, biodiversity maintenance and carbon sequestration (Casasola et al. 2009). The lack of information about ecosystem services related to carbon under specific SPS conditions in the Peruvian Amazon is a gap we need to fill. Specifically, there is limited information in the Amazon about the differences between SPS and prevalent land use for raising cattle on degraded land, particularly in relation to GHG emissions and carbon capture. A mechanism by which SPS can contribute to the mitigation of GHG emissions is the reduction of enteric methane emissions. Specifically, these emissions from ruminants could be mitigated by supplying forages, either herbaceous and shrubby or tree-legumes containing secondary plant metabolites such as condensed tannins and saponins (Martin et al. 2016). Reports in the literature indicate between 5% and 10% emission reduction compared to similar diets lacking the aforementioned components (Molina-Botero et al. 2019). This mechanism requires further studies before it can be included in inventories of enteric methane emitted by herbivores, especially because of the diversity of forages that prevail in the Amazon region of Peru.

The Amazon region requires development and field evaluation of financial mechanisms for the promotion of SPS to match farmers investment needs with national and international financial sources. Investment in livestock activity based on SPS at the Peruvian Amazon could not be considerably leveraged by the smallholder; thus, financial incentives from external agents are important to consider. Regarding the credit system in Peru, though bank loans are granted by some financial entities, such as Corporación Financiera de Desarrollo (COFIDE) and Banco Agropecuario (AGROBANCO), unattractive proposals are often offered to the smallholder. For instance, short and medium-term credits, no grace period, and annual interest rates between 20% and 25% for working capital and between 17% and 23% for fixed assets (AGROBANCO 2017). In addition, because of the several requirements imposed by private banking to farmers to accept credit, applications are not completed, especially those related to handing over of a property title or financial guarantee (AGROBANCO 2020). Besides, agricultural activity is considered as a risky investment by financial entities because this sector is vulnerable to extreme climate changes and farmer payment defaults. In favor of this, an active role from the government is important to generate financial mechanisms for the implementation of pastoral systems, such as SPS, which give the smallholders access to loans with lower interest rates and longer payment periods. Thus, interventions on grassland areas of 104 farms to convert them into SPS were fostered in countries, such as Colombia (Pagiola and Rios 2013; Rivera et al. 2013). In addition, granting of credits with differentiated interest rates of 2%, 4%, and 5% for small, medium, and large cattle ranchers, respectively, and a grace period of up to 2 years have been established by the second-tier bank FINAGRO and implemented, among others, by Banco Agrario de Colombia as a strategy to finance the purchase and planting of tree species, electric fences, windbreaks, and others, which support the implementation of SPS (Banco Agrario de Colombia 2020).

This also occurs in other parts of Latin America in which, as indicated by Calle et al. (2013), lack of capital and the high cost of establishment and management represent the two most important barriers to adopting these systems. Furthermore, as described by Saunders et al. (2016), the costs of establishing and subsequently managing, agroforestry systems are generally higher than those of conventional woodlands and forests since individual trees require protection from livestock, while the forest canopy requires active management in order to maintain the productivity of both the grass sward and the trees to produce high-quality timber. However, when both the potential economic and environmental benefits associated with agroforestry systems are identified and assessed, the combined returns are potentially greater than those of plantation forests alone.

Working through cooperatives or associations can also benefit agribusiness as an incentive. In Uruguay, Paraguay and Costa Rica, cooperatives control the dairy chain, providing more profits and lower transaction costs to members. In Nicaragua, Ecuador and Paraguay, small-scale farmers are organized in associations or cooperatives that emphasize a vertical integration, organizational model, market articulation and business strategies (FAO 2012). Cooperatives and farmer associations offer the possibility to implement collective voluntary approaches and achieve competitive levels similar to those of larger companies (Liendo and Martínez 2011).

8.4.4 Planning and Policies

In order to promote SPS practices, support of governments at local and national levels and the engagement of both the private sector and all key local institutions are required. Strengthening institutional capacities of local and regional governments for improving their planning and evaluation processes are also necessary. Effective policies targeting both the demand and supply-side of cattle value chains are needed to generate market opportunities, increasing in this way the livestock competitiveness and sustainability in the country. Additionally, the Peruvian Government has to establish clear policies that ensure the sustainable use of degraded areas and the conservation of protected zones. Regions targeted for intervention should be aligned to specific ecological zoning protocols. However, ecological zoning has not been carried out in the Peruvian tropics. Implementing a system to measure, report and verify emissions is also required by the agricultural sector as this will contribute to the promotion of SPS implementation based on its provision of carbon sequestration. Furthermore, the lack of property rights among farmers is widespread and affects decision-making processes, including implementation of long-term investments such as SPS; therefore, specific policies need to be implemented in the public sector in order to solve this constraint. In this regard, it is important to mention that government incentivization of decentralization in the livestock sector has had consequences for smallholders. Land consolidation under private land developers has reduced farmer land holdings in the past 30 years, facilitated by a series of government legislative actions. In 2002, Law N° 28059 and Legislative Decrees 994 and 1089 promoted private sector investment in land for development purposes (World Bank 2017). However, the legislation had the added effect of increasing land prices beyond an affordable level for farmers entering agriculture, leading to an increasing number of small farmers becoming renters, rather than purchasing land outright (World Bank 2017). A study by Pokorny et al. (2021) found that of cocoa farmers interviewed in San Martín, many of which keep cattle, fewer than 20% held a legal title for the land they occupied. This lack of formal land tenure documentation and consequent lack of tenure security is understood to extend to farmers producing other commodities in the region. Land tenancy laws can incentivize limited-length land rental contracts, which in turn de-incentivize investments in the land that farmers may never realize the benefits of, i.e., improved soil quality and structure, improved forage production, and increased dairy cattle productivity from SPS (Frey 2009).

8.4.5 Environmental Conditions

Farmers producing on degraded pastures have raised concerns about nutrient depletion, soil fragility, decreased soil fertility, and a rising need for synthetic fertilizers (Calle et al. 2009). The prolonged dry season was also associated with high rates of tree mortality during the SPS implementation period (Hoch et al. 2012). Under increasingly volatile climate conditions, more severe droughts during the summers pose a major threat to more widespread adoption of SPS. An environmental barrier of somewhat lesser importance to consider is the presence of dangerous wildlife near farms (Bussoni et al. 2015). In the Madre de Dios region of Peru, farmers reported disruptions in fruit production on SPS by monkeys, while other SPS adopters in the region lost calves to hunting jaguars. Increased biodiversity was noticed by farmers in studies from Lee (2020) and Calle et al. (2009), as well as a 2016 study from Solymosi et al. (2016). While this is often listed as a benefit and an ecological improvement, many farmers remain wary of the losses to harvests wildlife can be responsible for, as well as the dangers predators can pose to livestock (Bussoni et al. 2015; Calle et al. 2009; Peri et al. 2016).

8.5 Initiatives of the Peruvian Government to Promote SPS

Silvopastoral systems in Peru largely aim to create productive regimes out of improved fallows abandoned during a period of civil unrest during the 1980s and 1990s in which the ruminant populations were decimated (Cotta 2017; Vera 2006). The Peruvian Government has defined the Nationally Determined Contributions (NDC), which includes a reduction of 30% of GHG emissions by the year 2030 (GTM-NDC 2018). This projected GHG reduction considers, among other strategies, the recovery of degraded soils via SPS in the Peruvian Amazon to mitigate 1.1 Mt CO_2 eq arising from intervention on 119,000 ha. Furthermore, Peruvian Amazonian departments have already started the development of action plans and related policy for "Low -emission rural development strategies" which have the potential to be scaled. However, this initiative is not well articulated with the national government, and there is a lack of a sense of urgency for the protection of forests.

Since 2018, the Peruvian Government is taking action to promote the adoption of new paradigms for consumption and low carbon production. The normative and institutional framework that accompanies this approach is observed in the Climate Change Framework Law, the National Agrarian Policy, the Forestry and Wildlife Law, the National Competitiveness and Productivity Plan, the Guidelines for green growth, and the National Livestock Development Plan, among others. The Peruvian Government is also advancing in the cross-sectoral coordination to guide the identification and implementation of the NDCs through the Multisectoral Working Group. However, this group is temporal and has made progress especially on the identification of the measures to achieve NDCs in the different sectors, but little progress has been made on the implementation. Currently, there is a lack of a coordination mechanisms within the agricultural sector in order to align the technical, financial and political efforts for implementing the identified actions to reduce emissions from this sector. Although few advances towards implementation exist, the Peruvian Government has started allocating public funding to overcome some of the barriers for the transformation of the livestock sector in the Amazon. For example, in 2019, the Peruvian Government, through the Ministry of Agriculture, in coordination with sub-national governments implemented 600 hectares of silvopastoral systems based on forage pastures associated with native trees used as live fences in paddocks, the use of electric fences for rotational grazing and the implementation of protein banks. The purpose of this intervention was to promote sustainable livestock production in the provinces of Tambopata and Tahuamanu (Madre de Dios department), as well as to contribute to the fulfilment of the NDC goals of the agricultural sector, specifically the Mitigation Measure: Implementation of management techniques of pastures through silvopastoral systems to reduce GHG in the jungle. This activity shows the first steps to promote sustainable livestock production at national level. However, rolling out an ambitious plan will demand to move forward alongside a holistic approach that supports sustainable livestock farming production and monitor deforestation trends in Peru. This process should involve all stakeholders in the livestock farming supply chain, including producers, local governments in livestock farming departments, and the private sector.

8.6 Conclusions

Silvopastoral systems in the Amazon region of Peru varied depending on local initiatives and local conditions of each department. Silvopastoral systems have the potential to serve as an overall national and regional management strategy to reduce deforestation and recover degraded land in the Peruvian Amazon, to improve livestock productivity in a sustainable way and, ultimately, to strengthen the resiliency of small- and large-scale farmers while helping to mitigate emissions. However, studies on adoption of SPS in the country have so far been limited and occurred spontaneously and empirically. Barriers to establish SPS need to be worked by the producers, and others by the State at different levels (local, regional and national government). Development of policies and adequate financial incentives are required to expand SPS. Furthermore, adoption and implementation of SPS on degraded lands will require a suite of strategies to disseminate information, train personnel (train-the-trainer type programs) and follow up with land managers at the farm level, including the need of training materials that directly highlight the benefits of implementing SPS. While the benefits of implementing these systems, such as the ecosystem services and the economic factors, can be numerous and, to some extent, a function of the potentially diverse nature of the system's components and the specific environment, a dedicated effort should be made to fund research and extension activities that aim to clearly define the benefits of silvopastures. It is imperative that the Peruvian Government continue promoting SPS on degraded lands to recover them and achieve the NDC commitments, generating at the same time better conditions to motivate farmers to adopt or scale up SPS.

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Chapter 9
Silvopastoral Systems in Colombia: From Pilot Farms to NDCs

Julián Chará, Enrique Murgueitio, Fernando Uribe, Marcela Modesto, and Manuel Gómez

Abstract This chapter analyzes the process of adoption of silvopastoral systems in Colombia from pilot farms where silvopastoral models were developed, to more than 4000 farms implemented in the project Mainstreaming Sustainable Cattle Ranching and the further developments based on the lessons learnt from this experience. This project introduced environmentally friendly cattle production on more than 100,000 ha, promoted the establishment of 38,390 has of silvopastoral systems (SPS), improved stocking rates and productivity in intervened farms, enhanced biodiversity and incorporated/protected 50 globally endangered plant species on the farms, and sequestered 1.56 million Mg of CO_2eq. The main results and achievements of the process are highlighted as well as the technical, financial and knowledge barriers and challenges faced. It also analyzes the lessons learned and how they were used to design the NAMA of sustainable bovine livestock that aims to scale up silvopastoral systems and increase efficiency and sustainability of cattle farming in the country to increase dairy and beef production while reducing their impact on climate change and natural resources.

Keywords Silvopasture · Payment of Environmental Services · Live Fences · Scattered trees · Adoption · NAMA

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9.1 Introduction

Cattle production is a very important productive activity for the Colombian economy with a long tradition and deeply rooted in the culture of rural areas. According to FEDEGAN (2018), the livestock sector accounts for 6% of national and 19% of agricultural employment, generating approximately 810 thousand direct jobs. In 2018, livestock contributed 1.3% to the national GDP, 21.8% to agricultural GDP, and 48.7% to livestock GDP (FEDEGAN 2018). Colombia's cattle population, as reported by ICA (2023), stands at 29,301,392 head, marking a 4.7% increase compared to 2022. This positions Colombia as the twelfth-largest cattle inventory globally and the fourth largest in Latin America, after Brazil, Argentina, and Mexico (FAO 2022). The cattle are distributed across 633,841 farms, spanning approximately 34 million hectares (ICA 2023), accounting for over three-quarters of the country's agricultural land and leaving a substantial spatial, environmental, and carbon footprint (Zuluaga et al. 2021).

Despite recent improvements in production indicators, they still lag behind those of more developed countries in South America and other regions around the world. While concerns about the adverse effects of cattle farming are growing, the predominant production systems in the country remain reliant on grass monocultures and low-tech practices, resulting in suboptimal production parameters and negative impacts on soil health, the environment, and climate (González et al. 2015). Among the most significant impacts are deforestation, destruction and degradation of ecosystems, loss of biodiversity, greenhouse gas emissions, soil erosion and compaction, contamination of watercourses, and disruption of hydrological regulation (Chará and Giraldo 2011).

Recognizing the detrimental effects of conventional livestock farming practices and the need for improved production parameters, initiatives have been undertaken in Colombia to reduce the environmental footprint of cattle farming while enhancing its productivity and competitiveness. Notably, the promotion of silvopastoral systems (SPS) has emerged as a pivotal endeavor due to the environmental and productive benefits they offer. The project *Mainstreaming Biodiversity in Sustainable Cattle Ranching*, carried out from 2010 to 2020 played a central role in the development and promotion of silvopastoral systems in five regions of Colombia, along with supporting the formulation of public policies that foster sustainable livestock practices and silvopastoral systems, including the formulation of the NAMA for Cattle Ranching. This project builds upon the insights gained from the project *Integrated Silvopastoral Approaches to Ecosystem Management* carried out from 2002 to 2007. This text provides an overview of the primary silvopastoral systems developed in Colombia, tracing their journey from pilot farms to national-level proposals, assessing their impact, and informing the development of public policies to promote their adoption.

9.2 Pilot Farms

Although several institutions have worked on the development of agroforestry and silvopastoral proposals in Colombia, the pioneering initiatives that have consistently contributed to the successful implementation and management of SPS are El Hatico Natural Reserve and Hacienda Lucerna in Valle del Cauca, and Hacienda El Chaco in the Magdalena Valley in Tolima (Calle et al. 2013; Zapata Cadavid et al. 2019). These cattle farms have served as research and demonstration sites for silvopastoral systems and have been visited by thousands of producers, technicians, students, scientists, government officials and development agencies from Colombia and other countries of the world. According to Calle et al. (2013) these pilot farms have played a fundamental role in the development of silvopastoral systems in Colombia, as they have demonstrated the sustainable nature of these systems and have facilitated their promotion.

El Hatico Natural Reserve is located in the Cauca River Valley in a traditionally agricultural region that is now dominated by sugarcane crops. In this reserve, the introduction of silvopastoral systems started in the 1970s when the owners began to allow the regeneration of trees in the pastures with species such as *Prosopis juliflora*, and *Guazuma ulmifolia*, among others. During the 1980s and early 1990s the farm implemented mixed fodder banks with *Gliricidia sepium*, *Trichanthera gigantea* and *Leucaena leucocephala*, that were cut and used to supplement lactating cows as a partial replacement of protein in the commercial feed. Early in the 1990s the reserve started the development of intensive silvopastoral systems (iSPS) with high density of *L. leucocephala* shrubs combined with the grasses *Cynodon plectostachyus*, and *Megathyrsus maximus* with medium size trees. Thanks to the good results of this model, all pastures were gradually replaced with iSPS between 1996 and 2005. According to Montoya-Molina et al. (2016) this system produced 27% more biomass and 64% more protein than pasture monoculture and eliminates the need of chemical fertilizers. This resulted in an increase of milk production from 7436 to 18,486 liters ha^{-1} yr^{-1} and the stocking rate from 3.35 to 5.04 cows ha^{-1} (Calle et al. 2022). According to these authors the experience of El Hatico has demonstrated that (i) biodiversity conservation at farm-scale has to include both the protection of natural ecosystem remnants and the sustainable management of productive areas and (ii) the use of agroecological principles in cattle production can result in higher yields, reduced production costs, improved agricultural products, and multiple ecosystem services.

Another pioneering farm in the introduction of SPS in Colombia es Hacienda Lucerna. It is also located in the Cauca Valley region at 1000 m.a.s.l. with 1400 mm of average rainfall per year. Late in the 1980s the farm started the implementation of mixed fodder banks with *Gliricidia sepium*, *Trichanthera gigantea* and *Morus alba*, to supplement pigs, calves, and lactating cows as a partial replacement of commercial feed. Since 1991 it started the replacement of pasture monocultures by intensive silvopastoral systems with *Leucaena leucocephala* mixed with the grasses *Cynodon plectostachyus* and *Megathyrsus maximus* (cvv Mombaza and Tanzania).

With the implementation of SPS the farm replaced the use of 200 kg N ha^{-1} yr^{-1}. The change also allowed increasing the carrying capacity from 3.5 to 4.85 animals ha^{-1} and milk production from 9000 to 16,346 liters ha^{-1} $year^{-1}$ (Molina et al. 2013; Zapata Cadavid et al. 2019). In recent years the farm has also implemented a iSPS with *Guazuma ulmifolia* planted at high density for direct browsing by heifers and cows. This is an important development for areas with low drainage that are limiting for *L. leucocephala*.

Hacienda El Chaco is located in the Magdalena river Valley in the Tolima Department, at an altitude of 605 m.a.s.l. (Calle et al. 2012). The farm started introducing silvopastoral systems based on native trees at low density in the 1980s. Currently the whole pasture area has been transformed from pasture monocultures to silvopastoral systems including pasture with scattered medium size trees *Erythrina fusca*, *Prosopis juliflora* and *Gliricida sepium*, iSPS with *L. leucocephala* (approx. 10,000 plants ha^{-1}) combined with *Pseudosamanea guachapele*, *Azadirachta indica* and *Tectona grandis* planted in rows every 30 m for timber production (Mahecha et al. 2011) (Fig. 9.1). This is complemented by a 3.7 ha fodder bank of *Gliricidia sepium* whose leaves are harvested, sundried and supplemented to lactating cows and calves (Calle et al. 2012). The areas under silvopastoral systems are divided by several km of live fences of *Gliricidia sepium, Erytrhina fusca,* and *Ceiba pentandra*. Stocking rate in the iSPS was 4,46 AU ha^{-1} with average milk production of 14 L day^{-1} for early lactation cows (Sierra et al. 2017). When used for beef cattle, the average stocking rate was 2.5 AU ha^{-1} and beef production reached 1036 kg ha^{-1} yr^{-1} (Mahecha et al. 2011). The areas with cattle production under silvopastoral systems are complemented by forest remnants and riparian corridors. In terms of diversity conservation El Chaco hosted more than 24 plant species with diameter at breast height (DBH) higher than 2.5 cm (Hernández M. Personnal

Fig. 9.1 Silvopastoral systems in Hacienda El Chaco. Tolima, Colombia. (Photo: A. Galindo)

Communication), 43 bird species and 13 dung beetle species (Giraldo et al. 2018a, b). El Chaco was one of the reference farms for the project MSCR that contributed to the promotion of sustainable cattle ranching among farmers from the Tolima department and from other regions of the country.

9.3 Integrated Silvopastoral Approaches to Ecosystem Management Project

The "*Integrated silvopastoral approaches to ecosystem management*" (RISEM) project was carried out between 2002 and 2008 in Costa Rica, Nicaragua and Colombia by CATIE, NITLAPAN and CIPAV, respectively. In Colombia, it was developed in the middle basin of the La Vieja river in the Andean zone of the country. Based on the experience of CIPAV in the reference farms and in other projects in the country, the project promoted different SPS arrangements suitable for the region.

The farms included in the project in Colombia were 104 with a total area of 2947 ha in which land use change was promoted in degraded cattle ranching areas through the establishment of environmentally friendly silvopastoral systems (Calle 2020). The project's main tool to stimulate changes by farmers was a Payment for Environmental Services (PES) scheme through which landowners were paid for the global environmental services or benefits they produced (carbon sequestration and biodiversity conservation) to the extent that they adopted the changes from pastures without trees to silvopastoral models and conserved the native forests in their farms (Pagiola et al. 2004). For the development of the PES scheme, the project considered 28 different land use types that ranged from degraded pastures, through different silvopastoral modalities, to secondary and mature forests (Pagiola et al. 2004; Ruiz et al. 2011). This process was complemented with the provision of technical assistance to some of the farms involved.

Through this project, important changes in the tree cover of the participating farms were achieved. Pastures without trees were reduced by almost 700 ha over the course of the project, which is equivalent to a 60% reduction in area, in favor of livestock systems with tree cover, which increased by 802 ha (Table 9.1). In addition, live fences increased from 2.1 km to 357 km during the life of the project and the area of riparian corridors and the protection of the forests present in the properties increased (Ruiz et al. 2011). These changes were maintained and increased even the end of the project (Pagiola et al. 2016; Zapata et al. 2015; Calle this volume). The establishment of the SPS also contributed to increase forage production and animal stocking rates in the participating farms.

From the experience of the project, it is possible to highlight the following facts (Ruiz et al. 2011; Calle 2020): (i) The project demonstrated that silvopastoral systems are a good strategy to change the attitude of producers towards biodiversity. Once they are convinced of the "productive" benefits of the system and implement

Table 9.1 Land use changes on cattle farms with payment for environmental services and technical assistance in the RISEM project in La Vieja river catchment, Colombia (Ruiz et al. 2011)

Land use category	Baseline (Ha)	2007 (Ha)	Variation (Ha)
Improved pasture without trees	731	240	−491
Natural pasture with low tree density	6	44	38
Improved pasture without trees	1099	896	−203
Improved pasture with low tree density	55	372	317
Natural pasture with high tree density	0	34	34
Improved pasture with high tree density	2	240	238
Live fences (km)	2	357	355
Fodder Bank	5	29	24
Secondary growth forest	49	45	−4
Intensive Silvopastoral System	0	152	152
Forest	590	622	32

it, over time they become interested in the "ecological" benefits that silvopastoral systems provide, i.e., interest in issues such as the diversity of both flora and fauna becomes an incentive that over time they begin to discover. (ii) Payment for environmental services proved to be a valuable tool for the process of environmental conversion of cattle ranching by inducing the implementation of more environmentally friendly systems. (iii) Technical assistance increased the adoption of silvopastoral systems; An econometric analysis showed that technical assistance had a significant effect on the level of adoption of silvopastoral systems (Pagiola et al. 2010). (iv) The project induced significant changes in land use on farms that received payment for environmental services, well above the control group in terms of the area impacted and the extent of the changes (Zapata et al. 2015; Calle 2020). In addition, they adopted good management practices and eliminated or reduced other environmentally harmful practices such as the use of herbicides and fire as a tool for weed control (Calle et al. 2009).

9.4 The Mainstreaming Sustainable Cattle Ranching (MSCR) Project

Based on lessons learned from the RISEM project, the Mainstreaming Sustainable Cattle Ranching project was designed and implemented in five regions of Colombia between 2010 and 2020. The objective of the project was to achieve the sustainable use of natural resources on cattle ranches through the adoption of biodiversity-friendly silvopastoral systems that improve productivity and conservation of globally important biodiversity and reduce soil degradation. The project was developed in five regions of the country through a partnership between the Colombian Federation of Cattle Ranchers (FEDEGAN), the Centre for Research on Sustainable Agricultural Production Systems (CIPAV), Fondo Acción and The Nature

Conservancy (TNC) (Fig. 9.2). It was carried out with resources from the government of the United Kingdom and the Global Environment Facility (GEF), in addition to financial and in-kind contributions from the four partners, under the supervision of the World Bank (Chará et al. 2011).

The main objective of the MSCR Project was "to promote the adoption of environment-friendly silvopastoral production systems for cattle ranching in Colombia's project areas, to improve natural resource management, enhance the provision of environmental services (biodiversity, land, carbon, and water), and raise the productivity in participating farms". It had three main components: (i) Improving productivity in participating farms in project areas, including the design and implementation of SPS arrangements and the provision of training and

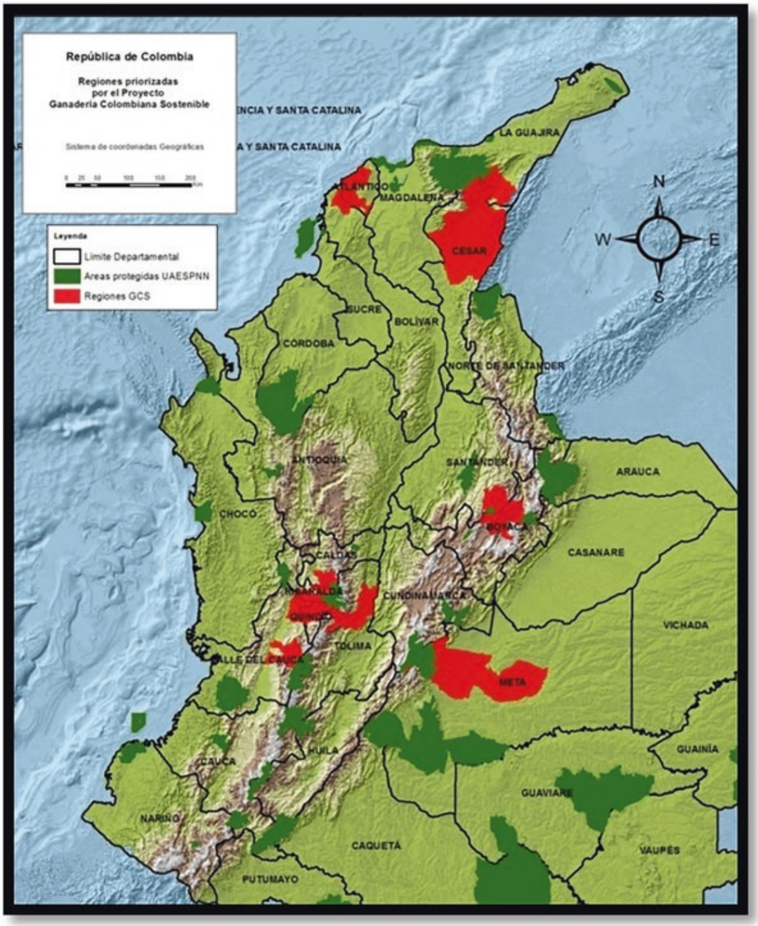

Fig. 9.2 Areas of intervention of the MSCR Project (orange) and connection to protected areas (green) in Colombia

technical assistance to farmers. (ii) Increasing connectivity and reducing land degradation through differentiated PES schemes and (iii) Strengthening of subsector institutions, and dissemination and M&E efforts contributing to the broader adoption of environment-friendly SPS in Colombian cattle ranching (World Bank 2020).

Figure 9.3 summarizes the land use categories promoted in the project and the conventional systems that were replaced in participating farms. The promoted systems included mature and secondary forests and different types of SPS such as scattered trees in pastures, agroforestry systems, living fences and wind barriers, fodder hedgerows and intensive silvopastoral systems.

A total of 4100 farmers were beneficiaries of the project and received technical assistance and other instruments to promote the adoption of SPS. More than 100,000 has, formerly under conventional extensive systems were transformed into sustainable production including 33,750 has of SPS and 4650 has of intensive SPS (World Bank 2021). Additionally, a total of 18,000 has of mature and secondary forest were preserved in project farms (Proyecto GCS 2020). A total of 24,416 farmers, farm workers and technical advisors were informed and trained in sustainable cattle ranching in farm visits, workshops and field demonstrations (Proyecto GCS 2020). The pilot farms El Hatico, Lucerna and El Chaco, and the 50 demonstrative farms implemented during the project were paramount in the process of knowledge transfer and sensibilization of farmers as they were visited by 10,350 cattle ranchers, technicians and local authorities to see the process of implementation and productive advantages of the SPS promoted (World Bank 2020). In terms of productivity, the areas under SPS implemented in the project contributed to improve the stocking rate by 15% and the production per animal by 37%. In addition, there was a reduction in production costs (Proyecto GCS 2020).

According to World Bank (2020) these are the main lessons learnt from the project:

- The project demonstrated the environmental, productive and economic advantages of SPS and that farmers were willing to convert degraded pastures to SPS thanks to the technical assistance and training provided to influence behavioral changes, and to the financial incentives to invest in SPS.
- In order to be more effective, the technical assistance and communications to promote SPS should focus on highly motivated farmers and organizations and should be offered in clusters at a landscape scale.

Fig. 9.3 Land use categories promoted in the MSCR Project (1–6) and conventional land use farming types that the project aims to replace with silvopastoral systems (7–8)

- The implementation of demonstrative farms was determinant to increase the interest of nearby farmers in adopting new/improved technologies.
- To increase the adoption of SPS in Colombia and other countries, it is key to convince farmers of the value of SPS investments and to help them overcome the upfront costs of its implementation.
- Private sector efforts and investment alone are not sufficient to drive a transformational change of the livestock sector in Colombia. To be successful it also requires a strong commitment of the public sector with sustained public finance and a clear policy supportive framework.
- PES schemes were effective to incentivize SPS implementation, but they should be kept simple so that farmers understand the potential benefits.

9.5 Silvopastoral Systems Promoted in the Project

9.5.1 Scattered Trees in Pastures

This refers to pastures in which trees, shrubs or palms are incorporated in densities greater than 25 individuals per ha. The establishment of pastures and trees can be done simultaneously, or the latter can be incorporated into already established pastures. Trees associated with pastures generate various benefits for the production system such as shade, nitrogen fixation, soil improvement, wood for posts, firewood and other uses, fruits, and forage (Zuluaga et al. 2011) (Fig. 9.4a). Trees contribute to improve the quality of adjacent forage (Bernardi et al. 2016; Debaux Junior et al. 2017) due to their effect on soil environment and nutrient cycling through litter fall (Apolinario et al. 2016).

In warm climates, scattered trees contribute to animal welfare and improve animal production and reproduction since they mitigate heat stress (Broom et al. 2013;

Fig. 9.4 (**a**) Scattered trees in pastures with *Inga sp.* and star grass, *Cynodon plectostachyus* Pinzacua Farm. Alcalá, Colombia. (Photo: J. Chará); (**b**) Live fences in San Jose Farm. Salento, Colombia. (Photo: C. Pineda)

Bussoni et al. 2015). In addition, they also generate environmental benefits as trees provide resources and habitats for local fauna and contribute to connectivity between forest fragments and carbon sequestration (Harvey et al. 2006; Giraldo et al. 2018a, b; Tarbox et al. 2018).

9.5.2 Live Fences and Windbreaks

Live fences are lines of trees used instead of wooden or cement posts to support barbed or electrified wire in boundaries and paddock divisions (Zuluaga et al. 2011). They can be composed of one or several tree species (Fig. 9.4b). Their greatest advantage from a productive point of view is that they avoid the costs of purchasing and periodically replacing posts. In addition, they can provide shade, firewood or wood for various uses, and contribute to improving the soil in their area of influence (Debeaux Junior et al. 2017). Some species also provide fodder that can be used in critical periods through pruning or livestock grazing (Zapata Cadavid and Silva Tapasco 2020). Others also provide pods and fruits that are consumed by livestock and provide valuable nutrients (Ruiz-Nieto et al. 2020).

Live fences are very important landscape elements, as they contribute to connectivity between forest fragments and facilitate wildlife transit (Harvey et al. 2005). If not severely pruned, over time they can become biological corridors, thus contributing to the conservation of an important portion of biodiversity (Zuluaga et al. 2011). Additionally, the implementation of live fences eliminates the need to extract trees from the forest for posts, thus contributing to the protection of this resource. In the coffee-growing zone of the country, live fences with species such as *Gliricidia sepium* and *Trichanthera gigantea* predominate (Zapata Cadavid and Silva Tapasco 2020), while in high Andean zones a greater number of trees can be found. For example, a study in the cold zone of Boyacá department found that small-scale producers used 39 tree species as living fences, including *Sambucus nigra*, *Alnus acuminata*, *Fuchsia magellanica* and *Eucalyptus globulus* (García et al. 2021).

Windbreaks are single or multiple strips of trees strategically integrated into the agricultural landscape planted in one or several layers, with the main purpose of reducing the negative effect of winds and frost on pastures, animals and crops (Giraldo et al. 2018a, b; Smith et al. 2021). They are similar to live fences, but the rows of trees are left to grow freely, have at least two types of heights or strata and can be double or triple. They are arranged perpendicular to the flow of the desiccating winds of the pastures (Baker et al. 2021). These agroforestry arrangements are of great importance especially during the dry season, when air currents contribute to dehydrate pastures, decreasing the availability of forage for livestock. They are also a fundamental tool to attenuate the effect of frost on pastures and other forages in the cold regions (Oberschelp et al. 2020; Baker et al. 2021). In the high Andean zones of Colombia single or double lines of *Sambucus sp.* are frequently used as windbreaks to prevent frost in adjacent pastures and provide a source of forage to animals as this species tolerates low temperatures (Galilndo et al. 2003; Grajales et al. 2015).

They are an alternative for the separation of pastures and, like live fences, can provide forage, wood, firewood and fruits. Because of their characteristics, they can host important elements of biodiversity such as birds, insects and other organisms useful in the natural control of grass and livestock pests, and in the recycling of nutrients. They also play an important role as biological corridors that allow the connection of forest patches in the agricultural landscape.

9.5.3 Intensive Silvopastoral System (iSPS)

Intensive silvopastoral system (iSPS) is a livestock agroforestry arrangement that combines forage shrubs in high density (five thousand or more per hectare) for direct livestock grazing, always associated with improved pastures and legumes, and variable amounts of timber, fruit or other trees (100–600 per ha) (Chará et al. 2019; Pachas et al. 2019). The system requires to be managed under rotational grazing with constant provision of water and mineralized salt, and 12–24 hour grazing periods followed by 40–50 day resting periods (Calle et al. 2012; Murgueitio et al. 2016; Zapata Cadavid et al. 2019). It is characterized by a very high natural production of forage biomass of high nutritional quality per unit area, which, in turn, manages to maintain high loads of cattle for beef, milk or dual purpose (Murgueitio et al. 2015). The system favors a greater recycling of nutrients and replaces the need of chemical fertilizers for pasture development due the nitrogen fixation and enhanced soil biological activity (Vallejo et al. 2010).

Intensive silvopastoral systems also generate a beneficial microclimate both for animal production and for the recovery of entomofauna, the habitat of local and migratory birds, and the provision of wood and fruits for different uses in the medium and long term.

The main species used in iSPS in Colombia is *L. leucocephala*, a legume tree from Mexico that during the second half of the twentieth century was studied as a forage in Australia, Mexico, Argentina, Cuba and Colombia (Suárez et al. 1987; Pachas et al. 2019). With the lessons learned from these experiences, in Colombia in 1990, innovative producers from the farms El Hatico, Lucerna and El Chaco, evaluated designs with higher density of bushes of *Leucaena leucocephala* var. Cunningham, the cultivar with the greatest advantages for browsing due to its flexible branches (difficult to break), high nitrogen fixation, lower mimosine content (a toxic amino acid), drought tolerance, high regrowth capacity, total acceptance by ruminants and persistence after planting (Uribe et al. 2011; Murgueitio et al. 2016). Intensive silvopastoral systems with L. leucocephala have been successfully implemented in Colombia both for dairy production as described previously for the pilot farms (Rivera et al. 2019) and for beef production (Chará et al. 2019a) (Fig. 9.5a, b). For areas with more acidic soils, *Leucaena diversifolia* has been proposed by CIAT

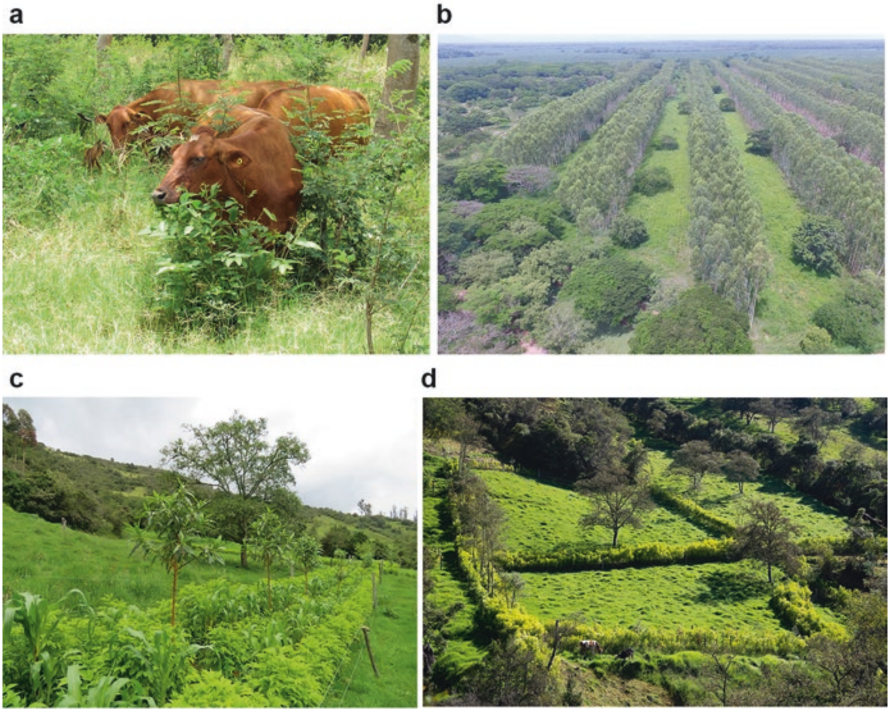

Fig. 9.5 (**a**) Lucerna cows browsing in an ISPS with *G. ulmifolia* and *L. leucocephala*, Hacienda Lucerna, Bugalagrande, Colombia. (Photo: J. Chará); (**b**) ISPS with *L. leucocephala* and *Eucalyptus sp*. La Luisa Farm, Codazzi, Colombia. (Photo: L. Solarte); (**c**) Fodder hedgerow with *Sambucus sp.*, intercropped with maize and *Alnus acuminata* trees. La Estancia farm. Belén, Colombia. (Photo: J. Vanegas); (**d**). General view of La Estancia farm with hedgerows and fodder bank with *Sambucus sp.* (Photo: C. Pineda)

in mixtures with Brachiaria hybrid cv Cayman. The species also tolerates cattle browsing and improve productive and environmental parameters of pasture monoculture (Enciso et al. 2019; Vazquez et al. 2020).

Another species used in iSPS is *Tithonia diversifolia* a shrub also originally from Mexico and Central America that tolerates soils with lower pH and higher altitude than *L. leucocephala* (Rivera et al. 2021). ISPS with this species were proposed in the MSCR project for the Orinoco foothills in Meta, the coffee ecoregion and Boyacá and Santander, and it has also been established in the Caquetá department (see Solarte et al. this volume). In this department iSPS with *T. diversifolia* produced 44% more fodder biomass and 58% more milk production per ha (Rivera et al. 2015) and reduced enteric emissions by 10% (Rivera et al. 2022) and manure emissions by 20% (Rivera et al. 2023) when compared with conventional Urochloa-Brachiaria pastures.

9.5.4 Fodder Hedgerows

These are linear arrangements consisting of strips of forage shrubs planted at high density. Each strip can have two or four rows of shrubs planted at 1 m between lines and 0.5 m between plants that can be complemented with a central line of trees at a distance of three meters from each other (Giraldo et al. 2018a, b). For farms below 2000 meters above sea level in the tropics, it is recommended to plant 5000 or more shrubs per kilometer and above that altitude the density can be 2000–3000 shrubs per kilometer. Forage biomass is cut and offered to the animals at the grazing site or transported to the milking site to be supplied fresh or in silage. The species used varies according to their range of adaptation; in low areas (i.e. under 1400 masl) the species indicated are *T. diversifolia*, *Guazuma ulmifolia* and *L. leucocephala*; *T. diversifolia* is also suitable for areas with a maximum altitude of 2200 masl and above this altitude the species with best performance is *Sambucus sp.* (Grajales et al. 2015; Murgueitio et al. 2016) (Fig. 9.5b, c). Forages can be intercropped with native and/or timber trees and crops for human consumption.

9.5.5 Mixed Fodder Banks

These are intensive crops whose purpose is to produce leaves and stems of high nutritional value for animal feed by means of cutting and hauling systems. Within the fodder banks, herbaceous, arboreal and shrubby plants can be considered, sown and managed at high density (ten thousand or more per hectare). As far as possible, they should consist of several species and be associated with crops for human consumption, fruit or timber trees and palms. They should have a good fertilization regime to ensure good forage production (Zuluaga et al. 2011).

Forage shrubs are characterized by their high protein content (generally above 20%), vitamins and some minerals, which complement the grass-based livestock diet (Simbaya et al. 2020). Because they have deeper roots than grasses, they can maintain better production in the dry season and help conserve the soil. Among the species most commonly used in fodder banks in Colombia are *Trichanthera gigantea*, *T. diversifolia*, *Morus alba*, *L. leucocephala*, sugarcane (*Sacharum officinarum*), *Guazuma ulmifolia* and giant taro (*Alocacia macrorhyza*) (Zuluaga et al. 2011; Zapata Cadavid and Silva Tapasco 2020).

9.5.6 Mature and Secondary Forests

As mentioned previously, the project promoted the conservation of 18,000 has of forest within the farms and contributed to their connectivity through other land uses that facilitate the transit of species. Mature forests were considered those with minimal or no intervention during the last decades, with a canopy cover greater than 80%. Forests harbor a high level of biodiversity and provide important environmental services related to the regulation of the hydrological cycle, pollination and soil protection, among others.

Secondary forests, according to Smith et al. (1997) are the successional woody vegetation that develops on land whose original vegetation was destroyed by human activities. The structure and composition of the secondary forest changes widely with respect to the primary forest and also changes throughout the succession. A secondary forest can also be a native forest with moderate interventions in recent decades (Zuluaga et al. 2011). Among the main benefits of secondary forests, when allowed to grow in replacement of pastures or degraded areas, are the following: (i) they contribute to soil improvement through the transfer of nutrients from deeper layers and the contribution of organic matter; (ii) they contribute to regulating the hydrological cycle; (iii) they modify the microclimate by reducing temperature fluctuations and increasing relative humidity; (iv) they harbor important levels of biodiversity and (v) they have a high carbon capture and storage rate.

9.6 Effect of Silvopastoral Systems Promoted on Biodiversity

According to the monitoring activities carried out in the MSCR project, there was an important contribution to the protection of biodiversity in the participating farms and surrounding areas (World Bank 2020). This is a result of, among other factors, the increase in tree cover on farms due to the 38,000 ha of silvopastoral systems implemented, the protection of natural habitats such as riparian corridors, forests, wetlands and watercourses, and the implementation of good practices that involve reducing the use of pesticides and burning as a management method.

An important tool used in the project to improve ecological connectivity in ranching landscapes through the conservation and restoration of biological corridors and riparian forests was the development of a short-term Payment for Environmental Services (PES) scheme that helped finance the shift to land uses (both conservation and productive) that were more compatible with biodiversity (Pagiola et al. 2011; Calle and Murgueitio 2020). A total of 1866 ranchers who increased tree cover on their farms and chose to conserve forests, riparian corridors and wetlands also received short-term PES during the life of the Project. As a result, the Project promoted the conservation of 18,000 hectares of forests and the ecological restoration of riparian forests on participating cattle ranches (Calle and Murgueitio 2020; Proyecto GCS 2020).

The project also worked to motivate ranchers to plant and protect native tree and palm species of high conservation value in forests, stubble, crops, riparian corridors and even in pastures on their farms (Calle 2011). The Project provided participating producers with 3.1 million trees for different uses, half of which were species of special conservation interest. In recognition of their special effort to adopt one or more focal species, PES-eligible ranchers received an additional bonus for caring for these native trees on their farms (Chará et al. 2011). In total, project promoted the conservation of 50 focal species, which are native trees and palms of global conservation importance that can be planted or managed in silvopastoral systems and riparian forests in order to improve the connectivity and conservation value of ranching landscapes (Calle et al. 2017). The 50 focal species selected for the project belong to the families Lauraceae, Arecaceae, Fabaceae, Meliaceae, Bignoniaceae, Anacardiaceae, Malvaceae, Euphorbiaceae, Sapotaceae, Moraceae, Podocarpaceae, Boraginaceae, Apocynaceae, Escalloniaceae, Combretaceae, Fagaceae, Lamiaceae, Juglandaceae, Lecythidaceae, Urticaceae, Zygophyllaceae and Malvaceae (Calle et al. 2017).

The results of the monitoring of plants, birds, dung beetles and other organisms carried out in the project indicate that SPS in all their types contributed to the conservation of biodiversity in the cattle ranches. Table 9.2 presents a summary of the number of species of woody plants, birds and dung beetles found in SPS in five

Table 9.2 Richness of species of woody plants (DBH > 2.5 cm), birds and dung beetles in different land uses of MSCR regions

	Native forests and riparian corridors	Scattered trees in pastures	ISPS	Live Fences	Treeless pastures (control)
Coffee ecoregion					
Plants	185	15	18	25	1
Dung beetles	46	20	27	16	17
Birds	91	58	90	36	55
Orinoco foothills					
Plants	306	33	8	4	0
Dung beetles	19	9	10	6	16
Birds	37	46	35	16	36
Cesar river valley					
Plants	292	44	7		1
Dung beetles	21	15	21		15
Birds	31	85	52		51
Lower Magdalena					
Plants	22	19	12	3	0
Dung beetles	12	7	7	7	0
Birds	7	40	10	18	13
Boyacá - Santander					
Plants	204	44	11	12	0
Dung beetles	16	2	6	6	8
Birds	28	12	44		21

DBH Diameter at breast height

project regions (Giraldo et al. 2018a, b; Proyecto GCS 2020). Chará-Serna et al. (this volume) analyzes the main effects of SPS on biodiversity in tropical countries.

Conservation land uses (forests and riparian corridors) generally retain the greatest total richness of plant and beetle species, and in most cases, also a greater diversity of birds. Although the areas of forest that still exist in the cattle ranches are relatively small, they are fundamental for the conservation of the species present in each region. In the case of the Cesar River, forests and riparian forests are home to 83% of the plant species found, making the protection of these fragments key to biodiversity conservation (Giraldo et al. 2023). Although silvopastoral systems, especially trees dispersed in pastures, host about 10% of the plant species, some of them are rare species in the region and with some category of threat (Giraldo et al. 2023). Silvopastoral systems can contribute to increase connectivity between patches of natural vegetation, since the treeless pastures represent a barrier to their mobility for many of the bird species and other organisms present in forests (Tarbox et al. 2018).

For native beetle species, forest represent a very important habitat (Giraldo et al. 2018a). Although some generalist beetle species successfully establish in open areas, rarer or specialized species require tree cover in productive areas. Scattered trees in paddocks, live fences, forage hedgerows and iSPS are key for larger beetles, which make an important contribution to the ecological function of dung and soil removal in paddocks (Giraldo et al. 2011; Montoya-Molina et al. 2016). Likewise, once silvopastoral systems are consolidated, trees increase the availability of food, shelter and nesting sites for birds in productive areas, which is reflected in the abundance and richness of species.

9.7 Effect of Silvopastoral Systems on Farm Productivity

Silvopastoral systems produce more biomass, dry matter, energy and protein than pasture monoculture and therefore can generate more milk or beef per hectare and, at the same time, reduce the dependence of external inputs including feeds and fertilizers (Chará et al. 2019; Ribeiro et al. 2016). Higher biomass production is generally a result of an improved nutrient cycling, nitrogen fixation by legume trees, improved soil water holding capacity due to shading, and improved management (Murgueitio et al. 2016). Biomass production in SPS can be 15–230% higher in relation to pasture monoculture (Pachas 2010; Gaviria et al. 2015). In ISPS, protein intake is also improved considerably with the inclusion of fodder shrubs such as *L. leucocephala* and *T. diversifolia* that have up to three times more protein than tropical grasses (Rivera et al. 2019). In the north of Colombia DM production of degraded pastures can be increased from 7 (Cajas-Girón et al. 2011) to 19.6 Mg ha^{-1} $year^{-1}$ with the implementation of ISPS (Chará et al. 2017).

An analysis carried out in 110 farms in five regions of the MSCR project showed that silvopastoral systems increased the carrying capacity by an average of 23% in all project regions, as compared to the control pastures. Additionally, an average milk production of 2610 liters ha^{-1} yr^{-1} was found, which represents an increase of 37.1% with respect to conventional systems (Giraldo et al. 2018a, Proyecto GCS 2020). The results indicate that the permanent supply of forage in SPS and the increased carrying capacity favor milk production per unit area, which is directly reflected in higher income for producers. This result is also influenced by the better management of rotation and use of grasses in their optimal stage thanks to the information and technical assistance provided by the project (Proyecto GCS 2018, 2020).

Silvopastoral systems also demonstrated to be more resilient to climate change than traditional pasture systems. On demonstrative farms implemented by the project, SPS reduced losses in biomass production by as much as 20% during the dry and wet seasons when compared with farms with conventional extensive grazing management (Ramírez and Pérez 2019).

9.8 Colombian NAMA of Sustainable Bovine Livestock

As mentioned above, one of the objectives of the MSCR project was to influence public institutions and policies in order to include sustainable livestock and silvopastoral systems in government strategies related to environmental and production issues. One of the main results of the project in this direction was the design of the Nationally Appropriate Mitigation Action (NAMA) of Sustainable Bovine Livestock with the aim of reducing GHG emissions generated by the beef and dairy supply chains, mainly in the primary production level, and increasing the amount of carbon stored in cattle ranches and in the landscapes where they are located (Banco Mundial et al. 2021).

The bovine NAMA takes advantage of the experiences of the MSCR project to scale up sustainable cattle production systems in 22 departments and seven of the ten ecoregions in which cattle production is distributed in the country. To move cattle ranching towards a sustainable, low-carbon growth path, the bovine NAMA prioritizes strategic lines of action aimed at reconversion and the development of production processes that are efficient in the use of natural resources, under a nature-based solutions and circular economy approach (Banco Mundial et al. 2021). These actions include:

- Sustainable intensification of livestock production through knowledge management and the establishment of intensive and non-intensive silvopastoral systems.
- Liberation of areas currently used for cattle production and implementation of ecological restoration strategies.
- Optimal use of residues from the marketing and processing stages of the beef supply chain.

The first two actions focus directly on livestock farms, while the third action focuses on the beef market stages, specifically on the activities of cattle auction sites, fairs and abattoirs, since these are where significant GHG emissions are generated.

The NAMA is an integral part of the country's commitment to reduce GHG emissions by 51% in 2030. GHG emissions produced by cattle ranching in 2020 are estimated at 40.5 Gg CO_2eq and are projected to increase considerably if the current growth trajectory continues (IDEAM et al. 2021). The implementation of the strategies proposed by the bovine NAMA could reduce these emissions by around 20% of expected net emissions by 2030 (IDEAM et al. 2021). To achieve this, the NAMA projects the establishment of 1.43 million hectares of silvopastoral systems and the conservation and restoration of 68,000 hectares of natural ecosystems within the farms. Additionally, 2.1 million hectares will be under improved management that includes the promotion of best livestock practices (Banco Mundial et al. 2021). Although a relatively small portion of the country's farms are still being intervened, meat and milk production is expected to increase by 3% and 7%, respectively, while reducing livestock emissions by at least 20% (IDEAM et al. 2021). According to Tapasco et al. (2019) the alternatives promoted in the MSCR project such as good pasture management and the implementation of intensive and non-intensive silvopastoral systems could provide up to 77% of the national goal of the NDC for the agricultural sector.

The NAMA implementation will facilitate the sector's transition to low-emission and more resilient growth, in line with national policy goals and priorities, by generating better income opportunities for livestock farmers and employment opportunities for rural inhabitants, given that the nature-based solutions proposed by this policy imply diversification of employment, greater resilience to environmental shocks, and greater coordination within production chains.

9.9 Conclusions

Cattle production is a crucial sector in the Colombian agricultural economy, and its growth is expected to continue due to both external and internal demand for beef and dairy products. The country possesses significant potential to enhance productivity and meet market demands effectively.

Silvopastoral systems that integrate trees, shrubs and pastures into livestock systems are a successful alternative for the rehabilitation of livestock lands in different regions of Colombia. These systems' heterogeneity and habitat conditions contribute not only to biodiversity conservation, complementing the role of forests, but also to improved meat and milk production, increased farm income, and enhanced livelihoods.

The MSCR project stands as the country's most substantial initiative towards transforming livestock production systems, aiming to achieve greater efficiency, conserve diversity, reduce greenhouse gas emissions, and enhance livestock resilience to climate change.

The project drew upon valuable insights gained from pilot farms and lessons derived from the regional project to effectively apply them across diverse regions of the country, using tools and incentives available. In order to promote widespread adoption, it is crucial to overcome the barriers associated with initial capital requirements and the limited awareness among producers and technicians regarding these systems. To overcome capital barriers faced by farmers in implementing sustainable production systems, the utilization and analysis of incentives such as low-interest loans, payment of environmental services, and differentiated markets are deemed critical. Moreover, the provision of technical assistance and training to farmers has proven instrumental in transforming their perspectives and capacities to embrace more sustainable production methods.

Establishing alliances and cooperation programs to share knowledge and best practices, while promoting investments in sustainable livestock production, is essential. Collaboration among various stakeholders, including governments, producers, industries, non-governmental organizations, and civil society, holds the key to success in this endeavor.

The project has contributed to the formulation of public policies aimed at improving the sustainability of livestock production, addressing its impact on climate change, and bolstering income generation for farmers. The Colombian low carbon development strategy recognizes the importance of intensifying cattle production and converting pasture areas for achieving emission reduction targets outlined in the Nationally Determined Contributions (NDC) for 2030.

Thanks to the livestock Nationally Appropriate Mitigation Action (NAMA), designed based on project lessons and the results achieved in five regions, there is now a clear roadmap for scaling up silvopastoral systems. This roadmap sets the stage for livestock to make a substantial contribution, aiming for an 80% reduction in emissions with sustainable production based on the adoption of silvopastoral systems.

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Chapter 10
Agro-Silvopastoral Systems for the Andean-Amazonian Foothills of Colombia

Antonio Solarte, Catalina Zapata, Adrián Rico, and Julián Chará

Abstract The Andean-Amazonian piedmont region of Colombia is recognized for its richness in terms of biodiversity and, at the same time, for the high deforestation that threatens it. This is the case of the Department of Caquetá, which has the highest rates of deforestation in the country. In this department, the colonization processes were developed mainly through extensive cattle ranching to occupy the territory and obtain economic benefits in the short term. This production system is continued until the present day. In this context, the document presents an intervention approach at the farm and landscape levels, to conserve and restore forests and wetlands, and promote the sustainable intensification of extensive cattle ranches. Different options of agro-silvopastoral systems are presented, including improved pasture management, live fences, scattered trees in pastures and mixed fodder banks for feed and food security.

Keywords Colombian Amazon · Livestock agroforestry · Sustainable cattle raising

10.1 Introduction

In Colombia, the transition between the Andes and the Amazon is widely recognized for its enormous richness and diversity of fauna and flora species, as well as its important role as a bridge to facilitate connectivity, migration, and diversification of species (Clerici et al. 2019). The Andean-Amazon piedmont is an important water pantry of the large Amazon River basin (Peña et al. 2016).

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Throughout history, the settlement of the Amazon region in Colombia has been linked to the extractive economic dynamics of its natural resources; first gold in colonial times and later products such as cinchona (*Chinchona sp.*) and rubber (*Hevea brasiliensis*); in recent times, crops for illicit use such as coca (Arcila-Niño and Salazar-Cardona 2011).

Between 1950 and 1970, peasants from other regions of the country began to colonize the Andean-Amazon piedmont region (Salazar 2007). This colonization generated the greatest transformation and consolidation of anthropic activity and, at the same time, the greatest economic and social dynamics in the Colombian Amazon. These spatial dynamics of settlement continued with new vectors of occupation and colonization, from the periphery to the center in the Amazonian Forest (Salazar and Riaño 2016; Arcila-Niño and Salazar-Cardona 2011).

During the last decade, Caquetá has been the department with the largest deforested area at the national level, responsible for 22% of the total area in 2021 (IDEAM 2022b) concentrating deforestation in the municipalities of Cartagena del Chairá, San Vicente del Caguán and Solano. The change in land use is oriented towards land grabbing, conversion of forest to pasture, illicit crops, development of unplanned transportation infrastructure, illegal mineral extraction, and the expansion of the agricultural frontier in non-permitted areas (IDEAM 2022a, b).

According to a study developed by SINCHI on typologies of predominant productive systems in Caquetá, cattle ranching is the main activity in 68% of the farms studied (Jiménez et al. 2019). The department ranks fifth in cattle inventory and third in milk production at the national level, with 2,198,256 head of cattle (7.5%) (ICA 2022) and 1,948,167 liters of milk per day (8.9%) (DANE 2020), respectively.

According to the interventions carried out in the department through the different institutions present in the region, different designs of agro-silvopastoral systems have been promoted, with different levels of complexity in terms of implementation, management, labor availability, costs and acceptance by the producer.

The intervention model is based on three pillars: conservation and restoration, adaptation to climate change and sustainable intensification of livestock (Solarte et al. 2017), which is based on adequate planning, intelligent grassland management and increased tree cover in grazing areas in different agrosilvopastoral arrangements (Chará et al. 2019).

Agrosilvopastoral systems have a positive impact on the production and quality of forage, increase the carrying capacity and the production of meat and milk per hectare, while reducing the environmental damage caused by extensive livestock activity, providing a suitable environment to improve the edaphic biota and fauna associated with the system, making it a recommendable option for the producer (Gutiérrez and Mendieta 2022).

This chapter presents a description of the Andean-Amazonian piedmont and the experiences of agrosilvopastoral systems and their main limitations for adoption, as well as strategies for their scaling up.

10.2 The Context of the Andean-Amazon Piedmont Region

The eastern Andean Mountain range in Peru, Ecuador and Colombia that borders the Amazon basin is the region known as the Andean-Amazon piedmont (Hernandez and Naranjo 2007). In Colombia, it corresponds to the eastern slope of the eastern cordillera, a strip of territory that communicates the Andean and Amazonian biomes, corresponding to the western Amazonian or piedmont subregion, in a part of the departments of Cauca, Caquetá and Putumayo (Salazar and Riaño 2016) (Fig. 10.1).

In Colombia, the transition between the Andes and the Amazon is a region of interest for biological conservation and research, widely recognized for its enormous richness and diversity of fauna and flora species, as well as for its important role as a bridge to facilitate connectivity, migration and diversification of species (Clerici et al. 2019). The region has about 29 ecosystems of terrestrial and aquatic environments, which are distributed in ecoregions of tropical rainforest, Andean forests and paramos (Barrera et al. 2007).

The Andean-Amazon piedmont is an important water pantry of the large Amazon basin (Peña et al. 2016). The high rainfall in the eastern Andes is the result of the aerial rivers formed by the interaction between evapotranspiration from the Amazon forests and the air currents that flow from the Atlantic Ocean to the Andean orographic barrier, which provide water to the Caquetá and Putumayo rivers, tributaries of the Amazon River, and supply water to communities and population centers located in the foothills and the Amazon plain (Poveda et al. 2006).

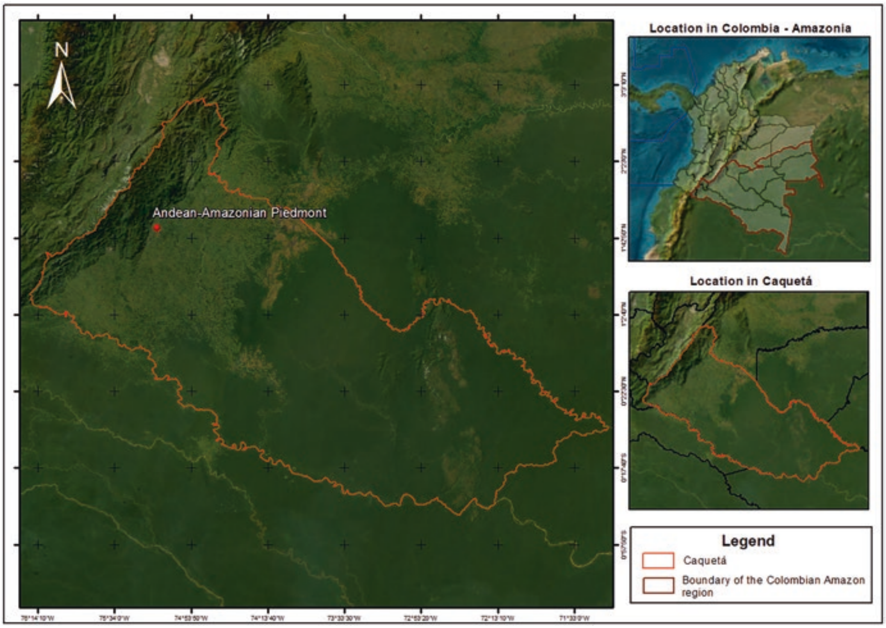

Fig. 10.1 Map of the Andean-Amazonian piedmont in Colombia

The Andean Amazon piedmont has been inhabited for 3000 years by different indigenous peoples (Salazar 2007). Throughout history, the population of this region in Colombia has been linked to the extractive economic dynamics of its natural resources: first gold in colonial times and later products such as cinchona (*Chinchona sp.*) and rubber (*Hevea brasiliensis*), to supply markets in the United States and Europe. In recent times, illicit crops such as coca, timber extraction, illegal mining and hydrocarbon exploitation appeared (Arcila-Niño and Salazar-Cardona 2011).

Between 1950 and 1960, the Colombian government initiated a strategy to promote the colonization of the Andean-Amazon piedmont of Caquetá. Consequently, the department has the highest urban and rural population density rates in the entire Amazon region of Colombia (Salazar and Riaño 2016).

With the signing of the peace agreement between the government and the FARC-EP guerrillas in 2016, there was an increase in deforestation in the region as the control and pressure exerted by the guerrillas throughout the territory was reduced (Murillo et al. 2020; Prem et al. 2020; Rodriguez et al. 2017). Consequently, during the last 6 years the department of Caquetá has led the ranking of departments with the highest deforestation and in 2021 contributed 22% of the total deforested area in Colombia, particularly in the municipalities of Cartagena del Chairá, San Vicente del Caguán and Solano (IDEAM 2022b).

Deforested areas are mainly used for land grabbing, extensive cattle ranching, illicit crops, illicit mineral extraction, illegal logging and the expansion of the agricultural frontier in non-permitted areas (IDEAM 2022a,b).

10.3 Cattle Ranching in the Andean-Amazon Piedmont in the Department of Caqueta

10.3.1 Evolution of Cattle Ranching in the Amazonian Foothills

Since the mid-nineteenth century, cattle ranching has been associated with the transformation of the landscape in Latin America, intensifying its impact in the second half of the twentieth century. The introduction and wide acceptance of grass species of African origin mainly Brachiarias and the changes in the genetics of cattle through the introduction of crossbreeds and breeds have contributed to this fact. This process, which began in Brazil in the 1950s, was supported by governments and research and development institutions, then spread to other countries in the region (Van Ausdal and Wilcox 2013). In the case of Colombia, the main advance of cattle ranching in the Amazon region has occurred in the foothills of the department of Caquetá.

According to Michelsen (1990), the gradual growth of areas under extensive grazing in the department and the arrival of dairy processing companies led Caquetá to become important as a milk-producing region based on dual-purpose models in which part of the breeding cows in the cattle herds were destined for milking.

Since the early 1990s, research centers such as the International Center for Tropical Agriculture (CIAT), the Colombian Agricultural Institute (ICA), the Colombian Agricultural Research Corporation (Agrosavia), the University of the Amazon, and private enterprise initiatives, Nestlé and Fondos Ganaderos, began a process of identification, validation and incorporation of tropical pasture and legume resources to improve productivity and reorient livestock farming toward more intensive systems. According to Rivas and Hollmann (1999), during this period improved varieties of *Brachiaria sp*. and legumes such *as Arachis pintoi* were incorporated in partnership between CIAT and Nestlé.

Pioneering research led by Agrosavia proposed different tree and shrub species for arrangements such as protein and energy banks, forest or tree stands, live fences, strips of shrub and tree species, and herbaceous forage management (Cipagauta and Andrade 1997; Cipagauta et al. 2002; Escobar and Cipagauta 2005).

Beginning in 2000, organizations focused on the promotion of productive alternatives and rural development, such as research centers, academia, the cattle-raising association, the dairy sector and NGOs started the promotion and research on sustainable cattle-raising models. The Universidad de la Amazonia led the creation of a silvopastoral network of producers in three municipalities of the Colombian Amazon piedmont, with the purpose of adopting and validating sustainable production alternatives (Rodriguez et al. 2006).

Nestlé and the Center for Research on Sustainable Agricultural Production Systems (CIPAV) jointly developed the project Environmentally Sustainable Milk (LAS) between 2008 and 2011, which promoted the development of silvopastoral systems in several nuclei of farms in the department of Caquetá (Tafur et al. 2011, which allowed the scaling up of these initiatives in 2015 by Nestlé with support from the Inter-American Development Bank (IDB) to expand the silvopastoral systems to 100 farms (Nestlé 2011).

From 2010 to date, national and international cooperation projects related to climate change and biodiversity have prioritized the development of sustainable cattle ranching initiatives in the Colombian Amazon, with special attention to the departments where deforestation figures have increased, as is the case of Caquetá. Among the alternatives promoted, the component of innovation and pasture management and silvopastoral systems stand out.

10.3.2 Livestock Production in the Andean-Amazon Piedmont in Caqueta

According to UPRA (2018), cattle ranching in the department of Caquetá occupies 1,628,761 ha. However, the area considered suitable for this activity is 1.3 million ha, as protection zones, riverbanks, slopes and wetland areas, among others, must be excluded.

According to ICA (2022), the department's cattle population reached 2,198,256 head of cattle in 2021, which places Caquetá fifth in the country with 7.5% of the national cattle herd. The department's cattle herd has grown steadily over the last decade, especially since 2016 (FEDEGÁN 2022), after the signing of the peace agreement between the national government and the FARC - EP guerrilla (*Fig. 10.2*).

Most of the cattle herd inventory at the regional level is concentrated in the municipalities of San Vicente del Caguán (41.4% of the herd), Cartagena del Chairá (17%) and Puerto Rico (9.3%). In terms of composition, the most representative age group is females over 3 years with 31.7% of the herd, followed by calves under 1 year with 23.7%, females and males between 1 and 2 years with 10.9% and females between 2 and 3 years with 10.7% (ICA 2022).

Cattle raising is mainly oriented towards dual-purpose production (Torrijos 2022), whose main characteristic is the milking of the cow and suckling of the calf to supply fresh milk to dairy companies and the sale of the calf 2 or 3 months after weaning, when it enters the rearing and fattening process (Cipagauta et al. 2002). This system has been consolidated since the late 1970s when the dairy sector began to develop a stable market with the presence of the multinational Nestlé, which provided financing to farmers for herd technification and improvement with dairy breeds (Nestlé 2011).

Caquetá produces 1,948,167 liters of milk per day, which is equivalent to 8.9% of national production and places it in third place as a dairy producer after the departments of Antioquia and Boyacá (DANE 2020). Livestock activity is carried out on 20,512 farms (FEDEGÁN 2022), of which 41.9% have between 1 and 50 animals, 26.2% have between 51 and 100 animals, and 29.8% have between 101 and 500 animals (ICA 2022). These data show that livestock activity in the region is mainly small and medium scale (Torrijos 2022).

Olarte-Hurtado et al. (2022) evaluated the effect of forage production of 13 types of pastures between native and introduced on milk production in the Colombian

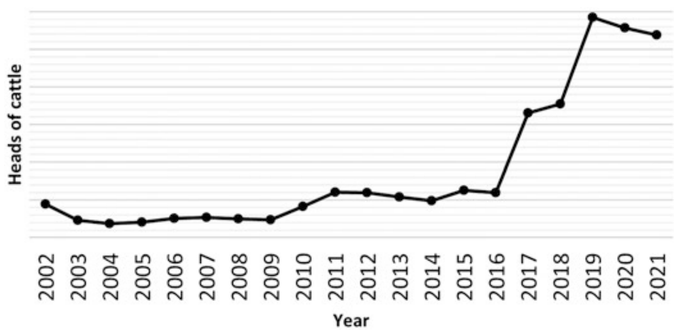

Fig. 10.2 Total cattle and buffalo inventory for Caquetá over a 19-year period. (Source: Subdirección de Salud y Bienestar Animal – Fedegán (FEDEGAN 2022))

Amazon, finding the highest milk production associated with pastures in *Pennisetum purpureum cv* OM22 (6.77 kg milk cow/day), *Brachiaria ruziziensis* (5.72 kg milk cow/day), *Homolepsis aturiensis* (5.5 kg milk cow/day), *Homolepsis aturiensis* (5.5 kg milk cow/day); The lowest in *Andropogon gayanus* (3.36 kg cow milk/day) and *Brachiaria brizantha cv* Toledo (3.73 kg cow milk/day). Suárez et al. (2013), in a characterization of cattle farms under the dual-purpose system in the department of Caquetá, found milk yields ranging from 1.26 to 4.54 kg cow^{-1} day^{-1} in three types of farms (small, medium, large) that differed mainly in the availability of forage for animal feeding and pasture rotation. Table 10.1 shows the productive parameters of dual-purpose cattle raising in the Caquetá piedmont.

Different studies conducted in Caquetá, mention that the animal load in the region is between 0.73 and 0.8 UGG ha^{-1} (Motta and Ocaña 2018; Pallares 2014) in

Table 10.1 Productive and reproductive parameters of the dual-purpose system in the department of Caquetá

Parameter	Unit	Authors					
		Cipagauta et al. 2001[a]	Cipagauta and Orjuela 2003[b]	Santana et al. 2009[c]	Tafur et al. 2011[d]	Torrijos et al. 2015[e]	Motta and Ocaña 2018[f]
Mean age at first parturition	Months	40.8				42.1	
Interval between deliveries	Days	462.4		401–700		480	
Lactation duration	Days	224			280		
Milk pruduction cow/day	Kg	4			4.8		6.08
Weaning age	Months			>10			9.15
Weaning weight	Kg	160		151–180	160	159.3	168.5
Daily weight gain	g/day		370–600			481	
Birth rate	%			56–65	60	72	

[a]Productive behavior of *Bos Taurus x Bos indicus* crosses in a genetic improvement process with dual purpose cattle from the Piedemonte Caqueteño. EPP n = 111, IEP n = 284, DL = 475
[b]Use of agrosilvopastoral techniques to contribute to optimize land use in the intervened area of the Amazon
[c]Prospective research and technological development agenda for the cattle chain in Colombia
[d]Construction of a baseline with 13 cattle producers in the municipalities of Curillo, Albania, Belén de los Andaquíes, Morelia, El Doncello, La Montañita, Valparaíso, and Florencia
[e]Values presented according to the monitoring of the Departmental Livestock Committee of Caquetá in the region
[f]*Braquiarias sp.* pasture subsystems were characterized in humid tropical herds in the department of Caquetá, Colombia N = 20

traditional extensive systems, which is characterized by the incorporation of cultural management practices, both of the pasture and of the animals, aimed at preserving and, sometimes, enhancing the productive capacities of the livestock agroecosystem; the fundamental basis of production is the natural or introduced pasture of low productivity (Cajas et al. 2011), but with good practices of pasture rotation and implementation of agrosilvopastoral systems can reach from 1.43 UGG ha^{-1} to 3.65 UGG ha^{-1} (Lopera-Marín et al. 2019a; Rivera et al. 2015).

10.4 Approach to the Intervention of Alternatives for the Sustainability of Livestock Landscapes

The intervention model is based on three pillars: (i) conservation and restoration, (ii) adaptation to climate change and (iii) sustainable livestock intensification (Fig. 10.3). The approach must start with larger-scale environmental land-use planning processes that make it possible to reduce deforestation and zone the areas dedicated to livestock farming, through a combination of policies that include regulations, command and control mechanisms and incentives (Fig. 10.4).

Sustainable ecological intensification is proposed as an alternative close to agroecology, organic agriculture and agroforestry, which seek to take greater advantage of ecological processes for agricultural production (Tittonell 2014).

Along the same line of thought, one of the alternatives proposed for this productive reconversion of livestock production corresponds to reorienting extensive grazing systems towards systems capable of producing meat and/or milk, while at the

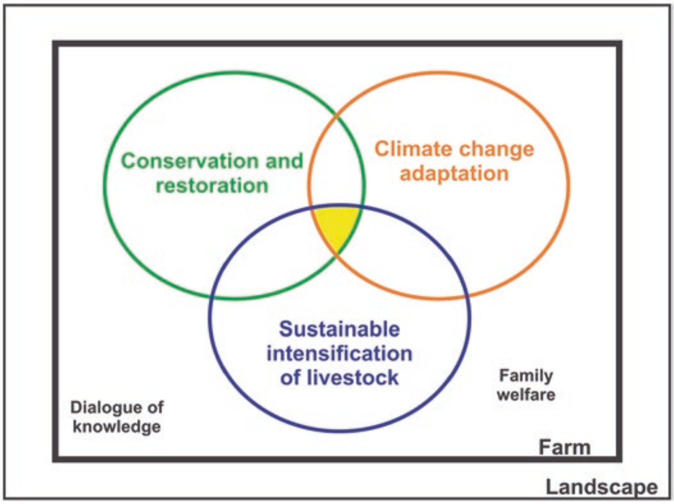

Fig. 10.3 Approach for intervention in livestock production systems. (Adapted from Solarte et al. 2017)

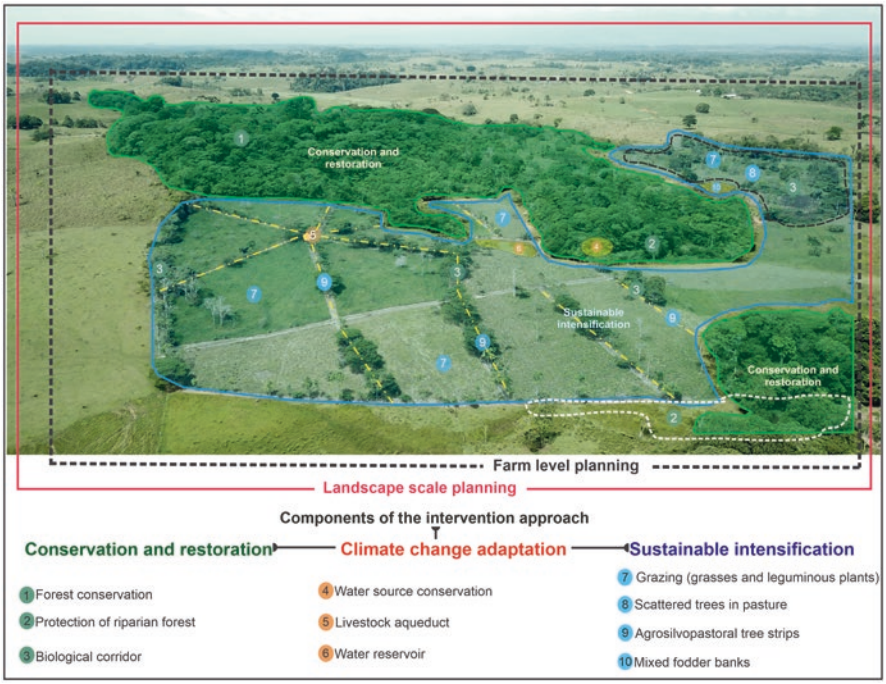

Fig. 10.4 Approach to landscape scale planning in the Andean-Amazonian foothills

same time conserving ecosystems, based on the use of agroforestry as a means of production (Tittonell 2014).

Along the same line of thought, one of the alternatives proposed for this productive reconversion of livestock production is to reorient extensive grazing systems towards systems capable of producing meat and/or milk, and at the same time conserving ecosystems, based on alternatives generically known as agrosilvopastoral systems (SPS).

SPS are a form of livestock agroforestry, in which forage plants such as grasses and leguminous plants are combined in the same space with shrubs and trees for animal feed and other complementary uses (Murgueitio and Ibrahim 2001).

Within this same category, agrosilvopastoral systems are ecological intensification processes that seek to improve family welfare and build sustainable livestock farming adapted to climate variability (Solarte et al. 2017). A sustainable livestock intensification process at the farm and landscape scale must combine at least three elements (Chará et al. 2020):

(i) adequate planning, which allows the identification of areas dedicated to production and those dedicated to ecosystem conservation and restoration including the protection of springs, watercourses and wetlands;

(ii) a transition from traditional extensive management to intelligent grassland management, including rotational grazing with adequate stocking rates, division of paddocks, and provision of water through livestock aqueducts; and
(iii) an increase in tree cover in grazing areas through different agrosilvopastoral arrangements that contribute to improving productivity, animal welfare and the provision of environmental services, while contributing to the connectivity of protected areas.

Climate change scenarios for the department for the period 2011–2040 project an increase in temperature between 0.8 and 1 °C, an increase of up to 10% in precipitation in the highlands (mountain range), and a decrease of up to 19% in the foothills and the Amazon plain of Caquetá (IDEAM et al. 2017). In this sense, livestock farms should be prepared to face temperature increases and seasons of lower and higher precipitation with actions to adapt to climate change.

Solarte et al. (2022a) identified three climate signals (high precipitation and flooding; low precipitation and drought; and increased temperature) that affect livestock families in the Amazon piedmont and 13 adaptation measures for livestock activities related to efficient water managment, soil and pasture management, and animal welfare. The measures are listed below:

1. Conservation of water sources
2. Water harvesting
3. Livestock aqueduct
4. Vegetation cover
5. Tree cover in pastures
6. Adequate pasture management
7. Tracks for cattle transit
8. Transitory use of shade cloths
9. Crossbreeds and adapted breeds
10. Mixed Fodder Banks
11. Forage conservation
12. Improvement of buildings
13. Semi-confinement of livestock

10.4.1 Alternatives for the Sustainability of Livestock Landscapes

According to the interventions carried out by different institutions in the department, nine agrosilvopastoral arrangements have been promoted, which vary in their level of complexity in terms of implementation, management, labor availability, costs and acceptance by the producer (Table 10.2). These include scattered trees in pastures, live fences, sustainable pasture division, tree strips, woodlots or stands, mixed fodder banks, forage hedges and intensive silvopastoral systems (Fig. 10.5).

Table 10.2 Level of requirements for the establishment and management of each system according to its complexity

System	Level of requirements per system				
	Investment	Labor	Management	Knowledge	Technical assistence
Scattered Trees in Pasture	Low	Low	Low	Medium	Low
Live Fences	Low	Low	Medium	Medium	Medium
Sustainable Pasture Division	Medium	Medium	Medium	Medium	Medium
Pastures division with tree strips	Medium	Medium	Medium	Medium	Medium
Pasture division with agrosilvopastoral strips	High	High	Medium	Medium	Medium
Woodlots or stands	High	High	Medium	Medium	Medium
Mixed Fodder Banks	High	High	High	High	High
Forage Hedges	High	High	High	High	High
Intensive Silvopastoril Systems	High	High	High	High	High

High Medium Low

These systems are designed to produce beef and milk, and also allow the generation of wood, firewood, fruits and other associated goods, where one or more species from different strata interact in the same space and time (Murgueitio et al. 2016). These strata usually associate pastures of the genus *Brachiaria sp.* and *Urochloa sp.*; herbaceous legumes (*Arachis pintoi, Pueraria phaseoloides),* shrubs, and multipurpose trees (*Cratylia argentea, Tithonia diversifolia (Hemsl.) A.Gray, Trichanthera gigantea, Leucaena sp., Mimosa trianae, Gmelina arborea, Cariniana pyriformis*) and/or by plant succession management (*Inga sp., Bellucia pentámera, Psidium guajava, Zygia longifolia, Vismia baccifera, Piptocoma discolor*, among others (Annex 1).

- ***Scattered trees in pastures (STP)***

As its name indicates, this arrangement refers to natural or improved pastures in which trees or palms are incorporated in densities greater than 25 individuals per hectare in linear or random arrangements. This system can be established by planting and protecting the trees in the pastures in formation or already established. However, the most effective and least costly way to establish this arrangement in the region is through the management of plant succession in which trees and shrubs that grow spontaneously in the paddocks are managed (Tafur et al. 2011). This requires thinning and pruning the existing vegetation in the paddock, to achieve the desired

Fig. 10.5 Main silvopastoral models promoted in Caqueta department, Colombia. (1) Scattered trees in pastures, (2) Pasture division with tree strips, (3) Pasture division with agrosilvopastoral tree strips. (4) Mixed fodder banks, (5) Live fences, (6) Intensive silvopastoral system with *T. diversifolia*

density of trees and shrubs, and to allow optimal development of pastures, avoiding competition for light. Likewise, it should be considered that not all plant species are desired in a paddock, so it is necessary to select the trees/shrubs that are of interest in the system and in the pasture (Sotelo et al. 2017).

This plant succession management is a valuable tool and the most economical for the recovery of the tree cover of the pastures, as it does not require the removal of animals from the pastures, or the construction of protective fences for the trees and the labor needed is low (Zapata and Silva 2020).

Another alternative for the successional management of vegetation in the region proposed by Cipagauta & Orjuela (2003), is to form small circular or square areas in the center or corners of the pastures to provide shade and protection to livestock during the hottest hours of the day through the generation of microclimates generated by the associated species, to improve the well-being of the animals and the biological activity of the soils.

- ***Live fences (LF)***

Live fences are lines of trees on the main divisions and boundaries of pastures that are used to replace wooden posts or other materials traditionally used to support barbed or electrified wire on cattle ranches. It consists of the establishment of trees or shrubs of different strata to delimit paddocks, crops, and boundaries, as protection to prevent the passage of animals and generate a comfortable and favorable microclimate for animal production (Arango et al. 2016), forming a live fence in dense rows or hedge style, at a distance of approximately two to three meters between trees (Cipagauta and Orjuela 2003). Over time, live fences can become biological corridors that contribute to wildlife conservation (Sotelo et al. 2017).

Another type of implementation of live fences is the so-called sustainable division of pastures (SDP), proposed by Torrijos et al. (2016) for the region, a linear arrangement of trees protected by an electric fence; these divisions improve the forage supply in the paddocks, also allowing the adjustment of the carrying capacity and the occupation and rest times.

These systems with multipurpose tree arrangements can have benefits such as: the production of firewood, stakes for other live fences, fodder production, green manure, posts and wood for other uses and other products, the greatest advantage is that the tree can last 30 years or more.

- ***Pasture division with tree strips (PDTS) and agrosilvopastoral tree strips (PDAS).***

Tree strips contemplate two types of designs. The first design consists of trees in strips and establishes a matrix of grasses and forest species in separate strips and can be composed of one, two or three rows. The spacing between the strips (alleys) allows the formation of corridors through which cattle circulate, facilitating grazing and allowing natural connection between paddocks (Barrera et al. 2017).

The second design consists of placing tree and shrub species along a dividing fence between two paddocks, in a space 10–20 m wide along the length of the paddock. These strips provide shade areas for adjacent paddocks and allow the introduction of short-cycle crops while the tree species develop. Species that provide shade for livestock and those that are of high commercial value in order to protect them from being consumed or damaged by livestock, they should be sown in double furrows, five or six meters apart and 1.5 m from the fence. Between the tramlines, cover legumes and short-cycle crops are planted. This type of arrangement facilitates natural regeneration and the biodiversity of species, and they become biological corridors that cross the grazing areas and serve for the movement of birds and other species of fauna. It is also attractive for the producer because of its ease of management and because he can obtain products from short-cycle crops, which help to compensate for the non-use of the grazing area and amortize the costs of establishment and fences, while the tree species develop (Cipagauta and Orjuela 2003).

- ***Mixed Fodder Banks (MFB)***

Mixed fodder banks combine high protein value shrubs and grasses that provide energy to the animal's diet (Tafur et al. 2011) and forage, fruit and medicinal species that provide food sovereignty for the family. These are small areas located near the corral, milking facilities and the house, where the associated species are densely cultivated to provide abundant good quality forage as a supplement to pasture fodder or as a staple food in semi-intensive and intensive livestock management systems. An alternative to conserve a high volume of forage in optimal conditions of nutritional quality is the ensilage of the harvested material in the banks through the use of plastic bins (Cipagauta and Orjuela 2003).

The mixed bank requires cutting, transporting and chopping the forage to offer it to livestock, which, together with maintenance and fertilization, generates a relatively high demand for labor; for this reason, its adoption is limited by producers in some areas of the department. Among its advantages is the good availability of quality forage that contributes to increased production, reducing supplementation costs and providing a source of feed for critical periods (Zapata and Silva 2016).

- ***Forage Hedges (FH)***

Fodder hedges are strips 2–3 m wide that serve the multiple functions of dividing paddocks, producing fodder for livestock feeding and allowing the development of trees. They integrate the characteristics of multi-layer live fences and mixed fodder banks into a kind of complex live fence, considered an intensive linear silvopastoral system. It is a strip of three meters wide, delimited by an electric fence made up of trees and forage plants in three lines: one line of trees, and on each side, forage plants in line. These systems act as a windbreak and biological corridor, allowing the integration of livestock production with forestry production (Zapata and Silva 2020).

- ***Intensive silvopastoral systems (iSPS)***

Intensive silvopastoral systems (iSPS) are characterized by combining forage shrubs at high density (more than 5000 plants per hectare) and improved pastures, with trees dispersed or in strips at densities of 30–50 individuals per hectare (Zapata and Silva 2020; Uribe et al. 2011). These systems improve carrying capacity (Murgueitio et al. 2011), serve to rehabilitate degraded lands, increase the production of livestock goods with low demand for agrochemicals, and at the same time generate ecosystem services such as water quality and quantity, biodiversity conservation and reduction of greenhouse gases. In the case of the Amazonian piedmont, the most suitable shrub species is *Tithonia diversifolia*.

10.4.2 Productive, Social and Environmental Contributions of Agrosilvopastoral Systems

Agrosilvopastoral systems have a positive impact on the production and quality of forage, increased stocking rate per area and meat and milk yields per hectare, while reducing the environmental damage caused by extensive livestock farming, providing a suitable environment to improve the soil biota and fauna associated with the system (Gutiérrez and Mendieta 2022).

- ***Productive aspects***

Silvopastoral systems contribute to an increase in forage production, forage quality and animal comfort, which is reflected in higher production per animal and per unit area. The efficiency of agrosilvopastoral systems in beef production can be up to 12 times higher compared to extensive monoculture pastures, with the need for less grazing area (Mauricio et al. 2019). The diversification of forage species in the pasture should consider the inclusion of legumes, due to their potential nutritional value and capacity to fix nitrogen, which improves the production and nutritional quality of grasses and soil fertility (Sánchez and Villaneda 2009), improving production per animal by 20–40% (Pérez et al. 2019).

López-Vigoa et al. (2017), mention that agrosilvopastoral systems achieve guaranteed weight gain of between 0.42 and 1.10 kg animal^{-1} day^{-1} and a meat production per hectare between 500 and 1340 kg year^{-1}, approximately. In mixed fodder banks, an improvement of up to 38.33% in weight gain is achieved, reaching 0.6 kg animal^{-1} day^{-1}, with silage supply in conditions of the Colombian Amazon, with respect to traditional management (0.33 kg animal^{-1} day^{-1}) (Cipagauta and Orjuela 2003).

For agrosilvopastoral systems, Lopera-Marin et al. (2019a) reported an increase in production from 3.83 l cow^{-1} day^{-1} in continuous grazing with alternate rotations without forage trees or shrubs to 5.03; 4.37 and 3.91 l cow^{-1} day^{-1} in intensive silvopastoral systems, mixed fodder banks and trees dispersed in paddocks respectively, in conditions of the Amazonian piedmont of Caquetá. Likewise, Rivera et al. (2015), in a work in the same region evaluated an intensive silvopastoral system with *Tithonia diversifolia*, and found that milk production went from 4.59 kg cow^{-1} day^{-1} (3556 kg/ha/year) in a conventional system without trees to 4.92 kg cow^{-1} day^{-1} (5615 kg ha^{-1} year^{-1}) in the intensive silvopastoral system thanks to the increase in production per cow and the increase in the carrying capacity of the system.

In another study, Álvarez et al. (2021) evaluated the effect of different levels of tree cover on milk production in dual-purpose livestock systems in conditions of the

Colombian Amazon under grazing of *B. decumbens*, and found that milk production increased in pastures with medium (4.43 kg cow^{-1} day^{-1}) and high (4.39 kg cow^{-1} day^{-1}) tree cover, compared to those with low tree cover (4.13 ± 0.21 kg cow^{-1} day^{-1}).

Considering the results of these studies, the use of herbaceous and woody legumes as protein banks, or in association with existing grasses, leads to improve availability, supply, and quality of the diet of cattle throughout the year, giving the possibility of increasing milk and meat production per hectare compared to pasture monocultures (Aguilar et al. 2019; Mahecha et al. 2011).

- ***Socioeconomic aspects***

Agrosilvopastoral systems generate economic benefits for cattle-raising families due to the profitability of milk, meat and products derived from the tree layer (poles, wood, firewood, fruit, etc.). These systems have lower production costs and higher gross profit per liter of milk compared to farms with traditional management and the benefit/cost ratio is improved in these arrangements, exceeding the minimum threshold (1 point) up to three times, while conventional farms are below it (Lopera-Marin et al. 2019b). When performing economic analyses related to profitability indicators (NPV: net present value, B/C: benefit/cost ratio, IRR: internal rate of return, LEV: land expectation value) at different temporal spaces, these indicators increase with time, since they depend on the structure of the agrosilvopastoral arrangement; where the B/C is higher in the protein banks – PB (1. 64), intensive silvopastoral system – iSPS (1.61) and forage hedges – FH (1.57); it presents lower values in improved pasture (1.17) and improved pasture plus legumes (1.18). As for the IRR, they are perceived with higher values in systems with greater complexity (iSPS and PB) reaching up to 30% profitability (Sotelo et al. 2017).

These systems contribute to an increase in family income to the extent that the agrosilvopastoral systems are properly established and managed, and favor the generation of more legal jobs per year and ensure the participation of new generations (Lopera-Marin et al. 2019b). In addition to the above, they are a sustainable alternative to change the current poor image of livestock farming, not only increasing production (milk, meat and goods), but also recovering the landscape and producing ecosystem services (Mauricio et al. 2019).

- ***Environmental aspects***

Agrosilvopastoral systems generate ecosystem services that generate ecosystem restoration, connectivity from forest patches to denser forests, protection and conservation of water, generate microclimates, soil protection and climate change mitigation and adaptation.

These types of sustainable livestock systems are strategies that reduce deforestation to establish pastures, because they provide sufficient and quality forage availability for animals, which reduces pressure on forests, water resource conservation and biodiversity (Baldassini and Paruelo 2020). They provide diverse habitats that conserve biodiversity, where they constitute new scenarios or habitats (Williams et al. 2020) that provide refuge to wild animals and especially to the fauna present in the soil (Gutiérrez et al. 2020; Chávez et al. 2016), being systems in dynamic and constant development (Ruiz et al. 2007).

Likewise, they generate microclimates, where Barragán et al. (2017) found a reduction of the maximum temperature on grass without cover and agrosilvopastoral systems of up to 3.7 °C, where it was evidenced that animals in agrosilvopastoral systems with tree cover grazed up to 1.8 hours more, compared to animals that were exposed to direct solar radiation. Under tropical environments, it is reported that under the shade of trees, reductions in rectal temperature of 0.5 °C and skin temperature of 3 °C were observed, compared to animals grazing in the open (Ferreira-Britto 2010); thus, improving animal comfort (Murgueitio et al. 2019).

Agrosilvopastoral systems are also an option to reverse the processes of rangeland degradation (Nair et al. 2009), by increasing the physical protection of the soil and contributing to the recovery of fertility with the intervention of leguminous plants that fix nitrogen in the soil and trees with taproots that take advantage of the deep layers and recycle nutrients (Alonso 2011), incorporate organic matter to the soil, retaining moisture and increasing biota; and at the same time, with the capacity to increase biomass production, generate environmental services of carbon sequestration and biodiversity (Murgueitio et al. 2019).

They contribute to the direct storage of carbon in the short and medium term (decades to centuries) in trees and soil, and indirectly reduce greenhouse gas emissions (Nair et al. 2009). According to the Nationally Appropriate Mitigation Action – NAMA for Sustainable Cattle Ranching in Colombia, the Colombian cattle herd in 2020 (baseline year) totaled 33.2 million t CO_2 eq emitted, of which 1,427,837 t CO_2 eq year^{-1} were from the Southeast ecoregion, of which Caquetá is part. They also determined the carbon dioxide removal potential of five agrosilvopastoral systems on pastures without cover (Table 10.3).

In a study on carbon stored in the tree stratum of cattle-ranching and natural systems in the municipality of Albania, Caquetá, Colombia, it was found that the highest CO_2 storage occurred in forest with 124.52 t CO_2 ha^{-1}, followed by areas of natural regeneration (32.32 t CO_2 ha^{-1}), agrosilvopastoral system (2.59 t CO_2 ha^{-1}), traditional pasture (0.69 t CO_2 ha^{-1}) and improved pasture of the genus *Brachiaria sp.* (0.37 t CO_2 ha^{-1}) (Rojas-Vargas et al. 2019).

Table 10.3 Carbon removal potential for different land uses in the Southeast ecoregion

System	Removal (t CO_2 eq ha^{-1} year^{-1})
Pasture improvement	0.296
Live fences	3.7
Scattered trees in paddocks	1.08–5.4
Mixed Fodder Banks	3.88
Forage hedges	9.1
Intensive silvopastoral systems	11.5

Source: Banco Mundial et al. 2021

Landholm et al. (2019), estimated the greenhouse gas mitigation potential of agrosilvopastoral systems in Caquetá, modeling scenarios in improved pasture -IP, forage bank -MFB and agrosilvopastoral system -SPS, finding that the carbon sequestration of the three modeled technologies differed substantially in relation to a degraded pasture -DP (1.4 Mg CO_2 ha^{-1} $year^{-1}$), where total carbon stocks amounted to 0.57; 6.24 and 2.06 Mg CO^2 ha^{-1} yr^{-1}, respectively, for the IP, MFB and SPS technologies during the 25-year period considered. They also observed that for each of the future scenarios, total GHG emissions are reduced in relation to the base scenario DP; presenting an average GHG mitigation potential of −1.4; −2.4 and −5.8 Mg CO_2 ha^{-1} yr^{-1} for the modeled IM, MFB and SPS scenarios.

The SPS, by including trees and shrubs in the livestock systems, increases up to 4.6 times the carbon storage in the aerial biomass with respect to traditional systems without trees, reaching a carbon stock of 8.69 and 1.88 Mg C ha^{-1}, respectively, results obtained in conditions of the Colombian Amazonian piedmont (Villegas et al. 2021).

Silva-Olaya et al. (2021), in their evaluation of soil health, detected the benefits (chemical, physical and biological) promoted by the long-term implementation (15 years) of agrosilvopastoral management on extensive pastures in the Amazon region, becoming an important strategy to restore degraded land pastures and recover soil health, among them the improvement of soil organic C in the SPS favored biological activity, also mitigating the processes of physical soil degradation caused by livestock activity.

Extensive conversion of forests to pasture managed to degrade the soil's capacity to provide all measured ecosystem services, with a greater impact on the reduction of soil C storage (47%), support for plant growth (40%) and erosion control (31%) (Silva-Olaya et al. 2022).

On the other hand, Rivera et al. (2021) in conditions of the Amazon piedmont, determined the effect of SPS on N_2O and CH_4 emissions from manure of dual-purpose cows, finding that the traditional system -ST emitted 52.48% less N_2O-N in the soil, and in the case of CH_4 the pastures under SPS emitted 23.89% less of this gas. As for urine emissions, cumulative fluxes of CH_4 and N_2O were 76.46 and 42.02% lower in SPS, and in feces emissions were 34.27 and 1.14% lower in these same systems with respect to the ST; concluding that the silvopastoral systems have the capacity to generate lower emission factors from urine (N_2O-N) and feces (CH_4) deposited in the pastures, so they can be systems that mitigate the emissions of these gases in livestock systems.

In a study on the effect of *Tithonia diversifolia* (Hemsl.) A. Gray on methane (CH_4) emissions, they found that a diet of *B. humidicola* (85%) + *T. diversifolia* (15%) generated lower CH_4 emissions produced by enteric fermentation (g/animal/d) compared to a diet of only *B. humidicola*. The inclusion of *T. diversifolia* reduced absolute CH_4 emissions ($P = 0.016$), Ym and emissions intensity (per unit of fat, protein and milk yield corrected per kilogram of fat and protein) in both moderate and rainy seasons ($P < 0.05$); where these types of systems can be a tool to both mitigate enteric CH_4 emissions and increase animal productivity and therefore reduce emissions intensity (Rivera et al. 2023).

10.4.3 Barriers to Adoption and Strategies for Scaling Up Sustainable Alternatives

Despite the environmental, economic, and social benefits of agrosilvopastoral systems that have been discussed and documented in the literature (Gutierrez and Mendieta 2022; World Bank et al. 2021; Rivera et al. 2021; Mauricio et al. 2019; Lopera-Marín et al. 2019a, b; Aguilar et al. 2019; Sotelo et al. 2017; Murgueitio et al. 2019), barriers of different types persist that prevent reaching a larger scale of adoption.

A study conducted in Caquetá by Sandoval et al. (2021), in which they compared different groups of SPS adopters vs. farms with traditional livestock management, found that improved pastures (*Brachiarias sp*.) are more widely adopted than SPSs as a technology that has been incorporated in the region for several decades.

In the case of SPS, the study reported that simpler systems such as dispersed trees in paddocks and mixed fodder banks are adopted first. Subsequently, more complex systems are adopted in terms of establishment and management, requiring greater investment, including pasture renovation and the division of paddocks with trees in strips, rotational grazing and water management with a livestock aqueduct.

The following were identified as factors that positively influenced adoption: participation in projects, training and having established conservation agreements as part of land management. These factors are related to common requirements of cooperative projects that have promoted SPSs in the region.

To determine the barriers to adoption and strategies for scaling up, Solarte et al. (2022b) identified the following categories: social; skills and knowledge; economic; environmental; and technical-operational. From this study the following considerations are highlighted:

For the group of social barriers, resistance to change and attitudes towards new technologies of the families are identified, which requires policies to promote sustainable livestock farming that are inter-institutionally coordinated, both with the public and private sectors and that incorporate gender and generational change.

There is a lack of knowledge about sustainable livestock models and alternatives, both among producers and technical assistants, and there are limitations in agricultural extension services. There is a need to work on knowledge management, since there is information that is not available; on capacity building for human resources at the producer and technical levels; and on improving agricultural extension services.

In terms of economic aspects, the need for financing to establish the SPS and credit payment conditions are identified as factors limiting the possibility of establishing the SPS. There is an opportunity to organize the cattle ranch towards sustainable conservation production, including diversification of activities, access to incentives in environmental markets, the creation of differentiated products with added value, and the design of special lines of credit with adequate conditions for users.

Environmental barriers include the region's climate and soil conditions and pasture degradation processes, the availability of conservation areas and water sources for livestock farming. To overcome these barriers, it is necessary to work on the environmental management of the property, the conservation and restoration of ecosystems, and research and monitoring processes to evaluate progress.

Technical and operational barriers include the low level of administration, the limited availability of plant material adapted to local conditions, agricultural machinery, labor, and transportation of materials to the farms. Progress is needed in the technical, administrative and financial management of the cattle ranches, establishing production records and costs through specialized technical assistance.

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(ii) Implementing sustainable land use systems to contribute to forest conservation, climate protection (REDD+) and the peace-building process in Colombia (Project 18_III_106_COL_A_Sustainable Production Strategies)

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Annexes

Annex 1. Species Used in Silvopastoral Systems and Their Different Uses

STP scattered trees in pastures, *LF* live fences, *SPD* sustainable division of pastures, *PDTS* pasture division with tree strips, *PDAS* pasture division with agrosilvopastoral strips, *WS* woodlots or stands, *MFB* mixed fodder banks, *FH* forage hedges, *iSPS* intensive silvopastoral systems, *FW* fire wood, *W* wood, *WF* wildlife feed, *HF* human feed, *S* shade, *LF* livestock feed

Source: Calle and Murguetitio 2020; Ángel et al. 2017; Barrera et al. 2017; Martínez et al. 2017; Castañeda-Álvarez et al. 2016; Ángel et al. 2014; Pimentel et al. 2014; Álvarez et al. 2013; Hurtado and Guayara 2013; Tafur et al. 2011; Guayara et al. 2009; Cipagauta and Orjuela 2003

No	Stratum	Common name	Scientific name	Agrosilvopastoral system where is used									Use					
				STP	LF	SPD	PDTS	PDAS	WS	MFB	FH	iSPS	FW	W	WF	HF	S	LF
1	Graminea	Sugar cane	*Saccarum officinarum* (L.)							X								X
2	Graminea	Cuba 22	*Pennisetum purpureum x P. glaucum*							X								X
3	Graminea	Grama dulce	*Paspalum notatum* Flugge	X	X	X	X	X	X		X	X						X
4	Graminea	Guaduilla	*Homolepis aturensis* (Kunth) Chase	X	X	X	X	X	X		X	X						X
5	Graminea	Guinea Mombasa	*Megathyrsus maximus* (Jacq.) *cv Mombasa*	X	X	X	X	X	X	X	X	X						X
6	Graminea	King Grass Morado	*Pennisetum purpureun x p. typhoides*							X								X
7	Graminea	Manradu	*B. brizantha* cv. Marandu	X	X	X	X	X	X		X	X						X
8	Graminea	Pasto brizantha	*Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf.	X	X	X	X	X	X		X	X						X
9	Graminea	Pasto Caimán	Brachiaria Híbrido BR02/1752 cv. Cayman	X	X	X	X	X	X		X	X						X
10	Graminea	Pasto decumbens	*Brachiaria decumbe*ns Stapf.	X	X	X	X	X	X		X	X						X

(continued)

No	Stratum	Common name	Scientific name	Agrosilvopastoral system where is used									Use					
				STP	LF	SPD	PDTS	PDAS	WS	MFB	FH	iSPS	FW	W	WF	HF	S	LF
11	Graminea	Pasto Elefante	*Pennisetum purpureum* (Schum)							X								X
12	Graminea	Pasto humidicola	*Brachiaria humidicola.* (Rendle) Schweick	X	X	X	X	X	X		X	X						X
13	Graminea	Pasto Imperial	*Axonopus scoparius* (Hitchc)							X								X
14	Graminea	Pasto llanero	*Brachiaria dictyoneura*	X	X	X	X	X	X		X	X						X
15	Graminea	Pasto Mulato II	*Brachiaria* híbrido cultivar (cv.) Mulato II (CIAT 36087)	X	X	X	X	X	X		X	X						X
16	Herbaceous legume	Campanilla	*Centrosema molle* Mart. ex Benth.	X	X	X	X	X	X	X	X	X						X
17	Herbaceous legume	Campanita ó zapatico	*Clitoria ternataea L.*	X	X	X	X	X	X	X	X	X						X
18	Herbaceous legume	Frijolillo	*Desmodium orinocense* (DC.) Cuello	X	X	X	X	X	X	X	X	X						X
19	Herbaceous legume	Hoja de plata ó pega-pega	*Desmodium heterocarpon* (L.)	X	X	X	X	X	X	X	X	X						X
20	Herbaceous legume	Kudzú	*Pueraria phaseoloides* (Roxb.) Benth	X	X	X	X	X	X	X	X	X						X
21	Herbaceous legume	Mani forrajero	*Arachis pintoi* (Krap. Y Greg.)	X	X	X	X	X	X	X	X	X						X

22	Shrub	Avocado	*Persea americana*					x		x						x	x	
23	Shrub	Araza	*Eugenia stipitata*					X	X	X					X	X	X	
24	Shrub	Boca de Indio, indio viejo	*Piptocoma discolor* (Kunth) Pruski	X	X				X	X	X	X					X	X
25	Shrub	Bohío	*Clitoria fairchildiana* (R. Howard)						X	X	X	X						X
26	Shrub	Bore	*Alocasia macrorrhiza* (L) Schott						X	X	X	X				X		X
27	Shrub	Mexican sunflower	*Tithonia diversifolia* (Hemsl.) Gray						X	X	X	X						X
28	Shrub	Cítrics						X		X						X	X	
29	Shrub	Cratylia	*Cratylia argentea* (Desvaux) O. Kuntze)						X	X	X	X					X	X
30	Shrub	Golgoto	*Hibiscus rosa-sinensis* L.						X	X	X	X						X
31	Shrub	Leucaena	*Leucaena diversifolia* (Schltdl.) Benth.						X	X	X	X					X	X
32	Graminea	Maize	*Zea mays*				X	X		X					X	X		
33	Shrub	Matarratón	*Gliricidia sepium* (Jacq.) Stend						X	X	X	X						X
34	Shrub	Morera	*Morus alba* L.						X	X	X	X				X		X

(continued)

No	Stratum	Common name	Scientific name	Agrosilvopastoral system where is used									Use					
				STP	LF	SPD	PDTS	PDAS	WS	MFB	FH	iSPS	FW	W	WF	HF	S	LF
35	Shrub	Nacedero	*Trichanthera gigantea* (Bonpl.) Nees						X	X	X	X					X	X
36	Shrub	Papaya	*Carica papaya*					X		X					X	X	X	
37	Herb	Pinaple	*Ananas comosus (L.) Merr.*						X	X	X	X						
38	Shrub	Platain	*Musa* sp					X	X	X					X	X		X
39	Shrub	Cassava	*Manihot esculenta*					X		X					X	X		
40	Arboreal	Abarco	*Cariniana pyriformis* Miers.		X	X	X	X	X		X	X		X			X	
41	Arboreal	Acacia	*Acacia mangium* Wild		X	X	X	X			X	X		X			X	
42	Arboreal	Aceituno	*Vitex cymosa* Bertero ex Spreng	X			X	X	X					X	X	X	X	
43	Arboreal	Achapo	*Cedrelinga cateniformis* (Ducke)Ducke	X	X	X	X		X					X			X	
44	Arboreal	Ahumado	*Minquartia guianensis* Aubl.	X	X	X	X		X		X			X			X	
45	Arboreal	Arrayan	*Eugenia anastomosans* DC.	X	X	X	X		X		X			X			X	
46	Palm	Asai	*Euterpe precatoria Mart*	X				X	X	X					X	X	X	
47	Arboreal	Balso lano	*Ochroma pyramidale* (Cav. ex La.) Urb.	X					X					X			X	

48	Arboreal	Bilibil	*Guarea guidonia* (L.) Sleumer	X					X				X	X	X		X	
49	Arboreal	Cocoa	*Theobroma cacao* L.	X				X	X						X	X	X	
50	Arboreal	Capirona, resbalamono	*Calycophyllum spruceanum* (Benth.) K.Schum	X	X	X	X	X	X		X	X		X				
51	Arboreal	Caracolí	*Anacardium excelsum* (Kunth) Skeels		X	X	X	X			X	X	X	X			X	
52	Arboreal	Carbon	*Zygia longifolia* (Humb. & Bonpl. ex Willd.) Britton & Rose	X	X				X				X				X	
53	Arboreal	Castaña del barsil	*Bertholletia excelsa Bonpl.*					X	X	X					X	X	X	
54	Arboreal	Cedar	*Cedrela odorata* L.	X	X	X	X		X					X			X	
55	Arboreal	Chilco	*Miconia elata*	X			X		X				X	X			X	
56	Arboreal	Chocho	Ormosia nobilis	X			X		X					X			X	
57	Palm	Chontaduro	*Bactris gasipaes*	X				X	X	X					X	X	X	
58	Arboreal	Cobre	*Andira inermis* (W. Wright) Kunth ex DC.	X	X	X	X		X				X	X			X	
59	Palm	Coconut	*Cocos nucifera* L.	X				X	X	X					X	X	X	
60	Arboreal	Dormilon	*Albizia carbonaria* Britton	X	X	X	X	X	X		X	X		X			X	
61	Arboreal	Guamo machete	*Inga spectabilis* (Vahl) Willd.	X	X	X	X	X	X		X	X	X	X	X	X	X	

(continued)

No	Stratum	Common name	Scientific name	Agrosilvopastoral system where is used									Use					
				STP	LF	SPD	PDTS	PDAS	WS	MFB	FH	iSPS	FW	W	WF	HF	S	LF
62	Arboreal	Guamo rabo de mico	*Inga edulis* Mart	X	X	X	X	X	X		X	X	X	X	X	X	X	
63	Arboreal	Custard apple	*Annona muricata*					X		X					X	X	X	
64	Arboreal	Guava	*Psidium guajava* L.	X				X	X				X		X		X	
65	Arboreal	Guayabo coronillo	*Bellucia pentamera* Naudin	X					X				X	X	X		X	
66	Arboreal	Lacre	*Vismia baccifera* (L.) Planch. & Triana	X					X				X	X	X		X	
67	Arboreal	Macano	*Terminalia amazonia* (J.F. Gmel.) Exell		X	X	X							X			X	
68	Arboreal	Madura plátano, canalete	*Jacaranda copaia* (Aubl.) D. Don	X	X		X	X	X				X	X			X	
69	Arboreal	Mango	*Mangifera Indica* L.	X				X	X						X	X	X	
70	Arboreal	Marfil	*Siparuna decipiens* (Tul.) A.DC.	X	X	X	X		X		X			X			X	
71	Arboreal	Melina	*Gmelina arbórea* Roxb	X	X	X	X	X			X	X	X	X			X	X
72	Arboreal	Nogal cafetero	*Cordia alliodora* (Ruiz & Pav.) Oken		X	X	X	X						X			X	
73	Arboreal	Oji ancho	*Hieronyma alchorneoides* Allemão		X	X	X	X	X		X	X		X			X	

74	Arboreal	Orejero	*Enterolobium schimburgkii* (Benth.) Benth.	X	X	X	X		X		X			X			X	
75	Arboreal	Pata de vaca	*Bauhinia arborea* Wunderlin	X	X				X				X	X			X	X
76	Arboreal	Pizamo, Cachimbo	*Erythrina ulei* Harms*Erythrina fusca Lour.*	X	X	X	X				X		X	X			X	X
77	Arboreal	Roble, Ocobo, Guayacan rosado, Flor morado	*Tabebuia rosea* (Bertol.) A. DC.	X	X	X	X	X	X	X	X	X		X			X	
78	Arboreal	Samán	*Samanea saman* (Jacq.) Merr.	X	X	X	X		X					X			X	
79	Arboreal	Sangregado	*Croton lechleri Müll.Arg.*	X					X					X			X	
80	Arboreal	Tabaquillo, nacedero blanco	*Isertia laevis* (Triana) B.M.Boom		X	X	X										X	
81	Arboreal	Tachuelo	*Zanthoxylum rhoifolium* Lam.	X	X	X	X						X	X			X	
82	Arboreal	Uva Caimarona	*Pourouma cecropifolia* Mart.	X				X	X	X					X	X	X	
83	Arboreal	Yopo	*Mimosa trianae* (Benth) .	X	X	X	X	X			X	X	X	X			X	

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Chapter 11
Agroecological Transition for Sustainable Cattle Ranching with Silvopastoral Systems in the High Andean Slopes of Colombia

Claudia Durana, Enrique Murgueitio, and Jhon Jairo Lopera-Marín

Abstract Dairy cattle ranching in the high Andean zone is a socioeconomic important activity, relatively efficient compared to other cattle raising systems in Colombia's lowland tropics. However, it relies heavily on imported inputs (fertilizers, concentrated feed, pesticides, etc.) and is highly vulnerable to economic and environmental changes because of the ecosystem conditions in a region that is also recognized for its biodiversity richness and its ecosystem services. Silvopastoral systems are a sustainable production alternative for agroecological intensification of dairy livestock farming. To implement these systems, conventional dairy farmers need to make profound changes and a gradual transition of the production process. An integrated approach is proposed combining land use planning -considering land capability- and the introduction of mixed pastures, trees, and shrubs in the production system, together with the management of local resources and forest conservation. This chapter presents a case study of a dairy cattle ranch transformation in a high Andean hillside area in Colombia, that made land use changes based on conservation criteria in rural landscapes and the application of agroecological principles in its production practices. The most outstanding achievements were the maintenance of the economic viability of the production system in a period of financial crisis for the country's dairy industry, thanks to a greater efficiency in the use of non-renewable energy and nitrogen (external inputs). At the same time, the system preserved and restored forest areas and increased connectivity between forest fragments. Agroecological production also enhanced biodiversity conservation and the provision of ecosystem services such as water regulation and plant and soil carbon storage.

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Keywords Agroecological transition · Agroecology · Silvopastoral systems · Sustainable dairy farming

11.1 Introduction

Because of the growing global population, it is estimated that the demand for meat and dairy products will continue to increase and double by 2050 in relation with 2010 levels, especially driven by urban consumers in developing countries (Peters et al. 2013; Herrero et al. 2009). The challenge of increasing livestock production per area unit and, at the same time, restoring and conserving areas of natural ecosystems, requires the integration of agroecological principles into agricultural production (Zuluaga and Etter 2018). This challenge requires technological and institutional innovations where local actors play a fundamental role (Tapasco et al. 2019).

The Northern Andean zone is a globally significant region for biodiversity conservation (Orme et al. 2005). Specialized dairy livestock is part of the productive matrix in Colombian high mountain areas between 2000 and 3200 m.a.s.l., with average temperatures between 12 and 17 °C (Murgueitio 2008). It produces 24% of the country's total milk in 3.5% of the total grazing areas, and is developed mainly in small and medium-sized farms (UPRA 2020; FEDEGAN 2022) that include highland and hillside areas. In the last ones, current livestock production models have greater impacts on ecosystems (Zúñiga et al. 2013).

The importance of high Andean ecosystems and the complexity of dairy production in these areas requires the development of new ways of land use that contribute at once to biodiversity conservation, ecosystem services provision and social development in these rural landscapes. It is suggested that failures in natural resources management in agricultural production are caused by a linear vision framed in a human dominance position over nature (Berkes and Folke 1994) which is materialized in extractive systems where economic rationality prevails. This process, where economic efficiency is the main criterion, generates unforeseen results and unexpected effects that impact the productive activity itself and other social sectors (Giampietro 2003). The possible solutions, framed within the same paradigm, are partial and ineffective. For this reason, different fields of environmental and social studies are proposing a change of the approach to address the sustainability problem (Giampietro 2003; Berkes et al. 2000).

Along these lines, agroecology appeared in the second half of the twentieth century as a new science with a systemic and interdisciplinary vision that also validates other types of knowledge with the objective of achieving food security, social justice, and environmental sustainability in agricultural production (Altieri 1995; Gliessman 1997; León-Siccard 2014). With the current global food, energy and climate crises, its importance has grown to demand its application on a larger scale, which implies the development of gradual and consistent transition processes towards sustainability, as well as the generation of knowledge to support them (Altieri and Nicholls 2020, 2022).

The agroecological transition of productive systems has been studied with different methods, including indicators to evaluate the application of agroecological principles at various scales, as well as the agroecological structure (Altieri 2022; León-Sicard et al. 2018). In livestock systems, different types of indicators have been proposed, among which the following stand out: (a) Vegetation cover, (b) Plant diversity, and (c) Soil organic matter (Sarandon and Flores 2014). These environmental indicators are integrated in other studies with economic and social variables to analyze sustainability (Astier et al. 2011). Also, the socioecological metabolism approach is applied to livestock production systems, analyzing the energy efficiency, nutrient balance, life cycle and ecological footprint (Denoia et al. 2008; Funes-Monzote 2009; Jiménez-Castro and Elizondo-Salazar 2014; Llanos et al. 2018; Rotz et al. 2020).

In Colombia, sustainability analysis in dairy production systems has been addressed by identifying the main challenges of the conventional model based on external inputs (Carulla and Ortega 2016; Holmann et al. 2003), comparing different indicators according to their intensification level (Ruiz et al. 2019), developing life cycle analysis (Rivera et al. 2014), and non-renewable energy and nitrogen balances (Benavides Patiño 2016). Other livestock studies in the Colombian Andes extend the production system sustainability to livestock landscapes that are crucial for food production, livelihood support, and biodiversity conservation (Calle et al. 2012; Gu and Subramanian 2014). Due to the socioeconomic importance of dairy cattle ranching in the high northern Andean mountains, and the environmental problems of the current production models, it is urgent to develop strategies to promote more sustainable systems (Mahecha et al. 2002; Carulla and Ortega 2016).

Silvopastoral systems (SPS), with the incorporation of agroecological principles in their design and management, are part of the set of solutions to global environmental problems, including increasing carbon sequestration and reducing the use of non-renewable energy in the production process (Murgueitio et al. 2011, 2013a; Silva Parra et al. 2019; Chará et al. 2019). Silvopastoral systems are also a technological alternative that sustains productivity while replacing excess of synthetic nitrogen and other chemical inputs to the system, such as pesticides and other synthetic fertilizers (Márquez et al. 2010; Castaño Quintana et al. 2019; Lopera-Marín et al. 2020a). All this could be achieved using agroecological principles such as the promotion of functional diversity, the use of local resources and solar energy, and the protection of soils. The integration of nitrogen-fixing plants, phosphorus-solubilizing species, trees, and shrubs into the livestock system, contribute to increase organic matter content and soil moisture, with direct effects on forage production and self-regulation of the system (Márquez et al. 2010; Zapata Cadavid and Silva Tapasco 2016; Pezo 2019; Lopera-Marín et al. 2020b).

11.2 Silvopastoral Systems (SPS): An Agroecological Option for Livestock Sustainability on High Andean Slopes

11.2.1 General Information on Sustainable Livestock Farming with SPS and Agroecological Principles on High Andean Slopes

High Andean or mountain areas are crucial for ecosystem services related to biodiversity, which benefit local farmers and the society (Hall et al. 2015; Castaño 2002; Cuesta et al. 2012). Part of the remaining biodiversity in these sites is found within cattle ranches where relicts of native forests are preserved (Chaves et al. 2007). In addition, milk production, which was traditionally carried out in areas of high plateaus and low slopes near urban centers, has increasingly spread to hillsides or mountain areas (Hall et al. 2015), where ecosystems are more fragile and production conditions are less favorable, presenting lower productive performance and more impact on the environment and natural resources (Agudelo et al. 2003; Zúñiga et al. 2013).

The characteristics of dairy cattle production and the biological importance of high Andean slopes urgently require the generation of knowledge on sustainable cattle ranching models with mountain SPS (Gómez Mora et al. 2005; Hall et al. 2015). Sustainable cattle ranching is based in the use of primary production of grasses and other fodder species grown under agroecological principles and with local resources to feed domestic herbivorous animals (Dietl et al. 2009). On the matrix of grasslands managed with agroecological principles, it is possible to incorporate shrubs and trees in Silvopastoral Systems (SPS) in different arrangements achieving multiple purposes: (a) Protect and use water, soil and local biodiversity rationally in synergistic relationship with domestic animals for the production of high quality and strategic food, (b) Promote formal employment, (c) Afford good quality of life for people in the countryside, (d) Enhance animal welfare, and (e) Generate ecosystem services for all, among others (Murgueitio et al. 2020). The introduction of tree and shrub species in agricultural production based on agroforestry recreates some of the conditions of the forest for the self-regulation of the production system (Montagnini 2017).

In SPSs forage plants are combined in an intentional, intensive, integral, and interactive manner with trees and shrubs for animal nutrition and complementary uses (Jose et al., Chap. 1, this volume; Montagnini 2008; Murgueitio et al. 2011; Calle et al. 2012; Chará et al. 2017; Calle 2020). Silvopastoral systems can also be integrated with conservation and ecological restoration actions in rural landscapes (Calle, Chap. 3, this volume; Calle et al. 2012; Calle and Holl 2019). In this land use strategy, grazing is reduced to agroecologically appropriate areas and released areas are devoted to conservation, ecological restoration and connectivity corridors, while the pasture matrix is diversified (Lopera et al. 2015). Trees, shrubs, legumes, and grasses associated with livestock can become a production subsystem, in which forestry generates a long-term income, optimizing, together with cattle production, productivity and profitability indicators per unit area (Chará et al. 2019). In addition to the benefits for livestock farmers, SPSs contribute to climate change mitigation by capturing carbon and reducing greenhouse gas (GHG) emissions (Mahecha et al. 2002; Murgueitio et al. 2013a; Peri et al. 2019).

In the mountain regions, SPSs are especially relevant considering that livestock production occupies areas that were previously covered by forests strategic for the conservation of rural-urban ecosystem balances (Calle and Holl 2019). SPS are based on developments and applications supported by research in the last decades on different plant species adapted to these areas (Murgueitio et al. 2013b). Some of these are *Tithonia diversifolia* (Hemsl.) A. Gray (Mahecha et al. 2021), *Sambucus peruviana* H.B.K. (Cárdenas et al. 2011; Grajales Atehortúa et al. 2015; Rodríguez Molano et al. 2019; Durana et al. 2022), *Alnus acuminata* H.B.K. (Silva-Parra et al. 2018; Escobar et al. 2020a, b), *Smallanthus sonchifolius* (Poepp. & Endl.) H. Rob. (Lopera-Marín et al. 2020b). Other studies have focused on the silvopastoral arrangements (Murgueitio et al. 2013b; Escobar-Pachajoa et al. 2019) and the evaluation of their impact on grass pest management (Lopera et al. 2015; Ochoa et al. 2017). However, although SPS generate recognized benefits, their implementation is more complex than conventional systems and therefore it requires to provide technical assistance and reinforce the farmer's knowledge (Lopera et al. 2015).

11.2.2 Benefits of SPS in Mountain Areas

In general, SPSs contribute to the generation of a more suitable environment for livestock production, given that: (i) Trees and shrubs roots take nutrients in deeper layers and produce plant litter that enriches the soil with organic matter, while preventing erosion (Zapata Cadavid and Silva Tapasco 2016). (ii) Foliage diversity generates better soil cover, as well as greater production of quality forage (Grajales Atehortúa et al. 2015; Navas-Pandero et al. 2021). (iii) The improved soil cover increases water retention and infiltration rates, reducing runoff, landslides, and gully formations (FAO 2018). (iv) The different strata of vegetation, especially trees, act as a barrier preserving humidity and protecting pastures from frost and wind (Snyder and de Melo-Abreu 2010).

In hillside or mountain areas, agroecological transition with SPS requires to combinate different actions in the production system that should be carried out simultaneously to condition the agroecosystem and obtain benefits for livestock, while contributing to biodiversity conservation and ecosystem services generation. These practices are complemented by proper livestock management applying business and zootechnical concepts (Rivera et al. 2014) that generate employment and better opportunities in the countryside. These practices include rotational grazing with electric fences in small paddocks with short consumption periods and adequate pasture recovery times (Bacab et al. 2013), division into groups of cattle by age, supply of water in each paddock, and the use of animal draft power

(Mahecha-Ledesma et al. 2022). This should be complemented with animal genetic selection according to environmental conditions, adequate reproductive management, and administrative efficiency (Murgueitio et al. 2016).

11.3 El Silencio Nature Reserve: A Case Study of Agroecological Transition and Sustainable Livestock Production on High Andean Slopes in Colombia

11.3.1 Location and Description of the Farm

El Silencio Nature Reserve stands in the upper part (hillside areas) of the municipality of San Francisco (Cundinamarca, Colombia) at 4° 57′ 21″ N and 74° 14′ 20″ W, in the western mountain range of the Bogota Plateau known as El Tablazo. This is part of a biological corridor of Low Montane Rainforest relevant for water regulation (Holdridge 1966; CAR 2019). The elevation of the property ranges from 2650 to 2850 m.a.s.l., with an annual rainfall of 1500 mm, an average temperature of 14 °C (minimum of 8 °C and maximum of 18 °C), undulating topography and moderate to steep slopes (>45 °C).

It is a private property where people from three generations participate in the management. It has an area of 114 ha that includes 42 ha of protected Andean cloud forest with oak trees (*Quercus humboldtii* Bonpl.), and about 20 ha in ecological restoration, altogether with more than 600 species of plants and 120 species of birds (Fig. 11.1).

Fig. 11.1 Panoramic view of meadows and live fences on a hillside area in El Silencio Natural Reserve. (Photo: Adolfo Galindo)

In the reserve the main economic activity is milk production with Holstein cattle. On average, 37 cows with a production of 17.2 L/cow/day are milked (twice a day) in the paddocks using a portable milking equipment. The cattle production area has a diversity of forage with mixed grasses (*Cenchrus clandestinus, Lolium perenne, Lolium multiflorum, Holcus lanatus, Dactylis glomerata, Trifolium repens, Trifolium pratense, Lotus uliginosus, Desmodium spp, Taraxacum officinale, Acmella sp.*). The SPS establishment includes live fences, windbreaks, hedgerows, and forage banks with species such as *Tithonia diversifolia, Sambucus. peruviana, Alnus acuminata, Acacia melanoxylon,* and *Eucalyptus globulus*, among others. The Nature Reserve has also areas for agricultural production with short-cycle crops and some annual crops for human-animal food security, horse breeding, as well as areas for ecotourism activities (Fig. 11.2).

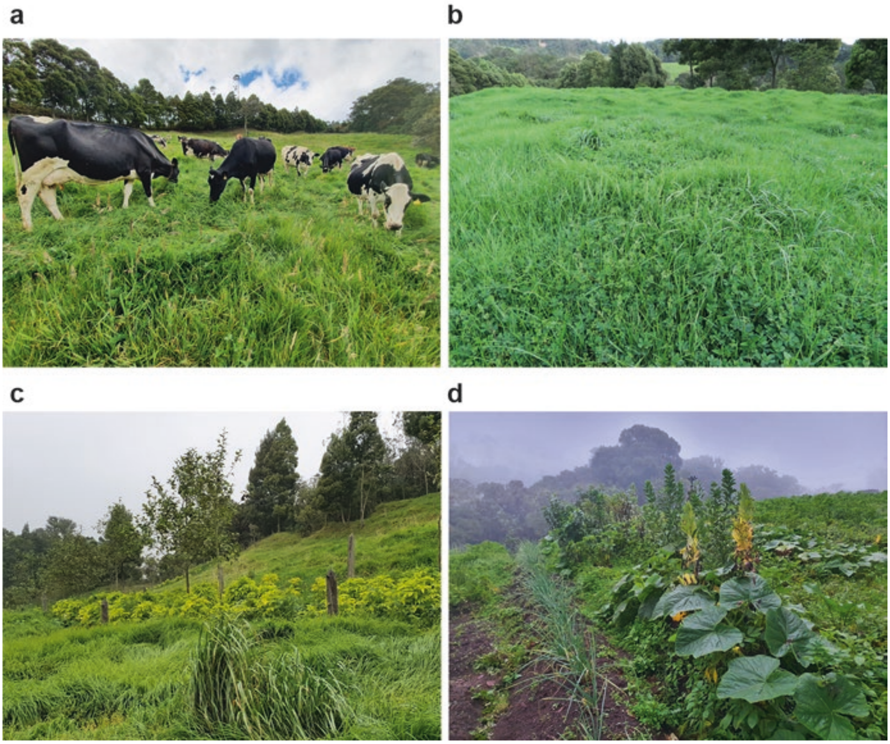

Fig. 11.2 (**a**) Holstein cows grazing in mixed pastures; (**b**) Mixed pastures with grasses and legumes; (**c**) SPS with forage hedges of *S. peruviana* and *A. acuminata* trees. (**d**) Short-cycle crops for human and animal food security. (Photos **a**, **c**, **d**: Claudia Durana; Photo **b**: Adolfo Galindo)

11.3.2 Analysis of the SPS Agroecological Transition in El Silencio Nature Reserve

To identify the relevant factors for the agroecological transition process and its impact on the sustainability of the system, we used information from the farm over a period of 16 years and analyzed it taking into account the following management stages: (a) Low intensification conventional management from 2006 to 2011, (b) Intensification process with improved farm management and increased use of external inputs from 2012 to 2016, and (c) Incorporation of agroecology and SPS from 2017 to 2021. A conceptual and methodological framework was adapted to evaluate the sustainability of the farm at the different stages, considering its technical and economic viability, its environmental feasibility and its desirability or correspondence with societal objectives (Giampietro and Mayumi 2000; Serrano Tovar 2014). Changes in management practices at each stage are presented, as well as the evolution of sustainability indicators over time.

11.3.3 Changes in Land Use and Management Practices in the Agroecological Transition Process

11.3.3.1 Land Use

A gradual change in land use was carried out applying conservation tools to increase the connectivity of forest patches and other conservation areas. Since 1997, vegetation cover was increased with the establishment of live fences with *Acacia melanoxylon*, tree corridors, restoration areas, silvopastoral systems with eucalyptus trees (*Eucalyptus globulus*) and iSPS with elderberry (*Sambucus peruviana*) (Fig. 11.3).

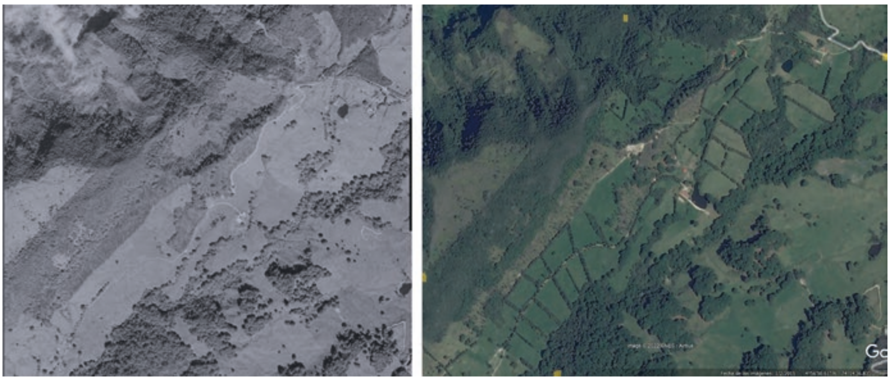

Fig. 11.3 Comparison of land use changes in El Silencio Nature Reserve in images of 1997 (left) and 2021 (right)

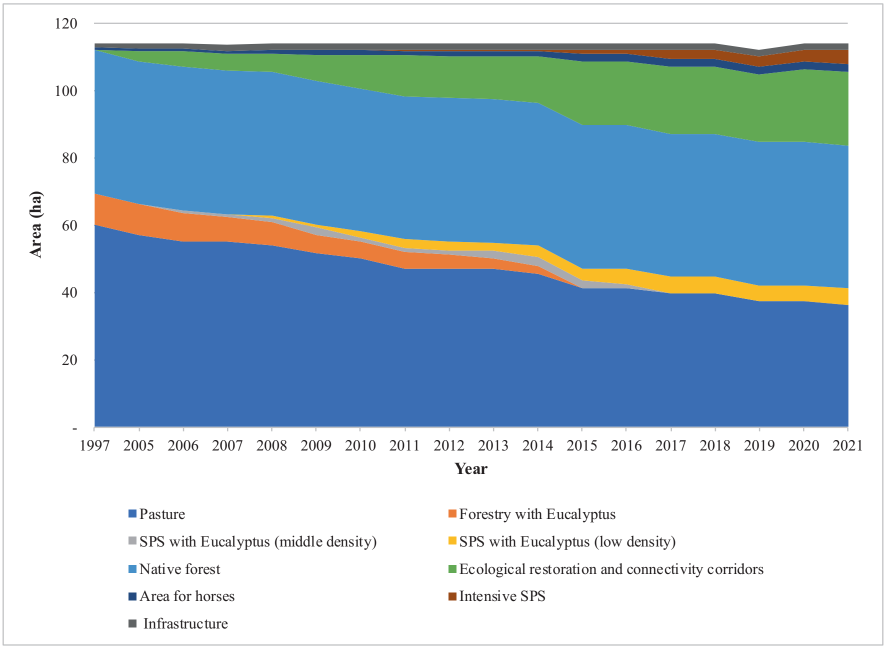

Fig. 11.4 Changes in land use in El Silencio Nature Reserve between 1997 and 2021

Between 2006 and 2021, effective grassland areas were reduced by 30%, and areas dedicated to cattle production by 15%. The native forest increased its area by 50% through plant succession processes and assisted natural regeneration on springs and margins of streams, also through the release of unproductive areas for ecological restoration, as well as the establishment of 5.4 km of live fences, 1.6 km of tree corridors between 5 and 20 m wide (Fig. 11.4). During this period, the total inventory of cattle and the number of milking cows were reduced by 9.47% and 11.90%, respectively, and annual milk production increased by 9.77% (Table 11.1).

11.3.3.2 Evolution of Land Use Changes in El Silencio Nature Reserve Between 2006 and 2021, and Their Effects on the Livestock Inventory and Milk Production

Between 2012 and 2016 (intensification of the conventional model) nitrogen fertilizer application increased up to 60 kg/ha/year in each cattle rotation area. However, this amount applied is below what is normally used on specialized dairy farms in the high tropics (Holmann et al. 2003; Carulla and Ortega 2016; Ruiz et al. 2019). In 2015, ENSO (El Niño-Southern Oscillation phenomenon characterized by increased temperatures and drought) became a constraint for nitrogen application due to the lack of soil moisture required for fertilizer assimilation. Due to this and the strategy

Table 11.1 Evolution of land use changes in the El Silencio Natural Reserve between 2006 and 2021, and their effects on the cattle inventory and milk production

Year	Pasture	Native forest	Forestry	Eucalyptus low density	SPS with eucalyptus	iSPS (hedgerows)	Ecological restoration	Total cattle	Lactating cows	Milk production
	Ha							N°		L/year
2006	57.2	42.4	9	0	0	0	4	95	42	198,402
2007	56.6	42.4	9	0	0	0	4	88	38	213,295
2008	54.2	42.4	9	0	1	0	5.4	90	40	241,679
2009	53	42.4	9	0	0	0	7.6	92	39	223,072
2010	53	42.4	0	9	0	0	7.6	93	43	229,658
2011	50.7	42.4	0	8	0	0.3	10.6	91	43	249,909
2012	49	42.4	0	0	5	0.3	15.3	92	43	247,256
2013	49	42.4	0	0	5	0.3	15.3	90	45	293,530
2014	48	42.4	0	0	5	0.3	16.3	92	43	265,545
2015	46	42.4	0	0	5	0	18.6	83	40	223,000
2016	44	42.4	0	1	5	0	19.6	84	34	231,449
2017	42.1	42.4	0	0	5	2.5	20	82	37	242,890
2018	42	42.4	0	0	5	2.6	20	85	40	257,251
2019	41.6	42.4	0	0	5	3	20	81	35	215,344
2020	40.1	42.4	0	0	5	3.5	21	87	37	225,670
2021	39.6	42.4	0	0	5	4	21	86	37	217,792

SPS silvopastoral system, *iSPS* intensive silvopastoral system, *L* litres of milk

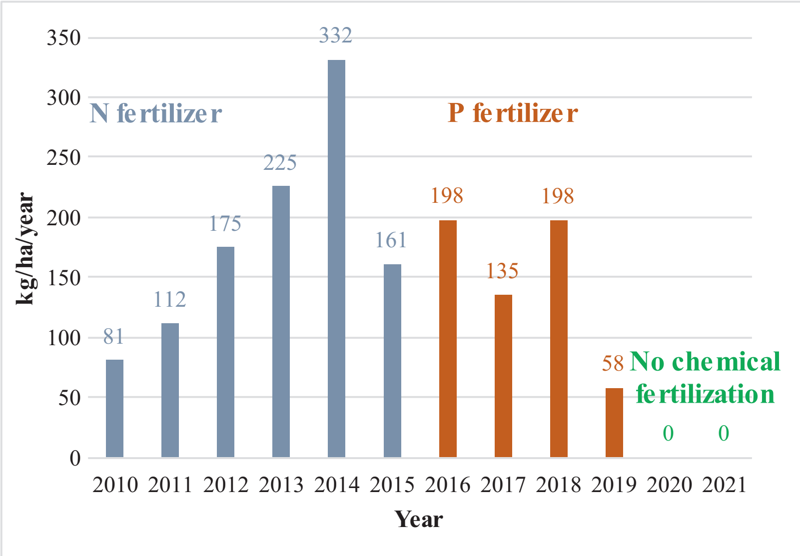

Fig. 11.5 Changes in chemical fertilization with N and P between 2010 and 2021

to reduce chemical insecticide applications to control sucking insects, in 2016 an adjustment was made to fertilization, reducing nitrogen, and increasing the proportion of phosphorus until reaching zero chemical fertilization as of 2020 (Fig. 11.5). It is worth mentioning that since 2010 fertilization with chemical synthesis products was complemented with equine manure compost, between 2010 and 2021 the accumulated application was 1000 m^3 equivalent to 2.3 m^3/ha/year.

The increase of P in fertilization, the use of horse manure compost and the extension of the pasture resting period, allowed the emergence of other plant species in the padocks (especially creeping legumes, slow-growth grasses, and broadleaf plants) for the nutrient supply to the soil through biological and biochemical routes such as nutrient cycling, solubilization of P immobilized by ions and fixation of atmospheric nitrogen. In addition, these plants also enhanced the supply of forage biomass for the cattle. The botanical composition in the paddocks between 2017 and 2021 presented an increase of leguminous plants from 5% to 17%, highlighting species such as *Trifolium repens* and *Lotus uliginosus* and several weeds of the Asteracea family such as *Taraxacum officinale* and *Acmella sp*; decreasing by 20% the presence of *Cenchrus clandestinus* (main pasture of these milk production systems). Likewise, the proportion of *Lolium sp*. was doubled and the presence of *Holcus lanatus*, a native species of interest for its energetic contribution to the diet of cows in production, was increased (Fig. 11.6).

The reduction in nitrogen and P fertilizer applications, the increase in the diversity of plant species in the paddock and the longer pasture recovery times in the cattle rotation, improved the natural regulation of the grass-sucking insects. These phytophagous insects that include the grass bug (*Collaria scenica, Collaria oleosa*),

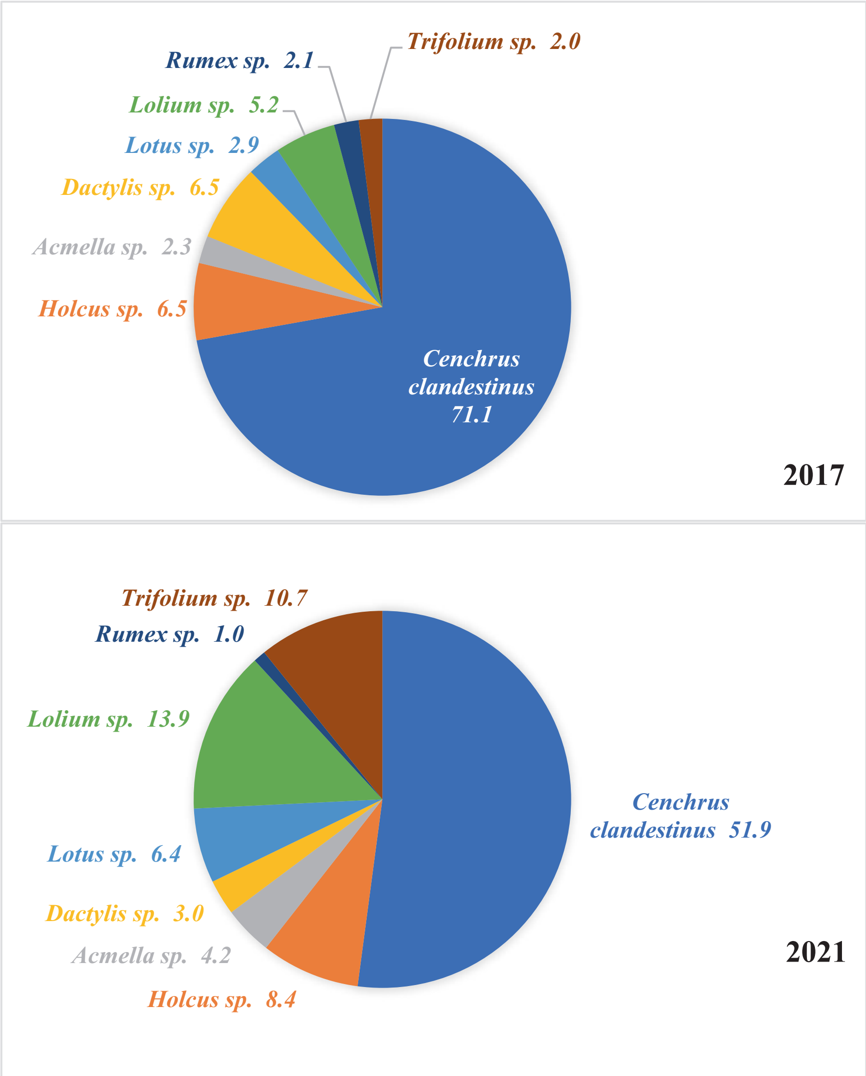

Fig. 11.6 Change in botanical composition (%) of grasslands used for dairy production between (**a**) 2017 and (**b**) 2021 in El Silencio Nature Reserve

the grass sharphooter (*Draeculacephala sp.*) and recently the grass spittlebug (*Zulia carbonaria* and *Mahanarva phantastica*) increase their incidence in monospecies pastures with high fertilizer application (Ochoa et al. 2017). The reduction of their incidence due to agroecological practices, allowed that as of 2018 no synthetic product was applied for their control (Fig. 11.7). Recent evaluations demonstrated cost reductions in insecticide application of up to 75 USD/ha/year (Lopera-Marín et al. 2020a). Also, the labor required was redirected to other activities within the

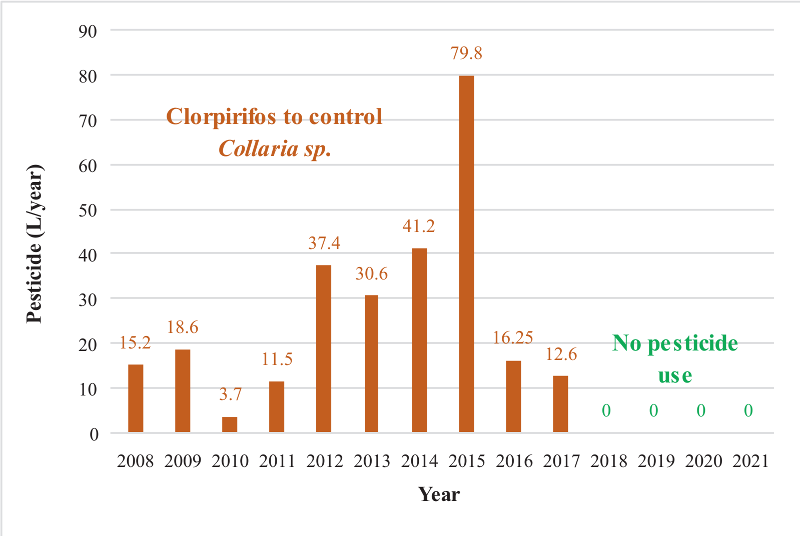

Fig. 11.7 Amount (L) of insecticides used between 2008 and 2021 for the control of grass-sucking insects in El Silencio Nature Reserve

production system, avoiding the exposure of people to toxic substances and improving their quality of life.

11.3.3.3 Paddock Rotation and Supplementation of Cows in Production

The division of pastures with fences increased the number of paddocks from 10 to more than 40, with an average area of one (1.0) ha each. Cattle groups increased from three to five, being categorized by age, physiological and productive stages: lactating cows, calves, heifers, prepartum cows and non-lactating dairy herd. This management allowed offering fresh forage through grazing strips to all groups twice a day. The management involved the use of electric fences to guarantee the occupation and rest periods of each grazing area, in addition to the livestock water supply network, which always offered fresh, good quality water.

Initially, the rotation of paddocks with one day occupation per strip was carried out with a maximum of 60 days of rest (return of the cattle), however, in the dry season it was reduced to 30 days, affecting the physical structure of the soil and its forage production capacity. With the increase in the number of paddocks, group management, agroecological management of grass-sucking insects, increased plant diversity, and the incorporation of SPS, pasture rest was extended to 90 days (in the dry season it is reduced to 60 days).

The supplementation of cattle with grain from balanced feed (concentrate) is one of the main practices of the conventional model of milk production in the high tropics. However, with the incorporation of ISPS with fodder hedges and fodder banks, concentrate supplementation has been reduced (without the use of balanced feed in rearing females up to 5 months of age, and cows close to calving). Currently, the farm has 3.5 km of *Sambucus peruviana* forage hedges with approximately 20,000 plants. According to green forage production evaluations, each plant produces in average 2.5 kg three times per year. This is a forage that has been used on the farm to supplement all livestock groups, replacing concentrate for calves and heifers, and eliminating the purchase of silage (corn silage and other forages) in times of drought or high rainfall.

The effect of replacing 35% of commercial concentrated feed by leaves and green stems of *Sambucus peruviana* on the production and chemical quality of milk was evaluated by Durana et al. (2022). A significant difference ($p < 0.05$) of 4% in milk production was found in favor of the control diet treatment (commercial concentrate), but there was no significant difference between treatments in the variables related to compositional quality of the milk. When comparing the economic surpluses of each diet, it was identified that replacing 35% of the balanced feed with forages increased the gross income from milk sales by 14% (Durana et al. 2022).

11.3.3.4 Input Reduction

As mentioned above, the agroecological transition process in the farm has resulted in a reduction in the use of the main external inputs such as chemical fertilizers, insecticides and other toxic substances that were eliminated in the productive process and replaced by organic fertilizers (Table 11.2). The use of antiparasitic

Table 11.2 Changes in the use of external inputs in the milk production system in the different stages of management between 2008 and 2021 in the El Silencio Nature Reserve

Stage	Year	Insecticide (L)	Chemical fertilizer (kg)	Organic fertilizer (m^3)
Conventional low intensive management	2008	15	4280	0
	2009	18.6	4300	25
	2010	3.7	4320	108
	2011	11.5	5680	70
Intensification in the use of external inputs	2012	37.4	8940	188
	2013	30.6	11,520	0
	2014	41.2	16,680	70
	2015	79.8	8780	99
	2016	16.25	11,000	75
Agroecological transition	2017	12.6	7300	10
	2018	2	7980	3
	2019	0	2600	201
	2020	0	0	79
	2021	0	0	126

products, antibiotics and hormones also decreased, and the spread of insecticides against the hematophagous horn fly (*Haematobia irritans*), was also discontinued.

11.3.4 Sustainability Indicators

The effect of the different management practices was measured with technical, economic, and environmental indicators by applying the conceptual framework proposed by Giampietro and Mayumi (2000). Economic variables were measured from 2006 to 2021, and environmental variables from 2010 to 2021.

11.3.4.1 Technical and Economic Viability of the Production System

The technical and economic viability of the system was defined by productivity, cost efficiency and profitability variables (Table 11.3). Costs were established with constant 2021 prices for labor, pasture maintenance expenses, milking, external inputs, electricity, veterinary services and medicines, artificial insemination, pesticides, and transportation with actual farm values.

Productivity per hectare increased in the agroecological transition stage (between 2017 and 2021) when compared with the conventional management stage (between 2006 and 2011), but it was lower than the productivity per hectare during the conventional intensification period (between 2012 and 2016) (Fig. 11.8). However, milk yields were maintained with agroecological production above 6000 L/cow/year, with a more stable behavior in the production per animal and close to what is recommended for organic milk production based on forage resources (5000 L/cow/year) as suggested by Dietl et al. (2009). In terms of milk chemical quality, fat content increased by 5% and protein by 10% between 2008 and 2022. However, these increments were not proportionally reflected in the price per liter due to external factors.

Cost efficiency is related to the number of cows milked and the weight of fixed costs, especially labor costs. Between 2020 and 2021 there was a reduction in cattle inventory affecting this indicator, although it remained at competitive values in the international market (below 0.28 USD considering the analysis with constant prices of 2021 and the value of the currency at 4000 COP) (Carulla and Ortega 2016). It is important to highlight that labor presented a higher share of costs in the initial management and in the agroecological transition periods compared to the intensification stage with external inputs (Fig. 11.9). This indicates that the resources for milk production went to the workers and not to commercial inputs, most of which are imported. However, in the cost structure remains that of commercial concentrate for milking cows, still representing 33% of total costs in 2021.

Profitability depends on production levels, costs, and milk prices. The latter showed higher values between 2008 and 2012. Between 2012 and 2015, in the years of greater intensification with external inputs, profitability was reduced, despite

Table 11.3 Technical and economic feasibility indicators in El Silencio Nature Reserve between 2006 and 2021

Stage	Year	Milk production	Cost efficiency		Profitability	
		L/year	Cost/L (COP) (C)	(USD)	Price/L (B)	(B-C)/C (%)[a]
Conventional low intensive management	2006	198,402	1029	0.26	1371	33
	2007	213,295	993	0.25	1376	39
	2008	241,679	1038	0.26	1538	48
	2009	223,072	1136	0.28	1479	30
	2010	229,658	1056	0.26	1411	34
	2011	249,909	1091	0.27	1410	29
Intensification in the use of external inputs	2012	247,256	1121	0.28	1397	25
	2013	293,530	1086	0.27	1273	17
	2014	265,545	1094	0.27	1296	18
	2015	223,000	1178	0.29	1290	10
	2016	231,449	1132	0.28	1397	23
Agroecological transition	2017	242,890	1073	0.27	1389	29
	2018	257,251	983	0.25	1281	30
	2019	215,344	1084	0.27	1279	18
	2020	225,670	990	0.25	1343	36
	2021	217,792	1054	0.26	1383	31

C cost, *B* benefit

[a]**(B-C)/C (%):** Profitability (B/C) is calculated as the surplus (benefits minus costs) over costs. It is calculated in the unit of a liter of milk with the benefits as the price of milk, which is the value that comes in from the sale of milk, and the costs, considering the cost of producing a liter of milk. The percentage resulting from dividing the surplus per liter (price per liter minus cost per liter) by the cost per liter, represents the percentage of profit over the investment (labor, inputs, electricity, transportation, among others) in the production process

high production levels. This was aggravated by the drought of 2015 due to ENSO. Although in 2019 there was an internal crisis that affected profitability, this was recovered for 2020 and 2021.

With the agroecological transition, production was maintained, profitability increased compared to the intensification stage with external inputs, and costs were reduced while labor participation in them increased and milk quality improved. Similarly, milk production was maintained despite the effects of ENSO, low rainfall in 2019, some sanitary problems in the herd between 2020 and 2021, and the increase in chemical fertilizer prices in 2021. The information of loss of profitability in milk production is a nationwide phenomenon caused by the rise in input and labor costs and the low increase in milk prices (FEDEGAN 2022), where the most affected producers were those with models of high dependence on imported inputs.

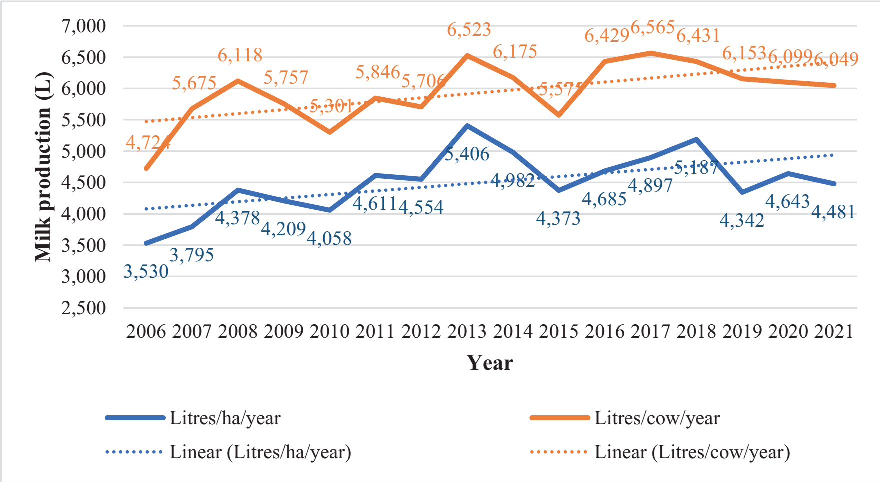

Fig. 11.8 Annual productivity per animal and per hectare between 2006 and 2021 in El Silencio Nature Reserve

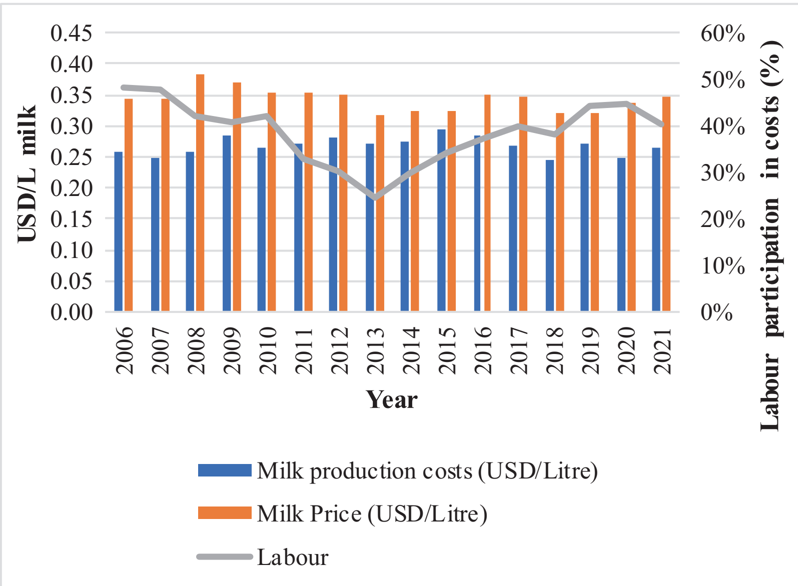

Fig. 11.9 Costs and prices per L of milk and labor participation between 2006 and 2021 in El Silencio Natural Reserve

11.3.4.2 Environmental Feasibility of the Production System

Environmental feasibility is another condition for the sustainability of the systems that implies efficiency in the use of natural resources and in the emission of pollutants. In this case, non-renewable energies (NRE) that enter the system through external inputs, fuels and electricity are compared. Likewise, nitrogen input through chemical fertilizers and balanced feed is also analyzed in terms of utilization efficiency. The conversion values correspond to the NRE used in the manufacture and transport of external inputs (Table 11.4). The formula of Energy Output (EO) in meat and milk over Energy Input (EI) in external inputs and energy sources (EO/EI), reflects the efficiency in the use of NRE coming from these inputs in the system, with the highest values showing greater efficiency in the transition process from the conventional model to agroecological production.

As for the efficiency in the use of NRE from external inputs, it was lower during the intensification stage and higher during the agroecological transition. Commercial concentrate is one of the NRE sources that continues to be used, considering that they cause dependency and increase production costs, but maintain production. However, *Sambucus peruviana* forage, according to the results of research in milk production, will begin to replace the milk cows balanced feed (Durana et al. 2022).

The energy efficiency decreased during the period with higher intensification and increased to in the years with agroecological production. These values were above

Table 11.4 Environmental feasibility of the production system from energy efficiency, N efficiency and GHG emissions through external inputs between 2010 and 2021 in El Silencio Nature Reserve

Stage	Year	Energy efficiency		N inputs efficiency		Emissions	
						Productive area	Whole farm
		EO/EI	MJ/kg FPCM	NI/NO	g N/kg FPCM	CO2eq/ha/year	
Conventional low intensive management	2010	1.26	2.57	0.53	10.9	771	383
	2011	1.22	2.64	0.46	11.9	917	455
Intensification in the use of external inputs	2012	1.00	3.22	0.39	14.1	1182	587
	2013	1.07	2.99	0.27	16.8	1323	657
	2014	0.88	3.63	0.22	23.0	1474	732
	2015	0.73	4.49	0.34	17.6	1355	673
	2016	0.93	3.44	0.45	12.8	1095	543
Agroecological transition	2017	1.09	2.94	0.49	11.3	969	481
	2018	1.28	2.45	0.60	8.5	868	431
	2019	1.23	2.62	0.96	6.8	664	330
	2020	1.43	2.24	1.07	5.6	614	305
	2021	1.45	2.21	1.14	5.3	579	287

EO energy output (in meat and milk), *EI* energy input in external inputs, fuel, and electricity, *NI* N input in fertilizers and feed, *NO* N Output in milk and meat, *MJ* Mega Juoles, *FPCM* fat and protein corrected milk, *CO2eq* carbon dioxide equivalents, *ha* hectares those found in conventional specialized dairies in cold climates in Colombia that are between 0.51 and 0.73 for medium and high intensification systems (Benavides Patiño 2016). The same is reflected in the index of quantity of non-renewable energy used to produce 1 kg of milk (MJ/kg FPCM). In the agroecological intensification stage (between 2017 and 2021) this value was on average lower than that of organic farms supplementing with grain and reporting an index of 2.6 MJ/kg FPCM but was higher than in the organic production farm without supplementation with an index of 2 MJ/kg FPCM (Rotz et al. 2020).

Regarding nitrogen entering the system through chemical fertilizers and feed, efficiency is measured by the ratio of N Input (NI) over N Output (NO) (NI/NO) which represents the units of synthetic nitrogen required to produce one unit of N contained in milk protein. This index increased with the intensive use of fertilizers and was subsequently reduced with the introduction of SPS and agroecological management. Likewise, the amount of nitrogen used from fertilizers and concentrates per kg of milk produced was reduced in the agroecological production stage with values below 6 g N/kg FPCM (Fig. 11.10). Studies in dairies in Costa Rica and the United States reported averages of 16.95 gN/kg milk and between 22 and 24 g N/kg milk produced, respectively (Jiménez-Castro and Elizondo-Salazar 2014).

The overall analysis of this case study of the El Silencio Nature Reserve shows the evolution of milk production and its economic and environmental effects through the three stages described above. Agroecological intensification stands out for maintaining high productive and financial indexes while significantly reducing the negative environmental externalities of the high external input model. Table 11.5 summarizes the transition of the farm according to agroecological principles, agroecological practices and the results achieved:

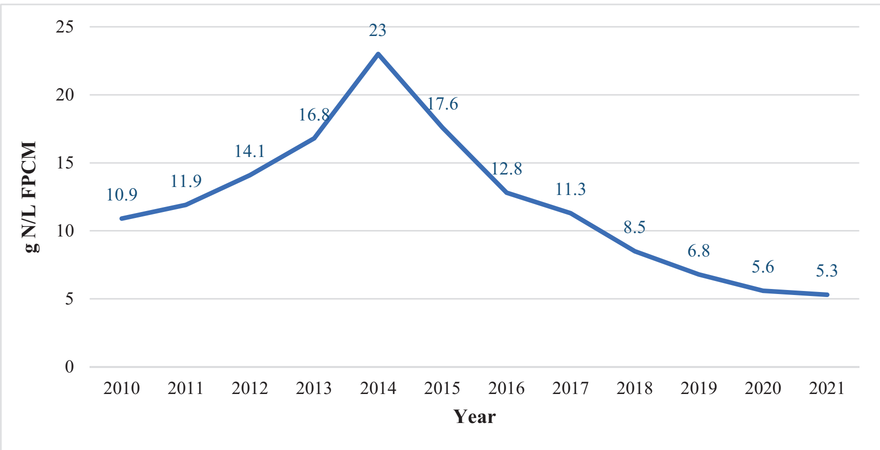

Fig. 11.10 Nitrogen from fertilizers and concentrates per kg of FPCM in El Silencio Nature Reserve over time

Table 11.5 Summary of the transition of El Silencio Nature Reserve according to agroecological principles, agroecological practices and results achieved

<table>
<tr><th>Agroecological principle</th><th>Practices implemented</th><th>Observed results</th></tr>
<tr><td>Improved biomass recycling and nutrient cycling.</td><td>Reduction of nitrogen applications.
Application of vermicompost, microorganisms and rocks instead of chemical fertilizer.
Application of biochar.
Windbreaks and live fences.
Fodder hedges.
More native forests and more connectivity between forest fragments.</td><td rowspan="6">Improved working conditions by replacing some activities such as irrigation, chemical fertilization, and pesticide application with manual and specific activities in the SPS.
Increased production of fodder biomass.
Increased forage quality.
Moderate stocking rate is maintained.
Increased functional biodiversity.
Milk production is maintained.
Improved compositional quality of milk (more protein and total solids).
Reduction of external inputs with elimination of chemical fertilizers and reduction of feeds
Reduction of production costs (10–15%).
Total elimination of the use of chemical pesticides in pastures.
Reduction of erosion.
Increased water retention in the soil with less irrigation demand.
Increased welfare and comfort of livestock.
Greater resilience in very wet or dry seasons.
Milk demand for ecological products.</td></tr>
<tr><td>Improved functional biodiversity</td><td>Application of vermicompost, microorganisms and rocks instead of chemical fertilizer.
Application of biochar.
Windbreaks and live fences.
Fodder hedges.
More native forests and greater connectivity between forest fragments.
Introduction of leguminous plants in grasslands
No control of weeds in grasslands
Reduction of endoparasite treatments and elimination of Ivermectin's.</td></tr>
<tr><td>Increased biomass production, more organic matter, and increased soil biological activity.</td><td>Longer pasture rotation (longer resting periods).
Application of vermicompost, microorganisms and rocks instead of chemical fertilizers.
Application of biochar.
Windbreaks and live fences.
Fodder hedges.
More native forests and more connectivity between forest fragments.
Reduction of endoparasite treatments and suspension in the use of Ivermectin's.</td></tr>
<tr><td>Increased conservation and regeneration of soil, water, and agricultural biodiversity.</td><td>Longer pasture rotation (longer resting periods).
Application of vermicompost, microorganisms and rocks instead of chemical fertilizer.
Use of biochar.
Windbreaks and live fences.
Fodder hedges.
More native forests and more connectivity between forest fragments.</td></tr>
<tr><td>Diversification of species and genetic resources in the agroecosystem in time and space and at the landscape scale.</td><td>Mixed pastures of grasses, legumes, and shrubs.
Windbreaks and live fences.
Fodder hedges.
More native forests and more connectivity between forest fragments.</td></tr>
<tr><td>Increased biological interactions and synergies among components of agricultural biological diversity.</td><td>Mixed pastures of grasses, legumes, and shrubs.
Windbreaks and live fences.
Fodder hedges.
More native forests and more connectivity between forest fragments.</td></tr>
</table>

11.4 Conclusions

The case study of the El Silencio Natural Reserve demonstrated the approach to sustainability in milk production in the high-altitude tropics with good levels of productivity and profitability while achieving a better compositional quality of milk. It also allowed the release livestock areas for the conservation of native forests, along with the establishment of other biodiversity conservation tools.

The case study shows that productive and environmental conversion with agroecological processes in sustainable livestock models requires the implementation of simultaneous actions, generating synergies and reducing the use of external inputs. With the increase in prices, profitability is better compared to the model of intensification with external inputs since the increase in chemical fertilizers cost does not affect the system's economy. Less dependence on external inputs contributes to reduce production costs, and to distribute the benefits among the people working in the farm, while the enriched agroecological base increases and sustains production levels, improving product quality. This would give the possibility of obtaining added value for its characteristics, traceability, and environmental benefits, as well as the opportunity to access new markets (organic, sustainable, agroecological and others) and be more competitive.

The incorporation of SPS in agroecological transition processes allows for greater efficiency in the use of non-renewable energy and nitrogen from external inputs, as well as lower GHG emission levels. Despite the inherent demand of more complex management and the conditions of high Andean slopes or mountain areas, it is shown that these are a sustainable option for livestock intensification due to its economic viability, its environmental feasibility, and its concordance with social objectives like social welfare, biodiversity conservation and environmental services.

A comprehensive understanding of the system based on a set of indicators of different dimensions, such as those presented in the case study, can lead to better decision making and the development of instruments to promote the conversion to a more sustainable model within a rural landscape. Agroecological intensification with SPS is part of a necessary process of energy transition, climate change mitigation and biodiversity conservation in rural landscapes.

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Chapter 12
Silvopastoral Systems with Native Tree Species in Venezuela

Eduardo Enrique Escalante and Héctor Fabio Messa

Abstract This chapter describes the main silvopastoral developments in Venezuela with an emphasis on the use of native tree species in the states of Guarico, Cojedes, Barinas, Apure and Portuguesa in the Venezuelan Llanos and in the states of Lara, Falcon, Anzoategui, and Trujillo in the semi-arid life zones of the country. The main arrangements promoted are living fences, scattered trees in pastures, trees in rows, grazing in tree plantations and intensive silvopastoral systems. Cattle breeding is concentrated in the savanna zone (Llanos) an area with a well-defined dry season (mainly Tropical Dry Forest), in which scattered trees that supply fruits and legumes to livestock during the dry season predominate. The tree species with more consumption by cattle are legume trees such as *Samanea saman*, *Albizia guachapele*, *Enterolobium cyclocarpum*, *Cassia moschata*, *Prosopis juliflora*, *Acacia macracantha*, and *Gliricidia sepium*. On the other hand, in the arid and semi-arid zones of the country in the northern coastal region, there is a predominance of goat production. As in the plains, the presence of legume species, mostly of the Fabaceae family, play a significant role in the diet of animals. Other non-leguminous species that are also consumed by domestic animals are *Guazuma ulmifolia*, *Bulnesia arborea*, *Spondias mombin*, *Ceiba pentandra*, *Anacardium excelsum*, *Platymiscium pinnatum* and palms, such as *Attalea butyracea*, *Copernicia tectorum* and *Acrocomia aculeata*, and valuable wood species like *Cordia alliodora*, *Cordia thaisiana*, *Tabebuia rosea*, *Swietenia macrophylla* and *Tabebuia chrysantha*. Of the tree species whose foliage, pods and fruits are consumed by ruminants, *Samanea saman* is the most important as a scattered tree in the Tropical dry forest of Venezuelan Llanos. The chapter will analyze the growth rate and timber production of native species under silvopastoral arrays and the impact of the systems on economy, carbon sequestration, animal welfare and biodiversity.

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12.1 Introduction

For centuries, cattle raising has been an activity of extensive areas in Venezuelan savannas known locally as Los Llanos, an area mostly of Tropical Dry Forest, with total annual precipitation ranging from 1200–1800 mm year^{-1}, and average temperature of 25–27 °C. The Llanos are an extensive region of northern South America, which includes part of the territories of Colombia and Venezuela, with a total area of 355,112 km^2. The territory corresponding to Venezuela is 68% (241,000 km^2), generally characterized by a flat topography, an average altitude of 150 masl, and an average slope of 70 cm per km (Andressen and López 2015).

The Venezuelan Llanos are divided in two major landscapes: open habitats (savannas) and forest habitats (forests). Savannas cover approximately 75% of the surface of the Llanos; the rest is covered by semi-deciduous, deciduous and gallery forests (Utrera 2003). Geographically there are three types of savanna plains: Eastern plains, Central plains (high central plains and low central plains) and Western plains (high and low) (Andressen and López 2015).

According to Ramia (1967), savannas are classified into three main types: The Lowland-Bank savannas (Sabanas de banco-bajío y estero), savannas of *Paspalum fasciculatum* (Western savannas) and *Trachypogon* sp. savannas (Eastern savannas). The lowland-bank savannas are located mainly in the western plains of Venezuela. The *Paspalum fasciculatum* savannas include large open areas, with physiognomic and environmental characteristics similar to those described for the lagoons, estuaries and shallows in the south of the Apure river, and the *Trachypogon* savannas cover an extensive area in the Eastern Plains (35,000 km^2), with dominance of grasses of the genus *Trachypogon*, deep sandy soils, poor in nutrients and well drained, which are usually interspersed with scattered trees and shrubs, constituting the predominant vegetation formation in those landscapes.

12.2 Plants with Fodder Potential in Venezuela

12.2.1 Plants with Fodder Potential in the Venezuelan Central Llanos

The region of the Central High Plains is formed by the states Anzoategui, Guarico and Cojedes, and the southern areas of Aragua, and has an estimated surface of 28,700 km^2. According to Holdridge (1968) it is composed by three main ecosystems: Tropical Dry Forest, Premontane Dry Forest and Premontane Humid Forest.

Fig. 12.1 Pastures in the Tropical Dry Forest of Aragua state during the dry season with presence of Guacimo (*Guazuma ulmifolia*) providing shade and shelter. (Photo: E. Escalante)

The whole region is bi-seasonal with an intense period of rains between May and October (wet season) and a dry season from November to April, with a severe scarcity of forage during these months (Fig. 12.1).

The vegetation of the central plains has numerous plant species consumed by cattle, mostly legumes with high protein content and nutritional value. However, a significant number of tree species with forage potential have not yet been evaluated. In the south of Aragua state, including the Tropical dry forest, the Dense deciduous forest, the Espinal Llanero and the Chaparral, the natural shrub vegetation of the plant formations, constitutes a forage resource available for livestock feeding (Cecconello et al. 2003). In that area, 30% of the trees and shrubs species evaluated have fodder value and the forage offer for ruminants, ranges between 640 and 3997 kg DM ha^{-1} (Baldizán and Chacón 2007).

As mentioned earlier, fruits and pods from woody legumes provide an important resource during the dry season in the tropical dry forest. Crude protein (CP) of whole fruits in this region ranged from 4% to 22% (Cecconello et al. 2003). The fruits with highest protein content were those of *Chloroleucon mangense* with 22%, followed by those of *S. saman* with 14.04% and *Acacia macracantha* with 10.85%. The percentage of crude protein in seeds ranged between 16% and 21.26%, with the highest value in *C. mangense* with 21.16%. The ruminal degradability of DM was higher in whole fruits than in seedless fruits, with highest values in *S. saman* and *Enterolobium cyclocarpum* with 62% and 81% respectively. These species also had the highest degradability with a total index of approximately 90% (Cecconello et al. 2003).

Casado et al. (2001) studied the forage potential of a deciduous forest in the Guarico state. Plant species with the highest frequency index were *Acacia macracantha* with 30% followed by *Chloroleucon mangense* with 17%, and *Caesalpinia coriaria* with 13%, all of them of high acceptability of forage and fruits by the cattle. They also found that 81% of the identified species had a medium to high acceptability value (Casado et al. 2001). It was also estimated that the fruit production of *A. macracantha* was on average of 12.8 kg per tree.

According to Domínguez et al. (2007) the Fabacea family predominated in terms of the number of species and frequency of individuals. The most important were *Acacia macracantha, Calliandra affinis, Cassia moschata*, *Fissicalyx fendleri, Lonchocarpus sp*., *S. saman, Senna obtusifolia, Senna spectabilis* and some species of the genus *Inga*. Other species with forage value found in the same study were *Genipa americana, Spondias mombin, G. ulmifolia* and *Oyedaea verbesinoides*. Other species less frequent, but no less important because of their high acceptability by cattle in the region are *Acrocomia aculeata*, *Enterolobium cyclocarpum* and *Senna atomaria,* representing 16% of the total species found in the study (Casado et al. 2001). In other study in two forests in northeastern Guarico state Rengifo et al. (2008) identified also some species with forage potential such as *Acacia glomerosa*, *Pereskia guamacho*, *Caesalpinia granadillo*, *Pithecellobium unguis-cati*, and *Trichanthera gigantea*.

In Northeast Guárico state, Miliani et al. (2008a) evaluated the DM forage supply with three treatments: grazing in a pasture with *Cynodon nlemfuensis*, grazing with restricted access to the forest for 5 hours and grazing with free access to the forest. The total DM for *C. nlemfuensis* was 2227 and 2467 kg DM ha^{-1} for the dry and rainy season respectively. The supply of DM increased to 10,800 and 5926 kg DM ha^{-1}, in treatment with forest for the same previous seasons. The contribution of leaf litter, foliage and fruits of the forest species in the dry season contributed to a higher DM supply when compared to the rainy season. Therefore, the forest component grazing doubles DM in the rainy season and was five times greater in the dry season. It is concluded that through the use of the forest resource, animals tend to diversify their diet, improving their selection capacity (Miliani et al. 2008b).

12.2.2 Trees and Woody Shrubs with Potential as Fodder in the Forests of the Western High Plains

The forage potential of a tropical dry forest (deciduous forest), with acid soils and low fertility, in Mesa de Cavacas, Portuguesa state, was studied by Solórzano et al. (2004). The study conducted on ten farms allowed the identification of 89 plant species, of which 46 (53.7%) were arboreal, 25 (28%) shrubby, three palm species and the rest herbaceous.

In the study, producers identified the 30 species that were consumed by cattle, of which the most important were *Samanea saman*, *Cassia moschata*, and *Spondias* *mombin*, followed in order of preference by *Guazuma ulmifolia*, *Mangifera indica* and *Genipa americana*. Other species of importance and forage potential were *Cochlospermum vitifolium*, *Acrocomia aculeata*, *Anacardium excelsum*, *Attalea butyracea*, *Crescentia cujete*, *Cassia siamea*, *Gliricidia sepium*, *Inga spp.*, *Trichanthera gigantea* and *Enterolobium cyclocarpum*. Producers reported that cattle consumed only the fruits of 50% of the species and the leaves of 36% of species. Only in 14% of the species were both the fruits and foliage consumed, among them *C. moschata*, *G. ulmifolia*, *S. saman*, *S. mombin* and *M. indica* (Solórzano et al. 2004).

In the same state, Ojeda et al. (2012), determined the preference of woody plants by cattle in a silvopastoral system with access to a tropical semi-deciduous forest, evaluating the epidermal fragments in fecal samples. Twenty-two species of woody plants were identified in the area, grouped into 11 botanical families with 40.9% of the species within the family Fabaceae. The woody species of highest selectivity by cattle during the dry season were *Inga laurina, Machaerium humboldtianum, S. saman* and *Sida acuta* (Ivlev index = 0.60 ± 0.09) (Ojeda et al. 2012). Therefore, the design of silvopastoral systems in the tropical forest should consider the promotion of woody plants of forage value, without affecting the biodiversity of these ecosystems (Ojeda et al. 2012).

In another study Cardozo (2008) listed a group of plant species whose fruits had great potential as fodder in silvopastoral systems, most of them in the flooded savannas. The species identified were *Spondias mombin*, *Maclura tinctoria*, *Licania pyrifolia*, *Vitex orinocensis*, *Cordia tetrandra*, *Genipa americana*, *Attalea butyracea*, *Bactris balanophora*, *Crescentia cujete* and *Inga spp*.

Another important group of plants in silvopastoral systems are fodder species consumed directly by livestock in the field or under the cut and carry practice; the most used are *Leucaena leucocephala*, *Gliricidia sepium*, *Morus alba*, *Trichanthera gigantea*, *Tithonia diversifolia* and *Moringa oleifera*.

12.2.3 Plants with Fodder Potential in Northwestern Venezuela, Zulia and Trujillo States

According to Torres (2007), the nutritional advantages offered by the foliage of some perennial woody species for animal feed are known by the producers of the lowland area of Trujillo state. However, these species are not part of the strategy of bovine feeding as an essential source of nutrients and only constitutes another element of the livestock ecosystem. Considering this situation, in recent years several studies have been carried out to characterize representative forages of Trujillo state (García and Medina 2006), (García et al. 2008a, b, 2009a, b), the authors have carried out bromatological studies of species with greater forage potential for bovines, sheep and goats in the Tropical Dry Forest of the lower Andean foothills of Venezuela.

According to García et al. (2008a) the most consumed species by cattle, sheep and goats in Trujillo were *Chlorophora tinctoria, Pithecellobium pedicellare* and *Morus alba.* The sheep and cattle, eagerly consumed the biomass of *M. alba, C. tinctoria, G. ulmifolia, P. pedicellare* and *L. leucocephala*, while the most desired species by goats was *C. tinctoria*. Goats also preferred foliage with lower content of Neutral Detergent Fiber (NDF) and low concentrations of total polyphenols.

Also in Trujillo, through descriptive analysis (DA), principal components analysis (PCA) and linear correlations (CL) the nutritional composition of the foliage of 20 forage species was characterized, the legume species studied were: Hueso de pescado (*Pithecellobium pedicellare*), Matarratón (*Gliricidia sepium*), Leucaena (*Leucaena leucocephala*), Saman (*Samanea saman*), Cuji (*Acacia* spp.), Cadeno (*Bauhinia cumanensis*), Mucuteno (*Cassia alata*) and Burra (*Pentaclethra macroloba*); while the non-legumes were: Mora de palo (*Chlorophora tinctoria),* Morera *(Morus alba*), Guacimo (*Guazuma ulmifolia*), Caujaro (*Cordia alba*), Vero (*Bulnesia arborea*), Olivo (*Capparis odoratissim*a), Naranjillo (*Trichanthera gigantea*), Boton de Oro (*Tithonia diversifolia*), Moringa (*Moringa oleifera*), Neem (*Azadirachta indica*), Cayena (*Hibiscus rosa-sinensis*) and Flor amarilla (*Wedeliaaff caracasana*) (García et al. 2009a, b).

It was possible to verify that the legume species exhibited marked differences in the phytochemical pattern of the biomass, compared with the rest. The tannins precipitating the legumes affected the digestibility of the nutritive fractions, while the phenols and sterols present in the non-legumes exhibited greater antinutritional potential in this type of species (García et al. 2009a, b).

12.2.4 The Fodder Potential in Arid and Semi-arid Zones of Northern Venezuela

Plant biodiversity is also of major importance in the dry tropical forest in the arid and semiarid environments of Lara and Falcon states in Venezuela. Goat production in those areas greatly depend on fodder provided by small trees and shrubs whose leaves, flowers and fruits are the main diet of the goat livestock (Escalante et al. 2011).

Other arid zones of the country are located in Nueva Esparta, northern part of Anzoategui and Zulia states. The shrub desert ecosystems are the driest in the country with an average annual rainfall of 125–250 mm. Primary vegetation does not exist due to the exposure to overgrazing and the extremely low annual rainfall in those ecosystems.

The arid and semiarid ecosystems of Venezuela occupy 4.6% of the national territory, 41,023 km^2 (4,102,300 ha). The predominant soils are shallow, stony with little development (entisoles), and poor in organic matter. Shrubs and thorn scrub predominate in the vegetation, and herds are poor with low productivity and low profitability. This activity, together with the indiscriminate use of trees for the obtaining of firewood and poles, causes a constant loss of vegetation cover, favoring wind and water erosion and leading to desertification. Due to years of exhausting use, based on the breeding of goats without herd management and sanitary control, and the free grazing of the semi-natural vegetation, the desertification process has been intensified in the arid and semiarid environments, as well as the loss of biodiversity.

In the tropical dry forest of the semiarid of Lara, Falcon and Yaracuy states, 14 species of legumes native to the forest were evaluated (Nouel and Rincón 2004). These species were selected by direct observation of the consumption of grazing animals and by the traditional knowledge of producers in the study area. As a result of the selection, the following were identified: Chiquichiqui (*Cassia tora*), Sierra (*Acacia tamarindifolia*), Cujicillo (*Mimosa trianae*), Caudero (*Mimosa gritty* and *Mimosa caudero*), Brusca (*Cassia occidentalis*), Palo de arco (*Apoplanesias cryptopetala*), Carbonero or Tiamo (*Acacia polyphylla* or *Acacia glomerosa*), Tiamo blanco (*Piptadenia robusta*), Espinillo (*Parkinsonia aculeata*), Uveda or Cuji negro (*Acacia macracantha*), Platanico (*Cassia emarginata*), Uña de gato (*Pithecellobium dulce*), Bolsa de gato (*Diphysa carthagenensis*), Cuji (*Prosopis juliflora*) and *Haematoxylum brasiletto*; of the mentioned species, the nutritional Crude Protein value (CP) of plants of the genera Acacia, Mimosa and Prosopis was evaluated. The highest percentages of CP, corresponded to leaves of *A. macracantha* with 34.3% (pods 13.4%), and *A. tamarindifolia* with 35.1%; followed by *Mimosa arenosa* (21.9%), *A. glomerosa* (20.0%) and *P. dulce* (19.4%) (Nouel and Rincón 2004).

Goat diet depends on a few palatable plant species of each day most scarce flora. The most common species belong to the Acacia, Prosopis, Pithecellobium, Capparis and Cercidium genres, being the most important Cuji (*Prosopis juliflora*), Yacure (*Pithecellobium unguis-cati*) and Yabo (*Cercidium praecox*), whose flowers had a protein content of up to 27.6%.

Colmenares et al. (2013) made a study with the aim to identify authoctonous species that strengthened the forage offer for goat herds. The identification was made from the knowledge dialogue, with conversations aimed at recognizing the species considered by the producers as preferred goat feed. There were 24 species recognized, 17% of them considered important. Of the plants considered beneficial, 100% of the herders considered Cuji (*Prosopis juliflora*) as a fundamental contribution to the diet, others of importance were *P. dulce* (60%), *Cordia dentata*, *B. cumanensis*, *C. biflora*, *C. flavens* and *L. noodosum*. Of the total number of species, 40% corresponded to trees, given the eating habit of the goats in semiarid environments (Colmenares et al. 2013).

12.3 Main Silvopastoral Systems of Venezuela

12.3.1 Scattered Trees in Pastures

Most of Venezuelan livestock areas and the "Llanos", are characterized by the presence of many plant species, mostly scattered trees or deciduous trees and shrubs in secondary forests, whose foliage, pods and fruits are consumed by cattle, being part of the diet of many ruminant species, especially during the dry season, when the forage supply from the grass is greatly reduced.

The plant species with highest consumption by cattle, are legume trees such as Saman (*Samanea saman*), Masaguaro (*Albizia guachapele*), Caro Caro (*Enterolobium cyclocarpum*), Cañafistola (*Cassia moschata*), Cuji (*Prosopis juliflora*), Cuji negro (*Acacia macracantha*) and Matarratón (*Gliricidia sepium*) (Escalante 1985, 2017). Other non-leguminous species that are also consumed by domestic animals are Guacimo (*Guazuma ulmifolia*), Vera (*Bulnesia arborea*), Jobo (*Spondias mombin*), Ceiba (*Ceiba pentandra*), Mijao (*Anacardium excelsum*), Roble (*Platymiscium pinnatum*) and palms, such as Palma de agua (*Attalea butyracea*), Palma Llanera (*Copernicia tectorum*) and Palma Corozo (*Acrocomia aculeata*). All these trees are combined in the Tropical Dry Forest with other valuable wood species such as Pardillo (*Cordia alliodora*), Pardillo Negro (*Cordia thaisiana*), Apamate (*Tabebuia rosea*), Caoba (*Swietenia macrophylla*) and Araguaney or Flor Amarillo (*Tabebuia chrysantha*) (Escalante 1985; Escalante et al. 2011).

Of the trees whose foliage, pods and fruits are consumed by ruminants, *Samanea saman*, formerly known as *Pithecellobium saman* and *Albizia saman* is the most important species in the Tropical dry forest of Venezuelan Llanos, providing numerous goods and services, such as the production of nutritive pods with 15–18% crude protein, shade, shelter and livestock protection, nitrogen fixation, and timber for ceilings and parquet floors. Also, as it is a deciduous tree, the litter contributes to the cycling of nutrients and the extended canopy modifies the microclimate giving comfort to the animals, by reducing the temperature during the hottest part of the day. This species has been widely studied in areas where it is a frequent and dominant species in silvopastoral systems (Escalante 1997). One of the least studied environmental services provided by *S. saman* is the provision of habitat for countless species of plants (Bromeliaceae, Orchideae, and some mosses, lichens, ferns and cacti), some of them parasites, and species of small animals, mainly insects (Morales 2005; Molina Prieto 2008) (Fig. 12.2). This characteristic has been seen and corroborated in populations of *S. saman* in Venezuela, Colombia, Ecuador, and Central America.

When eating the saman pod, the cattle perform a pre-germination treatment on the seed, so when it is expelled, it is accompanied by a nutritious material (excrement) and germinates easily (Lozada and Graterol 2003).

Saman is not only preferred by farmers because it provides shade and shelter to animals, but also for its valuable fruit called "Samana" consumed by animals during the dry season, for its wood quality and for the nitrogen fixation. In a study in the central savannas of Portuguesa state, it was reported that the content of nitrogen and organic matter (OM) in the soil was higher, and their concentration decreased from

Fig. 12.2 *Samanea saman* tree providing habitat for a high diversity of plant species. (Photo: E. Escalante)

the proximity of the tree trunk towards the open savanna grassland (Solórzano et al. 1998).

In Venezuela, saman wood production has major relevance in Zulia state. In the years between 1982 and 1998, saman sawmill wood represented 80% of the total wood production in the state, with the highest wood production in 1998 (10.641 m^3), 90% of the total (9430 m^3) in the Perijá Region of the Zulia state (Moreno and Daal 1998). For trees with diameter at breast height (DBH) in a range between 52 and 77 cm, the estimated volume was 1.0–1.2 m^3 per tree, with maximum values of up to 3 m^3 sawmill wood for old trees (Fernandez and Gutierrez 1985).

Also in Zulia, in the southern part of Maracaibo Lake, Fernández and Gutiérrez (1985) determined that a saman average canopy cover per hectare was 6.4% (640 m^2), with highest value of 63%. The study showed that the average number of saman trees per ha was five for highest canopy paddocks, with some trees shading more than 1100 m^2 of soil surface for trees with up to 29 m of canopy diameter and estimated age between 50 and 60 years.

12.3.2 Alternate Strips with Alleys

The System of Alternating Strips with Alleyways is the most complex of all, but it is also the one that provides more goods and services. Generally, the strips are formed by 3–5 rows of woody legume trees and/or species of high timber value, separated by alleyways of 12–24 m wide, depending on the preferences of the producer (Fig. 12.3).

Fig. 12.3 Silvopastoral system with tree alleys of *Samanea saman*, *Cordia thaisiana* and *Tabebuia rosea* in La Esmeralda Farm, Tachira state, Venezuela. (Photo: E. Escalante)

The system could be planted with one species or with a combination of two to four species to reduce its vulnerability. The combination could be made by planting each row with a single species or by alternating tree species in the same row. The latter option is desirable to increase the resilience and adaptability of the system in the face of climate change, and to enhance the biodiversity of the area. The distance between trees in each row ranges from 3 to 10 m depending on the characteristics of each species in terms of canopy conformation, and on the management of the trees during the growing stage that includes periodic pruning and thinning to improve timber production and reduce the competence between species and with the grass.

The strips are made up of rows of woody species to provide shade, protection and comfort to the animals, along with other multiple benefits, including nitrogen fixation (for leguminous species) and wood production, rods and fence poles, as well as the supply of a friendly and appropriate habitat for epiphyte plants, insects, birds and small mammals and reptiles, thus favoring biodiversity, in addition to contributing to the mitigation of extreme temperatures.

12.3.3 Cattle Grazing in Forestry Plantations

Extensive pasture grazing has been done in commercial plantations of Pino Caribe (*Pinus caribaea*), Melina (*Gmelina arborea*), Teca (*Tectona grandis*) and *Acacia mangium* in the eastern and western savannas of Venezuela.

In the highlands of the Venezuelan Andes, it is common to see silvopastoral systems of Aliso or Jaul (*Alnus sp.*) with Kikuyo grass (*Cenchrus clandestinus*) or with Capin Melao grass (*Melinis minutiflora*). In these systems the Aliso, in spite of not being a legume species, fixes nitrogen and protects livestock from low temperatures, either as a live fence or windbreaker, in addition to providing wood for construction, crafts and other uses (Escalante 1985).

In the last 30 years, there has been a notorious increase in the practice of silvopasture and intercropping in commercial forest plantations in Venezuela (Escalante et al. 2011). DEFORSA, a recognized company in the paper industry in Venezuela, intercropped in eight-meter alleys, coffee, rice, maize and black beans in between tree rows of eucalyptus (*Eucalyptus urophylla*) plantations, and also established extensive grassland areas (3000 ha) in the field within the eucalyptus rows, for beef and dairy production, with white Brahman cattle and buffaloes (Fig. 12.4).

12.3.4 Living Fences

Living fences are recognized as the most ancient and widespread agroforestry practice in Venezuela. Almost in every life zone, linear plantations are found, dividing grazing plots or established as perimeter fences between farms or along road borders. *Gliricidia sepium* is by far the most used species, together with some valuable timber trees such as *Cordia alliodora, C. Thaisiana*, *Cedrela odorata*, *Tabebuia rosea*, *Tabebuia chrysantha*, *Swietenia macrophylla*, *Gmelina arborea*, and *Tectona grandis*. Lozada and Graterol (2003) reported the presence of living fences of

Fig. 12.4 Brahman cattle grazing in a silvopastoral system with *Eucalyptus urophylla* in DEFORSA, Cojedes state, Venezuela. (Photo: E. Escalante)

Cedrela odorata in Rosario de Perija municipality in Zulia state with a growth a rate of 8.2 m^3 km^{-1} $year^{-1}$.

In the coffee production areas, it is common to find living fences with *Erythrina spp.* and *Bursera simaruba*, and in the Andes *Alnus acuminata* is also used (Escalante 1985).

Currently, living fences have gained recognition as a connectivity element in the landscape that has been fragmented by intense deforestation. Those long linear plantations help birds, small mammals, and insects in their dispersion and movement in the ecosystem giving them greater chances of survival (Escalante 2017). Table 12.1 presents some of the most important arboreal and shrub species identified and studied in silvopastoral systems in Venezuela (Fig. 12.5).

12.4 The Silvopastoral Experience at Fundacion Empresas Polar and Fundacion Danac

The Sustainable Tropical Agriculture Program, currently known as the Centro Nacional de Capacitación para Pequeños Productores Agropecuarios (CNCPPA), emerged in 1996 as a result of an alliance between Fundación Empresas Polar, Fundación Danac and the Faculty of Agronomy of the Central University of Venezuela (FAGRO-UCV), in San Javier, Yaracuy state; proposed as an initiative to have a permanent offer of technological innovations in sustainable agriculture and to contribute to the formation and training of talents (farmers, professionals and students) in the knowledge and application of the principles and practices of sustainable agriculture in Venezuela (Escalante & Guerra 2015; Escobar et al. 2000).

12.4.1 Silvopastoral Systems of the Integral Farm of Sustainable Tropical Agriculture

1. Pasture System in Alleys of Matarratón (*Gliricidia sepium*) and Leucaena (*Leucaena leucocephala*).

The pasture system in alleys of *L. leucocephala* and *G. sepium* covers a total area of 10 ha. The paddocks were divided with electrified fences into 0.25 ha modules for a total of 40 modules. *G. sepium* and *L. leucocephala* were established in double rows separated at 5 m and with a distance between rows and between plants of 1 m (1 m × 1 m × 5 m) for an initial planting density of 3333 plants per ha. The predominant grasses are Estrella (*Cynodon nlemfuensis)*, Guinea (*Megathyrsus maximus*), *Brachiaria mutica* and Caribe (*Eriochloa polystachya*) (Messa-Arboleda et al. 2009).

The herd is managed under rotational grazing, with an occupation time of 2 days and 74 days of rest, and an average stocking rate of 2.2–2.5 AU ha^{-1} (1 AU equals 450 kg LW). However, in the dry season and due to the lower availability of fodder,

Table 12.1 Arboreal and shrub species important in silvopastoral systems in Venezuela

Family	Species	Common name	Main use, function and services							Cited by
			F	Fr	NF	Sh	T	FW	She	
Acanthaceae	*Trichanthera gigantea*	Naranjillo, Yatago, Nacedero	X			X			X	Solórzano et al. (2004), García et al. (2008a), Rengifo et al. (2008), Messa-Arboleda et al. (2009), Camacaro et al. (2013), Farreras and Schargel (2015)
Anacardiaceae	*Anacardium excelsum*	Mijao		X		X		X	X	Escalante (1985), Solórzano et al. (2004), Domínguez et al. (2007), Camacaro et al. (2013)
Anacardiaceae	*Spondias mombin*	Jobo		X		X	X		X	Solórzano et al. (2004), Domínguez et al. (2007), Cardozo (2008), Camacaro et al. (2013)
Anacardiaceae	*Mangifera indica*	Mango		X						Solórzano et al. (2004)
Arecaceae	*Attalea butyracea*	Palma de agua				X				Escalante (1985), Solórzano et al. (2004), Cardozo (2008), Farreras and Schargel (2015)
Arecaceae	*Copernicia tectorum*	Palma llanera				X				Escalante (1985)
Arecaceae	*Acrocomia aculeata*	Corozo		X		X				Escalante (1985), Casado et al. (2001), Solórzano et al. (2004), Messa-Arboleda et al. (2009)
Asteraceae	*Tithonia diversifolia*	Botón de oro	X	X					X	García et al. (2008a)
Betulaceae	*Alnus acuminata*	Aliso			X	X	X	X	X	Escalante (1985)

(continued)

Table 12.1 (continued)

Family	Species	Common name	Main use, function and services							Cited by
			F	Fr	NF	Sh	T	FW	She	
Bignoniaceae	Crescentia *cujete*	Totumo, Taparo	X	X		X				Solórzano et al. (2004), Cardozo (2008), Messa-Arboleda et al. (2009)
Bignoniaceae	*Tabebuia chrysantha*	Araguaney				X			X	Escalante (1985)
Bignoniaceae	*Tabebuia rosea*	Apamate					X			Escalante (1985), Camacaro et al. (2013)
Bombacaceae	*Ceiba pentandra*	Ceiba				X	X		X	Farreras and Schargel (2015)
Boraginaceae	*Cordia alliodora*	Pardillo				X	X			Escalante (1985), Camacaro et al. (2013)
Boraginaceae	*Cordia thaisiana*	Pardillo negro				X	X			Escalante (1985), García et al. (2008a), Rengifo et al. (2008)
Burseraceae	*Bursera simaruba*	Indio desnudo				X			X	Escalante (1985)
Cactaceae	*Pereskia guamacho*	Guamacho	X			X		X		Rengifo et al. (2008)
Fabaceae	*Inga interrupta*	Guamo	X	X	X	X				Camacaro et al. (2013)
Fabaceae	*Inga* spp.	Guamo	X	X	X	X				Domínguez et al. (2007), Cardozo (2008), Farreras and Schargel (2015)
Fabaceae	*Albizia guachapele*	Masaguaro	X	X	X	X	X		X	Camacaro et al. (2013)
Fabaceae	*Cassia moschata*	Cañafistola		X	X	X		X	X	Escalante (1985), Solórzano et al. (2004), Domínguez et al. (2007), Camacaro et al. (2013)
Fabaceae	*Cassia siamea*	Acacia		X	X	X				García et al. (2009a, b)

(continued)

Table 12.1 (continued)

Family	Species	Common name	Main use, function and services							Cited by
			F	Fr	NF	Sh	T	FW	She	
Fabaceae	*Chloroleucon mangense*	Palo fierro	X		X		X		X	Casado et al. (2001), Cecconello et al. (2003)
Fabaceae	*Enterolobium cyclocarpum*	Caro caro		X		X	X		X	Escalante (1985), Casado et al. (2001), Cecconello et al. (2003), Solórzano et al. (2004)
Fabaceae	*Pithecellobium dulce*	Uña de gato	X	X	X	X			X	Nouel and Rincón (2004), Camacaro et al. (2013)
Fabaceae	*Gliricidia sepium*	Matarratón	X		X	X	X	X		Escalante (1985), Solórzano et al. (2004), García and Medina (2006), Messa-Arboleda et al. (2009)
Fabaceae	*Leucaena leucocephala*	Leucaena	X		X	X		X		García et al. (2008a), Messa-Arboleda et al. (2009)
Fabaceae	*Samanea saman*	Saman, Lara	X	X	X	X	X		X	Escalante (1985, 2017), Moreno and Daal (1998), Solórzano et al. (1998), Cecconello et al. (2003), Morales (2005), Domínguez et al. (2007), Molina Prieto (2008)
Fabaceae	*Erythrina fusca*	Bucare	X		X	X			X	Camacaro et al. (2013)
Fabaceae	*Acacia macracantha*	Cují negro	X	X	X	X		X		Escalante (1985), Casado et al. (2001), Domínguez et al. (2007), Rengifo et al. (2008)

(continued)

Table 12.1 (continued)

Family	Species	Common name	Main use, function and services							Cited by
			F	Fr	NF	Sh	T	FW	She	
Fabaceae	*Caesalpinia coriaria*	Dividive	X	X	X	X		X	X	Casado et al. (2001), Camacaro et al. (2013)
Fabaceae	*Prosopis juliflora*	Cují	X	X	X	X		X	X	Escalante (1985), García et al. (2009a, b), Messa-Arboleda et al. (2009)
Fabaceae	*Mimosa trianae*	Cujicillo			X	X		X	X	Nouel and Rincón (2004)
Fabaceae	*Cassia occidentalis*	Brusca	X		X	X				Nouel and Rincón (2004)
Fabaceae	*Acacia polyphylla*	Carbonero			X	X			X	Nouel and Rincón (2004)
Fabaceae	*Acacia macracantha*	Uveda, Cuji negro	X		X	X			X	Nouel and Rincón (2004)
Fabaceae	*Platymiscium pinnatum*	Roble	X		X	X	X		X	Escalante (1985, 2017)
Fabaceae	*Pithecellobium unguis-cati*	Yacure, Taguapire	X		X	X			X	Rengifo et al. (2008)
Fabaceae	*Cercidium* praecox	Yabo	X		X	X			X	–
Meliaceae	*Cedrela odorata*	Cedro				X	X			Escalante (1985), Lozada and Graterol (2003), Farreras and Schargel (2015)
Meliaceae	*Swietenia macrophylla*	Caoba					X			Escalante (1985), Camacaro et al. (2013), Farreras and Schargel (2015)
Moraceae	*Maclura tinctoria*	Mora	X			X	X	X		Cardozo (2008)
Moraceae	*Morus* spp	Morera	X							García et al. (2008a), Messa-Arboleda et al. (2009)
Myrtaceae	*Eucalyptus urophylla*	Eucalipto				X	X			Escalante & Guerra (2015)
Pinaceae	*Pinus caribaea*	Pino caribe					X		X	Escalante (1985), Escalante et al. (2011)

(continued)

Table 12.1 (continued)

Family	Species	Common name	Main use, function and services							Cited by
			F	Fr	NF	Sh	T	FW	She	
Rubiaceae	*Genipa americana*	Caruto		X		X	X			Domínguez et al. (2007), Cardozo (2008), Camacaro et al. (2013)
Sterculiaceae	*Guazuma ulmifolia*	Guácimo	X	X		X		X	X	Escalante (1985), Casado et al. (2001), Solórzano et al. (2004), Domínguez et al. (2007), García et al. (2008b), Rengifo et al. (2008), Camacaro et al. (2013)
Verbenaceae	*Tectona grandis*	Teca					X			Escalante (1985), Escalante & Guerra (2015)
Zygophyllaceae	*Bulnesia arborea*	Vera	X	X		X			X	Escalante (1985), García et al. (2009a, b)

F forage, *FR* fruits, *NF* nitrogen fixation, *SH* shade, *T* timber, *FW* firewood, *She* shelter

Fig. 12.5 Linear plantation of Teca (*Tectona grandis*) alongside perimeters of a silvopastoral system in a tropical dry forest at Danac Foundation, Yaracuy state, Venezuela. (Photo: E. Escalante)

the occupation time is reduced to one day and consequently, the rest time decreases to 37 days. *G. sepium* and *L. leucocephala* are periodically pruned to keep it accessible to the cattle (Messa-Arboleda et al. 2009).

2. Enhanced pasture with high density scattered trees

The improved pasture with scattered trees is located on a low terrace with flat to undulating relief, covers a total area of 3.3 ha and is divided into two plots of 1.68 ha each. The predominant grass is *M. maximus* combined with the following trees: *Samanea saman*, *Guazuma ulmifolia*, *Enterolobium cyclocarpum* and *Pterocarpus officinalis*; established by natural regeneration at a density of 120 trees ha^{-1} (Messa-Arboleda 2009). This system is used for grazing growing animals, mainly replacement females, with a stocking rate of 1.0–1.5 AU ha^{-1} (Messa-Arboleda 2009).

3. Mixed fodder bank of Matarratón (*Gliricidia sepium*), Naranjillo (*Trichanthera gigantea*) and Morera (*Morus spp.*).

As of the year 1997, the establishment of a mixed fodder bank began, by planting in alleys *G. sepium*, *T. gigantea* and *Morus spp.*, and covers an area of 1.1 ha. The mixed bank is a multilayer system, consisting of *G. sepium* in rows spaced 5 m × 0.6 m between plants, with *T. gigantea* and *Morus spp.* established at 1 m × 0.6 m in the alleys. The plants of *G. sepium* were established with sexual seed collected in the area and the plants of *T. gigantea* and *Morus* spp., by vegetative seed. The species were established in a nursery and after three to four months of age were transplanted at the beginning of the rainy season. The system is managed under cutting and hauling, for the supplementation of cows in production and calves, through fresh consumption, silage, and for the elaboration of multi-nutritional blocks with flours obtained from sun-dried foliage. The plants are pruned every 3–4 months, at an approximate height of 1.0–1.5 m and the stems are distributed between the rows of the legume; providing soil coverage, barriers for erosion control and organic matter (Messa-Arboleda 2009).

4. The Multilayer Silvopastoral System

The multilayer silvopastoral system covers an area of 4.4 ha and has been jointly developed by Fundación Danac and the CNCPPA since 2002 (Messa-Arboleda et al. 2009). The system consists of three plant layers, whose components fulfill different functions and services, and *Megathyrsus maximus* grass.

(a) Tree Layer: made up of leguminous species that produce fruits, wood and firewood, such as *S. saman*, *P. juliflora* and *C. moschata* mixed with Corozo palm (*Acrocomia aculeata*). In this stratum, timber species of high commercial value such as *Tectona* grandis, *Cordia thaisiana*, *Swietenia macrophylla* and *Tabebuia rosea* are also included for timber production.
(b) Shrub layer: constituted by *L. leucocephala*, established at high density in quadruple strips and pruned at 1 m height to facilitate accessibility (browsing) of forage by cattle.
(c) Herbaceous stratum: conformed by *Megathyrsus maximus*, provides fodder for animals, in addition to soil cover and organic matter.

The multilayer system, was divided into modules or paddocks of 0.2 ha, by electrified fences and managed under rotational grazing. The incorporation of cattle into the system began in 2007 with heifers, with a low stocking rate (1 AU ha^{-1}) to avoid damaging the developing trees. As of 2008, adult bovine animals were introduced, and the animal load in the system was progressively increased (Messa-Arboleda et al. 2009; Escalante 2017) (Fig. 12.6).

5. Live fences of *Gliricidia sepium*, Linear Plantation with oil and timber palms and Biological Corridors

The integral farm has some segments of live fences, composed mainly by *Gliricidia sepium* to provide shade and forage for the animals. Also, there are linear plantations and scattered of oil palms, such as *Elaeis guineensis, Acrocomia aculeata and Bactris gasipaes*. The fruits of these palms are used as a source of energy for lactating cows (fresh and ground and silaged with lime) and for poultry (the whole fruit is offered). A part of the oil palm plants (*Acrocomia aculeata*) is associated with a productive decontamination system that is integrated into the pig production of the farm.

As an alternative for the use of space, the conservation of wildlife habitats and the expansion of small-scale timber production on the farm, among others; since 2002, the species *T. grandis, C. thaisiana, S. macrophylla and T. roseae*, located 4 m apart between trees, were established on the perimeter of the area (700 m) of the improved pasture with scattered trees. The farm also has a collection of Totumo (*Crescentia cujete*) of 0.1 ha whose fruits were used to feed lactating cows and poultry.

Fig. 12.6 Multilayer silvopastoral system in the integral farm of sustainable tropical agriculture. Danac Foundation. (Photo: E. Escalante)

12.4.2 Cattle Production

The dual-purpose cattle herd of the integral farm is made up of *Bos taurus* x *Bos indicus,* with a predominance of the *Holstein* x *Cebu* and *Swiss Brown* x *Cebu* crosses. Cows are managed under rotational grazing in silvopastoral systems, with an average stocking rate ranging from 2.2 to 2.5 AU ha^{-1}. The animals are supplemented according to their physiological state and in pre-established amounts according to the management of the farm. For this, forage of *G. sepium*, *T. gigantea* and *Morus spp*., silages made with Cassava (*Manihot esculenta)* (root + foliage), *Sorghum vulgare* and/or *S. officinarum* (sugarcane) and *Canavalia ensiformis*; ground fruits and silage of Oil palm (*Elaeis guineensis*) (partially saponified with calcium) and multi-nutritional blocks *ad libitum.* Growing females (post-weaning) graze in an improved pasture with scattered trees with average animal load of 1.5 AU ha^{-1} (Messa-Arboleda et al. 2009).

The total availability of plant biomass in the pasture in alleys showed average values of 3.31 and 3.87 t DM ha^{-1} $cycle^{-1}$ during the dry and rainy periods respectively. Of the total available biomass per year (40.65 t DM ha^{-1}), about 92% is contributed by grasses (*Cynodon nlemfuensis, M. maximus, Brachiaria mutica* and *Echinochloa polystachya*) and the remaining 8% by shrub legumes (*G. sepium* and *L. leucocephala)* (Messa-Arboleda et al. 2009).

12.4.3 Environmental Benefits

From the environmental point of view, there is evidence that demonstrates that the establishment and management of the different productive components of the integral farm have contributed to the conservation and improvement of the soils, increased the vegetal cover, animal welfare, the protection of water sources, carbon sequestration in the soil and in the aboveground biomass. They have also contributed to the compensation of greenhouse gas emissions and increased biodiversity associated with the production system (birds, mammals, reptiles, insects and plants), it has also favored connectivity between forested patches surrounding the farm and contributed to the beauty and aesthetics of the landscape (Messa-Arboleda et al. 2009).

Regarding the carbon storage in the system, different land uses linked to the bovine subsystem of the integral farm and a fragment of primary forest (control) adjoining the farm were evaluated (Messa-Arboleda 2009). The total carbon in the system (organic soil carbon + total carbon above ground) in the primary forest was 3.2 times higher than the average value of the systems intervened (73.88 Mg ha^{-1}). The systems with anthropic intervention presented total carbon storage values in a range of 63.79–100.69 Mg ha^{-1}, for the sugarcane and the improved pasture with scattered trees, respectively.

Evaluations made in the tree component in multilayer silvopastoral systems determined that among the legume trees *S. saman* was the species with the best growth and development, while in terms of timber trees, *T. grandis* presented the largest Annual Average Increase for diameter at breast height, (DBH), Total Height (TH), and Fuste Height (FH), with values of 1.75 cm $year^{-1}$, 1.09 m $year^{-1}$ and 0.51 m $year^{-1}$ respectively; followed by *Cordia thaisiana* (Messa-Arboleda et al. 2009).

12.4.4 Biological Corridors

Motivated by the presence of a fragment of primary forest and a gallery forest surrounding the Quebrada Naranjal, apparently separated by anthropic intervention, on the integral farm from 1997–1998, the area was reforested and manages natural regeneration in a strip of approximately 300 m of length and 15–20 m wide, with what is currently achieved connectivity between both natural formations, providing spaces for the protection and mobility of different wildlife species present in these forests (Messa-Arboleda et al. 2009).

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Chapter 13
Silvopasture in Panama: An Overview of Research and Practice

Ryan Dibala, Shibu Jose, Jefferson Hall, and Diana María Bolívar-Vergara

Abstract In this paper, we provide an overview of livestock production and silvopasture in the Central American country of Panama. We begin with a brief background on the history of cattle ranching in Panama to provide historical and cultural context for current trends and practices. We touch briefly on modern-day livestock production, the adoption of silvopasture, and existing agricultural policies that affect land use and management. We then explore how climate change is affecting livestock production in Panama and highlight several government programs that have been implemented to help mitigate the worst impacts of climate change. The main body of this paper reviews silvopasture research conducted in Panama, both biophysical and social. In addition to presenting peer-reviewed studies, we describe the application of several ongoing silvopasture projects that are currently being funded in Panama. We conclude the paper with several suggestions on how to increase the national spread and adoption of silvopasture along with recommendations for future research.

Keywords Silvopasture · Panama · Intensive Silvopastoral systems · Livestock production

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13.1 Introduction

Deforestation and forest degradation have resulted in the widespread loss of native forests across much of the world. Livestock production is blamed as one of the key drivers for a great proportion of the deforestation in Latin America (Wassenaar et al. 2007). Of the 22 million hectares of forest lost between 1960 and 1995, 21 million hectares were then used for cattle production (Broom et al. 2013). According to Lamb et al. (2005), the expansion of cattle pastures has degraded and homogenized landscapes, reducing overall biodiversity and ecosystem services. Additionally, according to Steinfeld et al. (2006), the rapid growth of global livestock production has been responsible for as much as 18% of the world's greenhouse gas emissions. The livestock sector now faces its own threats, as climate change has begun to compromise agricultural productivity around the world (Thornton et al. 2009).

Today, there is an urgent need to promote the adoption of alternative sustainable ranching practices that aim to intensify livestock production while treading more lightly on the land (Cribb 2010). One way to approach this is to cultivate forages and livestock amidst trees and shrubs in an integrated, intensively managed system known as silvopasture (Ibrahim et al. 2010; Hall et al. 2011; Jose and Dollinger 2019). In Latin America, examples of silvopastoral systems (SPS) include scattered trees in pasturelands, managed plant succession, live fences, windbreaks, fodder tree banks, cut-and-carry systems, tree plantations with livestock grazing, pastures between tree alleys, and intensive silvopastoral systems (Murgueitio et al. 2011a; Calle et al. 2012). Silvopasture, and agroforestry in general, aims to optimize agricultural production and environmental conservation through a process known as overyielding, where the productivity of the inter-crop exceeds the productivity of the systems managed separately from one another (Pent 2020). These efficiency gains have the potential to produce more food without using more land, water, and other inputs (Herrero et al. 2010).

13.2 History of Ranching and Land Use in Panama

In Panama, cattle-ranching began in the mid-1500s with the arrival of the earliest Spanish settlers who cleared tropical forests to create large haciendas where European mixed-breed cattle were raised (Heckadon-Moreno 1984; Calvo-Alvarado et al. 2009). In the 1800s, landless peasants moved into frontier areas – many of which were along the Pacific coast of the central western region – to clear land and create more cattle pasture (Heckadon-Moreno 1984; Griscom and Ashton 2011). Widespread deforestation resulted throughout the twentieth century due to government incentives for agricultural expansion, predominantly for cattle-ranching activities (Heckadon-Moreno 1984; Griscom and Ashton 2011). By the 1940s, pasture improvement was becoming the norm with the planting of exotic grasses and the raising of heat tolerant Brahman cattle breeds (Calvo-Alvarado et al. 2009; Griscom and Ashton 2011). Between 1950 and 1970, green revolution technologies and a steady stream of government and international loans resulted in a doubling of the area devoted to national pasture production (Jaen 1985). Over the past 30–40 years, high cattle stocking rates, repeated burning, and removal of native vegetation has degraded pasture lands, resulting in severe erosion and an overall decline in productivity throughout the country (Janzen 1988; Griscom and Ashton 2011).

Although pastures replaced at least 70% of Panama's native forests (Love et al. 2009), more recent forest cover change analyses have reported modest forest cover gains for the country (Wright and Samaniego 2008; Metzel 2010). From 1992 to 2000, Panama experienced a limited forest transition when previously deforested areas were reclaimed by natural secondary forest succession (Wright and Samaniego 2008). During that same period, the proportion of the population employed in agriculture declined by 31% (Wright and Samaniego 2008). More recently, researchers studying tree cover change between 1998 and 2014 in southwestern Panama found that all tree cover types increased in extent, with non-forest and riparian tree cover contributing 21 and 31% of tree cover gains, respectively (Tarbox et al. 2018).

Of Panama's 7.49 million ha of land area, approximately 4.30 million ha (57.5%) are covered by forest, 2.15 million ha (28.6%) by pasture, and 0.19 million ha (2.6%) by crops (MiAmbiente 2017). Panama ranks number 86 out of 209 countries with 1.73 million head of cattle, 0.12% of the world total (FAOSTAT 2010). Although not as productive as some other countries, cattle ranching represents an important part of the country's agriculture sector, with pasture making up 71% of all agricultural land in Panama (CNA 2000). Beginning in the early part of the twenty-first century, international social, economic, and political forces provoked a systemic shift from small-scale to large-scale ranching throughout the country (Dagang and Nair 2003). Ranching quickly became a tenuous enterprise for smallholders who were not operating at larger economies of scale and many small farms were consolidated into larger landholdings (Dagang 2007). Today, a wave of smallholder ranchers are looking for new opportunities in the eastern part of the country where frontier expansion and forest clearing for pasture establishment is rampant on the border of Darién National Park and surrounding indigenous reserves (Arcia 2017). In 2018, cattle production (heads of cattle) in Darién province was quickly growing (230,200), trailing behind only Veraguas (252,400) and Chiriquí (316,800) provinces (CNA 2000).

13.3 Adoption of Silvopasture in Panama

Today, many Panamanian livestock producers still practice extensive continuous grazing, maintain less than one head of cattle ha^{-1}, and manage their livestock non-intensively (Dagang 2007). Some are absentee landowners, attending to their animals only once every 2 weeks. The most ubiquitous example of SPS seen in Panama is the use of living fences. Living fences consist of closely-spaced trees delimiting a field boundary to which fencing material (e.g. barbed wire) may be attached (Love et al. 2009). Due to their low establishment cost, relative permanence, and lack of interference with field crops, Panamanian landowners tend to be more accepting of establishing trees in living fences. Garen et al. (2011) presented evidence indicating that Panamanian ranchers in Coclé and Los Santos provinces demonstrate active and diverse tree planting and protecting behaviors. However, these behaviors were limited to the planting of living fences, dispersed fruit trees (most of which were near the homestead), and the retention of preferred naturally regenerated trees. Similarly, Love and Spaner (2005) reported that silvopasture was limited to the retention of fodder trees (e.g. *Guazuma ulmifolia*, *Enterolobium cyclocarpum*), whose forage was used as supplemental feed. One study examining the adoption of agroforestry practices at five sites across Panama (including sites located in livestock producing regions) listed preferred on-farm agroforestry practices and omitted silvopasture entirely (Fischer and Vasseur 2002).

When compared to its neighbors Costa Rica and Colombia, Panama lags behind in SPS research, technology innovation, and on-farm application. Relatively few Panamanian producers have adopted intensive silvopasture systems (ISPS), a successful model of SPS that is being widely promoted and adopted throughout Colombia and Mexico. ISPS integrates fodder shrubs planted at high densities (more than 10,000 plants ha^{-1}), intercropped with improved forages and timber trees that can be directly grazed by livestock (Murgueitio and Solorio 2008; Chará et al. 2019a). ISPS in Colombia have recorded sustained high milk and meat production for two decades with no evidence of declining yields (Molina et al. 2008; Chará et al. 2019a, b). Although in Panama, there have been several demonstration plots with ISPS in the provinces of Chiriquí (Murgueitio et al. 2011b), Coclé, Darién, and Los Santos (Murgueitio et al. 2011a), the technology has yet to be widely adopted and scaled up.

Part of the reason for this has been a lack of government-issued incentives for the nationwide development of sustainable agro-technologies. Instead, the Panamanian government has long-incentivized forest destruction and high-input agricultural intensification. Laws 24 and 25 of 2001, including the "Programa para la Reconversión Agropecuaria" (Agricultural Conversion Program), provided low-interest loans to producers interested in improving their production capacity. Unfortunately, this led to an emphasis on reducing the space and time in which cattle were raised, promoting environmentally damaging feed lots and fattening stables (Dagang 2007). Today, some farms are being managed with costly investments in animal genetics, feed supplementation, and pasture improvement. According to Dagang (2007), 17% of pasture in Panama has been planted with improved grasses. Nonetheless, effective animal husbandry, holistic farm planning, and long-term sustainability have often been ignored.

13.4 Responding to Crisis: Climate Change and Livestock Production in Panama

Panama's long history of incentivizing forest destruction and high-input agriculture appears to be slowing due to public recognition and acceptance of the climate change crisis. Under climate change scenarios, water will become the main limiting factor to all livestock systems (Steinfeld et al. 2006; de Fraiture et al. 2010) and in Panama, extended droughts have become increasingly common. In 2015, an El Niño Southern Oscillation (ENSO) event resulted in the third longest dry season on record (173 days), with over 90% of Panama experiencing severe drought conditions (Paton 2016; Bretfeld et al. 2018). The drought differentially affected the growth and water use efficiency of trees in Panama (Sinacore et al. 2019) and greatly reduced pasture forage productivity and longevity. Ranchers in Los Santos province reported the deaths of over 500 cattle, with scores more losing over 115 kg, a weight translating to an economic loss of $150 per head (Cortez 2013). According to the Panama Canal Authority, the most recent ENSO event in 2019 resulted in the driest dry season in the history of the Panama Canal. That year, water levels in the Panama Canal became so low that draft limits were imposed on ships, forcing them to lighten their loads to ride higher in the water column. This resulted in a 15 million dollar revenue loss (Fountain 2019).

With climate change directly affecting the national economy, initiatives were finally proposed to mitigate and adapt to the risks it poses. In 2014, former president Juan Carlos Varela announced the “Alianza por el Millón” (Alliance for a Million), a commitment to reforesting at least one million ha before the year 2035. In May 2020, president elect Laurentino Cortizo announced his “Panamá Agro Solidario” proposal which would, among other things, provide zero-interest loans of up to $100,000 from the Agronomy Development Bank to help ranchers develop new technologies, improve production, and adapt to climate change. Water deficiencies in the dry season result in the degradation of streams and rivers when animals are given direct access to riparian areas. To prevent this, experts recommend that producers construct subterranean water storage areas (to avoid surface evaporation and soil salinization) connected to nearby rivers that refill during the rainy season. Water can be gravity fed to pasture parcels or delivered to paddocks with solar-powered pumps. Concomitantly, funding should support research and development into drought and high temperature-resistant plant and animal genetic materials (Esquivel 2016).

Unfortunately, government-funded projects related directly to agroforestry and SPS are relatively scarce. The country is still plagued by inter-institutional fragmentation and lack of coordination, resulting in limited efficiency and the duplication of efforts (Sánchez 1995; Fischer and Vasseur 2002). One nationally funded SPS project started in 2016 when the government announced its “Agua para Todos” (Water for All) initiative under the National Hydric Security Plan. The plan focuses on developing multipurpose reservoirs in the Rio Indio watershed, an important water source for Lake Gatun and the Panama Canal. A secondary component of the project is to establish 35 ha of SPS in the form of dispersed trees, living fences, and forage banks on farms within the watershed (MiAmbiente 2017). The most successful SPS applications in Panama have been initiated and funded by external organizations, which will be discussed later in the chapter.

13.5 Silvopasture Research in Panama

Research conducted on SPS in Panama is relatively limited. One of the first studies on SPS in Panama was done by a graduate student at the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE) in Costa Rica. In that study, Bolivar Vergara (1998) compared the production and nutritive value of the improved grass *Brachiaria humidicola* growing in the understory of an *Acacia mangium* plantation (photosynthetically active radiation (PAR) reduced by 35%) with that growing in a grass monoculture in Veraguas province. The author also examined differences in soil humidity, grass leaf to stem ratio, and percent of dead material and concluded that grass growing in the *A. mangium* SPS produced significantly more dry matter (DM) throughout the year than the grass growing in the monoculture. She also reported that mean soil humidity was significantly higher in the SPS (Table 13.1).

Bolivar Vergara (1998) also reported significantly greater soil nitrogen (N) and phosphorus (P) in the SPS. She attributed the greater grass DM production in SPS to higher soil moisture, N, and P content under the trees (Fig. 13.1). In a similar study in the humid tropics of Costa Rica Bustamante et al. (1998), found a 17% increase in DM production of *B. humidicola* under *Erythrina poeppigiana* trees when compared to open monocultures.

In the Bolivar Vergara (1998) study, grass growing under *A. mangium* had 28% less dead material during the dry season which was explained by the warmer ambient temperatures (Wilson 1996) and reduced soil moisture content in the monoculture due to greater incident radiation. Although Bolivar Vergara (1998) reported relatively low overall nutritive value of *B. humidicola* (crude protein <5%, in-vitro digestibility 38–52%), crude protein content was 45% higher in the SPS than in the monoculture, most likely caused by the higher N content of the soil in the SPS. The ruminal degradability potential of the grass crude protein was also significantly

Table 13.1 Photosynthetically active radiation (PAR), soil humidity, and dry matter (DM) production in *Brachiaria humidicola* growing in a silvopastoral system (SPS) with *Acacia mangium* and in a monoculture

	PAR (μmol m^{-2} sec^{-1})	Soil Humidity (%)	Production (kg DM ha^{-1} month^{-1})
SPS	1397 (275)	24 (3.47)	2562 (867)
Monoculture	1950 (292)	22 (4.55)	1834 (864)
Minimum significant difference	69.9**	0.6**	524**

Adapted from Bolivar Vergara (1998); **Minimum significant difference (P< 0.01).

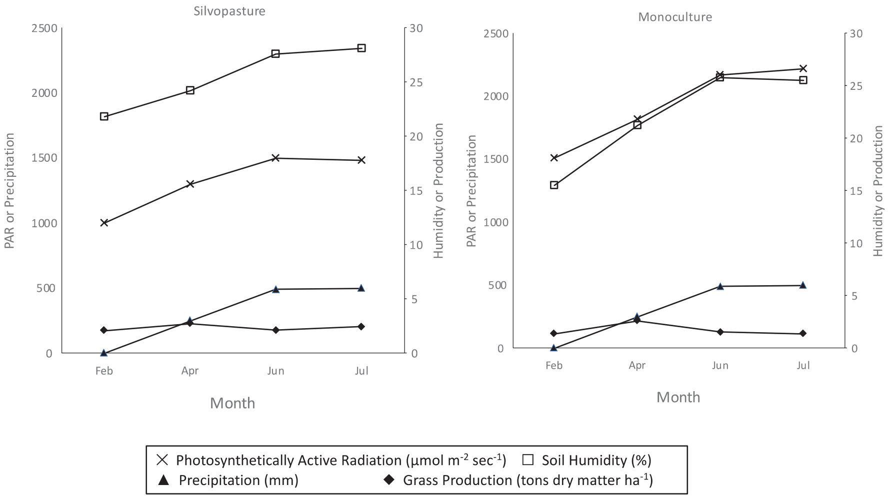

Fig. 13.1 Photosynthetically active radiation, precipitation, soil humidity, and grass dry matter production of *Brachiaria humidicola* in a silvopastoral system with *Acacia mangium* and in a monoculture over four different months. (Adapted from Bolivar Vergara (1998))

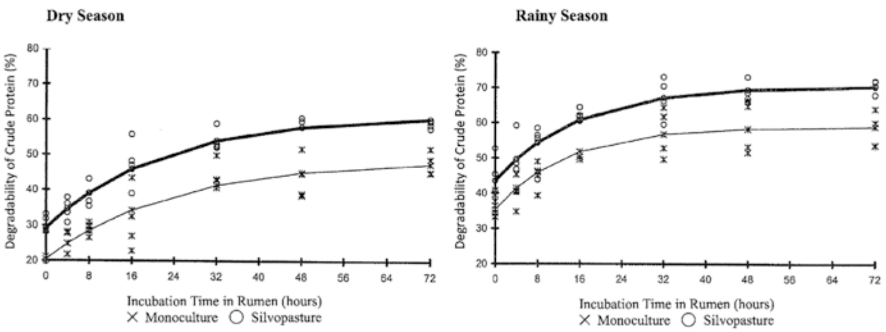

Fig. 13.2 Ruminal degradability of *Brachiaria humidicola* crude protein (%) growing in a silvopasture with *Acacia mangium* and a monoculture in two seasons. (Adapted from Bolivar Vergara (1998))

higher in the SPS, contributing to an increase in rumen microbial activity fundamental for improving the digestion of high fiber forages (Fig. 13.2).

Dibala et al. (2021) studied three cultivars of improved guinea grass (*Megathyrsus maximus*) growing under dense, and moderate tree canopies and compared them with grass monocultures in Los Santos province. The authors found that grass monocultures produced significantly more DM throughout the year than either of the tree canopy treatments. However, the cultivar *Massai* produced significantly more DM under a moderate canopy during the month of February (middle of the dry season) than any other treatment (Table 13.2). The authors attributed the observed productivity to numerically greater volumetric soil moisture under the moderate

Table 13.2 Grass DM yield for three cultivars of *M. maximus* in open, moderate, and dense treatments for February. Entries that share the same letter are not significantly different from one another

	Canopy cover		
Grass type	Dense	Moderate	Open
Massai	1132.5 ± 163.85a	1478.45 ± 198.95b	935.87 ± 70.19a
Mombaza	651.27 ± 153.87a	869.3 ± 100.46a	931.29 ± 117.74a
Tanzania	663.69 ± 74.30a	858.77 ± 75.30a	944.18 ± 122.81a

Adapted from Dibala et al. (2021)

canopy at that time of year. Nutritive value of the grasses also improved under increasing tree cover, with dense and moderate canopy treatments demonstrating significantly greater crude protein content than the monoculture. The authors recommended utilizing SPS seasonally in this region, when benefits to the animal can be maximized.

Another study in the same region examined the growth of *Albizia saman* saplings planted with and without fodder shrubs and improved grasses in an ISPS (Dibala et al. under review). The authors concluded that even in a water limited environment, *A. saman* moisture stress, growth, and survival was unaffected by the presence of closely neighboring grasses and fodder shrubs, making this species a good candidate for the overstory component of ISPS.

A different study conducted in the central Province of Colón looked at the growth, survival, foliar N, and water stress of the timber species *Tabebuia rosea* and *Cedrela odorata* when planted in isolation compared to when surrounded by the companion fodder species *Guazuma ulmifolia* and *Gliricidia sepium* (Plath et al. 2010). The planting regimes did not affect the performance nor foliar nitrogen concentration of the timber trees, but water stress (expressed in terms of $\delta^{13}C$ values) was significantly greater for trees growing in isolation. This finding suggests that trees surrounded by companion species may endure lower exposure to water stress than those planted in the open. Similarly, Paul and Weber (2016) found that the height increment of several native trees seedlings intercropped with *Zea mays* and *Cajanus cajan* was up to four times greater than that achieved in pure plantations.

Cerrud et al. (2004) characterized the arboreal components of SPS on 18 dairy farms across three townships in Chiriquí Province, Panama. The most common forms of SPS were dispersed trees and living fences. The author reported density, diversity, and use for both dispersed trees and living fences. Dispersed trees comprised 22 families (mostly Rutaceae, Bignoniaceae, and Papilonaceae) and 41 different species, with *Citrus sinensis*, *Cordia alliodora*, *Diphysa americana*, and *Tabebuia rosea* being most common. Tree densities reached as high as 18 ± 5 trees ha^{-1} in the District of Sortova. Cerrud et al. (2004) documented 18 different tree species used in living fences and reported that 90% of the farms in the District of Santo Domingo used improved grasses, the most popular being *Brachiaria decumbens* and *Cynodon dactylon*.

Love and Spaner (2005) used surveys to describe the use of pasture trees in 49 farms throughout the Province of Herrera, Panama. Sixteen trees were mentioned most frequently, all with a variety of uses (Table 13.3). Despite a demonstrated absence of protein banks, 62% of pasture owners reported retaining a total of 18 tree species for cattle fodder (Table 13.4). Only two of these species (*Enterolobium cyclocarpum* and *Guazuma ulmifolia*) were reported by numerous pasture owners (7 users and 24 users, respectively).

Ranchers relied heavily on few fodders during the dry season, with an average of 1.9 fodder species used (Love and Spaner 2005). Most ranchers relied on agricultural byproducts like sugar cane tops, maize stover, salt, concentrate, and cane molasses as supplemental feed during the dry season.

In a similar study, Garen et al. (2011) identified 99 tree species that cattle ranchers utilize, plant, or protect on their land. Most of the species mentioned in the study are native to Panama and provide multiple uses and values. However, preferences and motivations for tree planting differed between the two study sites. Interestingly, most of the ranchers interviewed expressed a desire to plant additional trees on their farms.

Velarde Adrade (2012) analyzed dual purpose cattle farms in Panama, Costa Rica, and Nicaragua where biophysical and socioeconomic factors were studied over the course of 12 months. The research conducted in Panama took place in Rio La Villa in Los Santos province. The author identified 41 tree species, 61% of which were used in living fences, 32% dispersed throughout pastures, and 6.8% in riparian

Table 13.3 Tree species mentioned most often (≥10% relative abundance) for pasture owner identified uses in a survey of 45 pasture owners in Herrera province, Panama

Species	Use category(ies)
Nance – *Byrsonima crassifolia*	FR, AS, P
Guácimo – *Guazuma ulmifolia*	FW, F, AS
Laurel – *Cordia alliodora*	FW, W, P
Cedro Amargo – *Cedrela odorata*	W, P
Corotú – *Enterolobium cyclocarpum*	F
Eucalipto – *Eucalyptus globulus*	M
Guanábana – *Annona muricata*	M
Pazmo – *Siparuna sp.*	M
Mango – *Mangifera indica*	AS, FR
Marañón – *Anacardium occidentale*	FR
Guava – *Inga vera*	WS
Espave – *Anacardium excelsum*	WS
Macano – *Diphysa americana*	P
Carate – *Bursera simaruba*	LF
Caratillo – *Bursera tomentosa*	LF
Balo – *Gliricidia sepium*	LF

Adapted from Love and Spaner (2005)
M medicinal, *F* fodder, *WS* water shade, *FW* firewood, *W* wood, *FR* fruit, *P* posts, *LF* living fence stakes, *AS* animal shade

Table 13.4 Fodder species mentioned by small-scale pasture owners as being purposefully retained in pastures or observed being consumed by cattle in Herrera province, Panama

Common name	Scientific name	Principal fodder type
Purposefully retained		Leaf fruit
Balo	*Gliricidia sepium*	X
Bobo	*Erythrina fusca*	X
Carate	*Bursera simaruba*	X
Corotú	*Enterolobium cyclocarpum*	X
Espave	*Anacardium excelsum*	X
Guácimo	*Guazuma ulmifolia*	X
Guachapalí	*Samanea saman*	X
Guava	*Inga vera*	X
Higo	*Ficus sp.*	X
Jobo	*Spondias mombin*	X
Leucaena	*Leucaena leucocephala*	X
Mango	*Mangifera indica*	X
Marañón	*Anacardium occidentale*	X
Nance	*Byrsonima crassifolia*	X
Palma real	*Attalea butyracea*	X
Palo Santo	*Erythrina poeppigiana*	X
Pito	*Erythrina costaricensis*	X
Palma Pacora	*Acrocomia aculeata*	X
Observed consuming		
Papo	*Hibiscus rosa-sinensis*	X
Caratillo	*Bursera tomentosa*	X
Caimito	*Chrysophyllum cainito*	X
Sapote	*Licania platypus*	X
Guayaba	*Psidiumguineense*	X
Ciruela	*Spondias purpurea*	X
Cañaza	*Bambusa sp.*	X
Lazo	*Matayba sp.*	X
Caoba	*Swietenia macrophylla*	X
Bamboo	*Bambusa sp.*	X
Tamarindo	*Tamarindus indica*	X
Aguacate	*Persea americana*	X
Laurel	*Cordia alliodora*	X
Naranja	*Citrus sinensis*	X

Adapted from Love and Spaner (2005)

forests. Species of major importance were *Guazuma ulmifolia*, and *Jatropha curcas,* two species used in living fences that have potential use as browse for livestock. Even though ranchers expressed a preference to keep trees confined to living fences and waterways, the authors noted a low density of trees along the rivers.

Milk production was analyzed over the dry season with and without the application of three different climate mitigation strategies: forage conservation, improved

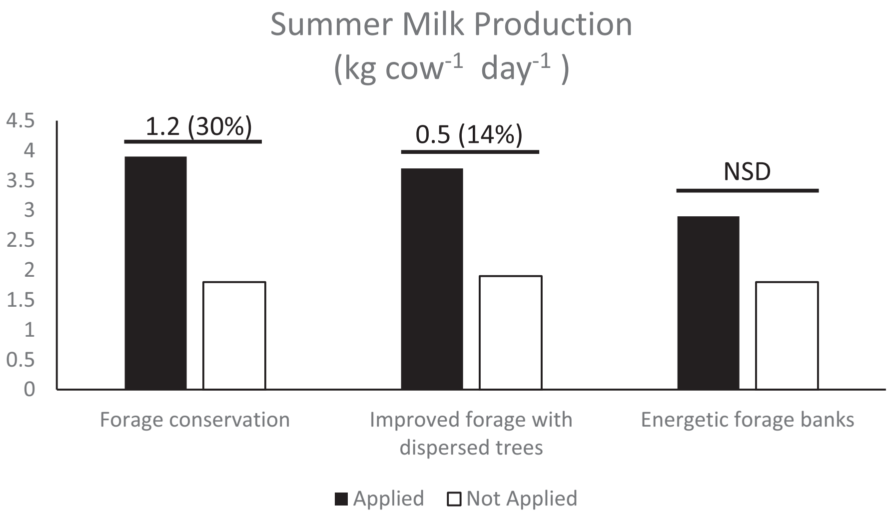

Fig. 13.3 Contribution of three adaptation measures to the production of milk implemented by producers of the watershed of Rio La Villa, Panama. (Adapted from Velarde Adrade (2012))

forage with dispersed trees, and energetic forage banks. Ranchers who actively conserved forage and provided their cattle with supplemental feed doubled milk production in comparison to those who did not adopt these practices. Cattle grazed on improved grass under dispersed trees produced 1.8 times more milk than those grazed on conventional pastures and those supplied with energetic forage banks did not differ from the control (Fig. 13.3).

13.6 Applied Silvopasture in Panama

There have been several applied SPS projects throughout the country that are worth noting. The Association of Livestock and Agro-Silvopastoral Producers of Pedasi (APASPE) received financial assistance from The Global Environmental Facility's (GEF) Small Grants Programme to establish more than 40 ha of ISPS, 25 ha of native trees, and 38 family forest gardens. This project implements diverse forms of SPS (living fences, natural regeneration, riparian restoration, ISPS), protects riparian corridors, and seeks to strengthen food security within the local community (Currea et al. 2020). A portion of the program provides "farmer to farmer" workshops on ecological restoration techniques coordinated by Yale's Environmental Leadership and Training Initiative (ELTI). This helps strengthen the planning capacity of landowners. Technical workshops are also given by visiting professionals from institutions like the Center for Research in Sustainable Agriculture (CIPAV).

In 2011, a small association of producers in Guararé, Los Santos province, received a grant from GEF that supported the planting of ISPS including the fodder species *Canavalia ensiformis*, *Leucaena leucocephala*, and *Tithonia diversifolia*. One producer reported sustainably raising her farm's carrying capacity from one to 4.16 animals ha^{-1} during the dry season (CATIE 2017).

Several national institutions are currently supporting projects on climate-smart ranching around the country. The Institute for Agronomic Research (IDIAP), Ministry of the Environment (MiAmbiente), and Ministry of Agronomic Development (MIDA) are all actively collaborating with scientists from CATIE to address issues related to deforestation, reforestation, sustainable production, climate change, and water conservation. A project collating SPS data from Honduras, Nicaragua, Costa Rica, and Panama aims to emulate previously conducted international research such as the Integrated Silvopastoral Approaches to Ecosystem Management Project that was conducted in Colombia, Costa Rica, and Nicaragua (Pagiola et al. 2005). Currently, MIDA is overseeing a Disaster and Risk Management project that involves improving feed storage capacity, protection of water sources, water reserve tanks, and the utilization of solar panels.

13.7 Conclusion

Even though adoption of SPS appears to be happening more slowly in Panama than in other Latin American countries, there has been a gradual paradigm shift among some producers who once viewed trees as something that just got in the way. Attitudes toward tree planting and agroforestry in Panama are generally positive (Simmons et al. 2002; Garen et al. 2009) and with climate change creating an urgency to find alternatives to unsustainable agriculture, this mindset is becoming even more prevalent.

However, it will take an even greater government initiative to scale up the use of SPS to a point at which it can begin to show impacts at the landscape-level. Startup costs for ISPS implementation can be as much as \$2000 ha^{-1} – an astronomically expensive investment for the average rancher – and there are still limited training and educational resources available to producers (Calle et al. 2013; Rusby 2020). An incentives-based approach is needed to create SPS leaders who help to educate and motivate their peers.

Future SPS research in Panama should focus on developing a better understanding of rancher's needs and objectives along with the reasons behind the lack of adoption of specific available technologies (Dagang and Nair 2003; Chará et al. 2019a). There is also a need to substantiate claims that silvopasture has increased biodiversity and animal carrying capacity in Panamanian pastures. Biophysical data on changes in animal weight in SPS will provide information relevant to ranchers in economic terms, possibly resulting in more rapid adoption rates.

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Chapter 14
Increasing Biodiversity in Livestock Production Systems: Plant Traits and Natural Regeneration Capacity of Woody Vegetation in Actively Managed Grasslands

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Abstract Species' natural regeneration capacity is an ecological property of plant communities that is key to restoring diversity after disturbances and to conserving the delivery of related ecosystem services within agroecosystems. Reduced diversity of trees and shrubs promoted by conventional and intensive livestock pastureland management can reduce capacity for natural regeneration of woody vegetation, negatively affecting current and future ecological processes. We evaluate the relationships between the cover of woody species with different plant traits and the abundance of naturally regenerated seedlings and saplings within conventional pastureland management. Four main dimensions of plant traits (leaf, stem density, canopy height and reproductive variability spectra) were measured for the 76 woody species most commonly found within conventionally managed pastureland in the Mesoamerican region. All these plant traits were correlated with species' abundance and natural regeneration capacity. Under current practices, there is a risk of decrease in functional diversity of woody components and their capacity to deliver ecosystem services due to loss of species with a low regeneration capacity. The development of livestock management strategies, like agroforestry and specifically silvopastoral

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systems that take into account woody plant traits and natural regeneration management, are important to conserve current and future agro-biodiversity and potential delivery of ecosystem services in agricultural landscapes.

Keywords Farm trees · Seedlings · Saplings · Woody cover · Population dynamics · Agricultural systems

14.1 Introduction

The global trend of species and genetic diversity decline continues in both wild and managed species, accentuating biodiversity losses resulting from habitat loss and deterioration with deforestation and agriculture (IPBES 2019; Jung et al. 2019). Agricultural lands can, however, potentially conserve an important fraction of local diversity (Pimentel et al. 1992; Harvey et al. 2006), helping to reduce biodiversity losses in different biomes (Estrada-Carmona et al. 2022) and crop systems (Esquivel et al. 2023) while providing agricultural net returns when planning is adapted to particular socio-ecological contexts (Wesemeyer et al. 2023). However, the proportion of local biodiversity able to colonize and maintain healthy populations under agricultural disturbances varies greatly according to taxa, landscape structure and management practices (Mendenhall et al. 2014; Santos-Gally and Boege 2022). Increasing the agro-biodiversity and associated wild diversity within farmlands, while efficiently sustaining agricultural production and provision of ecosystem services, is a challenging but necessary step to build multifunctional agricultural landscapes (Calle et al. 2013; Song et al. 2020), able to support biodiversity conservation, and a healthy and resilient food system globally (Frei et al. 2020).

Grasslands comprise 26% of the world's total land area and 80% of agricultural land covering a wide variety of ecosystems (Steinfeld et al. 2006), underlying the extent of livestock production systems and their role in the biodiversity crisis. Intensification of livestock systems conventionally relies on monocultures of exotic grasses plus fertilization, and chemical or mechanical weed control to sustain high biomass production for grazing cattle, supplemented with feed concentrates

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(Robinson et al. 2011). Grassland management homogenization exerts strong negative impacts on most native vegetation, including tree and shrub species that can colonize open areas after disturbances, providing habitat for other taxa, e.g., birds and mammals (Esquivel et al. 2008). As a result, natural vegetation within livestock landscapes is mainly limited to small fragments or isolated remnants within the grassland matrix (Esquivel et al. 2008), which reduces local biodiversity by 13–75% globally (Haddad et al. 2015). An increase in the actual cover and connectivity of these natural components remaining within livestock landscapes devoted to conventional dairy and beef production is necessary to increase the biodiversity conservation value and the delivery of ecosystems services from agroecosystems.

The combination of woody vegetation with crop and livestock production systems can increase agrobiodiversity, landscape heterogeneity and ecosystem services provision in agricultural landscapes. Agroforestry and specifically silvopastoral systems are designed to improve the spatial and temporal distribution of the woody components to increase agricultural resilience in diverse agroecosystems (Altieri 2004). Tree and shrub cover can occur in different arrangements both in subtropical and tropical agricultural landscapes, from polygonal (e.g., forest remnants and tree plantations) to linear (e.g., hedgerows and dry ditches). In the neo-tropics, woody components typically occur in the form of riparian forests, forest fallows, live fences and dispersed trees (Harvey et al. 2006). In Mesoamerica, 458 shade plant species have been recorded in four agroforestry systems and six countries, including the main crops of the region: coffee, cocoa, and livestock grasslands (Esquivel et al. 2023). This woody cover does not have a common origin. It is a mixed community including remnant individuals, which survived the cutting of the original vegetation, together with new colonizers dispersed from conserved forest fragments and individual woody plants deliberately sown or planted by farmers. Farmers actively manage woody resources to provide products such as firewood, timber, fruits and fodder for cattle, and functional services such as watershed protection and shade for cattle (Harvey et al. 2004; Gordon et al. 2010; Álvarez et al. 2020). Although farmers principally retain trees for their productive purposes, they may also provide habitats, resources, and landscape connectivity for animal taxa (Estrada et al. 2000; Harvey et al. 2004). Some literature has also compared animal diversity on agricultural land versus forest in the neotropics (Estrada et al. 2000) indicating, for example, that tree components can offer resources for 54% of terrestrial native mammals foraging inside and outside the forest (Daily et al. 2003), an important amount for biodiversity conservations goals.

Conversely, we are aware that the valuable remnant woody cover diversity in agricultural landscapes is threatened by decline under the continuity of conventional management practices, in particular intensive over-grazing and pesticide use (Gibbons et al. 2008; Fischer et al. 2009). Half of the tree species present in Mesoamerican livestock landscapes were found to have abundant seedlings, saplings and adult populations, whereas seedlings or saplings were absent for the other half of species indicating their lack of capacity to renew their populations under grazing disturbance (Esquivel et al. 2008). In the near future, the continuation of conventional homogenizing grassland and grazing management will probably decrease the remaining woody plant biodiversity in livestock farms to 50% of its previous level (Esquivel et al. 2008). Paradoxically the ecology of woody components within agricultural lands has not received attention beyond the identification of its taxonomic diversity and adult population abundances, despite the relevance of their functional attributes for biodiversity conservation objectives of trees and shrubs outside forests. We still do not know what are the morphological or physiological characteristics associated with the variation in capacity for natural regeneration amongst the species able to colonize and maintain their populations in livestock grazing areas. Filling this knowledge gap could inform efforts to reverse the biodiversity loss patterns of agricultural landscapes.

The capacity of woody vegetation to regenerate after disturbances is a key ecological property of plant communities, which can be of importance for current and future agroecosystem services. Despite the massive efforts in recent decades to evaluate the functional characterization of diversity worldwide (e.g. Wright et al. 2004; Díaz et al. 2002, 2007; Chave et al. 2009; Moles et al. 2007), we know comparatively little about the functional characteristics of woody plants regenerating in agricultural lands. For example, a diversity of whole plant, leaf and reproductive characteristics are needed for woody vegetation to provide food and habitat sources for diverse animal taxa within agricultural landscapes (Harvey et al. 2004). In addition, when some plant traits promote high tree and shrub abundance through natural regeneration after land use change more than others, they probably also affect other ecosystem processes, e.g. carbon sequestration and litter decomposition. The reduction of woody plant diversity could therefore impact future ecosystem services delivered by plant communities within agricultural landscapes such as nutrient cycling.

Only a few studies have determined the dynamics of woody vegetation in anthropogenic pasturelands under active grazing pressure (Arnaiz et al. 1999; Esquivel and Calle 2002; Esquivel et al. 2008; Derroire et al. 2016). These studies confirmed the importance of previously-existing woody vegetation to act as foci for tree species colonization within the pasturelands. In Andean moist pre-montane lands, for example, early regeneration (seedlings) of woody species were richer and more abundant in pastures below isolated trees with animal-dispersed seeds than in open pastures (without tree cover) under active livestock production (Esquivel and Calle 2002). Woody species with animal-dispersed seeds probably enhance seed rain input and provide favourable microsites for the germination of secondary species that could not reach, germinate or establish in open pasture sites (Holl 1999; McClanahan and Wolfe 1993; Guariguata et al. 1995; Robinson and Handel 1993; Toh et al. 1999). Unless a higher proportion of bird-dispersed species are able to reach pasturelands under remnant trees (Guevara et al. 1986), tree regeneration could be much more spatially constrained to colonization by wind-dispersed species into areas of grasslands adjacent to forest edges. However, dispersal of seeds by cattle may provide another pathway for some species. Therefore, certain species' functional characteristics can dominate woody plant communities of cattle pasture landscapes while others can be rare.

A limited number of studies have explored in depth the abundances of species with different functional traits in woody communities. Since several decades ago, community ecology searched for general rules associating species characteristics with biotic factors and environmental conditions (Keddy 1992). In this research, the links between species' population structures and ecosystem processes have generated contrasting interpretations. Some authors have suggested that disturbance responses involve demographic rather than physiological traits, therefore highlighting the independence of traits relevant to disturbance response from those involved in ecosystem effects and processes (Lavorel and Garnier 2002). In contrast, others argue that the presence and abundance of species in a habitat could be predicted from a particular subset of ecophysiological traits, with others being filtered out due to the environmental and biotic interactions (Keddy 1992). Therefore, the number, relative abundance, and functional identity of plant species can potentially influence ecosystem processes (Chapin III et al. 2000; Chapin et al. 2002). As postulated by Grime (1998) in the biomass ratio hypothesis, "the extent to which the traits of a species affect ecosystem properties is likely to be strongly related to the contributions of the species [. . .]". This theory explicitly takes into account the number, relative abundance and functional identity of the species present in specific habitats for understanding current ecosystem functioning (Garnier et al. 2004).

Species' capacity to successfully complete their life cycles in a specific habitat and their effects on the functional structure of woody plant communities have been almost exclusively studied in pristine forests or native grasslands. However, the natural regeneration of tree species has a key role in the community structure of agricultural lands that are adjacent to natural vegetation frontiers. This suggests that increasing our knowledge of natural regeneration in agricultural lands can be especially relevant in areas where pristine habitats are under high deforestation pressures, such as seasonal dry tropical forests in Mesoamerica. This is important for both biodiversity conservation and ecosystem restoration reasons, and also for the development of more sustainable agricultural management practices. While tropical dry forest represented 42% of the tropical vegetation worldwide in the 1990s (Murphy and Lugo 1995), it has become one of the most threatened tropical terrestrial ecosystems due to the conversion of these areas into livestock and crop agricultural lands (Sanchez-Azofeifa et al. 2005). This has resulted in the loss of biodiversity and ecosystem services (such as those linked to watershed protection and provisioning of timber and non-timber forest products), with detriment to the livelihoods of dependent communities (Lamb et al. 2005).

Knowledge about species natural regeneration capacity is especially relevant for restoration of anthropogenic-disturbed ecosystems (Chazdon and Guariguata 2016). This is particularly so for active pasturelands where woody cover has been depleted due to conventional grassland management carried out to maximize grass productivity (Nepstad et al. 1999), but where there is potential to increase biodiversity through adaptation of conventional intensive management practices (Esquivel et al. 2008). The study of natural regeneration processes beyond forest edges can inform improved management for the maintenance of plant communities, ecosystem processes and services within agricultural landscapes (Vesk and Dorrough 2006). Seed dispersal from remnant vegetation fragments, for example, is an important ecological process for woody species to colonize new open areas outside forest (Aide et al. 2000) but it is just the beginning of the colonization process. Beyond that, the relationships of species' abundance in early seedling and sapling developmental stages with their ecophysiological-morphological traits can potentially reflect species' "functional responses" that are key to successfully overcoming such selective pressures. At the same time, relationships between woody species' functional traits and population structure could help identify "constraints" to the completion of their life cycle in a specific habitat, adding functional information to the generally better-known descriptions of woody community structure.

Understanding the relationships between the seedling and sapling stages of woody species' population structure and their morphological traits can also provide useful information to guide restoration efforts in silvopastoral systems at landscape and regional scales. This could inform land managers' strategies to minimize risks and costs of revegetation activities by indicating which species have the greatest regeneration capacity and thus potential to contribute to landscape restoration goals (Vesk and Dorrough 2006). The selective pressures from environmental conditions, disturbances and biotic interactions distinctively impact species' life cycles at different developmental stages thus influencing their relative survival and abundance (Boege and Marquis 2005). At a community level, the relative abundance of species in combination with their population structure (for instance divided into the seedling, sapling, adult and diaspore developmental stages) can reflect their differential capacity to reproduce under the prevailing environmental conditions, in response to natural and anthropogenic disturbances like herbivores, droughts and deforestation (Kitajima and Fenner 2000; Esquivel et al. 2008). Each developmental stage has differences in ecophysiological and morphological attributes and constraints, and therefore different responses to the selective management pressures exerted over tree ontological development. Such knowledge can help shape existing woody species' populations, which can be used to promote more biodiverse woody vegetation communities in agricultural lands (Elger et al. 2009).

The abundance of adult tree cover in agricultural lands can be an important factor correlated with abundance at early developmental stages of natural regeneration (Esquivel et al. 2008) but it is not yet clear if plant traits can be helpful to predict natural regeneration abundance. Adult stages of plant woody components in active pasturelands result from a complex interaction between historic natural and anthropogenic disturbances, which will also probably shape future functional composition of woody plant cover. Previous natural disturbances when forest cover still dominated, prior to forest clearing, intensive land management, and land users' decision-making with respect to tree cover components in managed areas (e.g, windbreaks, isolated trees, riparian forests) and in their neighbourhoods (forest remnants), shape the woody cover present in active pasturelands. The functional characterization of the woody cover of active pasturelands has not been studied previously and could have huge importance for the restoration of agro-biodiversity. Firstly, this is due to the homogenization of anthropogenic disturbances, which is rapidly accelerating within diverse biomes due to conventional management across agricultural lands.

Secondly, it is due to the potential influence of woody plant components in driving the future functional characteristics of agricultural lands. Functional traits can help to identify the woody species able to proliferate within these areas but also those that need particular or additional management interventions to maintain their populations and to increase their associated biodiversity.

As a novel approach, here we evaluate the relationships of woody species' plant functional traits with the abundance of their naturally-regenerated seedlings and saplings. We use this to assess the capacity of woody cover diversity to facilitate natural regeneration under the ongoing disturbances generated by conventional livestock production. We investigated the factors determining the relative abundance of woody species in actively-managed pasture environments. We specifically researched whether functional traits (whole plant, leaf and reproductive) can be predictors of the abundance of species' natural regeneration. We assume that the historical and complex effects of natural and anthropogenic disturbances are the primary influence on the composition of tree and shrub cover. Our results provide the first functional characterisation of the natural regeneration of woody cover commonly found in agricultural lands of dry-to-humid transition forest areas in the Mesoamerican region.

14.2 Methodology

Morphological characteristics and population structure of early developmental stages were measured for 76 woody species commonly found in the anthropogenic grasslands used for dairy livestock grazing in the Mesoamerican region. Population structure was assessed by analyzing the abundance of two developmental stages: seedlings and saplings. Morphological characteristics were recorded for 17 plant traits, encompassing three main dimensions related to development and regeneration processes: leaf, reproductive and whole plant traits. To characterize the life history of common woody species in agricultural landscapes of the region, we selected traits from across a wide spectrum of those commonly measured for tropical woody species outside forest environments.

This study focused on active pasturelands with dispersed or scattered trees and shrubs, which represent a common silvopastoral system (SPS) in the Central American region (Harvey et al. 2007), known as SPS with Dispersed Trees. These pastures dominate the land use cover (46–85%) in the major livestock regions of countries like Nicaragua (Matiguás, Rivas, Rio Blanco) and Costa Rica (Rio Frío and Cañas), followed by remnant or riparian forests (2–16%), annual or perennial crops (6–14%) and forest secondary regrowth (3–7%). The densities of the isolated trees in this silvopastoral system varied between 8 and 33 trees/ha in these regions. Many farms included live fences (40–80%), however all the farms had isolated trees inside active pasturelands with different densities and spatial arrangements. Farmers kept these trees as sources of wood for house and fence construction, fruit for human consumption, and forage to feed cattle in dry seasons (Harvey et al. 2007).

The 76 woody species were surveyed on 46 active pastures located in Matagalpa, Nicaragua, Central America (12°31′ – 13° 20′ N, 84° 45′ – 86° 15′ W) managed under common practices in grazed pastures consisting of grasslands predominantly sown using exotic grasses established after removal of the original native forest cover. The original biome is tropical dry forest (subhumid) with semi-deciduous vegetation (Meyrat 2000); mean annual temperature is 24.5 °C and mean annual precipitation is 1576 mm, with rains between May and September (Holdridge 1984). The landscape consists of plains and undulating areas between 100 and 450 m a.s.l. and the soils consist mainly of vertisols, inceptisols and alfisols (Henríquez et al. 1995). The region is dedicated to cattle production, with 53% of the land under natural (i.e., not sown) grasses, 22% planted with improved exotic grasses, 10% under early secondary succession (tacotales) and only 5% under forest. Both woody community composition and grassland management have been described in a previous study (Esquivel et al. 2008).

14.2.1 Population Structure of Woody Plant Species in Active Pastures Within Silvopastoral Systems Containing Dispersed Trees

The abundance of woody plant natural regeneration was measured in plots established in the 46 pastures actively used for cattle grazing on 17 dairy farms, from which samples were collected for plant trait measurement. The selected farms were distributed to cover the different conditions of pastures in the region. Abundance was measured in the two early developmental stages of woody plants: saplings (plants with heights >30 cm and dbh ≤ 10 cm) and seedlings (plants with a height between 10 and 30 cm), which were assumed to be naturally regenerated following the conversion of the previous vegetation to pasture. Saplings were sampled in a mean of ten square plots per pasture (4000 m^2) and seedlings were sampled in a mean of 18 circular plots (126 m^2) per pasture. The total area of each pasture varied from 1 to 22 ha (mean 5.82 ± SE 1.34 ha). The grass composition was dominated (cover ≥ 70%) by one of three grass types: (i) *Urochloa* spp. [*Urochloa brizantha* (Hochst. ex A. Rich.) Stapf and *Urochloa decumbens* Stapf] previously named *Brizantha* spp. (B, n = 15); (ii) mixtures of *Cynodon nlemfuensis* Vanderyst and *Cynodon dactylon* (L.) Pers. (C, n = 13); or (iii) naturalized grasses (i.e., not planted or seeded) such as *Paspalum* spp. (N, n = 18). Plots were systematically distributed in the central area of each of the pastures, ensuring a non-grouped spatial arrangement. We identified the species of each individual sapling and seedling during the rainy season (May to late July) when environmental conditions allow both seed germination and seedling growing, and full canopy expression of woody species. Further details about sampling scheme, design, pasture management and woody species natural regeneration are available in Esquivel et al. (2008).

14.2.2 Morphology of Woody Species in Pastures Under Active Cattle Grazing

Plant traits were measured on adult individuals (defined as woody plants with dbh > 10 cm) randomly selected among those located in pastures and open site environments with canopies completely exposed to sunlight and following the general recommendations made by Cornelissen et al. (2003). Adult individuals of unknown origin (remnant from pre-pasture vegetation, subsequently planted or naturally regenerated) were randomly selected, avoiding only those with any evident trace of sickness or logging management. The reproductive traits were fruit and seed masses (Mass_see, Mass_fru), volumes (Vol_fru, Vol_see) and shapes (Sha_fru, Sha_see), and dispersal mode (or syndromes). The leaf traits were specific leaf area (SLA), leaf area (LA), leaf dry matter content (LDMC), total carbon, nitrogen and phosphorus contents (LNC, LCC and LPC), and foliar tensile strength (FTF). The whole plant traits were maximum tree height (H_max), leaf phenology (PHE) and wood density (WD). Species mean values for each trait were obtained from measuring three to five leaves or fruits collected from each of three to five trees or shrubs by species (Table 14.1).

Leaf and fruit traits were measured in mature and fully expanded leaves and fruits without obvious symptoms of pathogen or herbivore attack and without substantial cover of epiphytes. Leaf, fruit and seed samples were stored in a cool box or fridge until processing in the laboratory (within 48 h of collecting) and re-hydrated when necessary (6–12 h in a dark room). After LA measurement (using Leaf Area Measurement software LAM V 1.3, University of Sheffield, A.P. Askew, 2003) leaf samples were oven dried (60 °C for 72 h) and weighed to calculate LMDC and SLA, while composite samples were used for LNC, LCC and LPC quantification in the CATIE Soil Laboratory (Turrialba, Costa Rica). Fruit and seed samples were oven dried (60 °C) until reaching a stable weight to obtain FDM and SDM. Fruit and seed main dimensions (length, width and thickness or breadth) were used to calculate dispersule shapes Sha_fru and Sha_see (using the variance of three main dimensions divided by the largest value) and volumes Vol_fru and Vol_see (using spherical or ellipsoid geometrical formulas) accordingly. Plant trait measurement methodologies are available in more detail in Esquivel (2013).

Four dispersion modes (syndromes) describe the main vector involved in releasing the dispersule from the parental tree (Table 14.2): Autochory (autonomous), Anemochory (wind), Zoochory (animal dispersal) and Mammalochory (dispersal by big mammals including cattle). Maximum plant height (H_max) and PHE were measured using clinometers and visual estimations of the percentage of tree canopy covered by leaves (%) surveyed every 2 weeks over a year. A "tearing apparatus" provided by the DIVERSUS project was used to measure FTF. Wood density (WD) was the only plant trait obtained exclusively from literature and available metadata such as Chave et al. (2006) and the global wood density databases of Zanne et al. (2009).

Table 14.1 Plant traits and sampling effort for woody species commonly found in grasslands under active cattle grazing (active pasturelands) in Mesoamerica

Trait dimensions	Trait ID	Plant traits	Units/categories	Sample size (individuals/samples per species)
Whole plant	H max	Adult plant stature	m	3–5
	WD	Wood density	g cm^{-3}	Literature
	PHE	Leaf phenology	month	3–10
Leaf traits	SLA	Specific leaf area	mm^2 mg^{-1}	5–10
	LA	Leaf size	mm^2	5–10
	LDMC	Leaf dry matter content	mg g^{-1}	5–10
	LCC	Leaf total carbon content	%	5–10
	LNC	Leaf total nitrogen content	%	5–10
	LPC	Leaf total phosphorus content	%	5–10
	FTF	Physical strength of leaves	N	5–10
Reproductive traits	Sha_fru	Fruit shape	Unitless	3–5 fruits
	Sha_see	Seed shape	Unitless	3–5 seeds; 3–5 fruits
	Mas_fru	Fruit mass	g	3–5 fruits
	Mas_see	Seed mass	g	3–5 seeds; 3–5 fruits
	Vol_fru	Fruit volume	cm^3	3–5 fruits
	Vol_see	Seed volume	cm^3	3–5 seeds; 3–5 fruits
	Dis_mod	Dispersal mode	Autochory	Autonomous
			Anemochory	Wind
			Zoochory	Animal
			Mammalochory	Mammal
Abundances	Seedlings	Seedling abundance	Individuals (0.1 m ≥ height ≤ 0.3 m)	7 m^2 per paddock (total 126 m^2)
	Saplings	Sapling abundance	Individuals (0.3 > height & dbh ≤10 cm)	400 m^2 per paddock (total 0.5 ha)

14.2.3 Statistical Analyses

Two types of analysis were performed to provide different approximations to the relationships of woody species' plant traits with their seedling and sapling abundances: correlations and logistic regressions. First, Spearman Partial Correlation Analyses (CA) was used to evaluate interspecific relationships (cross-species

Table 14.2 Dispersule characteristics used to define the main dispersal mode traits (dispersal syndromes) of woody plant species commonly found in grasslands under active cattle grazing (active pasturelands) in Mesoamerica

Dispersal mode	Vectors	Dispersal mechanisms/Dispersule characteristics
Autochory (including Ballistochory)	Unassisted dispersal, bristle contraction or seed launching	The seed or fruit has no obvious aids for longer distance transport, falling passively from the plant or dispersule with hygroscopic bristles on the dispersule that promote movement with varying humidity. Restrained seeds are launched away from the plant by "explosion" as soon as the seed capsule opens. The main dispersal vector is the same parental tree
Anemochory	Wind dispersal	Minute dust-like seeds Seed with pappus or other hair, balloons or comas structures Flattened fruits or seeds with large wings Tumbleweeds, where the whole plant or in-frutescence with ripe seeds is rolled over the ground mainly by wind as dispersal vector
Zoochory and Mammalochory	Endo-zoochory (Internal animal transport)	Fleshy often brightly coloured berries, arillate seeds, drupes and big fruits that are evidently eaten by vertebrates (birds, bats or other mammals) and pass through the gut before seeds enter the soil elsewhere Those mainly consumed by wild animals were defined as Zoochory; those eaten exclusively by big mammals like cattle were defined as Mammalochory

Adapted from Cornelissen et al. (2003)

analysis, Poorter et al. 2008b) of seedling and sapling abundances with functional traits, while controlling for pasture type. Cross-specific correlation analysis was used to identify statistically significant linear abundance-trait relationship, their direction and strength (r). Second, logistic regression analyses were used to identify the significance of woody species' abundances in the two developmental stages with dispersal strategies or syndromes as categorical variables. All the analyses were done using an unbalanced species × traits database built using the mean abundances per plot (density) per species and per developmental stage in three pasture types dominated by different types of grass species (B, E and N), together with the mean values of the 17 plant traits per species.

The relationships of woody species' seedling and sapling abundances per pasture type with whole plant, leaf and reproductive traits were tested using Partial Correlation Analyses (CA). These partial correlation analyses remove the pasture type effect from the seedling and sapling abundance model, which avoids any confounding effect of pasture management over the correlations between abundances and plant traits. In order to do this, the residual values resulting from an ANOVA used to test possible effects of pasture grass type (B, E, N) on seedling and sapling abundances (with abundances previously rank-transformed to overcome lack of normality) were correlated with the RANG values of whole plant, leaf and reproductive traits using Pearson coefficients (see further details in Esquivel et al. 2008). Therefore, Partial Spearman Correlation analyses could be used to test the relationships of seedling and sapling abundances with plant traits without interference by grass-type effects. Partial Spearman Correlations were compared with additional Spearman coefficients calculated using the original values of seedling and sapling abundances and 16 traits (non-partial Spearman correlations) to confirm for difference in Spearman coefficients due to a confounding effect of pasture grass type.

According to the categorical nature of dispersal mode variables in contrast to the continuous nature of the abundance data, the strength of the relationships of seedling and sapling abundances with dispersal modes were evaluated using logistic regression. An un-balanced data set of 76 woody species × 16 traits was used because not all the plant traits were measured for all the species (missing values). A complete record of every plant trait was available for 25 woody species, generating a balanced sub-database of abundances for these 25 species. The Spearman-CA between plant traits and the abundances of seedlings and saplings were calculated using between 32 and 76 species per paired correlation analyses, varying depending on the traits considered. The normality assumption was held for the error term of all these models (Q-Q plot, $r^2 > 0.94$), as well as linearity (simple linear patterns in the graphic between partial residuals and each trait) and heteroscedasticity (no function pattern in the residuals against predicted scatter plot).

14.3 Results

14.3.1 Morphology of Woody Plant Species in Actively Grazed Pastures Within Silvopastoral Systems with Dispersed Trees

Whole plant, leaf and reproductive traits of tree and shrub species were significatively correlated with the abundance of their seedlings and saplings (natural regeneration) in the active pastures within silvopastoral systems (SPS) with dispersed trees (Table 14.3). This suggests that, although the variances explained were quite low, plant traits can potentially predict tree natural regeneration capacity in these disturbed environments. Species' abundances of seedlings and saplings were highly correlated (Table 14.3). Therefore, species with more abundant populations of seedlings were also the more abundant as saplings in active pasturelands (Fig. 14.1), but the species with more abundant natural regeneration also showed a tendency for certain functional characteristics (Table 14.3).

Overall, most reproductive, leaf and whole plant traits were correlated with both early developmental stages (9), but more traits were significantly ($p \leq 0.05$) correlated with abundance of saplings (10) than with seedlings (7) (Table 14.3). This indicates their association with successful woody plant natural regeneration in active pasturelands. In general, reproductive traits showed the highest positive correlation coefficients with abundances, with higher values for seedlings than for saplings. Vol_fru showed the strongest correlation with both seedlings and saplings,

Table 14.3 Spearman partial correlations coefficients (r) between the abundance of woody plant species' regeneration (seedlings and saplings) in active pasturelands (ANOVA residuals) with whole plant, leaf and reproductive traits (r- values (p-value) of the sampled n species); significance levels: **p < 0.001**, **p < 0.05**, **p < 0.10**

Trait groups	Traits	Seedlings	Saplings
Whole plant	H_max	0.25 (0.0003) 69	0.15 (0.0366) 69
	WD	0.05 (0.5278) 64	0.21 (0.0031) 64
	PHE	0.09 (0.2377) 58	0.02 (0.7644) 58
Leaf	SLA	−0.14 (0.1011) 44	−0.19 (0.026) 44
	LA	−0.18 (0.0357) 45	−0.19 (0.026) 45
	LDMC	0.15 (0.07) 47	0.23 (0.0063) 47
	LCC	0.13 (0.0767) 58	0.08 (0.2848) 58
	LPC	−0.08 (0.2847) 59	−0.12 (0.0995) 59
	LNC	0.13 (0.0732) 62	0.10 (0.1583) 62
	FTF	−0.05 (0.5221) 46	−0.01 (0.9198) 46
Reproductive	Sha_Fru	0.19 (0.0068) 68	0.15 (0.0329) 68
	Mas_Fru	0.23 (0.0124) 39	0.19 (0.0404) 39
	Sha_See	0.22 (0.0022) 62	0.21 (0.0038) 62
	Mas_See	0.10 (0.1975) 59	0.12 (0.1065) 59
	Vol_Fru	0.36 (<0.0001) 57	0.31 (<0.0001) 57
	Vol_See	0.29 (0.0001) 61	0.23 (0.0019) 61
Abundances	Seedlings		0.77 (<0.0001) 76
	Saplings		

followed by Vol_see, Mass_fru, Sha_see and Sha_fru. This may indicate the importance of seed dispersal limitation to rates of woody plant natural regeneration in active pasturelands within SPS with their low densities of dispersed adult trees.

For the majority of leaf traits showing significant correlations this was stronger for the abundance of saplings than of seedlings (Table 14.3) suggesting that these traits are most strongly associated with rates of survival and growth. LDMC was positively associated with seedling and sapling abundance, with SLA and LA negatively (Fig. 14.2). Whereas LCC and LNC were positively associated with seedling abundance, LPC was negatively associated with sapling abundance. H_max was positively associated with seedling abundance and to a lesser extent sapling abundance (Fig. 14.2), whereas WD was positively correlated with sapling abundance.

These results showed that plant traits are directly correlated with the abundances of woody plant natural regeneration in the presence of prolonged livestock management in SPS with dispersed trees. Taller woody species regenerate more successfully, having more abundant seedling and sapling populations in active pasturelands. In addition, woody species with more conservative leaf strategies (lower SLA and LA together with higher LDMC) were the more abundant species at both seedling and sapling stages. Those with higher LCC and LNC were more abundant as seedlings, meanwhile those species with denser wood, higher LPC and heavier seeds, have more abundant saplings populations. Finally, woody species with bigger and

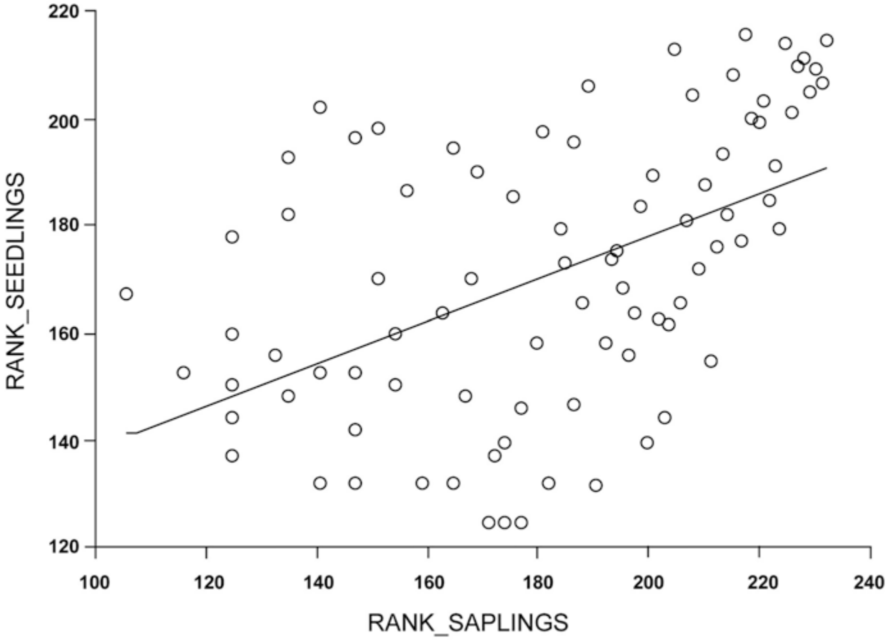

Fig. 14.1 Relationship between seedling and sapling abundances of woody species commonly found in active pasturelands in Mesoamerica. Spearman correlation analyses using abundances transformed to RANG values (r = 0.77, p value = <0.0001)

heavier fruits and bigger seeds with a higher shape score (a higher length:width ratio) have consistently more abundant seedling and sapling populations in active pasturelands.

14.3.2 Abundance of Woody Natural Regeneration and Dispersal Modes in Silvopastoral Systems with Dispersed Trees

Two dispersal modes were also correlated with woody species' seedling and sapling abundances (Table 14.4). While zoochory as a whole was negatively correlated with natural regeneration abundance, mammalochory specifically was positively correlated. No significant correlations of abundance were found with either anemochory or autochory. Species with mammalochory characteristics were frequently dispersed by cattle, which is likely to be a major factor in the higher abundance of their seedlings and saplings in actively-grazed cattle pastures. The majority of species with zoochory characteristics are dispersed by wild animals (e.g. birds, bats, etc.), which can have reduced abundance after conversion of forest to pasture.

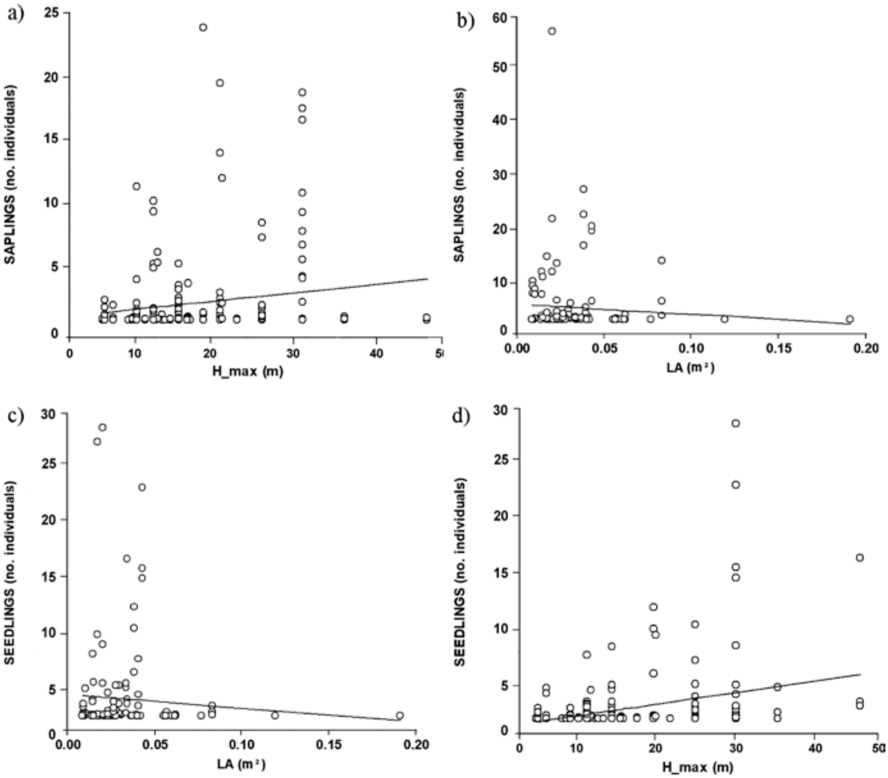

Fig. 14.2 Relationships of sapling and seedling abundances with some plant traits of woody plant species commonly found in Mesoamerican active pasturelands. Spearman correlation analyses for one whole plant trait (H_max = plant maximun height) and one leaf trait (LA = leaf area) with sapling and seedling abundances respectively: (**a**) $r_{H\_max} = 0.15$, $p_{value} = 0.0366$; (**b**) $r_{LA} = -0.19$, $p_{value} = 0.026$; (**c**) $r_{LA} = -0.18$, $p_{value} = 0.0357$; (**d**) $r_{H\_max} = 0.25$, $p_{value} = 0.0003$

Table 14.4 Spearman partial correlation (CA) coefficients between the abundance of woody plant species' natural regeneration (seedlings and saplings) in active pasturelands and their dispersal mode traits (dispersal syndromes). Significance levels are: **p < 0.001**, **p < 0.05**, **p < 0.10**

		Abundances			
		Seedlings		Saplings	
Dispersal mode	Dispersal vector	Est.	p-value	Est.	p-value
Mamalochory	Cattle	0.01	0.0108	0.01	0.0047
Zoochory	Wild fauna	−4.70E-03	0.0396	−3.70E-03	0.0908
Anemochory	Wind	4.10E-03	0.1519	3.20E-04	0.9101
Autochory	Parental tree	−3.70E-03	0.2372	−1.70E-03	0.5555

14.4 Discussion

14.4.1 Dispersal, Leaf and Whole Plant Traits Were Correlated with the Abundance of Woody Plant Natural Regeneration in Managed Grasslands

As predicted, dispersal, leaf and whole plant traits were correlated with the abundance of tree and shrub species' natural regeneration in active pasturelands within silvopastoral systems (SPS) with dispersed trees. These associations for the traits H_max, WD, LDMC, SLA, LA, LCC, LNC, LPC, Sha_fru, Sha_see, Mass_fru, Mas_see, Vol_fru and Vol_see indicate their potential role in the capacity of species to disperse into these disturbed cattle-dominated ecosystems and then establish and grow. Specifically, taller tree and shrub species, those with large and elongated diaspores within larger, elongated and heavier fruit, small leaves with high leaf dry matter, carbon and nitrogen contents, but low specific leaf area and phosphorus content, and denser wood, have a greater capacity for natural regeneration in these active pasturelands in SPS with dispersed trees. These morphological characteristics may enhance woody species' capacity to successfully overcome limitations in seed dispersal, seedling establishment and sapling survival, some of the main "bottlenecks" of natural regeneration, to maintain a viable population within active pasturelands, an ecosystem with persistent high levels of disturbance.

Maximum height (H_max) was the whole plant trait positively correlated with the abundance of woody species' natural regeneration in active pasturelands. In previous studies H_max has been found to be positively correlated with growth rates and negatively with mortality rates in several neotropical forests (Poorter et al. 2008a, b). In forest environments the correlation between maximum tree height and faster growth rates has been explained as an adaptive advantage to maximize capture of light, a vital resource but highly variable inside forests (see also Westoby 1998; Poorter and Rose 2005; Poorter et al. 2005). Light availability in open pasture sites, however, is probably not a limiting factor from the sapling stage onwards, and therefore woody species with high light requirements and faster growth rates can proliferate within these environments after successful initial establishment through the seedling stage. This is possible if they have been able to successfully overcome the first stages of seed dispersal, seedling establishment and survival of herbivore attacks within these highly grazed and browsed areas. The commonly named "gap colonizers", those species capable of quickly colonizing sporadically formed open areas inside the forest (caused mainly by treefall) could also have traits enabling colonization of open areas beyond the forest edge in the adjacent pasture matrix. Two of the most abundant tree species found in the active pastures of our study area, *Cedrela odorata* L. (Menalled and Kelty 2001) and *Cordia alliodora* (Ruiz and Pavón) Oken (Coll et al. 2008), have been classified as early successional and also have large maximum tree heights within these habitats. Their fast growth rates during the early developmental stages could be advantageous for colonizing pasturelands because tree seedlings can quickly escape from light competition with grasses increasing their chances for successful establishment in active pasturelands (per. obs).

Fruit and seed volume and shape were reproductive traits positively correlated with the abundance of woody plant natural regeneration. Tree and shrub species with elongated and large dispersules and heavy fruit were abundant in both developmental stages in the active pasturelands. These results suggest that both of these fruit and seed characteristics can have a key influence on tree regeneration capacity under grazing and managing disturbances in active pasturelands. Elongated and large dispersules associated with heavy fruit probably facilitated the seed dispersal and seedling establishment stages of natural regeneration in these grasslands. Seed size (measured as mass or volume) has been found to have a strong influence on dispersal distances (Jansen 2002; Jansen et al. 2004), germination, establishment and growth rates of seedlings (Mazer 1990; Paz et al. 2005), key factors for success in open pasture sites (Zimmerman et al. 2000). Large seeds carry more reserves that benefit seedling establishment in low-resource conditions and growth of larger seedlings with a higher probability of escaping from size-dependent mortality and from herbivore damage (Harms and Dalling 1997; Kitajima 2002). In open areas outside forest, like active pasturelands, tree species with bigger seeds probably also benefit from a higher content of nutrient reserves enabling greater seedling growth rate in low-fertility conditions, enabling them to quickly overcome the dense grass cover and survive herbivorous damage.

Woody plant species with bigger seeds were found to have more abundant seedling and sapling populations in these active pasturelands. Bigger seeds have been correlated with an increased capacity to grow under low resource availability (Westoby et al. 2002), lower seed production (Henery and Westoby 2001) and a reduced probability of reaching safe sites (Wright et al. 2006a, b). Our results add to this knowledge by showing that woody species with bigger seeds (by volume) are able to establish a more abundant seedling bank in grazed pasturelands. As stated by Westoby et al. (2002), the higher level of resources within bigger seeds probably increases the probability of successful seedling establishment in the presence of the environmental hazards that in active grasslands could be determined by low water and nutrient availability, high levels of grass competition and browsing damage (Zimmerman et al. 2000).

The longer dispersules, and bigger and heavier fruit, were also related to particular seed dispersal strategies, which probably increase the probability of seeds reaching safe sites, further increasing seedling establishment rates. Local fauna disperse smaller and more spherical seeds and fruits; wind disperses mainly the longer fruit with more elongated and lighter seeds; cattle disperse the more prominent and heavier fruit with heavier seeds (Esquivel 2013). In our research, we observed that woody plant species' regeneration abundance correlates with their main dispersal mode. Species dispersed by cattle (a particular kind of mammalochory) were the more abundant in the early developmental stages. Once consumed, cattle dung provides an enhanced microhabitat for seed germination and seedling establishment through a substrate that initially reduces grass competition and cattle damage through grazing and browsing and provides higher nutrient levels (Malo and Suárez 1995; Cosyns et al. 2005).

In contrast, those woody plant species with seeds mainly dispersed by wild fauna had lower abundance in the early developmental stages. These species tend to have more spherical, smaller and lighter dispersules. The highly fragmented woody habitat component of active pasturelands probably restricts wild fauna mobilization (Martello et al. 2023), restricting the seed rain to under tree canopies therefore limiting their relative abundance within these ecosystems as a whole (Esquivel and Calle 2002). Species dispersed by wild fauna like birds are more abundant below isolated trees in South American active pasturelands (Esquivel and Calle 2002). Species richness and abundance of seedlings below isolated trees can be three and five times higher than in open pasturelands respectively, particularly under the canopies of species dispersed by wild fauna (Esquivel and Calle 2002). Our results provide additional evidence of the relevance for biodiversity restoration in agricultural landscapes of placing woody elements in strategic locations within livestock areas such as live fences, scattered trees, riparian buffers and connectivity corridors (Montagnini et al. 2022).

Unless wind dispersed seeds can easily reach open pasture areas, this dispersal syndrome does not lead to higher abundance of woody plant species' natural regeneration in open and disturbed areas like active pasturelands. Species having morphological adaptations for dispersal of seeds by wind do not show higher abundance of either seedlings or saplings. Wind dispersed species in active pastures had lower seed masses than those dispersed by other vectors (Esquivel 2013). A lower seed size has been found in species with a high density of seeds per dispersule unit, which is associated with better colonization of ephemeral sites in space and time (Dalling et al. 1998; Moles et al. 2004; Moles and Westoby 2004a, b, c). Wind was probably a successful seed dispersal vector for seeds to reach the open pasturelands matrix, but successful establishment was restricted by dependency on reaching a successful microsite and growing quickly enough to avoid grass competition for light and water, which is much less likely with small seeds. Unless common wind-dispersed tree species like *Cordia alliodora* have sufficiently fast growth rates, it is probable that their further success in seedling and sapling establishment depends more on additional characteristics like defense against herbivore attack.

Appropriate strategies for rapid growth and resistance to and recovery from herbivore attacks are also required for woody plant species to increase their populations in active pasturelands together with an advantageous seed dispersal mode and high establishment rates. We found that SLA and LA were negatively correlated with both seedling and sapling abundances. The more abundant species have small but expensive leaves with a higher investment in carbon for their construction. Leaves with low SLA tend to be thick, dense, physically robust and less attractive to herbivores than leaves with a high SLA (Coley et al. 1985; Wright and Westoby 2002). Low-SLA leaves tend to be longer lived and may lead to longer plant lifespans (Sterck et al. 2006). Kitajima (1994) found that SLA was a good predictor of seedling growth and survival and Poorter and Bongers (2006) found that SLA was a good predictor of sapling height growth. Our results suggest, however, that SLA also has a key role in the survivorship of woody plant species at early developmental stages in active pasturelands, as species' seedling and sapling abundances increase consistently when SLA decreases. Tree and shrub species with a higher investment of biomass in producing their leaf area, may have had a good enough defense against herbivore attack and damage through cattle grazing and browsing.

Other leaf traits were also correlated with abundance in the two early development stages suggesting that these morphological characteristics can be important to increase woody plant species survival during natural regeneration in active pasturelands. LDMC was positively correlated with seedling and sapling abundance indicating a key role in enhancing establishment via defense against herbivory. Higher amounts of biomass invested in leaves probably enhances seedling and sapling defense against herbivores due to greater physical strength of leaves or due to reduced leaf palatability for consumers (Elger and Willby 2003). However, we didn't find a significant correlation between species' abundance and FTF to support this mechanism for the LDMC effect. While FTF measures leaf resistance to tearing, higher LDMC in leaves probably implies an increase of more recalcitrant C fractions like lignin, celluloses and hemicelluloses or other secondary metabolites that reduce leaf digestibility or palatability for cattle, so both traits may affect grazing palatability (Coley et al. 1985; Hanley and Lamont 2002).

Leaf carbon content (LCC) and LNC were both positively correlated only with seedling abundance, indicating that woody species with higher carbon and nitrogen content in leaves may have a particular benefit at the early developmental stage. LCC is positively correlated with defense against herbivore consumption and negatively with palatability as measured by the amount of structural carbon invested to construct one functional leaf and with leaf C/N-ratio (Schädler et al. 2003). Therefore, woody species with higher LCC probably experienced lower mortality rates due to herbivore attacks, allowing them to develop more abundant seedling populations. Unpalatable leaves have been found to have both low LNC and high leaf tensile strength, which depends on LDMC (Perez-Harguindeguy et al. 2000; Wardle et al. 2002). These traits are also linked to carbon-rich structural compounds and highly recalcitrant C fractions like lignin, which strengthen leaves significantly (Choong et al. 1992; Wright and Illius 1995) and determine leaf digestibility and litter decomposition (Swift et al. 1979; Melillo et al. 1982; Schädler et al. 2003; Cornelissen et al. 2004).

Contrary to the low palatability hypothesis, we found that LNC was also positively correlated with seedling abundance, indicating that other mechanisms linked to foliar nitrogen might contribute to development of seedling populations in active pastures. Higher LNC could be correlated with traits linked to more successful seed dispersal, germination and/or seedling establishment rates. Therefore, woody species that establish higher abundances of seedlings in active pasturelands, are likely to depend not only on the reduction of herbivore damage risk, but also other mechanisms evidenced by the correlations with other traits. In fact, as stated previously, seedling abundance was also positively correlated with H_max and dispersal traits, even more strongly than for sapling abundance, probably due to higher photosynthetic rates leading to higher growth rates allowing species to quickly escape from competition and herbivory. In addition, the establishment of high seedling abundance of woody plant species with higher LNC, as well as those with specific dispersal strategies like mammalochory, could benefit from additional advantages via cattle dung, which provide an enriched nutrient environment and physical defense against herbivores and grass competition. Both mechanisms contribute to the functional diversity of the woody plant community of active pasturelands.

Tree species with "high quality" leaves, e.g. high LNC, that are nonetheless well defended against herbivores, might have clear advantages in active pasturelands. Higher LNC has been related to higher photosynthetic rates in full sun exposure. In contrast, long-term shading of isolated plants generally results in leaves that have a lower photosynthetic capacity and nitrogen content per unit area, and a higher investment of total available nitrogen in chlorophyll and light-harvesting compounds (Evans 1996; Hikosaka and Terashima 1996; Evans and Poorter 2001). Apart from the decrease in leaf thickness, shading also causes a decrease in leaf density, the net result being a larger leaf area formed per unit of biomass invested in leaves (Poorter et al. 2005). Therefore, open pastureland the high sun exposure creates a favourable environment for woody species with high photosynthetic rates and low palatability. These characteristics could help to develop high rates of seedling establishment once they have been able to successfully overcome seed dispersal and germination barriers.

Other morphological characteristics were only correlated with the sapling stage of natural regeneration. Leaf phosphorus content (LPC) and Mass_see were plant traits marginally correlated with sapling abundance. Bigger seeds (by volume or mass) carry a greater investment of parental resources, which enables seedlings to grow quickly providing earlier escape from high mortality rates at early developmental stages. However, the lack of significant correlation between Mass_See and seedling abundance indicates the limits of the effect of this mechanism. Instead, the key mechanisms controlling seedling establishment and survival appear to be better linked to other morphological traits such as the negative correlations with LA, SLA and LPC but positive with LDMC, which may be associated with lower palatability, greater capacity to survive desiccation, and greater capacity to recover from damage. Interpretation of foliar nutrient content results must be treated with caution given the many factors that can influence this variable including maternal resources from the seed, environmental uptake or allocation within the plant (Pallardy 2008). Therefore, although there was a tendency for those woody plant species with more conservative leaf traits to have more abundant seedlings, the relationships of abundance with other traits indicate the value of further research to identify additional mechanisms that increase species' capacity to establish as seedlings and grow into saplings and then into mature trees or shrubs in the challenging environment of active pasturelands (Tuthill et al. 2023).

The management of the woody components of actively grazed pastures and live fences is common in silvopastoral systems in Central America (Harvey et al. 2007; Esquivel et al. 2023). This contrasts with the implementation of intensive SPS (iSPS) like forage-banks, which are usually restricted to particular localities and farms in this region, but are more frequent in South America (Murgueitio 2005). In typical dual-purpose livestock farmlands in both regions, many management activities directly affect the cover and composition of dispersed or scattered trees and shrubs in pastures and along fences (Esquivel and Calle 2002; Harvey et al. 2007; Esquivel et al. 2008). In the Mesoamerican region, for example in Costa Rica and Nicaragua, weeding activities and removal of saplings and seedlings can occur two to four times per year and, when it is carried out, sowing or enriching of the woody component of live fences can be done up to four times per year (Harvey et al. 2007). Farmer's decision-making varies according to socio-economic factors like economic resources, time and workforce availability, demand for wood for fuel, construction or other uses, and particular incentives like payments for environmental services (Pagiola et al. 2005; Harvey et al. 2007). Therefore, knowledge about woody species' natural regeneration capacity can inform farmers and technicians' decision-making about the valuable species that are a priority for active promotion of regeneration, specifically those with traits associated with limited capacity for natural regeneration (e.g., small fruit and seeds dispersed by wild animals). Such active intervention can increase the population size of these valuable species at early development stages. The result will be an improvement in the biodiversity and economic value of the extensive silvopastoral land use system, promoting multifunctionality across Mesoamerican agricultural landscapes.

14.5 Conclusions

Woody plant species' capacity to regenerate naturally in active pasturelands relates to four main plant trait dimensions, namely: reproductive, leaf, maximum height and wood density. The natural regeneration of species in actively grazed pasturelands within silvopastoral systems with dispersed trees was dominated by taller tree and shrub species, with greater investments in both leaf construction and dispersules (fruits and seed), with the latter associated with dispersal by cattle. More specifically, taller species and those with small and more conservative leaves (low LA and SLA, and high LDMC and LCC) and with expensive (big, heavy) and longer fruits containing big and long seeds dispersed by cattle were more abundant as both seedlings and saplings. Species with fruit and seed characteristics associated with dispersal by wild animal species were notably less successful at natural regeneration in active pasturelands.

Woody plant species with higher leaf carbon and nitrogen contents were more abundant as seedlings, potentially linked to the importance of these traits for early establishment, but they were not significantly correlated with abundance at the later sapling development stage. In contrast, woody plant species with conservative traits of denser wood and low foliar phosphorus were notably more abundant as sapling populations, which may be related to their greater resistance to the impacts of cattle browsing.

The benefits resulting from the higher biodiversity of SPS with dispersed trees in contrast to conventional grassland monocultures are clear and widely documented.

However, the results presented in this study indicate that, under actual management practices, the functional diversity of woody plant species may decrease in active pasturelands with dispersed trees through failure of dispersal, establishment or survival of certain functional species groups. As well as the potential negative consequences for biodiversity in the future, this may also restrict the capacity of the woody component of these ecosystems to contribute to the sustainability of production and delivery of other ecosystem services within this land use system covering a high proportion of Mesoamerica.

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Chapter 15
Sexual Reproduction in *Tithonia diversifolia* and the Implications for Its Use in Intensive Silvopastoral Systems

Rocío Santos-Gally

Abstract Intensive Silvopastoral Systems (ISPS) in Latin America represent a sustainable alternative to intensive livestock production as part of nature-based solutions to reduce climate change, increase the economic value of the livestock enterprise and thus provide better living standards to small-scale producers. The intentional integration of different vegetation strata (grass, herbaceous, shrubs, palms and trees) and livestock with intensive management promotes an increase in available forage biomass, improves soil quality, fosters a greater diversity of organisms and biological interactions and improves animal welfare. The use of *Tithonia diversifolia* in animal production in Latin America and the Caribbean has increased in recent years as it represents an alternative protein-rich forage for livestock, while also providing a source rich in nectar and pollen for insects and increasing cattle rancher's income as a result of higher productivity. The propagation of *T. diversifolia* has usually been carried out in a vegetative way, which results in higher implementation costs, reduces the genetic variability of crops and produces plants with weaker and more superficial roots. Reproduction via seeds would optimize its implementation in ISPS, which highlights the importance of identifying the viability of seeds from crosses between different individuals (outcross-pollination) or within the same individual (self-pollination). The aim of this work was to measure differences in the proportion of fruits/seeds produced from different hand-pollination experiments. In addition, I quantified the visitation rate of flower visitors as an indicator of potential pollinators. The results indicate that *T. diversifolia* is a self-incompatible species and requires the presence of pollinators, which ensure efficient pollen transfer among plants (allogamous), for its reproduction. The studied population was visited by 46 morphospecies of insects, one of which is classified as vulnerable in the red list of species. I conclude that to acquire a higher percentage of viable seeds for implementation in ISPS, the presence of genetically distinct individuals and the presence of pollinators is essential. I highlight the importance of this species as a source of nectar and pollen for pollinating insects, as well as increasing

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spatial heterogeneity, which could help to mitigate the current decline in insect populations.

Keywords Asteraceae · Hand-pollinations · Incompatibility system · Nature-based solutions · Pollinators · Sustainable livestock

15.1 Introduction

Cattle raising is a very old human activity that began with the domestication of sheep and goats in the Neolithic. Its importance has been captured since ancient times in Egyptian hieroglyphs dating back to 4500 years BC (Fig. 15.1). Livestock production is considered, along with agriculture, the first great economic revolution in history, as it represented an important step towards a sedentary lifestyle, as well as a vital source of protein (milk and meat), with a consequent growth in human populations (Renfrew and Bahn 1993). Mediterranean Dehesa or Montado, provide examples of livestock production where human interventions in ecosystems can be sustainable over time, with some of these sites dating from ca. 4500–3300 BC (Garrido et al. 2017; Ferraz-de-Oliveira et al. 2016). These semi-natural ecosystems (according to the legal context of the European Union) are characterized by complex biotic interactions and an appropriate balance between tree cover and different, complementary uses in the understory (i.e., between forest and agricultural uses), as well as grazing by different types of animals (cattle, sheep, goats and pigs) (Fig. 15.1). This ancient socio-ecological system involves various tangible material values, such as access to wild products (acorns, chestnuts, almonds, olives, cork, edible mushrooms, wood) or agro-tourism. Dehesas are an example that illustrates how livestock breeding can be done under the protection of trees while maintaining higher biodiversity compared with extensive cattle ranching. Indeed, Dehesas serve as a model ecosystem in ecological restoration (Gann et al. 2019).

In contrast, the tropics of America continue to lose forests at alarming rates. For example, wet and dry forest have been lost at a rate of between 3.8 (Achard et al. 2014) and 4.88 (Baccini et al. 2012) million ha/year, with a mean annual deforestation rate of 0.49% (Achard et al. 2014). This pressure on ecosystems is exerted in part due to conventional cattle ranching practices, which are developed in extensive areas of pasture without tree cover (Herrero et al. 2016), subjected to continuous overgrazing of low protein forages with low digestibility (Herrero et al. 2013). All this contributes to low stocking rates (± 0.6 Animal Units ha^{-1}), which means that tropical livestock production registers poor levels of productivity and competitiveness (González et al. 2015). Under such conditions, large areas of forest are continuously converted to new grasslands when pastures become unproductive due to soil erosion as a result of overgrazing, little moisture retention, and high temperatures due to lack of shade. Another factor that contributes to land transformation in the

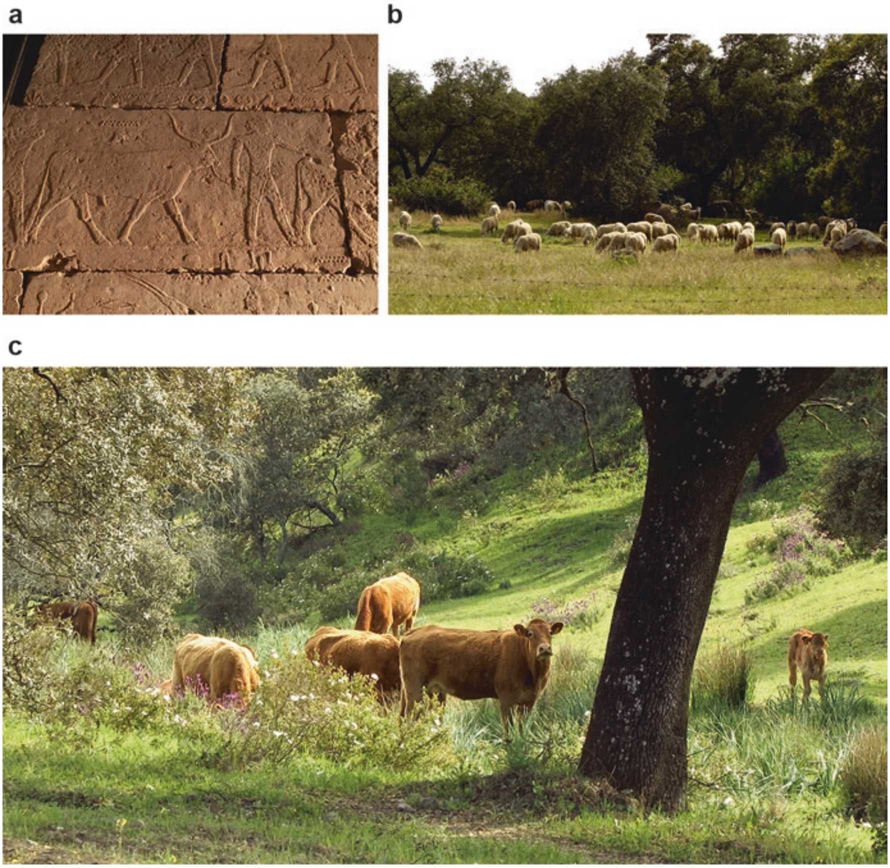

Fig. 15.1 (**a**) Domestication of cattle represented in an Egyptian Hieroglyph approximately 4500 BC. (**b**, **c**) Spanish Dehesa with *Quercus ilex*, *Q. suber* as tree strata and different shrubs and pastures as understory strata for the production of sheep (merino breed) and cattle (retinto x limousine). (Photos R. Santos-Gally)

tropics is the booming trade in feed for meat production. For example, meat, compared to other products of the European basic basket, contributes to more than 50% of the transformation of land for feed production (Crenna et al. 2019; Ministerio de Consumo/EC-JRC 2022; EC-JRC 2022). Cattle ranching conducted in this way has been recognized as one of the main contributors to global environmental problems, including deforestation, climate change and biodiversity loss (Herrero and Thornton 2013).

Driven by the growing demand for animal protein (Valin et al. 2014), the growth of the human population, and the increase in per capita income (Alexandratos and Bruinsma 2012), Latin America and the Caribbean lost approximately 2.8 million ha year^{-1} of forest cover between 2010 and 2018 (FRA 2020 RSS). If the trend in animal protein consumption continues, by 2050 a total of 517 million heads of cattle and buffalo are expected in the American tropics (Alexandratos and Bruinsma 2012). In such scenario, silvopastoral systems (SPS) are a necessary and sustainable alternative to increase the profitability of livestock production, freeing areas not suitable for livestock production for restoration, and thus allowing to protect some of the great biodiversity accumulated in the tropics.

Silvopastoral systems consist of a well-designed combination of different vegetation strata such as grasses, herbs, shrubs, trees and/or palms. The combination of these different vegetation strata promotes a more efficient use of solar energy in the conversion of food biomass, which can also add nutrients to the soil through the decomposition of leaves, the filtration of water by roots, climate buffering, among others (Ríos et al. 2007; Murgueito et al. 2013). This process of changing conventional agricultural practices (i.e. pasture monoculture), including a reduced dependence from external inputs (i.e. agrochemicals, food supplements) as well as the diversification of multipurpose species, can be considered a component within the "solutions based on nature". The tree cover favors the thermoregulation of cattle which, together with a better diet, translates into an improvement in milk and/or meat production, and in decreased methane emissions due to better health of the cattle, as a consequence of a more balanced diet and a less stressful environment (Broom et al. 2013; Calle et al. 2012; Chará et al. 2019). A silvopastoral system consisting of restoration plots of the native vegetation (e.g. in riverside and areas with slope not suitable for cattle ranching) and pastures enriched with forage trees would allow to increase plant cover, carbon fixation, as well as the reestablishment of ecological evolutionary processes and of the ecosystem services characteristic of the humid tropical forest of the region. The establishment of SPS would result in greater human well-being, both directly (increased production of food, wood of commercial value, food for livestock) and indirectly (improvement in ecosystem services such as biological control of pests, zoonotic disease outbreaks, crop pollination, regulation of water flow, reduction of soil erosion and protection from winds) (Fig. 15.2). Therefore, SPS constitute actions to protect, sustainably manage, and restore natural or modified ecosystems, addressing societal challenges (i.e. climate change, food and water security) effectively and adaptively, while providing human well-being and biodiversity benefits (Cohen-Shacham et al. 2016). SPS as nature-based solutions support sustainable socioeconomic development (Maes and Jacobs 2017), providing more productive and diverse agroforestry arrangements that provide animal welfare, contributing to climate change mitigation (Murgueitio et al. 2011).

In particular, intensive silvopastoral systems (ISPS) represent innovative "solutions" consisting of the arrangement of different vegetation strata (see SPS above) and where the stratum of high-protein forage plants (high N and P content) is planted in high densities within the paddocks. These plants are used for direct browsing by cattle, which considerably improves their protein intake. The use of electric fences for cattle rotation and permanent access to water within the paddocks is also important. The species currently used for the shrub strata within ISPS in Latin America and the Caribbean are *Leucaena leucocephala*, *Tithonia diversifolia* and *Guazuma ulmifolia* (Murgueitio et al. 2015). Planted at high densities (between 10,000 and

Fig. 15.2 Ecosystem services produced in Silvopastoral Systems. (Design and Photos by R. Santos-Gally)

40,000 ha^{-1}) within pastures, *L. leucocephala* facilitates high nitrogen fixation and transfer, while *T. diversifolia* favors the solubilization of phosphorus in acid soils, thus benefiting associated grasses (Ojeniyi et al. 2012; González 2013; Bacab et al. 2013). In ISPS, cattle feed better thanks to efficient and quality grazing on protein-rich forage. Animals suffer less heat stress, since the temperature in wooded paddocks can drop between 4 and 8 °C compared with open pasture areas, and the distances needed to access water or food are reduced through the presence of mobile drinkers and more biomass fodder. These arrangements in ISPS can result in an increase of five to ten times the amount of meat production, and up to an additional 80% in the volume of milk produced compared to conventional pastures (Thornton and Herrero 2010; González 2013; Bacab et al. 2013; Sanchez-Santana et al. 2018; Chará et al. 2019; Murgueitio et al. 2019). In addition, intensive livestock rotation results in an increase in stocking rate per ha that is four to five times higher than what is achieved in extensive livestock farming (Murgueitio et al. 2019). Expenditures on external inputs, such as fertilizers, can be reduced to zero due to the higher nitrogen fixation and other nutrients provided by forage shrubs (González

2013; Murgueitio et al. 2019). Forage biomass is also increased by up to 47% compared to that of a pasture monoculture, thus reducing the need for feed supplementation by more than half (González 2013; Calle et al. 2012). The multiple benefits that high-protein forage species provide to ISPS show the importance of ongoing agronomic and reproductive biology research.

15.2 Relevant Aspects of the Use of *Tithonia diversifolia*

Tithonia diversifolia has been introduced and propagated in most continents, mainly for ornamental use, green manure, erosion control and beekeeping. More recently, its use has increased as a forage species because of its high-protein content, with up to 28.8% of crude protein in its leaves and high content of P. In addition, it is suitable for different types of livestock (sheep, goats, pigs, cattle), has a wide edapho-climatic adaptation and it regenerates acid soils (Calle and Murgueitio 2008; Mauricio et al. 2017). The reproduction of *T. diversifolia* in ISPS has been carried out mostly vegetatively, because the sowing of seeds resulted in low germination (Zapata Cadavid and Silva Tapasco 2016). However, different studies have shown low germination in seeds that were not stored and sown 15 days after collection, while those sown 4 months after being stored at room temperature (19 °C) had significantly higher germination success, greater than 90% (Santos-Gally et al. 2020). With these results, it has been possible to determine the presence of dormancy in *T. diversifolia* (Muoghalu and Chuba 2005; Wen 2015; Santos-Gally et al. 2020, but see Rodríguez et al. 2019, for a different view) and a likely explanation for the differences in reported germination success (Ruiz et al. 2018). However, seed dormancy might not be the only explanation for the observed variance in germination success, which could also be related to sexual reproduction, that is, the production of viable seeds after fertilization.

Sexual reproduction is important because it implies the transmission of genes from one generation to another and the combination of genes from different parentals. In hermaphroditic plants (presence of both sexes in the same individual) it can be carried out by selfing or by outcrossing (Barrett 2014). Two opposing forces determine the evolution of the first, the advantage of transmitting 50% of self-compatible genes and inbreeding depression. Inbreeding depression refers to the reduction in viability and/or fertility of offspring derived from selfing compared to offspring produced by interbreeding between genetically different individuals. Selfing provides reproductive assurance, especially in ecological situations where the number of possible mates is scarce (in a colonization process or bottleneck), or where there is a scarcity of pollinators (poor dispersion of pollen grains) (Jarne and Charlesworth 1993). Crossing between genetically distinct individuals (outcrossing) provides offspring with a different genetic load than the parents, that is, a new combination of alleles that may be beneficial in adaptation to changing conditions (Linhart and Grant 1996).

In flowering plants different strategies promote cross-pollination. Spatial (herkogamy) or temporal (dicogamy) separation of the sexual organs reduces the probability of self-pollination. The self-incompatibility system is another mechanism that prevents self-fertilization and is one of the most widespread in angiosperms (Barrett 2014). A self-incompatibility system combines physiological, genetic (diallelic), sporophytic and biochemical mechanisms to avoid selfing, thereby promoting exclusive fertilizations if pollen is successfully transferred between mates (Takayama and Isogai 2005). In allogamous species, the production of viable seeds would be determined by the transfer of pollen between genetically different mates. Determining the production of seeds by self or cross pollination allows us to determine the presence of an incompatibility system. Because the importance of *T. diversifolia* for the implementation of ISPS through seeds, in this study we analyzed the proportion of flowers (namely florets in Asteraceae) that became fruits through different pollination treatments, specifically comparing the success of self-fertilization with that of outcrosses, to determine if *T. diversifolia* presents a self-incompatibility system.

15.3 Incompatibility System and Pollinators in *Tithonia diversifolia*

15.3.1 Study Species

Tithonia diversifolia (Hemsley) A. Gray is a perennial colonizing species in the Asteraceae family (La Duke 1982). It occurs naturally from tropical Mexico to Central America. The species is frequently found within different ecosystems, mainly in tropical humid forests, semi-deciduous forests, and oak-pine forests. It is commonly found along light gaps, roadsides and anthropized places. It grows in different types of soils (clay, sand, silt) from 0 to 2500 masl. Inflorescence (capitulum) has an average of 12.4 (± 0.38) ray sterile ligulate florets and 127.6 (± 3.64) central fertile tubular florets. Each hermaphroditic floret has stamens adnate to the base of the corolla tube, free filaments, and fused anthers protruding from the apex of the corolla. The anthers dehisce before the style protrudes the anthers, so it is likely that the species presents protandry (pollen maturation precedes stigma maturation). Each capitulum produces two types of achenes, central ones with fused squamellae pappus, subequal awns and pubescent pericarp and ray glabrous achenes without awns (Santos-Gally et al. 2020). Interestingly, the proportion of these two morphotypes varies between populations (Santos-Gally 2023), and so does their dormancy. In general, awned achenes germinate faster and to a greater extent than ray achenes (Santos-Gally et al. 2020). Dormancy is also reported in Africa and Asia (Muoghalu and Chuba 2005; Wen 2015), where the species has been widely used as an ornamental plant or for soil recovery.

15.3.2 Field Sampling and Study Site

Seeds were collected from a population composed of approximately 200 individuals, near Catemaco, Veracruz in southern Mexico. Heads were harvested from several plants. The seeds of each individual were separated and labeled. The average distance between sampled plants was more than 10 m, to reduce the probability of sampling related individuals. The seeds were stored for 4 months in dry conditions at room temperature (15–20 °C). Seeds were germinated on the surface of the soil in trays with a lid (20 × 15 cm) and commercial soil (a combination of oak leaves, peat and vermiculite) and then transplanted to a greenhouse until plants reached a height of 30 cm. In July 2019, 50 plants from 50 different individuals were transplanted to an experimental plot (10 × 10 m^2), approximately 20 km from the site where seeds were collected. The site where seeds were planted is found within a tropical lowland moist forest with an average rainfall of 2000–4000 mm and an annual mean temperature of 24 °C (Gutierrez-García and Ricker 2011). Plants were sown at a distance of 2 m. In March 2020 manual pollination treatments were carried out to determine the incompatibility system of the species.

15.3.3 Hand-Pollination Experiments

Hand-pollination was performed in the field to determine whether *T. diversifolia* presents an incompatibility system. I applied two hand-pollination treatments to 6519 florets from 29 individuals: self-pollination and cross-pollination, and 12,254 florets from 29 and 9 individuals for control and autonomous self-pollination, respectively. Florets for the cross-pollination treatments were emasculated before anthers dehisced. I randomly assigned each of the four treatments to four capitula at different positions in the plant. The number of replicates per treatment was balanced across individuals, except for autonomous self-pollination where only nine individuals were used (as in Hernandez-Marquez et al. 2022).

Capitula were marked and bagged with exclusion nets (0.1 mm pore size) avoiding possible contamination by pollen from other individuals. I performed hand-pollinations daily for 3 days on bagged capitula with pollen from a random donor to perform cross-pollinations, which consisted of transferring pollen to all open florets within the capitulum. Self-pollination involved no emasculated florets, which were hand-pollinated using pollen obtained from the same floret. In both treatments floret buds surrounding the pollinated florets were removed, to avoid confusion when collecting the achenes. Open-pollinated control involved capitula tagged with florets that opened on the days preceding the experiment or while it was taking place, and these florets remained available to visitors throughout the experiment. With the fruit/seeds produced by these capitula, I can determine if there is pollen limitation in the population or if manual pollinations were effective, which would be indicated by a lack of significant differences between cross and controls. Finally, a total of 25 capitula were bagged to determine if the plants can produce fruits through unmanipulated (automatic) self-pollination. Fruits were harvested 3–4 weeks after pollination, at which point I counted the number of achenes with seed and aborted seed (empty achene). I used a beta regression model with binomial distribution and logit link functions to test the effect of different treatments on the fruit set (florets to achene number). I included treatment as a categorical explanatory variable. For both analyses, I used the package betareg (Simas and Rocha 2006) in (R Team 2018). The ratio of the averages of self- and cross-pollination treatments was used to measure the self-compatibility index proposed by Becerra and Lloyd (1992), indicating self-incompatibility when values are equal to or lower than 0.75.

15.3.4 Pollinators

Pollinator censuses were carried out in the same plot as the pollination experiment. The site is within the region where the species occurs naturally and the observations of insect visitation were during the flowering peak in the experimental plot and for three consecutive days in March 2020. Diurnal observations were recorded for a total of 14 h^{-1} of diurnal pollinator censuses. Observation periods of 5-min were initiated at 10.00 h and continued until 18.00 h, when diurnal pollinator visitation declined markedly. Observers were rotated randomly among plots, changing every 5 min. For each flower capitulum, observers recorded the visiting species and if visits were legitimate (e.g. the body of the visitor came in contact with anthers and/or stigma) (as in Hernandez-Marquez et al. 2022). The number of flower heads observed was also recorded for each observation bout. To identify the most representative pollinators, three people captured specimens on the third day of observations during the peak of activity and individuals were later identified in the laboratory. I calculated the visitation rate (number of visits per 5 min) by the number of capitula in the plot and the importance value of the pollinator based on the visitation rate per capitulum.

I identified the five primary functional groups: bees, butterflies, flies, beetles, and bugs. Each group presents distinct taxonomic, morphological, and behavioral characteristics. Using these functional groups and their visitation rate, a pollinator importance value was calculated, to define whether the pollination system was specialist or generalist. Each visit was counted if the pollinator contacted the sexual organs (Hernandez-Marquez et al. 2022). Although this measure does not include quantification of pollen removed and/or deposited on stigmas, it can be used as a proxy for pollinator efficiency (Armbruster and Herzig 1984). An index to compare the importance of functional groups was obtained from Martén-Rodríguez et al. (2009). I standardized each value by dividing by the sum of the importance values of all functional groups of pollinators. The range of the index is from 0 to 1. Following Fenster et al. (2004) and Martén-Rodríguez et al. (2009), I considered the pollination system of *T. diversifolia* as specialized when the importance index of the primary pollinator functional group was higher than 75% and generalized when none of the functional groups of pollinators had importance values equal or higher than 75%. Due to the presence of the non-native species *Apis mellifera*, I calculated the importance index of the functional group with and without this species, to determine a possible effect of the bee on the index.

15.4 Results

15.4.1 Hand-Pollination Experiments

The proportion of florets converted to fruits differed significantly between treatments (Table 15.1). Autonomous and self-pollination showed significantly lower success compared with cross and control pollination ($P < 0.0001$). The mean proportion of fruits produced by cross-pollinations was 65.31%, whereas for self-pollination it was 36.2%, while for autonomous self-pollination it was 2% (Fig. 15.3). Under natural conditions (control treatment) I found that the proportion of florets was 74.72% and there was a non-significant difference with cross-pollination treatment ($P = 0.85$).

The value of the Self Compatibility Index was lower than 0.75 (SCI = 0.55) indicating that the species present a self-incompatible system.

15.4.2 Visitation Rate of Pollinators

A total of 895 insect pollinator visits were observed across 14.0 h of observations in March 2020. A total of 46 morphospecies were observed visiting the flowers of *T. diversifolia*. (Diptera, 15 spp.; Lepidoptera, 12 spp.; Hymenoptera, 11 spp.; Hemiptera, 6 sp.; Coleoptera, 2 spp). *Apis mellifera*, native bees and butterflies were the most abundant pollinators (Table 15.2). Based on these observations, I consider that *Tithonia diversifolia* presents a generalist pollination system, where all functional groups of pollinators presented importance indices <75%. Importance values were (in descending order) 32.5% for Hymenoptera (with *A. mellifera* 90%), 31.7% for Lepidoptera, 18.7% for Diptera, 15.4% for Hemiptera and 1.6% for Coleoptera.

Table 15.1 Beta regression model results of the effect of treatment on fruit-set following self-pollination, outcross-pollination, control (intercept), and autonomous self-pollination on *Tithonia diversifolia*

	Estimate	S.E.	z	*p*
Intercept	0.80	0.12	6.88	<0.000
Autonomous self-pollination	−3.55	0.255	−13.89	<0.000
Cross-pollination	0.03	0.18	0.191	0.85
Self-pollination	−1.64	0.166	−9.89	<0.000

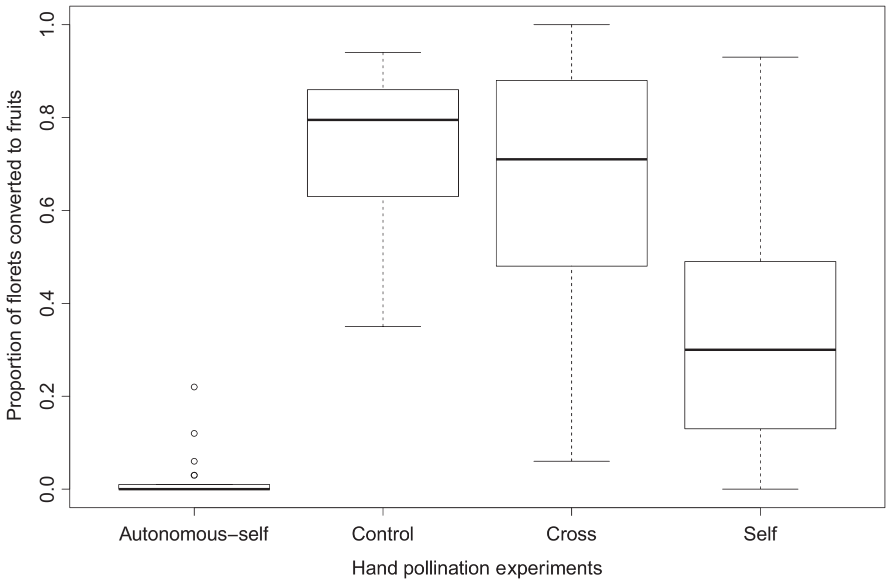

Fig. 15.3 The box plot shows the median for the fruit-set of four hand-pollination treatments conducted in *Tithonia diversifolia*, as well as the lower (Q1) and upper (Q3) quartiles, representing measures within the 9–95 percentile range

Table 15.2 Total number of pollinators that visited *Tithonia diversifolia* inflorescence

Order	Species name	Total number of visits/5 min/ Number of flowers
Short-tongued insect:		
Coleoptera		
	Coleoptera sp. 1	0.2
	Coleoptera sp. 2	0.2
Diptera		
	Muscidae sp. 1	0.4
	Muscidae sp. 2	0.2
	Muscidae sp. 3	0.2
	Muscidae sp. 4	0.2
	Muscidae sp. 5	0.2
	Muscidae sp. 6	0.2
	Syrphidae sp. 1	0.4
	Syrphidae sp. 2	0.6
	Syrphidae sp. 3	0.4
	Syrphidae sp. 4	0.2
	Syrphidae sp. 5	0.2
	Syrphidae sp. 6	0.4
	Syrphidae sp. 7	0.4
	Syrphidae sp. 8	0.4
	Eristalis sp. 1	0.4

(continued)

Table 15.2 (continued)

Order	Species name	Total number of visits/5 min/ Number of flowers
Hemiptera		
	sp. 1	2.6
	sp. 2	0.2
	sp. 3	0.2
	sp. 4	0.2
	sp. 5	0.2
	sp. 6	0.4
Hymenoptera		
	Apis mellifera	154.2
	Scaptotrigona sp.	0.4
	Bombus medius	5.6
	Exomalopsis sp.	0.2
	Apidae sp.	0.2
	Lasioglossum sp.	0.2
	Augochlora sp.	0.2
	Scoliidae sp.	0.4
	Vespidae sp. 1	0.2
	Vespidae sp. 2	0.4
	Vespidae sp. 3	0.2
Long-tongued insects:		
Lepidoptera		
	Urbanus sp.	4.2
	sp. 1	0.2
	sp. 2	0.2
	sp. 3	0.2
	sp. 4	0.4
	sp. 5	1.4
	sp. 6	0.2
	sp. 7	0.2
	sp. 8	0.2
	sp. 9	0.2
	sp. 10	0.2
	sp. 11	0.2

15.5 Implications of *Tithonia diversifolia* Reproductive System in the Implementation of ISPS

The results from the studied population indicate that *Tithonia diversifolia* is self-incompatible, although the self-incompatibility system is not perfect and there is moderate self-compatibility. Self-compatibility varies continuously, with some plants more self-fertile than others (Fig. 15.3), and thus such variation might also be present among populations of the same species (Cheptou et al. 2000). Because *T. diversifolia* is a good colonizer, commonly found in disturbed remnants of forest vegetation or roadsides, a plausible explanation for the transition from outcrossing to selfing would be the advantage of selfing individuals over outcrossing ones when mates or pollinators are scarce, known as the reproductive assurance hypothesis (Stebbins 1957). The autonomous self-pollination treatment resulted in seed production of less than 2%, indicating that *T. diversifolia* requires the presence of pollinators to carry out fertilization. What implications do these results have for the establishment of *T. diversifolia* in ISPS?

The presence of a self-incompatible system highlights the importance of having genetically different individuals to obtain the largest number of seeds. If we choose to establish a plot of *T. diversifolia* plants to obtain seeds, it is highly advisable to obtain seeds from a natural population that is as large as possible and choose seeds from individuals that are between 10 and 15 m away, with the purpose of favoring genets. It is also important to avoid collecting seeds from nearby individuals, so as to maximize the diversity of parental individuals for sexual reproduction and seed production and minimize the effects of inbreeding depression. Although in this specific study I did not analyze the presence of inbreeding depression, in self-incompatible species (e.g. *Raphanus sativus* and *Leontodon autumnalis*) there is evidence of a decrease in seed production in plants that are produced from self-pollination (Nason and Ellstrand 1995; Picó and Koubek 2003). Plants from crosses between relatives may present negative effects from reduced genetic variation, which can be expressed in reduced seed production, germination or growth (Cheptou et al. 2000).

Given the interest in *T. diversifolia* as a species with high forage potential, the results of this experiment suggest that care must be taken when establishing intensive forage shrub lines, to avoid negative effects due to inbreeding given that the success of seed production via selfing although low is not null. Vegetative reproduction is likely to result in a loss of genetic variability which could have undesired effects on growth and seed production. It is important in the future to investigate if decreased genetic variability could also impact forage quality. The pollination study indicates that the production of seeds via outcrossing, or through natural pollination, is more than 50% higher than through selfing, therefore the seeds that come from natural populations within the studied region can be used for future ISPS establishment. These results also highlight the importance of natural pollinators for seed production and successful reproduction.

Nectar and pollen production in ISPS is of crucial importance in the current pollinator decline. This crisis is reflected in the decrease in the number of pollinating insects (both wild bees and honey producers), which produce a significant amount of the foods consumed by humans because of their pollination services. In 2005, the annual contribution of pollinating insects to agriculture was estimated at US$153 billion (Gallai et al. 2009). The decline of insects can lead to a crisis in food production that would lead to an economic and environmental crisis. It is estimated that 87% of all plants on the planet depend on pollination for fruit production (Ollerton et al. 2011). *T. diversifolia* is a generalist species that contribute with nectar and pollen for 46 species in the studied population. Although an exotic bee (*A. mellifera*) was the most frequent visitor, in a hypothetical absence of this species, the second insect with the highest visit rate was *Bombus medius*, a native species registered as threatened according to the IUCN.

Although honeybees (*Apis melifera*) are not the only or most important insect that contributes to the production of fruits, it is true that they provide us with another very important food, which is honey. In Mexico, deforestation due to changes in land use has contributed to the reduction of food resources for honeybees. Currently, the purchase of sugar to feed bees to compensate the scarcity of natural food sources increase production costs thus reducing the profitability of beekeeping (Magaña and Leyva 2011). In addition to sugars, nectar contains amino acids, vitamins and minerals that are essential for bee health. In this sense, the ISPS through the trees and shrubs within the paddocks, become refuge sites and feeding areas for pollinating insects.

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Chapter 16
Silvopastoral Systems with *Leucaena leucocephala* and *Tithonia diversifolia* in Cuba

Tomás Elías Ruiz Vázquez

Abstract This chapter presents the main results of the research carried out in Cuba with *Leucaena leucocephala* and *Tithonia diversifolia*, and the main recommendations for their use in the livestock sector. The technology developed for *Leucaena leucocephala* during the 1980s and part of the 1990s for the use of this arboreal legume was transferred to producers since the mid-1990s. In that decade, a National Program was developed for the introduction of silvopastoral systems with *Leucaena leucocephala* in the livestock sector. Studies with *Tithonia diversifolia* began in 2006 and are still being developed based on materials (ecotypes) collected in the country. As a result of this process new technologies are available for its use in grazing or cut and carry systems both for ruminants and monogastrics. Starting in 2015, a National Program has been running in the productive sector for the use of protein plants in animal feeding, including *Tithonia diversifolia*. This review details the establishment, nutritional quality and management practices to optimize plant and animal production with this shrub and describes its impact on the environment and animal health. Finally, the factors that limited the adoption of these plants and expectations for the future are described.

Keywords Agronomy, Nutritional evaluation · Digestive physiology · Ruminants · Monogastrics

16.1 Introduction

Silvopastoral systems practiced in various regions of the world offer a large number of ecological and economic benefits (Jose 2019). Most studies have shown that silvopastoral systems generate increased forage and animal productivity (Jose and Dollinger 2019).

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In various areas of our continent, there is available information for the implementation of silvopastoral systems (SPS) on a commercial scale (Ruiz et al. 2003; Murgueitio et al. 2015). However, despite the overwhelming evidence of high productivity, profitability and sustainability of feeding ruminants with Leucaena, adoption has been relatively low (Mahecha 2003; Chará et al. 2019).

The barriers identified for the adoption of SPS with Leucaena are related to the high level of investment required for its establishment, the lack of support elements such as plant nurseries and skilled labor and the higher complexity of its management (Peri et al. 2019; FAO 2018; Ruiz et al. 1996; Mahecha 2003).

The information presented below is the product of the compilation of the main research carried out by an important group of leading scientists in the use of shrub plants in Cuba that allowed the development of a technological proposal and the definition of guidelines for their establishment and management in grazing systems.

16.2 Leucaena

Work with *Leucaena leucocephala* began in the 1970s and it was the pioneer species in the beginning of research with shrubs at the Institute of Animal Science (ICA) and the Experimental Station of Pastures and Forages "Indio Hatuey" (EEPFIH) in Cuba. The first articles on this species began to be published in 1985, although most of them were published between 1990 and 2009.

16.2.1 Evaluation of Ecotypes and Varieties

The genetic study of forage species in Cuba, either by the classical way or through biotechnology, has not had an appreciable development for leguminous species, much less for tree species (Febles and Ruiz 2012). The general breeding strategy has been based mainly on the introduction and evaluation of plants. An example of this is a study conducted at EEPFIH with the varieties CNIA-250, Cunningham, Peru and Ipil Ipil (Machado et al. 2006). The first three were evaluated for productive purposes, and the last one for inclusion in forestry areas. According to the studies carried out, these varieties adapt to a wide range of soils, including those of low fertility, with tolerance to alkalinity and salinity, but not to prolonged waterlogging (Machado et al. 2006).

The evaluation of a group of 90 ecotypes and varieties of *Leucaena leucocephala*, from the International Center for Tropical Agriculture (CIAT), carried out by Ruiz and Febles (2006) showed the possibility of grouping them according to their productive purposes, in addition to their capacity to produce seed. Forty-six percent of the ecotypes showed desirable characteristics for forage production, 35% for grazing and 16% for timber. For forage production, CIAT ecotypes 7415, 9421, 18477, 17223, 9379 and 9437 are recommended. The ecotypes 7488, 7356, 8815, 7965, Peru and 937 stood out for grazing. Analysis of the chemical constituents of 11 of these ecotypes and Leucaena varieties indicated crude protein (CP) levels of 18.7–24.7% as well as different levels of mimosine and 3-hydroxy-4-pyridone (DHP) that varied among cultivars and times of the year (La 2001). The grouping according to multivariate analysis made it possible to classify them into four groups according to their metabolites, which allows a better selection for their use in livestock farming. "*In situ*" degradability studies of dry matter (DM) and neutral detergent fiber (NDF) of these ecotypes showed levels of 65–80% and 52–70%, respectively, after 72 hours of ruminal fermentation. Ecotypes 17489, 9904 and 1774 had DM degradability above 80%. Mimosine was higher than 3% in the rainy season and lower than 2.5% in the dry season. In both seasons, total condensed tannins were less than 2.5% of DM.

This result made it possible to have a greater diversity of ecotypes and varieties to expand the use of this legume. In addition, an original, simple and practical methodology for tree evaluation was developed.

16.2.2 Seed Production

Research on the production of tropical tree legume seeds is relatively limited worldwide, and this is even more critical in Latin American countries. This hinders the possibility of obtaining quality seeds for productive purposes (Febles et al. 2012).

In studies developed with some of the varieties, it was found that 1868, 449 and 734 kg per ha were obtained for the Cunningham, Peru and CNIA varieties, respectively, with a germination of 57–90% (Pérez et al. 2006). Another group of 90 ecotypes of this species from CIAT yielded over 120 kg ha^{-1}. The outstanding ecotypes were Peru, CIAT 8069, CIAT 7452, CIAT 18480, CIAT 18475, and CIAT 7987. In addition, with Playa Rosario and Campina Grande varieties, it was possible to harvest between 400 and 500 kg of seed per ha (Febles et al. 1991).

One of the fundamental practices developed in Cuba for the production of *L. leucocephala* seeds is the pruning of the plants. According to Pérez et al. (2006) for the Peru variety, pruning is recommended every two years in June in order to achieve yields of approximately 900 kg of seed per ha. In the Cunningham variety, the highest yield (3000 kg ha^{-1}) is achieved by pruning every two years in December. Thanks to pruning, greater crop recovery is achieved, seeds can be collected in two harvesting periods and plant height is reduced, which facilitates the harvesting process.

It should be noted, as a contribution to knowledge, that recently harvested seeds can be stored under environmental conditions for up to 2 years using zeolite with a particle size <1 mm at a rate of 50 g per kg of seed (Febles and Ruiz 2006). When there is dormancy due to hard covers, seeds can be immersed in water at a temperature of 80–85 °C or higher for 2–3 minutes. With this method, a germination of 78–90% can be obtained when stored at 8° ± 2 °C when stored at room temperature for 30 months. Another alternative to improve germination is the use of sulfuric acid at concentrations between 50% and 70% for 2–3 minutes, although this method is not recommended for farmers (Febles 1980).

16.2.3 Agronomical Practices

Through research, all the essential aspects of Leucaena establishment were studied in depth and the necessary practical bases were laid to efficiently use the species and prolong its useful life for animal production (Ruiz and Febles 2012).

Another fundamental practice in seed preparation of this species is inoculation with *Rhizobium* in order to improve its nitrogen fixation potential. Leucaena is highly specific with respect to the *Rhizobium* strain with which it is associated (López 1987). In Cuba, seed is inoculated with specific strains of *Rhizobium sp.* collected and selected in the country, such as ICA 4006 and ICA 4010 for gray-brown soil, ICA 4033, ICA 4035, ICA 4036 and ICA 4037 for vertisol, and IH 016 and IH 024 for red ferrallitic soil (López 1987). Inoculation with *Rhizobium* generated an increase in plant growth between 45% and 78%. In addition, the efficiency of the strain increased when the seed was covered with calcium carbonate.

In the case of Cuba, the time of sowing and weed control had a great influence on plant growth (Ruiz et al. 1989). The best performance was found for plants planted between April and June, which corresponds to the rainy season, while the results were inferior for those planted at the end of the rainy season between September and October (Ruiz et al. 1989; Vargas and Franco 1998).

Regarding the level of weeding, it was found that the development of Leucaena is not affected when it is kept free of weeds during the first 60–80 days after planting. Growth decreases markedly and does not recover when weeds are not removed 20 days after sowing (Ruiz et al. 1990a).

An alternative method to depress weed competition, encourage weeding and improve land use is to intercrop short-cycle crops (Ruiz et al. 1990a). The intercropping of crops such as corn, vigna, sunflower or sorghum contributes to reduce establishment costs by 70% and to generate between 0.5 and 2.1 tons of feed per hectare according to the short-cycle crop selected (Ruiz et al. 2006). Several authors in Cuba agree with these results; according to Fernández (2011) protein banks can be formed with annual crops as a way to reduce costs. According to Milera et al. (2000), Reyes et al. (2000) and Padilla et al. (2001) the intercropping of temporary crops in the establishment of tree plants does not interfere with the yield of these plants and allows economic benefits due to grain production.

Regarding the planting method, research by Ruiz and Febles (2005) showed that the best depth in latosolic soil was 2 cm and in tropical brown soil between 2 and 4 cm, while the worst germinations and emergences occurred when sowing was superficial. In addition, Ruiz and Febles (1987) found that for grazing, the best results are achieved by planting double rows every three meters with 0.70 m between rows and 0.50 m between plants.

In works developed in Mexico by Ruiz et al. (1995), satisfactory results were obtained in the establishment of Leucaena when distances of 3 m between double furrows planted 1 m apart were used. In the province of La Havana, Cuba, good establishment was achieved with a distance of 5 m between rows, linked to the system of soil preparation by strips (Simón et al. 1998). According to Ruiz et al. (1996), it is advisable to plant the grasses when the Leucaena is 8–9 cm tall.

In Cuba it has been found that only in the initial growth stage is it necessary to apply fertilizer to accelerate the development of Leucaena so that it can compete favorably with weeds (Crespo and Curbelo 1991). In soils with low fertility (less than 2.5 and 6.8 mg/100 g of P_2O_5 and K_2O, respectively) this legume grows faster when applied 30, 45 and 50 kg ha^{-1} of N, P and K, respectively. It has not been found necessary to apply chemical fertilizer after the plants reach 150 cm in height (Crespo and Curbelo 1991).

According to Ruiz et al. (1988) the first grazing could be done at a height of 90–100 cm. With this practice the useful and future life of the pasture was not compromised, and a height of 126 cm, 6 branches per plant, a production of 39 g of DM per plant and a population of more than 9000 plants per ha were achieved. It was also observed that in the plants that reached a height of over 200 cm, 60% of their forage was not available to adult animals. Plants that started grazing below 100 cm allow the possibility of total consumption of the active parts of growth, controlling (Ruiz and Febles 2001), to a certain degree, the vertical development of the Leucaena and consequently postponing the need for pruning and increasing the useful life of the plantation. The height at which grazing should begin depends on the objective of the system (Ruíz et al. 2012a). When the objective is that the animals can only consume part of the foliage and that they do not affect the terminal growth points or the upper branches (so that the plant accumulates biomass reserves that will be used as food in the critical period of the year), or for shade purposes or to deposit on the ground, then it is necessary to start the exploitation with an average height of 2 m. This is generally obtained between 10 and 12 months, but will depend on the species or variety, soil fertility, climatic conditions and care since planting (Simón et al. 1998).

Leucaena leucocephala has also been evaluated and introduced into the productive sector in Cuba and in Mexico, Nicaragua and Venezuela. In the State of Colima, Mexico, 48% of the owners were able to initiate the management and utilization of Leucaena for animal feed 8 months after planting, while 38% had to wait 12 months to reach the exploitation stage due to the early entry of animals and ant attacks (Palma et al. 2000; Ruiz et al. 1995, 2004). In the same line of work, an analysis carried out by Ruiz et al. (1998, 2004) indicates that the components that had the greatest weight in the evaluation of the results of the study were the quality of soil preparation, weed control and intercropping of temporary crops, which were determinant for the establishment of this legume.

16.2.4 Leucaena and Rumen Physiology

One of the factors to take into account when offering significant amounts of Leucaena to domestic animals is the possible toxicity of mimosine and DHP, two compounds present in this species. In response to this, work was carried out to determine the degradation capacity of these compounds by grazing cattle. The result presented here is an important contribution in the field of rumen physiology of cattle consuming *Leucaena leucocephala* and allowed us to know the bases that govern the utilization of this legume (Galindo 2001; Galindo et al. 2012).

From this work, strains of ruminal bacteria capable of degrading mimosine and DHP were isolated, and their existence and persistence in the rumen of animals under normal grazing conditions was determined (Galindo et al. 1995). Additionally, it was possible to quantify the concentration of mimosine and DHP in the rumen of cattle, sheep and goats and it was determined that under the conditions evaluated the animals did not present mimosine in the rumen fluid and the levels of 3,4 DHP found were below the toxic range (Galindo et al. 1995, 2012). These studies made it possible to advance in the inclusion of increasing levels of L. leucocephala in animal feed, without the risk of intoxication.

On the other hand, it was determined that the ingestion of *Leucaena leucocephala* by cattle increased the population of rumen cellulolytic organisms and the activity of their enzymes, at the same time that it produced defaunating effects, which has potential effects on the reduction of rumen emissions (Galindo et al. 2003). Phytochemical screening of this species indicated the marked presence of tannins and alkaloids, and other compounds such as saponins, triterpenes, steroids, reducing compounds and flavonoids (La 2001).

Feeding a mixture of molasses and urea (3%) as a supplement to fattening bulls grazing Leucaena generated an increase of 2.64 and 8.9 times in the population of cellulolytic bacteria and fungi with respect to bulls supplemented only with molasses. The population of total cellulolytic organisms was 4.09 and 0.93×10^6 colony forming units per ml for honey/urea and honey, respectively. Ureolytic and amylolytic bacterial organisms were also higher with honey/urea, while total viable bacteria, proteolytic and those degrading mimosine and DHP were not modified by addition of urea in the final honey. These results allowed important practical corrections to be made, since there was a generalized belief that the nitrogen supply from Leucaena was sufficient for good rumen activity (Galindo et al. 2007; Castillo et al. 2002).

Nutrient digestibility when the legume was supplemented with 100, 200 and 300 g of honey indicated better nitrogen utilization efficiency with respect to the diet without supplementation, as well as better digestibility of the other nutrients (Galindo et al. 2012; Castillo et al. 2012). This corroborated the results in terms of ruminal digestion, which suggested supplementation to improve gains in fattening grazing cattle.

The effect of the inclusion of three levels of *Leucaena leucocephala* (20, 40 and 60%) in a ration with low quality star grass (*Cynodon nlemfuensis*) on feed intake behavior, nitrogen digestion and fibrous fractions in rams was evaluated (Delgado et al. 1996; Galindo 2001). According to Delgado et al. (1996) it is possible to include Leucaena at levels higher than 20% of the diet in rams, because the legume improves total fiber digestibility and DM intake. Ruminal digestion of the nitrogenous fractions allowed a better NNP ($N\text{-}NH_3$)-N_t ratio, suggesting a better status in the rumen for the benefit of microbial protein synthesis (Galindo 2001; Galindo et al. 2012). In the results of *in situ* ruminal degradability of nitrogen in Leucaena, a low effective degradability (53.67%) was observed, with a ruminal turnover constant of K = 0.044 (La 2001). Something similar occurred with the values of soluble and degradable nitrogen in this plant. According to Chongo et al. (1998) these values suggest that for every 100 g of protein on dry basis consumable by the animal, only 53.6 g are degraded in the rumen with 46.4% of protein undegradable in the rumen and there is a greater possibility of post-ruminal utilization, which should allow a direct contribution to the animal.

16.2.5 Animal Production

The studies developed by Ruiz et al. (2001) and Jordán (2001) indicate that in order to plant this legume in an operating livestock unit it is not necessary to remove the animals and hinder the zootechnical flow of the unit, since a percentage of the area can be planted each year and the farm can be started with the number of animals it can support, which was economically demonstrated.

16.2.5.1 Biomass Production

Studies developed in grazing systems with trees showed that with proper management, a low proportion of weeds and high values of improved grass base are achieved, compared to grass without trees or fertilization. This shows that there is no deterioration in the pasture, since an acceptable balance of the components is achieved (Ruiz and Febles 2001). The presence of the tree associated with the improved grass tends to produce greater stability of biomass production throughout the year compared to areas without trees and fertilization (Ruíz et al. 2012a). In a leucaena:guinea system evaluated for five years, in the fourth and fifth year of operation with animals, biomass production increased by 21 and 33% in the rainy season, and 37% and 67% in the dry season with respect to the third year, demonstrating a growing production as the system matures (Ruiz et al. 1998). The financial analysis of biomass production according to Cino et al. (2006) showed a rate of return (IRR) of 41%, which is very favorable from the production point of view.

Coppicing is an important element linked to the management of these systems, given that the height of the Leucaena plants in exploitation is the main concern for producers (Ruiz et al. 1990b; Ruiz and Febles 1999). In the case of Cuba, it was concluded that coppicing is not necessary until four years after planting if the system is well managed (Ruiz et al. 2000).

A coppicing strategy to restore biomass production of a silvopastoral system can consist of cutting all the Leucaena plants in the double rows, between the months of April and June to obtain a rapid recovery (Ruiz et al. 2003; Alonso et al. 2003). The coppice height in this strategy depends on the growth habit of the grass and will be 1 m in the case of guinea (which is an erect grass) and 0.5 m for star grass (which has a creeping habit). Fifty-four days after coppicing with the previous strategy, grazing can begin again, achieving an effective recovery of the biomass for all the components. According to Alonso (2004), coppicing increases the biomass production of Leucaena by 310% and that of the grass by 118%.

16.2.5.2 Dairy Cows

Research carried out by Jordán (2012) with dairy animals in Cuba showed that when Leucaena was associated with an improved pasture in 100% of the grazing area it significantly increased the stocking rate and production of dairy cows. The nutritional contribution of the Leucaena system allows a production of 8–9 liters per cow per day (Jordán 2001). The inclusion of Leucaena in the system increased production from 2790 to 6344 liters ha^{-1} $yr.^{-1}$ with Holstein cows while using only 33% of the concentrate used in the group that did not have access to Leucaena. The investigations carried out by Lamela (1989), Jordán and Funes (1995), Simón et al. (1998) provide complementary information for the best use of Leucaena.

According to Mejías (2008) and Iglesias et al. (2009), growing heifers grazing in systems with Leucaena, reached the reproduction age at 22 months and had a reproductive efficiency of 77% at first service with a body condition similar to that of heifers supplemented with concentrate (Mejías 2008; Iglesias et al. 2009).

16.2.5.3 Fattening

Silvopastoral systems with Leucaena have also proven their nutritional, productive and environmental benefits in fattening animals (Hernández et al. 1995). This system has allowed daily weight gains of 620 g per animal with a stocking rate of two animals per ha (Castillo et al. 1989). In another study in a silvopastoral system combining Leucaena and star grass, daily weight gains of 781 g per animal and a stocking rate of three animals per ha were achieved (Castillo et al. 2012). In this way, animal slaughter is achieved at 400–450 kg live weight at 26–27 months of age with hot carcass yield of 54% and only 7–8% fat. In order to improve growing performance Díaz (2008) recommended to supplement fattening animals with 1–2 kg of energy-protein sources with ingredients that are easily degraded in the rumen, in addition to bypassing nutrients, to guarantee the correct nutrition of microorganisms and animals of specialized genotypes such as Cuban Charolais.

Regarding economic performance, the use of leucaena had positive effects (Cino et al. 2006, 2011), as average costs (USD) of 0.84/kg live weight, cost per animal per day of less than one dollar and a positive benefit/cost ratio were recorded (Cino et al. 2006, 2011).

16.2.6 Environmental Benefits

An additional benefit that has been achieved in Cuba with the incorporation of Leucaena is the improvement of animal welfare by providing shade for livestock (Ruiz et al. 1994; Pentón and Blanco 1997). For this purpose, 2–3 years after planting, 1100 plants per ha are allowed to grow without pruning for shade. After four years, the free-growing tree population is adjusted to between 400 and 600 plants per ha to avoid a negative effect on grass growth and to incorporate new plants for animal feed (Ruiz et al. 1998). In this way, a base pasture is available with a more stable biomass production during the year and an acceptable quality, without the use of chemical fertilizers and generating an improvement in soil fertility. Another alternative to increase shade is the incorporation of other tree species, such as *Lysiloma spp., Gmelina arborea* and *Azadirachta indica*, among others that are characterized by their rapid growth and low palatability (Febles et al. 2001; Ruiz et al. 2001).

According to Jordán (2012), with the provision of shade in the system, the time dedicated to grazing increased and water consumption decreased, which represents an indicator of environmental comfort for the animals.

Regarding animal health aspects, studies on the behavior of gastrointestinal nematodes in systems with Leucaena showed a reduction in parasitic infestation by 66% compared to systems without the legume. The main parasite genera found were, in order of importance, *Haemonchus, Oesophagostomum, Cooperia* and *Ostertagia* (Soca et al. 2007). Likewise, an improvement in the body development of the animals and a decrease in the incidence of diarrheal and respiratory diseases were noted (Soca 2005).

Another aspect to highlight in these systems refers to the increase in the recycling of nutrients, particularly N, thanks to biological fixation and the important contribution of this nutrient to the soil through the decomposition of the litter it produces (Lok 2005). Additionally, in silvopastoral systems with Leucaena, there was an increase in soil structural stability as soil carbon storage increased (Lok 2012), with the additional environmental benefit of reduced methane gas emissions due to improved animal nutrition (Galindo et al. 2012).

Silvopastoral systems contribute to the improvement of the physical, chemical and biological characteristics of the soil, which in turn contributes to maintaining the productive stability of the system (Lok et al. 2005). According to Rodríguez et al. (2002), the taxonomic composition of the edaphic macrofauna in areas associated with grasses and Leucaena has a greater abundance and diversity of orders than in neighboring areas with monocultures of grasses (Rodríguez et al. 2002; Lok 2012). When comparing a soil from two livestock systems, it was found that the areas with Leucaena had 181 individuals per m^2 equivalent to 42 g of biomass per m^2 while the systems without Leucaena had less than 40 individuals per m^2 and 12 g of biomass per m^2 (Rodríguez et al. 2002).

In other studies with brown soils planted with a mixture of guinea likoni and star grass with Leucaena, three types, six classes, and seven orders of soil macroinvertebrates were recorded. The biomass found in this association was 23 g per m^2, which exceeded the monoculture area by 383%. On the other hand, in red soils with a predominance of guinea likoni and Leucaena, 3 types, 5 classes and 7 orders of macroinvertebrates were found with a density of 383 individuals per m^2, and a biomass of 67 g per m^2 (Rodríguez et al. 2002; Lok 2012).

The system also contributes to increase bird diversity. According to Alonso et al. (2004) bird presence can be observed in Leucaena systems from the first year, and the numbers of nests and of birds using the trees increased, as a sign of stability of the system.

Regarding biological control, it has been observed that in older systems there is an increase in a group of predatory species of *Heteropsylla cubana* - a defoliating insect - which does not allow it to reach harmful thresholds, both from a biological and economic point of view. *Chilocorus cacti* constituted the bioregulator with the highest incidence and stability, which is achieved progressively (Valenciaga 2003).

16.2.7 Impact on Production Systems

On livestock farms where this legume was introduced, profitability grew and the benefit:cost ratio increased in the range of 2.5–4.5. Economic analysis indicated that a lower proportion of income was needed to cover production and feed costs (Cino et al. 2006, 2011). Particularly positive aspects were the savings in the use of commercial feeds and fertilizers, improvement in animal production indicators and body condition. It is important to note that to obtain these benefits it is essential to carry out crop maintenance practices in a timely manner, especially crop cleaning during the establishment phase, and to avoid overgrazing. It is essential to have systematic technical assistance to guarantee the adequate establishment and management of the system. The results presented suggest that the technology obtained with Leucaena is an economically viable option for livestock production in Cuba and other tropical countries.

16.3 Tithonia

The Institute of Animal Science of Cuba began working with *Tithonia diversifolia* in 2006. Research on this plant arose from the need to find varied options for animal feed for monogastrics and ruminants from native species, since this shrub is a component of the Cuban flora. For all these reasons, the evaluated materials were obtained through a collection in different regions of the country with the objective of carrying out an integral study of the potentiality of this alternative source of forage. All this provided the possibility of having another shrub plant to be used in Silvopastoral Systems. The country is currently implementing a National Program for the use of protein plants in animal feed in the productive sector, which includes *Tithonia diversifolia*.

16.3.1 Plant Material Evaluation

A collection and analysis of the botanical and developmental characteristics of 29 materials of *Tithonia diversifolia* collected in the central-western region of Cuba was carried out (Ruíz et al. 2010). According to this analysis, 81.16% of the variability of the ecotypes collected was explained in the rainy season, while 94.34% was explained in the less rainy season. The variables with the highest preponderance were total leaves, green, yellow, dry and fallen leaves per plant and stems per plant, all with a positive relationship. Through an integrated analysis of the variables seedling height, height of the first green leaf, stem thickness and leaf characteristics, it is evident that there are plant materials of high (3, 5 and 23), medium (10, 16 and 24) and low bearing (13, 17 and 25) (Ruiz et al. 2019). All materials have slow growth in the first weeks after cutting for all measurements under study (Ruíz et al. 2013a). Additionally, new information is available on the behavior of materials 10, 23, 24 and 25 under grazing. All of these materials had good palatability and were consumed by animals. The number of stems per seedling was somewhat higher for material 10, although the rest presented adequate values. The material that presented the lowest weight of green leaves was 25. The information found allows having outstanding materials, as well as developing future work related to biomass production, either for cutting or grazing (Ruiz et al. 2015, 2019).

Similarly, the evaluation of Tithonia collections from the central-eastern region of Cuba was carried out and it was found that, in the province of Ciego de Avila, the materials that steadily exhibit higher growth in both the rainy and dry seasons are CA-3, CA-8 and CA-9, and those with lower growth are CA-1 and CA-6 (Ruiz et al. 2017b). In the Camagüey region the materials with the highest growth were Cm-1 and Cm-3, and in Sancti Spíritus SS-8 and SS-10 (Ruiz et al. 2017a). The plant materials that were evaluated during the dry season in Ciego de Avila, present higher calcium content and lower potassium, manganese and phosphorus content than those found in the Western zone of Cuba.

Regarding foliage consumption, it was found that nine of the materials had a foliage consumption of more than 50% by grazing animals, nine others had a consumption of between 20% and 40% of their foliage and only one was not consumed by the animals in the grazing tests. The materials with the best acceptance were 1, 9, 11, 13 and 15 whose foliage had a consumption of 77, 69, 69, 69, 80 and 75% of the available biomass, respectively (Ruiz et al. 2017a).

16.3.2 Seed

The works carried out indicate that the gamic seed of some of the selected materials of this plant can reach up to 73% germination (Ruíz et al. 2018). When germination and other morphological indicators of material 10 were evaluated, it was found that the germination percentage in laboratory was 54.9% and under nursery conditions in bags was 43.7% (Rodríguez et al. 2019b). This research also showed that the behavior of some morphological indicators under nursery conditions is adequate and allows obtaining vigorous seedlings ready for direct transplanting to the field 45 days after planting with heights greater than 25 cm and more than 8 leaves.

The experience in Cuba indicates that any serious seed production research program requires knowing the best harvest time for the species under study. In this regard, Padilla et al. (2018) determined that the highest germination percentage was obtained when dry bracts and peduncles were harvested and the worst when harvested green with wilted petals. However, the highest production of full seeds per bract occurred when green bracts without petals were harvested at the stage, although no significant differences were found for the production of pure germinable seed between the green bracts without petals and dry bracts and peduncles (brown color) because the highest germination percentage occurred in the latter (Padilla et al. 2018). In addition, a higher number and weight of filled seeds per bract was and 1000-seed weight is obtained. Other work (Padilla et al. 2020) carried out under field conditions confirms that the highest pure germinable seed yields are achieved when at harvest time yellow, carmelite, and dry bracts and peduncles predominate (Padilla et al. 2020). These results indicate the need to harvest when the seeds (achenes) achieve their maturation and formation from the phenological and physiological point of view.

In other research, different seed covers were evaluated under field conditions and it was determined that covering with bovine manure or plant residues had positive effects on plant population and forage production in three successive harvests of the plant. This work demonstrates that it is possible to use the gamic propagation route for this species because of its ability to produce seed and establish successfully in the field. This avoids the difficulties that arise in sowing with vegetative seed, such as transport and storage, which can only be carried out for short periods, so as not to affect the quality of the cuttings. In addition, sexual propagation has additional advantages, since it allows obtaining greater genetic variability and plants with more developed root systems with greater resistance to adverse environmental and edaphic conditions, mainly in the first weeks of establishment, and will allow the development of more vigorous plants (Padilla et al. 2020).

16.3.3 Evaluation of Nutritional Potential

According to the nutritional evaluations carried out in Cuba, the most outstanding plant materials were 5, 10, 16, 17 and 23 for the central-western region, which presented an adequate chemical composition and content of secondary metabolites (Scull et al. 2008). No major differences in digestibility were found in these materials that could modify the digestive utilization of ruminants (La et al. 2012). Under local conditions the best nutrient level was obtained between 70 and 90 days. The inclusion of *T. diversifolia* at a rate of 10% of the total dry matter generates a reduction in the population of methanogens and protozoa and an increase in the population of cellulolytic bacteria in the rumen (Galindo et al. 2010; Galindo 2013).

It should be noted that the mineral content (%) of the materials evaluated from the center-east of the country (2, 3, 12, 14, 17, 23 y 24), at different growth ages, is similar to that reported for the materials collected and evaluated in the central-western zone (Ruiz et al. 2018a; Scull et al. 2019). The production of gases (mL g^{-1} OMinc) and the degradability of organic matter indicated the highest values for materials 23 and 24. All the ecotypes of tithonia showed high N degradability, greater than 68% (Rodríguez et al. 2019a). It was concluded that the seven ecotypes of *T. diversifolia* evaluated had similar behaviors in terms of the variables and parameters studied to characterize their *in vitro* fermentation. The results of the *in situ* rumen degradability kinetics of DM, OM, neutral detergent fiber (NDF) and acid detergent fiber (ADF) suggest the high nutritional value of the evaluated plant materials (Valenciaga Gutiérrez et al. 2018).

16.3.4 Agronomical Practices and Biomass Production

According to the experience in Cuba, the plantation of tithonia to produce fodder could be done by using stems using indistinctly the basal or middle part with a thickness of 2–3 cm, at a depth of 0.10 m and a dose of 4–4.5 t of stems ha^{-1} (Ruiz et al. 2009), which achieves plants with better development, more population and greater biomass production. According to Ruíz et al. (2012b) higher tithonia yield was achieved at distances of 0.50–0.70 m between rows for both seasons of the year and the plantation should be cut at heights between 10 and 15 cm, with cutting frequency of 60 and 80 days in the rainy and dry season, respectively in rainfed conditions.

When the collection of available Tithonia materials was evaluated integrally in grazing, it was found that materials 15, 20 and 28 were not consumed by the animals, while materials 3, 7, 8, 9, 10, 11 and 12 were 100% consumed. Also considered adequate are ecotypes 1, 2, 5 and 6, which had 80% consumption of their foliage (Ruíz et al. 2013b). Tithonia should be planted for grazing at a distance of 3–4 m between rows. The beginning of grazing should be at a plant height between 1.00 and 1.50 m, after the establishment cut. The system can be used with an occupancy time of two days and a rest time of 45 to 60 days in the rainy season and 70 to 90 days in the dry season Alonso et al. (2015). The establishment of Tithonia under these conditions has a cost of USD 790.9 per hectare.

In relation to biomass production, materials 5, 10, 16 and 23 perform better when used for cutting and hauling and materials 3, 5, 10, 23, 24 and 25 are the most suitable for grazing production (Ruiz et al. 2017a).

16.3.5 Animal Production

As Leucaena, *Tithonia diversifolia* has been evaluated in the feeding of ruminant animals in several regions of Cuba. One of the alternatives proposed in the country is the replacement of concentrate with Tithonia meal in calves. According to Martínez et al. (2013) with the inclusion of Tithonia forage meal as a replacement of 15% of the protein source, daily weight gains of over 700 g per animal were achieved and the animals obtained a weight of over 100 kg at four months of age.

For grazing animals, in silvopastoral systems with Tithonia, a daily weight gain of 700 g per animal was achieved with heifers and the replacement of one kg of concentrate per animal per day without affecting animal performance (Ruiz et al. 2018b). According with Gutiérrez et al. (2010), in lactating goats, up to 50% of the protein material of the concentrate can be replaced by *T. diversifolia* flour and achieve a daily weight gain of 60–90 g.

In addition to research on the inclusion of Tithonia in ruminants, the use of this species in the feeding of monogastric animals has been evaluated in Cuba. In the case of fattening pigs, replacement levels of 5 and 10% of the commercial diet with Tithonia forage meal have been evaluated and weight gains of 201 g per animal in weanling pigs and 528 g per day in the growth-fattening phase (Mora et al. 2007).

Rodríguez et al. (2018a) developed several feeding studies in poultry using this shrub. The inclusion of Tithonia meal in replacement of commercial concentrate in hens did not affect growth during the rearing phase. The average weight achieved by the animals in this phase was 1372, 1377, 1385 and 1372 g for the inclusion levels of 0, 10, 15 and 20% of Tithonia meal, respectively. The inclusion of Tithonia had no effect on the health of animals that started laying at week 20 for all treatments (Rodríguez et al. 2018a). In laying hens, the effect of Tithonia forage (0, 10, 15 and 20% inclusion levels) was evaluated in isoenergetic and non-isoenergetic diets and there was no difference between the levels under study for laying, egg size and yolk coloration (Rodríguez et al. 2018b). In broiler fattening, results suggest that *Tithonia diversifolia* forage meal can be included up to 15% in broiler diets from 7 days of age without compromising productive performance (2.1 kg BW at 42 days) and health (Rodríguez et al. 2020). The use of sun-dried Tithonia foliage meal in the species studied contributes to improve the health status of the animals that consume it. According to the studies carried out, Tithonia meal can replace imported protein sources by 25% for replacement pullets and laying hens and 20% for broilers.

16.3.6 Associated Entomofauna

In a more detailed study on arthropods present in different Tithonia materials, in areas under cutting or grazing, it was found that visiting organisms are observed during the entire period evaluated. The most common organisms during all crop stages are dipterans and ants, although the most noticeable are bees when the plants are flowering (Valenciaga Valdés et al. 2018). Among the arthropods considered bioregulators, the most frequent were spiders, and Sirphidae (a common family of parasitoid flies) that exert natural control to numerous lepidopteran larvae. The materials under evaluation were not affected by pests.

16.4 Conclusions

This review details the practices of planting, establishment, nutritional quality and management of sustainable systems for the best production of plants and animals with Leucaena and Tithonia shrubs in Cuba. It also analyzes information related to environmental benefits, animal health and knowledge dissemination, as well as the factors that limited adoption and their productivity and expectations for the future. If through the information provided, we lead readers to reflect on the need to see the processes of nature as a whole and not in isolation, we will feel totally satisfied and highly rewarded.

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Index

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