Review Paper

Silvopastoral systems: A strategy for environmental resilience in livestock enterprises

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Abstract

Objective: To provide an information bank on the management and benefits of silvopastoral systems to enable the creation of environmentally resilient livestock enterprises.

Materials and Methods: Through a search for information, scientific papers on the impact of the conformation and management of silvopastoral systems on indicators of environmental resilience were compiled. For this purpose, Google Scholar, Springer, SciELO, Scopus, Redalyc and ScienceDirect were reviewed. Inclusion and exclusion criteria were established and only 63 documents were selected for inclusion in the information bank.

Results: The benefits of silvopastoral systems were explained for four indicators: preservation of soil health, mitigation of greenhouse gas emissions, conservation of biodiversity and promotion of animal welfare. Their effect on the improvement of soil physical, chemical and microbiological properties, reduction of CO_2 and CH_4 emissions, generation of food resources, as well as their performance as a source of refuge for wild animals and a comfort zone and welfare for livestock were discussed.

Conclusions: Silvopastoral systems promote environmental resilience, which is achieved by improving soil physical, chemical and microbiological properties, conserving biodiversity, promoting animal welfare and contributing to the mitigation of greenhouse gas emissions.

Keywords: biodiversity, mitigation, soil

Introduction

The management of pastoral animal husbandry enterprises, based on an environment poor in plant species and rich in the application of external inputs to eradicate plant and animal, non-livestock species, and promote the maximum possible yield of a few relevant plant species for livestock feeding, has been associated with the generation of fragile ecosystems, of poor environmental and economic resilience (Gómez-Villalva *et al*., 2019; Pérez-Sánchez *et al*., 2021). Environmental fragility originates in the scarce plant and animal biodiversity, which allows soil degradation, the extinction of plant biomass under extreme climatic conditions, as well as the interruption of mutualistic symbiont chains and the increase of the water footprint, among other consequences (Rodríguez-Moreno *et al*.; 2020; Yalta *et al*., 2021). In turn, economic fragility stems from a production cost that is dependent on fluctuations in the cost of external inputs. The latter are increasingly necessary to maintain or improve the production level of the animal husbandry enterprise (Rodríguez-Moreno *et al*., 2020; Aguilar-Jiménez *et al*., 2023).

El-Bilali *et al*. (2019) define sustainability as development that makes it possible to meet present needs without compromising the ability of future generations to meet their needs. Areas of broad plant biodiversity are environmentally and economically resilient ecosystems, because plant biodiversity favors mutualistic relationships that, in turn, promote healthy soils, a fundamental premise for sustainable plant production (Gutiérrez-Bermúdez *et al*., 2020; Lehmann *et al*., 2020). Pastoral or grazing areas with planned plant biodiversity, with the incorporation of herbaceous, semi-ligneous and ligneous species of medium to tall size, have been referred to as silvopastoral systems (SPS) and have been identified as an option in the design and implementation of resilient animal husbandry enterprises (Díaz-Lezcano *et al*., 2020; Peña-Domene *et al*., 2022).

SPSs can be an alternative in the management of natural resources to reverse damage to

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ecosystems disturbed by human activity, in which ecosystems with low plant and animal biodiversity were established in the search for maximum yield (González-Valdivia *et al*., 2018). In addition to obtaining direct anthropocentric consumption and use satisfiers, agricultural enterprises must pay attention to the provision of ecosystem services: clean water, healthy soil formation, microclimate due to aerial vegetation cover, pollination, among others (Gómez-Villalva *et al*., 2019; Peña-Domene *et al*., 2022).

The adequate planning of the plant components of a SPS promotes healthy soils, capable of producing higher yields due to their abundant biology, extensive plant and animal biodiversity, in addition to intervening in the mitigation of greenhouse gas emissions and contributing to animal welfare and the resilience of animal husbandry enterprises (González-Valdivia *et al*., 2018; Vásquez *et al*., 2020; Deniz, 2021; Oyelami, 2022). However, it is necessary to compile and critically analyze the scientific evidence about the shaping and management of SPSs to achieve positive environmental impacts and resilient and sustainable animal husbandry enterprises (Améndola *et al*., 2016; Hanisch *et al*., 2019). The objective of this scientific literature review was to provide a bank of information about the influence of the conformation and management of SPSs as grazing areas on indicators associated with environmentally resilient animal husbandry enterprises.

Materials and Methods

Through a search for information, scientific papers about the impact of SPS formation and management on indicators of environmental resilience were compiled. These included soil health, mitigation of greenhouse gas (GHG) emissions, biodiversity and animal welfare. The strategy followed for the search was based on the selection of keywords to obtain information on each indicator. The keywords that were connected with the Boolean operators AND, OR and NOT, according to the meaning of the phrase were: silvopastoral system, soil health, soil organic matter, soil bulk density, soil fauna, soil minerals, carbon sequestration, GHG mitigation, methane, climate change, biodiversity, animal welfare, animal production, sustainability, ecological resilience. The search was conducted in Google Scholar, Springer, SciELO, Scopus, Redalyc and ScienceDirect. Scientific and literature review papers were considered, as well as books and theses. The search was prioritized with the filter for information published as of 2019. The following criteria were used to select the information.

Inclusion criteria:

- Documents that clearly and accurately describe the impact of SPSs or traditional animal husbandry systems, and both, on soil physical, chemical and microbiological properties, carbon sequestration, GHG emissions, biodiversity and animal welfare indicators.
- Documents detailing the impact of SPSs or traditional animal husbandry systems, and of both, on environmental sustainability and resilience.
- Papers that consider SPSs based on native tree species.

Exclusion criteria:

- Papers that do not clearly and concisely describe the effect of SPSs or traditional animal husbandry systems, and of both, on the environmental resilience indicators considered in this work.
- Documents that consider SPSs based on exotic tree species.

Eighty-six documents were identified, which could be included in the review. After reading the title, 9 were discarded. Seventy-seven were reviewed in full, of which 14 were rejected, i.e. only 63 were selected for inclusion in this review.

Results and Discussion

Soil health in silvopastoral systems. Sustainable soil management is based on the maintenance and improvement of soil health over time, so as to avoid compromising the support services it provides to the ecosystem (FAO *et al*., 2015). Soil health can be evaluated through the state of its physical, chemical and microbiological properties (Cabrera-Dávila *et al*., 2021; Castillo-Valdez *et al*., 2021), since the management of this resource in production systems alters them significantly, mainly when energy inputs are lower than outputs (Castillo-Valdez *et al*., 2021). Compaction, salinization, acidification, loss of nutrients or organic matter (OM), and of both, are considered types of soil degradation and refer to the alteration of its properties (FAO *et al*., 2015). Silva-Olaya *et al*. (2022) refer that, in soils with degraded conditions, SPSs help to better use the land, as the integration of multiple-use trees favors nutrient recycling and improves environmental conditions. Several studies have been conducted to determine the impact of these systems on soil quality, in terms of chemical, physical and microbiological properties.

Regarding physical properties, Contreras-Santos *et al*. (2020) found in a SPS, lower bulk density (BD) and mechanical resistance to root penetration (MRRP), up to 25 and 37 %, respectively, compared with a soil from a system without trees (SWT) (table 1). Oliva *et al*. (2016) referred a similar trend, with values up to 31 and 65 % lower in the soil of a SPS with regards to that of a SWT (table 1). Romero-Delgado *et al.* (2021) pointed out that ligneous species show higher root development than herbaceous species, which has a direct effect on improving soil aggregation and structuring levels and decreasing BD, compaction and MRRP.

Table 1 also shows the studies conducted by Bugarín *et al*. (2010), who after 14 months of evaluation of a SPS, recorded that the BD was maintained, despite sheep trampling. Escobar *et al.* (2020) found no differences in the MRRP when comparing the areas under the trees of a SPS and the open areas, which had 54 % higher soil depth. In the SPS under tree canopies, temperatures are usually lower than in open areas, which generates a more suitable microclimate for animals, so they tend to rest in these areas at various times of the day (Deniz *et al*., 2020). As a result, trampling in these areas increases, which can lead to higher soil compaction (Escobar *et al*., 2020; Romero-Delgado *et al*., 2021). However, it is encouraging that indicators such as BD and MRRP are maintained, despite this animal behavior.

Regarding chemical properties, the contributions of macronutrients and micronutrients to the soil via leaf litter and biological nitrogen fixation by systems with leguminous trees are shown (Bueno-López and Camargo-García, 2015; Oliva *et al*., 2016), which proves that SPSs have a positive effect on improving soil fertility. This was found by Escobar *et al*. (2020), who refer a saturation of bases (K, Ca and Mg) up to 54 %, higher in SPSs with 30 years of exploitation compared with open areas and under eight-year-old trees. Toledo (2016) and Vargas-Batis *et al*. (2020) consider base saturation as one of the properties that determine soil fertility. The above allows to infer that the longer the soil is maintained under silvopastoral management, its fertility will improve.

Another important aspect in determining soil health is the status of OM. Most soil ecosystem functions depend on it, which are essential for C sequestration, N mineralization, aggregation, promotion of plant health, and water and nutrient retention (Cruz-Macías *et al*., 2020; Hoffland *et al*., 2020; Núñez-Ravelo *et al*., 2021). It has been pointed out that soil OM comes from the microbial decomposition of plant (litter, exudates and root residues) and animal biomass residues, so a greater contribution of these residues is essential for its regeneration and increase (Crespo and Fraga, 2002; Haddix *et al*., 2020; Núñez-Ravelo *et al*., 2021). The table above shows the benefits of SPS in terms of the amount of soil OM when compared with SWT, and with regards to the increase in OM content over time, an issue that has been addressed by several authors (Hernández-Chavez *et al*., 2008; Bugarín *et al*., 2010; Oliva *et al*., 2016; Escobar *et al*., 2020).

Regarding soil organic carbon (OC) content, increases of up to 70, 12 and 47 %, respectively, have been reported in soils under silvopastoral management compared with SWT soils (Oliva *et al*., 2016; Contreras-Santos *et al*., 2020; Escobar *et al*., 2020). Likewise, Contreras-Santos *et al*. (2020) estimated at least 18 times more fine root biomass in soils under silvopasture when compared with SWT. The above-explained fact is in agreement with the report by Sanderman *et al*. (2017), who found that, in soils with higher plant diversity and biomass productivity, OC storage increased compared with conventionally managed areas. Haddix *et al*. (2020) reported that lower OC storage may undermine the long-term sustainability of food production and contribute to climate change. Lok *et al*. (2013) state that carbon stored in the soil can serve as an indicator of the efficiency, stability and functioning of forage systems, as it combines the effects of management, soil type, vegetation present and biological activity. Therefore, due to their positive effect on OC storage, SPSs contribute to sustainability.

Regarding microbiological properties, Gutiérrez-Bermúdez *et al*. (2020) and Cabrera-Dávila *et al*. (2021) indicated that a fundamental factor to achieve healthy soils is their biology, formed by microorganisms and macroorganisms, which exert the mining, movement, retention and recirculation of minerals in the soil-plant-animal complex. However, in turn, soil functioning and prosperity depend on the quantity and diversity of the root mass, for which soil biology demands broad plant biodiversity to create a soil profile with abundant and diverse root mass. In this regard, several studies (Hernández-Chavez *et al*., 2008; Escobar-Montenegro *et al*., 2017; Caicedo-Rosero *et al*., 2018; Escobar *et al*., 2020) have estimated higher diversity or abundance of edaphic microfauna and

Table 1. Contributions of silvopastoral systems to the soil.

Study	Components of SPS		Density of the tree species	Contributions to soil properties			Treatments and comparisons
	Trees	Herbaceous plants		Physical	Chemical	Microbiological	
Bueno-López & Camargo-García (2015)	*Leucaena leucocephala (Lam.) de Wit*	NS	10 000 plants/ha.		Contributed in seven months 250 kg N/ha.		It was not compared with SWT
Bugarín *et al*. (2010)	*L. leucocephala (Ll) and Leucaena glauca (L.) Benth. (Lg)*	*Urochloa brizantha (A. Rich.) R. D. Webster (Ub) and Clitoria ternatea L. (Ct)*	2 500 plants/ha in all the SPSs.	BD (1,33 g/cm3) was maintained in spite of sheep trampling.	In T1, T2 y T3, at 14 months of establishment of the SPS, increase of: -OM from 1,68 to 1,94 % -pH from 6,3 to 6,7 as average.		Four SPS: T1 (Ll+Ub) T2 (Lg+Ub) T3 (Ll+Ub+Ct) T4 (Lg+Ub+Ct) 1 SWT: T5 (Ub)
Caicedo-Rosero *et al*. (2018)	2 SPS; T1: *Alnus acuminata* Kunth T2: A*cacia melanoxylon* R. Br.	Forage mix of grasses in both SPS	NS			9 taxa in each SPS and 10 in T3. Haplotaxida with higher relative abundance in the three treatments (> 66,5 %). According to Shannon – Wiener index, T2 had higher diversity (1,161), followed by T3 (0,924) and finally T1 (0,902). According to Simpson index, T2 was the highest (0,531), followed by T1 (0,396) and T3 (0,394).	T3: SWT with forage mixture of grasses.
Camero-Rey & Rodríguez-Díaz (2015)	*Erythrina berteroana* Urb.	*U. brizantha cv.* Toledo CIAT 26110	Tree biomass production: 2724 kg DM/ha/year		Higher OM quantity in the SPS vs SWT (1,70 vs 1,20 %)	Higher quantity of earthworms in the SPS vs SWT (315 vs 262 earthworms/m2)	SWT of *U. brizantha* cv. Toledo CIAT 26110

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	Trees	Herbaceous plants		Physical	Chemical	Microbiological	
Contreras-Santos *et al.* (2020)	Four SPS (T1, T2, T3 and T4) with combinations of forage and timber shrubs and trees.	*Megathyrsus maximus* (Jacq.) B. K. Simon & S. W. L. Jacobs cv. Mombasa in the 4 SPSs	39 trees/ha in all the SPSs	Lower BD in the four SPS at 20 cm of depth (1,16-1,22 g/cm3) than in T5 (1,54 g/cm3). Lower MRRP at 20 cm of depth in the four SPS (1,93-2,26 MPa) than in T5 (3,07 MPa).	Higher accumulation of OC in the four SPSs (60,6-65,1 t/ha) than T5 (38,3 t/ha). Higher biomass of fine roots at 20 cm of depth in the four SPS (288,1-1 864,7 kg/ha) than in T5 (15,37 kg/ha).		T1: pasture + forage shrubs T2: pasture + forage trees T3: pasture + forage shrubs + forage trees T4: pasture + forage shrubs + forage trees + timber trees T5: pasture without trees
Crespo y Fraga (2002)	*Cajanus cajan* (L.) Millsp.	*Cynodon nlemfuensis* Vanderyst	3 300 plants/ha		In five months it contributed via litter: 973 g DM/shrub = 63, 10, 44, 30 and 6 kg/ha of N, P, K, Ca and Mg, respectively		They were not compared with SWT
	Albizia lebbeck (L.) Benth.	*C. nlemfuensis*	100 plants/ha		In four months it contributed via litter: 2 871 g DM/tree = 11, 1, 7, 9, and 1 kg/ha of N, P, K, Ca and Mg, respectively		

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	Trees	Herbaceous plants		Physical	Chemical	Microbiological	
Escobar-Montenegro *et al*. (2017)	SPS (T1) with *Guazuma ulmifolia* Lam., *Vachellia pennatula* (Schltdl. & Cham.) Seigler & Ebinger, *Psidium guajava* L., *Gliricidia sepium* (Jacq.) Kunth ex Walp. and *Caesalpinia velutina* (Britton & Rose) Standl.	*Andropogon gayanus* Kunth	Spatial distribution of scattered trees and live fences.		Similar values in the three treatments of: -pH (6,16-6,36) -OM (4,12-5,27 %) -N (0,2-0,26 %) -P (6,01-6,41 ppm) -CEC (36,9-47,2 Meq/100 g soil)	T1 with higher abundance of macrofauna (4 231 individuals) and richness (24 orders) than T2 (2 664 individuals and 22 orders) and T3 (2 985 individuals and 23 orders). Shannon index (H´) was higher in T3 (1,93) than in T1 (1,68) and T2 (1,69).	T2: SWT of traditional enclosed pasture (*Paspalum notatum* Flüggé, *A. gayanus* and undergrowth). T3: latifoliate forest (large proportion of deciduous xerophyte species).
Escobar *et al.* (2020)	Eight- and 30-year old *A. acuminata* trees	*Cenchrus clandestinus* (Hochst. ex Chiov.) Morrone	35 % of cover in arrangement of scattered trees and live fences	Lower depth of the soil in the areas under trees (22 - 25 cm) than in the open areas (34 cm). There were no differences among areas in MRRP.	Areas under the trees with higher quantity of OM (9,5-9,7 %) and OC (5,5-5,6 %) than the open ones (8,6 % OM and 5 % OC). Under 30-year old trees higher saturation of bases (K, Ca and Mg; 34,15 %) than in open areas (25,47 %) and under eight-year old trees (22,13 %).	In areas under the trees, higher quantity of: -Scarabaeidae: 11-26/m2 -Actinomycetes: 17-18 x105 CFU/g -PSM: 31-160 x104 CFU/g In open areas: -Scarabaeidae 3/m2 -Actinomycetes: 13 x105 CFU/g -PSM 6 x104 CFU/g	In the silvopastoral system the areas under the 8 and 30 year-old trees, and the open areas, were evaluated separately. Implementation of agroecological practices.

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Study	Components of SPS		Density of the tree species	Contributions to soil properties			Treatments and comparisons
	Trees	Herbaceous plants		Physical	Chemical	Microbiological	
Hernán-dez-Chavez *et al.* (2008)	2 SPS (T1 y T2): both with *L. leucocephala*	T1: *M. maximus*. T2: *Cynodon plechtostachyus* K. (Schum) Pilger.			Higher quantity of OM in T1 and T2 (4,4 % both) than T3 (3,0 %).	Higher quantity of taxa in T1 (6) and T2 (7) thn in T3 (3).	T3: SWT of natural pasture
Oliva *et al.* (2016)	2 SPS: T1: *Pinus patula* Schl. *et* Cham. T2: *A. acuminata*	NS	NS	Lower compaction in T4 (61,4 psi), followed by T1 (136,9 psi) and T2 (141,5 psi), higher in T3 (395 psi). Lower BD in T4 (0,55 g/cm^3), followed by T1 (0,69 g/cm^3) and T2 (0,64 g/cm^3), higher in T3 (0,93 g/cm^3).	Higher levels of P in SWT in open field. T4: forest. T1 (5,83 ppm) and T2 (5,81 ppm) than in T3 (4,22 ppm) and T4 (5,45 ppm). Higher quantity of OC (5,56 %), OM (9,58 %) and N (0,48 %) in T4 followed by T1 (OC: 5,34 %, OM: 9,2 % and N: 0,47 %) and T2 (OC: 4,76 %, OM: 8,2 % and N: 0,41 %), lower quantity in T3 (OC: 3,64 %, OM: 5,92 % and N: 0,31 %).		T3: SWT in open field. T4: forest.

CEC-cation exchange capacity, OC-organic carbon, BD-bulk density, OM-organic matter, PSM-phosphate-solubilizing microorganisms, NS- not specified, MRRP- mechanical resistance to root penetration, SWT – system without trees, SPS- silvopastoral system, T- treatment.

mesofauna, and both, in soils with SPS with regards to soils with SWT (table 1). The improvement in the microbiological part has a positive effect on the sustainability of the system, since soil biology plays an important role in the processing of organic residues, resulting in the storage of OM and OC (Sanderman *et al*., 2017; Núñez-Ravelo *et al*., 2021).

Mitigation of greenhouse gas emissions in silvopastoral systems. According to IPCC (2018), the increase in the concentration of GHGs, such as CO_2 and CH_4, in the atmosphere is related to the warming of the earth's surface, which can cause drastic changes in the climate pattern. Several studies (table 2) have found the potential of SPSs to carry out carbon sequestration and thereby contribute to mitigating the effects of climate change (Lok *et al*., 2013; Oliva *et al*., 2017; Vásquez *et al*., 2020). The inclusion of tree species in these systems increases their productivity and, in turn, nutrient recycling (Oliva *et al*., 2018; Azuara-Morales *et al*., 2020), which can translate into higher carbon sequestration compared with SWT. According to a paper by Oliva *et al*. (2017), the tree component of the SPS contributed 8,9 % of the carbon sequestered by the system; while the herbaceous one only contributed 1,6 %. Other authors (Landholm *et al*., 2019; Vásquez *et al*., 2020; Contreras-Santos *et al*., 2023) showed, at the system level, that the treatments with SPS showed higher carbon captures by 56, 321 and 37 %, respectively, compared with the evaluated SWT.

As discussed in the previous section, soil represents a storehouse for carbon recycled by plants. In this regard, Contreras-Santos *et al*. (2020) mentioned that SPSs have the capacity to capture atmospheric carbon and immobilize it in the soil, so they are of great importance in the recovery of degraded soils and GHG mitigation. This can be corroborated in the studies conducted by Pérez-Atehortúa *et al*. (2019) and Contreras-Santos *et al*. (2023), who found higher carbon sequestration (up to 23 and 31 %, respectively) in the soil of SPSs, compared with SWTs. According to these authors (table 2), this difference was associated with the increase in root biomass in the SPS, due to the development of the trees, since they observed that carbon sequestration in the soil increased proportionally with the increase in this biomass. This highlights the role of roots in the carbon cycle and the importance of considering the inclusion of trees in the design of agroecosystems due to their capacity for root development.

One of the risks of continuing to develop conventional production systems is the contribution they make to GHG generation. Lok *et al.* (2013) estimated that, after three years, 16,7 t C/ha were lost in the soil of a monoculture pasture system; while 10,9 t C/ha were stored in the soil of a SPS. Landholm *et al.* (2019) reported 76 % lower CO_2 emission in a SPS compared with one with degraded pasture. De Bernardi *et al.* (2020) determined that a SPS can capture up to 374 % more CH_4 than a conventionally managed agricultural land. In this regard, the authors commented that the CH_4 uptake capacity of the soil is related to CH_4 diffusivity. Therefore, it is influenced by BD, water content and soil temperature, properties that are favorably influenced by SPS.

Commonly used tree species in SPSs have potential to reduce CH_4 emissions due to their nutritive value and secondary metabolite content. Berhanu *et al.* (2019) estimated higher CH_4 concentration in the gas produced *in vitro* by *C. cajan* (52,2 %), corn stubble (31,7 %) and *Sesbania sesban* (L.) Merr. (31,0 %) with regards to *L. leucocephala* (25,4 %), *Moringa stenopetala* (Baker fil.) Cufod. (24,1 %), *Crotalaria juncea* L. (23,4 %) and Lablab *purpureus* (L.) Sweet (16,2 %). The above-cited authors point out that the concentration of CH_4 in the gas produced *in vitro* by the above-mentioned species is inversely related to their ability to reduce CH_4 production and to their crude protein content. Irawan *et al.* (2020) observed in an *in vitro* study that, in a cattle diet consisting of 25 % concentrate feed and 75 % forage of *Cenchrus purpureus* (Schumach.) Morrone and *L. leucocephala*, the addition of this tree (500 and 750 g/kg DM of the diet) positively influenced ruminal fermentation and reduced CH_4 production by up to 54,2 %. This reduction was associated with the existence of tannins in the tree, which contributes directly to the suppression of methanogens and indirectly through inhibition of protozoan growth (Wanapat *et al*., 2015). In turn, it can be ascribed to the improvement in the total digestibility of the diet, since there was a tendency that the higher the proportion of *L. leucocephala* in the diet, the lower the NDF contents (without *L. leucocephala* in the diet: 540,2 g/kg DM *vs*. *L. leucocephala* in the diet: 540,2 g/kg DM *vs*. with *L. leucocephala* (750 g/kg DM: 328,1 g/kg DM) and the ADF contents (without *L. leucocephala* in the diet: 312,9 g/kg DM *vs*. with *L. leucocephala* (750 g/kg DM: 198,0 g/kg DM) of the diet. Likewise, non-fiber carbohydrates were higher (without

Table 2. Contribution of silvopastoral systems to the reduction of greenhouse gas emissions.

Study	Evaluated treatments	Tree density, trees/ha	Sequestration, t/ha		CH_4	Storage	Time of evaluation	Observations
			C	CO_2				
Contreras-Santos *et al.* (2023)	SPS of *Erythrina fusca* Lour., *Pachira quinata* (Jacq.) W.S.Alverson, *Enterolobium cyclocarpum* (Jacq.) Griseb., *G. ulmifolia*, *Inga edulis* Mart., *Tabebuia rosea* (Bertol.) DC., *Samanea saman* (Jacq.) Merr and *M. maximus* cv. Sabanera Agrosavia	19,0	AB: 2,18 RB: 0,63 LB: 2,51 S: 28,05 To: 33,21			Plant tissue, soil and system	Two years	Higher accumulation of C in AB and S
	SPS of *E. cyclocarpum*, *E. fusca*, *Gmelina arborea* Roxb., *S. saman*, *G. sepium*, *Ficus* sp and *M. maximus* cv. Mombasa	81,0	AB: 4,51 RB: 1,16 LB: 3,09 S: 28,98 To: 37,70			Plant tissue, soil and system	Two years	Higher accumulation of C in AB, RB, LB, S and To
	SWT of *Bothriochloa pertusa* (L.) A. Camus		AB: 0,19 RB: 0,08 LB: 0,30 S: 23,54 To: 24,12			Plant tissue, soil and system	Two years	Control. Lower accumulation of C in AB, RB, LB, S and To
De Bernardi *et al.* (2020)	Natural pastureland				-9,5 $ngCH_4/m^2/s$	Flow of CH_4 in soil	NS	Control
	Agricultural land with H*ordeum vulgare* L. and *Glycine max* (L.) Merr.				-4,5 $ngCH_4/m^2/s$	Flow of CH_4 in soil	NS	Lower capture of CH_4
	SPS of *Pinus radiata* D.Don and *Dactylis glomerata* L.	727,0			-21,3 $ngCH_4/m^2/s$	Flow of CH_4 in soil	NS	Higher capture of CH_4
	Forestation of *P. radiata*	977,0			-22,5 $ngCH_4/m^2/s$	Flow of CH_4 in soil	NS	Higher capture of CH_4

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Study	Evaluated treatments	Tree density, trees/ha	Sequestration, t/ha		CH_4	Storage	Time of evaluation	Observations
			C	CO_2				
Landholm *et al.* (2019)	SWT of degraded pastures (*Urochloa spp*)			3,4 (1)		System	One year	Control (the C sequestration was not evaluated)
	SWT of cultivated pastures: *M. maximus*, *Urochloa humidicola* (Rendle) Morrone & Zuloaga y *Axonopus scoparius* (Flügge) Kuhlm.		0,38	1,3 (1)		System	One year	
	Forage bank and cultivated pastures		0,66	2,2 (1)		System	One year	
	SPS of *Calycophyllum spruceanum* (Benth.) Hook.f. ex K.Schum., *G. arbórea,* cultivated pastures and forage bank	104,0	1,6	0,8 (1)		System	One year	Higher sequestration of C and lower emissions of CO_2
Lok *et al.* (2013)	SPS of *M. maximus* and *L. leucocephala*	9,014,0	10,9			Soil	Three years	
	Grasses and mixture of creeping legumes		9,8			Soil	Three years	
	SWT of *M. maximus*		-16,7			Soil	Three years	C in the soil was reduced
Oliva *et al.* (2017)	Trees of *P. patula* associated with native herbaceous plants	625,0	8,2	30,2		Plant tissue	NS	Capacity of C capture of 42,7 %
	Native herbaceous plants		1,4	5,4		Plant tissue	NS	(15 to 20 days of age)
	Litter		1,1	4,1		Plant tissue	NS	
	Soil		81,2	297,3		Soil	NS	
	SPS as a whole		92,1	337,2		System	NS	

Table 2. Contribution of silvopastoral systems to the reduction of greenhouse gas emissions.

Study	Evaluated treatments	Tree density, trees/ha	Sequestration, t/ha		CH_4	Storage	Time of evaluation	Observations
			C	CO_2				
Pérez-Atehortúa *et al.* (2019)	SPS of *A. acuminata, Acacia decurrens* Willd. and *C. clandestinus*	285,0	AB: 1,9 RB: 2,1			Plant tissue of *C. clandestinus*	One year	Yields AB: 3,9 t/ha RB: 4,3 t/ha. Higher capture of C in RB
	SWT of *C. clandestinus*		AB: 2,0 RB: 1,6			Plant tissue	One year	Yields AB: 4,2 t/ha RB: 3,3 t/ha
Vásquez *et al.* (2020)	SPS of *A. acuminata,* pastures and weeds	Strips	B: 6,8 S: 101,3	396,4		Plant tissue and soil	Seven months	
	SPS of *P. patula,* pastures and weeds	Strips	B: 11,7 S: 49,0	589,3		Plant tissue and soil	Seven months	
	SPS of *Cupressus macrocarpa* Hartw. ex Gord., pastures and weeds	Live fence	B: 32,8 S: 17,2	550,2		Plant tissue and soil	Seven months	
	SPS of *Ceroxylon quindiuense* (H.Karst.) H.Wendl., pastures and weeds	Scattered trees	B: 57,8 S:121,6	658,0		Plant tissue and soil	Seven months	Higher retention of C and CO_2
	SWT of pastures and weeds		B: 1,7 S: 29,6	481,4		Plant tissue and soil	Seven months	

(1)-emissions, B-biomass, AB-aerial biomass, LB-leaf litter biomass, RB-root biomass, NS-not specified, S-soil, To-total.

L. leucocephala in the diet: 15,3 g/kg DM *vs* with *L. leucocephala* (750 g/kg DM: 36,3 g/kg DM). The existence of secondary metabolites in tree species used in SPS, which can contribute to the reduction of CH_4 emissions, has been documented by Sandoval-Pelcastre *et al*. (2020), who compiled information on the content of these compounds in 20 species.

From the information discussed in this section, it is confirmed that SPSs contribute to the sustainability of animal husbandry systems by mitigating GHG emissions; while they could represent a benefit for social actors, since in many countries in the region (Oliva *et al*., 2017) carbon sequestration is translated as an environmental service; while gaining access to other products for household use, such as timber and firewood.

Biodiversity in silvopastoral systems. The integration of biological variability at all levels, from genetic resources to species, ecosystems and landscapes, defines the term biodiversity. Oropesa-Casanova *et al*. (2020) pointed out that biodiversity is a reservoir of genetic resources that provides diverse ecosystem services and makes it possible to reduce the use of external inputs in agroecosystems. Appropriate management of biodiversity is a key aspect in the design of agricultural production systems, because it is the basis for life in the land and sustainability in agroecosystems (Sarandón and Flores, 2014). Its conservation depends on maintaining the functional integrity of the latter, as this is the best way to reduce the loss of species; it is also necessary to prioritize biodiversity conservation with emphasis on the definition of functional groups of organisms, identified on the basis of ecosystemic processes that have lower redundancy (Walker, 1992; Pascual *et al*., 2021).

González-Valdivia *et al*. (2018), in Estelí, Nicaragua, documented the existing diversity of malacofauna in two traditional SPSs: dry, shrub and deciduous forest (BS) and oak-pine forest (BP). The studied systems contained 47 of the 216 species of terrestrial mollusks recorded for Nicaragua, 41 of which were found in the BS and 22 in the BP, with 16 in common. Among the species identified, 13 may be potential vectors of livestock diseases or agricultural pests. The authors also identified four species categorized as endemic and two with potential for biological control, predators of other snails. In both systems, very rare species prevailed (24 and 11 for BS and BP, respectively), followed in descending order: rare, occasional and frequent. These conditions showed that the diversity of mollusks depends on the existence of a tree stratum. Therefore, in pastures and meadows it is convenient to have this component, as it can ensure the existence of niches that support the diversity of mollusks. In turn, when conserving biodiversity, trophic chains are present that can favor the presence and vigor of vegetation that feeds livestock, and others that can cause damage. However, the existence of functional groups of organisms with higher diversity favors the regulation of the functions that species fulfill in ecosystems and promotes their conservation (Walker, 1992).

In a commercial dairy farm with high plant diversity (grasses, *Tithonia diversifolia* (Hemsl.), *C. clandestinus* and *A. acuminata*), beneficial food chains for the growth of forage species were established by controlling the intensity of attack by the pests *Collaria* sp, *Draeculacephala* sp. and *Aeneolamia* sp. while improving the diet of grazing cows, which reduced the amount of canoe supplements and farm production costs (Lopera *et al*., 2017).

Regarding diurnal avifauna, Ordoñez-Solarte *et al*. (2015) compared three production systems (I-*Coffea arabica* L. in monoculture, II-*C. arabica* in agroforestry arrangement with *I. edulis*, III-SSP with *C. clandestinus* and *P. guajava* in monoculture) and in system I the lowest values were found in the Shannon and Simpson indices, number of species and abundance of individuals, with respective values of 2,16; 0,88; nine species and 202 individuals, respectively; while the other two silvopastoral arrangements recorded an average of 2,75; 0,93; 15,5 species and 426 individuals. These authors concluded that a plant canopy of greater botanical complexity promotes more niches for feeding, shelter and refuge for birds and, consequently, brings with it abundant biodiversity.

Marinaro and Grau (2015), in the Argentine Chaco, recorded higher variability in the Simpson index for birds and mammals in an animal husbandry landscape dominated by introduced grasses, compared with naturalized grassland and SPS (native trees-introduced grasses) livestock landscapes. From these findings, these authors indicated that botanically more complex landscapes, with the combination of plant, herbaceous and ligneous strata, promote greater homogeneity in the distribution of feeding, shelter and refuge niches and, therefore, better distribution of animal biodiversity. Therefore, they propose that animal husbandry landscapes should be complex in their botanical conformation so that pastoral animal husbandry to be a factor of biodiversity, with homogeneous distribution across the area they occupy, so as to reverse the environmental degradation associated with pastoral animal husbandry. In an analysis of indicator species, the aforementioned authors identified *Chunga burmeisteri* Hartlaub among the species associated with the SPS, which only nests in trees, so its presence was associated with the characteristic structure of these systems.

The information discussed here allows us to conclude that the use of SPSs avoids the simplification of animal husbandry systems, since functional groups of organisms are created and established, aimed at covering livestock production and maintain the functional integrity of the ecosystem. These systems resemble natural ecosystems, which ultimately has positive effects on biodiversity conservation.

Animal welfare in silvopastoral systems. Animal welfare contributes to the economic sustainability of animal husbandry systems in the face of growing consumer concern for purchasing products that incorporate practices that preserve animal health. This improves the marketing status of products that incorporate these measures in their production (Molina, 2021). Blanco-Penedo and Cantalapiedra (2020) and Szorobura *et al.* (2022) refer that the implementation of practices that reduce animal stress and contribute to their welfare will facilitate their adaptation to environmental changes caused by climate change, which will improve the resilience and sustainability of the system.

Social interactions, classified as affiliative and agonistic, develop among grazing cattle. The former are considered sociopositive to high productive behavior and the latter, detrimental. Améndola *et al*. (2016) reported that the frequency of affiliative interactions was 40 % lower among cows grazing a canopy of *C. nlemfuensis*, compared with those grazing a SPS of *M. maximus* and *C. nlemfuensis*, associated with planted *L. leucocephala* and scattered trees. These authors conclude that the silvopastoral environment promotes a more positive social interaction among animals and this leads to a higher degree of welfare.

Deniz (2021) when recording the microclimate characteristics of shaded and unshaded grazing areas, determined that shaded areas showed a microclimate with lower ambient temperature, wind speed and radiant heat load, but higher relative humidity than unshaded areas. This determined that during the hours and days with the highest heat load, cows sought the shaded areas. The authors conclude that planned silvopastoral arrangements or with the presence of trees can offer favorable microclimate conditions that translate into higher animal comfort, especially under conditions of high heat load environments.

Zúñiga-López *et al.* (2020) compared animal welfare indicators in cows grazing in an *A. acuminata*-*C. clandestinus* SPS and a *C. clandestinus* SWT. They observed that the number of *Haematobia irritans* L. flies per animal was higher in the SWT (56) than in the SPS (44). The average coat temperature was higher in SWT animals (37,4 °C) than in SPS (33,8 °C). Also, the level of soiling (0 clean animal - 3 dirty animal) and escape distance were lower in SPS (1,5 and 0,7 m) than in SWT (2,0 and 1,3 m). The differences were associated with the diversification of the SPS, given by the inclusion of trees and the subsequent generation of better distributed comfort spaces, which avoid the overcrowding of the animals in the moments of rest and rumination. In another study, Galloso-Hernández (2021) proved that water buffalo grazing on a SPS of *M. maximus* cv. Likoni and *L. leucocephala* cv. Cunningham spent more time grazing under the trees than in a SWT, where they spent more time in the thermoregulatory bath. In turn, this author determined that it is possible to dispense with these baths or wallows, and both, when managing buffalo under shaded conditions in a SPS.

The above-cited works prove that the generation of a microclimate by means of shade in SPSs has a positive effect on animal welfare, which can benefit productive performance by facilitating grazing in areas that reduce the animals' thermal stress. According to what was discussed in this section, it was found that SPSs provide comfort areas for the animals, which reduces their stress and improves their coexistence, which has a positive impact on their welfare.

Conclusions

Silvopastoral systems promote environmental resilience, which can be achieved by improving the physical, chemical and microbiological properties of the soil, conserving biodiversity, promoting animal welfare and contributing to the mitigation of greenhouse gas emissions.

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Conflict of interest

The authors declare that there is no conflict of interest.

Authors' contribution

- Laura Karen Trejo-Arista. Information search and analysis and paper writing.
- Enrique Cortés-Díaz. Information search and analysis and critical revision of the content.
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