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Intensive silvopastoral systems with *Leucaena leucocephala* in Latin America

Sistemas silvopastoriles intensivos con Leucaena leucocephala *en América Latina*

JULIÁN CHARÁ[1], JULIÁN RIVERA[1], ROLANDO BARAHONA[2], ENRIQUE MURGUEITIO[1], ZORAIDA CALLE[1] AND CAROLINA GIRALDO[1]

[1]*Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria, Cali, Colombia.* cipav.org.co
[2]*Universidad Nacional de Colombia, Medellín, Colombia.* medellin.unal.edu.co

Abstract

Leucaena leucocephala has played a key role in the development of sustainable cattle ranching in Latin America. This species is the backbone of the so-called Intensive Silvopastoral Systems (ISPS) that combine high-density cultivation of leucaena as fodder shrubs (4,000–40,000 plants/ha) with grasses and trees. The layers of vegetation added by shrubs and trees increase the system's capacity for transforming solar energy into biomass and enhance habitat complexity. Although part of the biomass is transformed into livestock products, a significant amount is deposited as litter on the soil and, along with the nitrogen fixed by leucaena and other trees, has positive effects on soil properties and grass production. The increased complexity of the system has measurable effects on biodiversity. ISPS with leucaena support more species of birds, ants, dung beetles and woody plants than conventional pasture monocultures, contribute to landscape-scale connectivity and provide environmental services. They also enhance animal welfare through reduced heat stress and improved availability and quality of fodder resources. ISPS contribute to climate change mitigation by improving above- and below-ground carbon sequestration and by cutting down greenhouse gas emissions per units of dry matter consumed and cattle product. Although these systems have been successfully implemented in Colombia, Mexico and other countries, their adoption is still limited in relation to the area suitable for their introduction.

Keywords: Biodiversity, carbon capture, environmental services, GHG emissions, soil protection.

Resumen

Leucaena leucocephala ha jugado un papel crucial en el desarrollo de sistemas sostenibles de producción ganadera en América Latina. Esta especie es la columna vertebral de los llamados Sistemas Silvopastoriles Intensivos (SSPi) que combinan el cultivo de leucaena como un arbusto forrajero en alta densidad (4,000 a 40,000 plantas/ha) con pastos y árboles. Los estratos de vegetación adicionados con los arbustos y los árboles incrementan la capacidad del sistema para transformar la energía solar en biomasa y aumentan la complejidad del hábitat. Aunque una parte de la biomasa es transformada en productos animales, una cantidad importante es depositada en el suelo como hojarasca y, junto con el nitrógeno fijado por la leucaena y otros árboles, tiene efectos positivos sobre las propiedades del suelo y la producción del pasto. El incremento de la complejidad del sistema tiene efectos medibles sobre la biodiversidad. Los SSPi con leucaena sirven de hábitat para más especies de aves, hormigas, escarabajos del estiércol y plantas que los sistemas convencionales, contribuyen a la conectividad a escala del paisaje y proveen servicios ambientales. También contribuyen a mejorar el bienestar animal a través de la reducción del estrés calórico y una mayor disponibilidad y calidad de recursos forrajeros. Los SSPi contribuyen a mitigar el cambio climático al mejorar la captura de carbono en la biomasa aérea y en el suelo y al reducir las emisiones de gases de efecto invernadero por unidad de materia seca consumida y por unidad de producto. Aunque han sido implementados con éxito en Colombia, México y otros países, su adopción es aun limitada en la región en relación con el área apta para su introducción.

Palabras clave: Biodiversidad, captura de carbono, emisiones de GEI, protección del suelo, servicios ambientales.

Correspondence: J. Chará, Centro para la Investigación en Sistemas Sostenibles de Producción Agropecuaria (CIPAV), Carrera 25 # 6-62, Cali, Colombia. Email: julian@fun.cipav.org.co

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Introduction

Silvopastoral systems (SPS) are defined by the intentional integration of livestock, trees, shrubs and grasses on the same land unit in order to optimize the beneficial interactions between components (modified from Jose et al. 2019). SPS allow the intensification of cattle production through natural processes and are acknowledged as an integrated approach to sustainable land use (Chará et al. 2019). Globally, the main SPS include live fences, windbreaks, scattered trees in pasturelands, managed plant successions, fodder tree banks (e.g. areas of cultivated protein-rich fodder plants), cut-and-carry systems, tree plantations with livestock grazing, pastures between tree alleys and intensive silvopastoral systems (ISPS) (Murgueitio and Ibrahim 2008; Murgueitio et al. 2011; Calle et al. 2012).

Intensive silvopastoral systems (ISPS) are a type of SPS that combines high-density cultivation of fodder shrubs (4,000–40,000 plants/ha) with improved tropical grasses and tree or palm species at densities of 100–600 trees/ha. These systems are managed under rotational grazing with ad libitum provision of water and mineralized salt in each paddock, and 12–24 hour grazing periods that alternate with 40–50 day resting periods (Calle et al. 2012; Murgueitio et al. 2016).

Such silvopastoral systems with high density of *Leucaena leucocephala* have been promoted in several Latin American countries, mainly Colombia and Mexico, but also in Paraguay and Argentina where they have shown important production and environmental benefits (Chará et al. 2019). However, their adoption is still very limited in relation to the area suitable for their introduction. According to Pachas et al. (2019) the area planted in Latin America ranges between 45,000 and 55,000 ha.

Here we review recent studies carried out in Latin America (with emphasis on Colombia) regarding the environmental benefits of leucaena-based ISPS, including their effects on soil, biodiversity, environmental services and climate change mitigation.

Soil and water conservation of *Leucaena leucocephala* silvopastoral systems

Several studies have shown positive effects of SPS on physical, chemical and microbiological soil properties (Martínez et al. 2014). The layers of woody vegetation added by shrubs and trees accelerate the transformation of solar energy into biomass and the penetration of roots into deep soil layers, from where they extract nutrients and water (Nair 2011; Chará et al. 2015). This structural complexity allows for more abundant and heterogeneous plant residues being deposited on the soil as dry leaves, branches, fruits, resins and exudates with beneficial effects on soil organic matter, nutrients and biota (Vallejo et al. 2012; Martínez et al. 2014). Such benefits are complemented by the effects of nitrogen-fixing trees and shrubs and other associations between trees and microorganisms that increase the availability of vital nutrients for biomass production (Malchair et al. 2010; Rey et al. 2014). Soil microorganisms and fungi, in particular mycorrhizal fungi, enhance the formation and stability of soil aggregates, which further improves aeration and root penetration (Gupta and Germida 1988).

ISPS improve decomposition and mineralization processes carried out by the soil microbiota. Vallejo et al. (2010) found a higher activity of β-glucoxidase, acid phosphatase and alkaline phosphatase in soils under ISPS with leucaena compared with pasture monocultures in the Cauca Valley, Colombia. This not only indicated higher microbial activity in soils with leucaena, but also explained why these systems were able to sustain forage and milk yields even without the application of external fertilizers, since these enzymes play a key role in the recycling and availability of nutrients and energy in the soil (Vallejo et al. 2010; Sierra et al. 2017). These processes were enhanced in ISPS when a third layer of *Prosopis juliflora* trees was added to the leucaena-pasture system, e.g. Vallejo et al. (2012) found significantly higher levels of organic C, total N, nitrates and available P and microbial biomass under the canopy of these trees. As a consequence, soils under leucaena ISPS had a higher organic matter content, lower bulk density and lower penetration resistance than soils under pasture monocultures (Vallejo et al. 2012).

Vallejo et al. (2010) found higher densities of macro- and micro-pores, lower bulk density (<1.4 vs. 1.52 g/cm^3) and lower penetration resistance (<3.3 vs. 3.98 MPa) in soils under leucaena than in soils under pasture monocultures. These traits are associated with improved water retention and reduced runoff. Studies carried out in Costa Rica and Nicaragua showed water runoff equivalent to 28–48% of the precipitation in pastures without trees compared with less than 10% in SPS (Ríos et al. 2007).

Atmospheric nitrogen fixation

During the establishment phase of ISPS *L. leucocephala* seeds are inoculated with specific strains of *Rhizobium* to enhance the fixation of atmospheric nitrogen and avoid the use of synthetic fertilizers. Nitrogen fixed by this mechanism becomes available for the system and contributes to increasing the productivity and nutritional quality of its components. Bueno and Camargo (2015) found an increment from 0.39 to 0.74% in the total soil N content 28 weeks after sowing leucaena, which represents 249 kg/ha of additional nitrogen. This economy in nitrogen fertilizer requirement contributes to meat and milk production, reduces financial costs and cuts down atmospheric N_2O emissions.

Contribution of systems with leucaena to the protection of biodiversity and the provision of environmental services

In general, shrubs and trees in SPS have been shown to enhance biodiversity by creating complex habitats for wild animals and plants (Harvey et al. 2006; Moreno and Pulido 2009), harboring a richer soil biota (Rivera et al. 2013; Montoya-Molina et al. 2016) and increasing connectivity between forest fragments (Rice and Greenberg 2004). In farmed landscapes, SPS provide food and cover for birds, serving as wildlife corridors where unique species assemblages are found (McAdam 2005; Murgueitio et al. 2011; Greenler and Ebersole 2015). In the Quindío region of Colombia, areas with SPS were found to have 3 times as many bird species as treeless pastures (Fajardo et al. 2010) and complemented the conservation value of forest fragments by providing temporary habitat for forest-dependent birds (Tarbox et al. 2018).

This type of effects was also found in ISPS with leucaena. In the Quindío region of Colombia, ant species richness was 62% higher in ISPS with leucaena than in treeless pastures, and the ISPS held 55% of the ant fauna present in adjacent forests (Rivera et al. 2013). This study showed that, although forests play an irreplaceable role in preserving unique species, the introduction of ISPS with shrubs and trees enhances the persistence of biodiversity at a landscape scale by facilitating movement between forest fragments. In the same region of Colombia, dung beetle abundance and diversity were significantly higher in ISPS with high density of leucaena than in control sites with pasture monoculture (Giraldo et al. 2011). A similar trend was found in the Cesar Valley in northern Colombia, where ISPS with leucaena had 18 dung beetle species (50% of which were also found in forest fragments), while the neighboring treeless pastures held only 10 species (Montoya-Molina et al. 2016).

Higher biodiversity in the grazing areas and their surroundings can provide important benefits for the farming system through enhanced pollination, pest control and soil water retention, among other environmental services. In the study by Giraldo et al. (2011), the higher abundance and richness of dung beetles were accompanied by a significant increase in the amounts of excavated soil and buried manure. This study showed an additional benefit of ISPS by reducing the abundance of hematophagous flies that affect cattle.

ISPS with leucaena have a range of positive effects on animal welfare. Nutrient availability and quality are enhanced compared with grass-only systems of the same age (Table 1). Shade reduces heat stress while complex vegetation offers the possibility of concealment for the cattle, reducing fear and anxiety (Broom et al. 2013). As mentioned above, animals also benefit from reduced populations of ectoparasites in ISPS (Giraldo et al. 2011; Bacab et al. 2013).

Contribution of leucaena ISPS to ecological restoration

Intensive silvopastoral systems contribute to ecological restoration in cattle ranching landscapes through three complementary mechanisms (Calle et al. 2011; Chará et al. 2015): 1) The farm-scale natural intensification of cattle production on the most suitable land allows the release of fragile or strategic land for the recovery of forests and other ecosystems; 2) ISPS generate environmental services, and their complex vegetation supports part of the local biodiversity; and 3) the high density of shrubs and shade trees in ISPS provides a

Table 1. Average composition of diets for cattle grazing in ISPS with *Leucaena leucocephala* (Ll) and a pasture monoculture in Colombia (forages were sampled at 45 days of regrowth).

Nutrient	Ll + *Cynodon plectostachyus*[1]	Ll + *C. plectostachyus*[2]	Ll + *Megathyrsus maximus*[3]	Ll + *C. plectostachyus* + *M. maximus*[4]	Control *C. plectostachyus* diet[1]
Crude protein (%)	13.9	15.7	14.2	15.5	10.8
NDF (%)	64.9	60.8	60.1	60.7	74.6
ADF (%)	41.9	38.6	41.2	38.4	43.0
Ether extract (%)	1.17	1.58	2.24	1.55	1.16
Gross energy (MJ/kg)	18.3	17.0	17.6	16.9	17.9
Ash (%)	9.6	10.8	12.3	11.9	10.2
Calcium (%)	0.42	0.45	0.61	0.43	0.37
Phosphorus (%)	0.33	0.27	0.27	0.26	0.33

[1]Molina et al. 2016; [2]Rivera et al. 2015; [3]Gaviria et al. 2015; [4]Molina et al. 2015. NDF: Neutral detergent fiber; ADF: Acid detergent fiber.

permeable matrix and facilitates the movement of plants and animals. In turn, this enhances seed dispersal and the spontaneous recovery of forests and ecosystem services at the landscape scale.

Invasive behavior of *L. leucocephala*?

Leucaena leucocephala is native to the Yucatán peninsula in Mexico. Invasive behavior of this species has been observed in the Galapagos Islands, Taiwan, Hawaii and the Ogasawara Islands, where it is considered a weed of riparian and coastal habitats because it forms dense stands and can inhibit the regeneration of native species (Calle et al. 2011; Campbell et al. 2019; Idol 2019). Based mostly on studies done in islands, some environmental agencies have expressed concern about the use of *L. leucocephala* in various types of livestock systems.

In Colombia, *L. leucocephala* grows spontaneously, forming homogeneous stands in disturbed sites, where it accelerates the recovery of degraded land. Native tree species that are unable to regenerate in open areas can become established under leucaena trees. Thus, instead of inhibiting the growth of native species, leucaena facilitates the establishment of shade-tolerant trees and woody plants, as has been shown to occur in the understory of tree plantations in Puerto Rico (Parrotta 1999) and experimental plots in Malaysian slopes (Osman and Barakbah 2011). In addition, nutrient-poor soils affected by severe degradation achieve a rapid physical, chemical and biological recovery under leucaena trees (Parrotta 1999).

Leucaena leucocephala has not invaded mature and well-preserved ecosystems in Colombia. As a typical pioneer tree, it will not spread in habitats with a dense canopy. Seeds require bare soil to germinate and young seedlings cannot tolerate light interception from grasses or weeds. Flooding, high elevation and soil acidity will also prevent its successful establishment. In short, although in other environments *L. leucocephala* could become a weed, in Colombia, far from behaving as an invasive species, it has played a key role in the rehabilitation or ecological restoration of degraded lands (Calle et al. 2011).

Costa and Durigan (2010) surveyed 11 distinct forest patches in Brazil covering 200 ha around a *L. leucocephala* stand established in 1983 without finding a single individual of the species beyond the limits of the planted stand. Even though leucaena regenerated abundantly under the planted trees in Brazil, the relative density of the species in the understory decreased with time and shade-tolerant native species gradually began to dominate. Costa and Durigan (2010) concluded that leucaena behaved as a ruderal species at their Brazilian study site, where it does not invade or threaten natural ecosystems or cause economic damage.

Contribution to climate change mitigation

The contribution of ISPS involving leucaena to climate change mitigation is a result of the improved carbon storage both above- and below-ground and the lower emissions of methane (CH_4) per unit of DM consumed and per unit of livestock product.

Carbon storage

Several studies have shown that incorporating trees in croplands and pastures results in greater net C storage above- and below-ground (Montagnini and Nair 2004; Montagnini et al. 2013). The above-ground carbon storage potential for SPS ranges between 1.5 t/ha/yr (Ibrahim et al. 2010) and 6.55 t/ha/yr (Kumar et al. 1998). In the Patagonia region of Argentina, 148.4 t C/ha were stored in SPS, approximately 85% of which was stored in the soil, 7% in below-ground biomass (understory and tree roots) and 8% in above-ground biomass. Below-ground biomass thus represented an important C storage pool in that ecosystem (Peri et al. 2017). These values are a direct manifestation of the ecological production potential of SPS, depending on factors such as site and soil characteristics, species involved, stand age and management practices (Nair et al. 2010). The amount of soil organic carbon (SOC) can be increased between 20 and 100% when N_2-fixing tree legumes are incorporated, since they enhance plant productivity (Kaye et al. 2000). To take full advantage of the sequestration potential and other benefits of trees, a careful selection of the species is required and both density and design of the arrangement should be managed to avoid competition for light or water.

Regarding SPS with high-density leucaena (10,000 plants/ha), Arias et al. (2015) found a mean carbon content in the biomass of 33.14 t CO_2-eq/ha, compared with 10.7 t CO_2-eq/ha in a conventional pasture monoculture in Colombia. Similarly, in Mexico López-Santiago et al. (2019) found that an ISPS with 36,000 leucaena plants/ha had 106.5 t CO_2-eq/ha in the biomass (above- and below-ground) compared with only 17.2 t CO_2-eq/ha in an adjacent grass monoculture. Soil organic carbon showed a similar pattern with 335.3 and 268.6 t CO_2-eq/ha in the ISPS and the pasture monoculture, respectively (López-Santiago et al. 2019). In ISPS, although part of the above-ground biomass is periodically consumed by cattle, the trees remain in the system and the average amount of biomass is higher than that of a pasture monoculture.

Reduction of GHG emissions

GHG emissions in cattle systems are explained largely by the formation of enteric CH_4, made worse by low digestibility of feed and low productive parameters. Slow growth and high age at slaughter contribute to a longer life and to higher emissions per kg of meat produced (Gerber et al. 2013).

In ISPS with leucaena, animals can consume between 24 and 27% of fresh biomass of this species (Molina et al. 2015, 2016; Gaviria et al. 2015), so the diet contains higher protein and lower neutral detergent fiber (NDF) concentrations than when animals are restricted to the resources available in pasture monocultures (Table 1).

An improved diet with a lower NDF concentration reduces CH_4 formation in the rumen. Additionally, production becomes more efficient in terms of lower age at first calving, shorter calving intervals, higher weight gains and increased milk yields, as a result of the higher DM consumption and improved energy, protein and calcium concentrations in diets in SPS with leucaena (Chará et al. 2019).

With regard to enteric emissions, a trial in Colombia, where diets of 25% *L. leucocephala*, 75% *Cynodon plectostachyus* and 100% *C. plectostachyus* were fed to heifers, CH_4 emissions fell from 30.8 to 26.6 g CH_4/kg DM consumed on the diet containing leucaena, with an ensuing reduction in energy loss (Molina et al. 2016). Similar results were found by Molina et al. (2015) when they included 24% *L. leucocephala* foliage in a diet based on *C. plectostachyus* and *Megathyrsus maximus*. In both cases, animals fed diets containing *L. leucocephala* had 15–20% higher DM intakes and daily weight gains than those with the grass-only diet, but CH_4 emissions did not increase to the same extent (149.4 vs. 144.9 g/animal/day for the ISPS and control system, respectively, according to Molina et al. 2016). Thus, heifers in ISPS emitted at least 33% less CH_4 per kg of weight gain than those in grass-only pastures. A possible explanation for these results is that *L. leucocephala* contains less NDF/unit of DM consumed (Table 1), which lowers CH_4 emissions (Archimède et al. 2011). The reduction could also be caused by the condensed tannin content of *L. leucocephala* (Barahona et al. 2003; Naranjo 2014), since tannins inhibit the growth of some ruminal microorganisms that produce CH_4 (Archimède et al. 2011; Huang et al. 2011). Condensed tannins present in *L. leucocephala* have lower molecular weight than those of other legumes, and have no noticeable effects on DM and fiber digestibility (Barahona 1999; Barahona et al. 2003). In an in vitro experiment, Rivera et al. (2015) reported a reduction of 13% in the production of CH_4 per kg degraded DM (P = 0.0016) when 25% of leucaena was included in a *C. plectostachyus* diet.

Regarding GHG emissions from the soil and pastures, ISPS with leucaena generated 30% less CO_2, 98% less CH_4 and 89% less N_2O soil emissions per ha per month, when compared with an adjacent conventional farm with irrigation and high fertilizer input (Rivera et al. 2019). As a result of this and of the lower enteric CH_4 production, the emissions of CO_2-eq per kg of fat and protein corrected milk (FPCM) and per kg of energy corrected milk (ECM) were 13.4 and 12.5% lower, respectively, than in a conventional high-input system similar to the farm's baseline condition (Rivera et al. 2016). Since no chemical fertilizers are applied usually and concentrate feed requirements are greatly reduced, ISPS can use 55–62% less non-renewable energy than a conventional system to produce a kg of ECM and FPCM.

Conclusions

Intensive silvopastoral systems with leucaena respond to the urgent need of providing beef and dairy products while delivering environmental services. They restore soils, sequester carbon and reduce the negative impacts of cattle on natural resources and climate. In Latin America, ISPS can also play a crucial role in improving the efficiency, resilience and profitability of cattle production, while enhancing product quality and animal welfare. *Leucaena leucocephala* has been essential in the development of ISPS due to its rapid growth and biomass production, high nutrient quality and tolerance to cattle browsing, among other characteristics.

However, technical, cultural and financial barriers have limited the adoption of ISPS and only a small proportion of the suitable land in Latin America is currently under these systems despite all proven and potential benefits. National policies should support ISPS adoption by providing specialized credit lines and technical support and facilitating the access to technical assistance, supplies and markets.

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(Note of the editors: All hyperlinks were verified 8 August 2019.)

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