Chapter 16
Intensive Silvopastoral Systems: Economics and Contribution to Climate Change Mitigation and Public Policies

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1 Introduction

It is predicted that the world's demand for animal protein will continue to grow during the following decades as a result of the increase in population and income per capita, and the greater percentage of people living in urban areas (Pingali and McCullough 2010; Rae and Nayga 2010; Alexandratos and Bruinsma 2012). The

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demand for meat is expected to grow by 73%, and milk and dairy products by 58%, from 2010 to 2030; this will lead to an increase in the global cattle population from 1.7 to 2.4 billion by 2030 (Alexandratos and Bruinsma 2012). Due to this projected increased demand and production, agriculture and livestock will continue representing an important economic sector in the world with an emphasis in developing countries (Alexandratos and Bruinsma 2012).

Latin America has had the highest growth in beef production during the last two decades. Cattle population in this region increased from 178 to 395 million heads during the last four decades and currently provides 39% of the world's meat production from grassland-based systems (Neely et al. 2009; Alexandratos and Bruinsma 2012). This growth has created threats for the environment and climate as it has occurred at the expense of natural ecosystems and has a significant contribution to the emissions of greenhouse gases (GHG), primarily methane (Steinfeld et al. 2006).

In Latin America, cattle ranching has traditionally relied on extensive systems, with low stocking rates (less than 0.6 Animal Units ha^{-1}) and grass monocultures (González et al. 2015). In Brazil, the country with highest sector growth in recent years, approximately 159 million hectares are used for cattle grazing (Barretto et al. 2013), of which more than 100 million are cultivated monoculture pasturelands (IBGE 2006; Guarda and Guarda 2014).

Besides its environmental impact, this type of monoculture production system provides limited feed quality during extreme seasonal events (high temperatures and drought), due to limited shade, poor soil quality, limited access to water, and poor animal condition and performance. In more developed countries cattle production has moved towards more intensive, large-scale, and specialized production units using mixed fodder species as well as grains and feed supplements (Robinson et al. 2011). This livestock intensification, although it alleviates the pressure to increase the area of rangeland, exacerbates the need for more cropland to be devoted to food production in other regions of the world, putting pressure on the land and natural resources (Pingali and McCullough 2010). However, as stated by Mottet et al. (2017), high grain intake (6–20 kg per kg of beef) is only found in feedlot beef production that generates just 7% of global beef output. The other 87–93% volume comes from different production systems where grass and leaves represent 48% of dry matter intake (Herrero et al. 2013), which emphasizes the importance of pasture for livestock production.

To a great extent, negative effects of cattle production are caused by inadequate practices and due to the fact that cattle ranching operates as an extractive activity with very low efficiency and poor management (Calle et al. 2012; Gerber et al. 2013). Recently, several studies have demonstrated the role of some forms of natural intensification on the provision of high quality food, the rehabilitation of degraded ecosystems, and the mitigation of climate change, and have proposed their use to increase production without the negative effects of industrialized systems (Calle et al. 2012, 2013; Gerber et al. 2013; Murgueitio et al. 2014).

Silvopastoral systems (SPS) have been proposed to reduce or reverse the negative environmental impact of cattle ranching and increase animal production and economic performance at the same time. Intensive silvopastoral systems (ISPS) include high density of fodder shrubs (>10,000 plants ha^{-1}) mixed with grasses that combine these advantages and naturally intensify production, reduce the use of external inputs (e.g., fertilizers and feed supplements), and the carbon footprint of beef and milk production (Chará et al. 2015; Murgueitio et al. 2015b), while improving farms' economic returns (Reyes et al. 2016). These intensive SPS have been promoted in several countries of Latin America. Here we describe the systems used, their advantages and developments, and their requirements in terms of research needs and public policy.

2 Intensive Silvopastoral Systems

Among agroforestry systems, those that intentionally combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees for animal nutrition and complementary uses are known as silvopastoral systems (SPS) (Murgueitio et al. 2011). Worldwide, the main SPS include live fences, windbreaks, scattered trees in pasturelands, managed plant succession, fodder tree banks (e.g. areas of concentrated protein-rich fodder crops), cut-and-carry systems, tree plantations with livestock grazing, pastures between tree alleys, and intensive silvopastoral systems (ISPS) (Murgueitio and Ibrahim 2008; Calle et al. 2012).

The main benefits of SPS compared to treeless pastures are: (i) increased efficiency of cattle production per ha (up to 4-fold) (Shelton and Dalzell 2007; Thornton and Herrero 2010; Murgueitio et al. 2011), (ii) reduced dependence on feed concentrates and grains due to the provision of higher quality forages (Mojardino et al. 2010; Barahona et al. 2014; Ribeiro et al. 2016), (iii) improvement of soil properties due to greater uptake and cycling of nutrients from deeper layers of soil, enhanced availability of nutrients from leaf-litter and increased nitrogen input by N_2-fixing trees (Nair et al. 2007; Vallejo et al. 2010; Cubillos et al. 2016), (iv) higher storage of carbon in both aboveground and belowground compartments of the system (Nair et al. 2010; Montagnini et al. 2013; Arias et al. 2015), (v) enhanced resilience of the soil to degradation, nutrient loss, and climate change (Ibrahim et al. 2010; Harvey et al. 2013; Murgueitio et al. 2013), (vi) improved habitat quality for biodiversity (Sáenz et al. 2007; Fajardo et al. 2010; Giraldo et al. 2011; Rivera et al. 2013; Montoya-Molina et al. 2016), and (vii) improved animal welfare (Broom et al. 2013).

Intensive Silvopastoral Systems (ISPS) are a type of SPS that combines high-density cultivation of fodder shrubs (4000–40,000 plants ha^{-1}) with: (i) improved tropical grasses; and (ii) tree or palm species at densities of 100–600 trees ha^{-1}. These systems are managed under rotational grazing with occupation periods of 12–24 h and 40–50 day resting periods, including *ad libitum* provision of water and mineralized salt in each paddock (Calle et al. 2012; Murgueitio et al. 2016; Roberts 2017, Chap. 4, this volume) (Fig. 16.1).

ISPSs respond to the urgent need to transform tropical cattle ranching into an environmentally friendly activity that can be profitable in the short and medium

Fig. 16.1 ISPS with *Leucaena leucocephala* (density of 10,000 ha^{-1}) and *Eucalyptus tereticornis* as windbreaks at 30 m spacing at La Luisa Farm, Cesar, Colombia. The plot in the lower right was grazed the day before (Photo: Luis Solarte)

terms and capable of generating environmental services, rural jobs and provide safe, high-quality food (meat, milk and fruits), hides and wood (Calle et al. 2012; Montes-Londoño 2017, Chap. 3, this volume). These systems are suitable for beef, milk, dual-purpose or specialized cattle farming as well as buffalo, sheep, and goats (Calle et al. 2012).

2.1 Agroecological Principles Applied in Intensive Silvopastoral Systems

Sustainable intensification of bovine livestock for climate change adaptation should apply agroecological principles to increase the efficiency of essential biophysical processes. One key principle of the agroecology strategy is designing agroecosystems that mimic the functioning of local ecosystems to resemble tight nutrient cycling, complex structure, and enhanced biodiversity. These systems can be more productive, pest resistant, and conserve nutrients (Doré et al. 2011; TWN and SOCLA 2015).

Several agroecological principles and strategies are applied at both designing and functioning of ISPS. The most important are: (i) use of several layers of vegetation (herbs, shrubs, trees, and palms) to maximize the transformation of solar energy into biomass, (ii) reduced dependency on agrochemical inputs and energy, emphasizing interactions and synergisms among biological components to enhance recycling and biological control, thus improving overall ecological efficiency and environmental protection (SOCLA 2014), (iii) incorporation and promotion of biodiversity into the system components and its surroundings, (iv) improvement of soil fertility with the presence of trees and shrubs that increase nitrogen fixation, phosphorus solubilization, and uptake of nutrients from deeper soil horizons (Vallejo et al. 2010; Nair 2011), (v) recovery of organic matter content and other important soil characteristics since trees deposit litter, protect soils from direct sunlight, and maintain soil humidity and temperature (McNeely and Schroth 2006), (vi) use of rotational grazing with short occupation and long resting periods to allow the recovery of forage biomass and soil biotic interactions, (vii) use of plants and animal breeds adapted to local conditions to improve resilience and reduce dependency on external inputs (Murgueitio et al. 2015b).

3 Contributions of ISPS to Improved Productivity

Grass is the most important feed resource for ruminants in the tropics. Under extensive grazing systems, cattle production is limited due to the poor quality of tropical grasses (with 2.5–7% of crude protein (CP) and 40–50% of dry matter (DM) digestibility) and to the reduced availability during the dry season (Wilkins 2000). As a consequence, cattle growth and milk production are low and decrease even more during the dry season.

Analysis of the continuously growing body of information on ISPS demonstrates that these systems produce more dry matter, digestible energy, and crude protein per ha, and have the capacity to increase milk or meat production while reducing the need of external inputs such as chemical fertilizers and concentrate feeds (Murgueitio et al. 2011; Ribeiro et al. 2016). Due to these characteristics, ISPS can improve productivity of grazing systems and reduce feed expenses in cattle production. The selection of the shrub species is a key factor for a successful ISPS (Calle et al. 2013) since it can provide up to 30% of additional DM in the system with higher nutrient quality and increased nutrient cycling. The most common species currently used are leucaena, *Leucaena leucocephala* (Lam.) de Wit., and the Mexican sunflower, *Tithonia diversifolia* (Hemsl.) A. Gray.

3.1 Leucaena leucocephala

Leucaena leucocephala is native to the Yucatan Peninsula of Mexico (Shelton 2005) where it was used by pre-Hispanic cultures as a source of food (seeds), wood, and firewood. It is a perennial drought-tolerant leguminous tree that grows well in

Fig. 16.2 Gyr x Holstein crossbred cattle grazing on an ISPS with *Leucaena leucocephala* in Tinajas Farm, Michoacán, Mexico (Photo: Julián Chará)

tropical and subtropical regions (Radrizzani et al. 2010) and is recognized as a high value fodder for cattle due to its high content of crude protein, its low content of fiber, and its palatability, tolerance to direct browsing by cattle and fast regrowth (Barahona et al. 2014; Kennedy and Charmley 2012; Murgueitio et al. 2015a).

Australian grazers were the first to plant commercial stands of *L. leucocephala* (Dalzell et al. 2006) and the first to cultivate it at high density and integrated to grasses in the 1970s (Shelton and Dalzell 2007). Approximately 200,000 ha of this highly productive grass–legume grazing system for cattle existed in 2010, many of them with more than 30 years in operation (Radrizzani et al. 2010). In Latin America, ISPS with this species have been adopted particularly in Colombia and tropical areas of Mexico, although the species is also used in other silvopastoral arrays in Africa, Cuba, Dominican Republic, Haiti, Central America, Venezuela, Peru, Brazil, Paraguay, and Argentina (Murgueitio et al. 2011). Leucaena is also used in agroforestry systems where it provides shade for coffee and other crops (Montagnini et al. 1992). Figure 16.2 presents an ISPS with Leucaena in Michoacan, Mexico where at least 5000 ha have been planted for both dairy and beef production.

Intensive silvopastoral systems with leucaena have higher production of biomass with higher nutritional quality than traditional monocultures of grasses. In ISPS established in dry regions of Colombia, biomass production, including grasses and leucaena, ranged from 15.6 to 19.2 Mg of dry matter (DM) ha^{-1} $year^{-1}$ and protein production from 2.86 to 3.12 Mg ha^{-1} $year^{-1}$. In Mexico, DM yield in ISPS with leucaena in three farms varied between 3.62 and 4.79 Mg ha^{-1} $rotation^{-1}$, more than three times higher than in an adjacent farm with a monoculture of star grass

Table 16.1 Nutritional characteristics of *Cynodon plectostachyus* (K. Schum.) Pilg, and *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs *var*. Tanzania in ISPSs with *Leucaena leucocephala* var. Cunningham in two regions of Colombia

		DM	NDF	ADF	CP	EE	Ca	P	Ash	GE
Region	Grasses	%								*Mcal/kg*
Valle del Cauca	*C. plectostachyus*	21.3	73.5	45.2	9.3	0.98	0.3	0.36	10.7	4247
	M. maximus	20.3	69.2	42.5	9.5	0.83	0.38	0.27	13.4	4054
	L. leucocephala	21.9	33.9	30.6	27.2	1.71	1.33	0.24	6.9	4682
Cesar	*C. plectostachyus*	22.3	66.8	35.4	9,8	0.9	0.43	0.59	8.9	3912
	M. maximus	21.9	70.1	43.6	11.1	0.8	0.45	0.26	10.2	3854
	L. leucocephala	21.8	25.5	16.6	28.4	2.56	1.39	0.27	6.7	4525

DM Dry matter, *NDF* Neutral Detergent Fiber, *ADF* Acid Detergent Fiber, *CP* Crude protein, *EE* Ether extract, *Ca* Calcium, *P* Phosphorus, *GE* Gross Energy

(*Cynodon plectostachyus* (K. Schum.) that produced 0.95 Mg of DM ha^{-1} rotation^{-1}. During the rainy season, DM production in ISPS per rotation varied from 4.8 to 5.4 Mg ha^{-1} and that of the grass monoculture reached 1.2 Mg ha^{-1} (Solorio-Sánchez et al. 2011).

In addition to the higher production and availability of biomass for cattle, the nutritional quality of this biomass is also improved, as fodder shrubs incorporated into ISPS contain almost three times as much protein as tropical grasses and have low fiber content with values under 41% of neutral detergent fiber (NDF) and 30% of acid detergent fiber (ADF) (Murgueitio et al. 2015a).

Table 16.1 presents information on the nutritional characteristics of two grasses, *Cynodon plectostachyus* (K. Schum.) Pilg, and *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs *var*. Tanzania in ISPSs with *L. leucocephala* var. Cunningham in two regions of Colombia.

The low fiber content in *L. leucocephala* generates advantages in terms of dry matter intake by grazing ruminants. This happens because the cell wall content of a plant is one of the physical factors with greater effect on feed consumption. As the fiber has a lower degradation rate in the rumen, it takes up more space in the digestive track (Barahona and Sánchez 2005).

Due to the low fiber content of leucaena, cattle grazing in ISPS with this species tends to have higher DM intake. Barahona et al. (2014) found that DM consumption of steers (250 kg of living weight) grazing in an ISPS with leucaena, *C. plectostachyus* and *M. maximus*, was equivalent to 2.65% of body weight, higher than those in a traditional system that consumed only 2.35%. In another study in Colombia, animals grazing in ISPS also had greater DM intake as a percentage of body weight (2.61% *vs*. 2.04%). The animals in the ISPS also had a higher intake of crude protein (954 g), calcium (62.1 g) and fat (94.2 g) per day than those grazing in a monoculture pasture (499 g, 36.2 g and 69.6 g respectively) (Cuartas et al. 2015).

In ISPSs with rotational grazing, the stocking rate ranges from 2.0 to 4.5 Animal Units (AU of 450 kg), five times higher than that of native grasslands and similar to that of improved grasses with irrigation and fertilization in the tropics (Calle and Murgueitio 2008a; Flores and Solorio-Sánchez 2012).

Due to these traits, in ISPS, production of beef or milk per animal and per hectare is increased. When compared with degraded pastures the amount of meat produced per ha in ISPS increased from 74 kg year^{-1} (stocking rate (SR): 0.55 ha^{-1}, daily weight gain (DWG): 370 g) to 1060 kg year^{1} (SR: 3.5 ha^{-1}, DWG: 830 g) (Mahecha et al. 2011). As a result, the amount of land required to produce a Mg of meat per year is reduced from 13.5 to 1 ha. Similar results were found in Mexico where production of meat increased from 456 kg ha^{-1} year^{-1} in an improved pasture to 1971 kg in an ISPS (Solorio-Sánchez et al. 2011). In other study Thornton and Herrero (2010) estimated a 2.7- and 4.8-fold increase in milk and meat production respectively when leucaena was incorporated in the diet with a reduction in the amount of GHG per unit of product.

3.2 Tithonia diversifolia

Tithonia diversifolia (Hemsl.) Gray, commonly known as Mexican sunflower, is a perennial shrub native from Mexico and Central America that is widely distributed around tropical and subtropical areas of America, Africa, and Asia thanks to its adaptation capacity to different environmental conditions (Sampaio et al. 2016). It is cultivated by its ornamental and therapeutic uses in different countries (Hui et al. 2009; Duarte and Bonissoni 2012) and also as green manure to improve soils and as forage for animal nutrition (Tiebre et al. 2012; Mauricio et al. 2014).

One of the most important attributes of this species is its wide adaptation capacity to tropical and subtropical environments and different rainfall regimes. Close to the Ecuadorian line, it grows from sea level up to 2500 m of altitude with rain fall values from 800 to 5000 mm per year (Calle and Murgueitio 2008b). It also has a wide range of adaptation to soil types from sandy- to clay-dominated and with a wide spectrum of fertility and high tolerance to acidic and very acidic soils, and soils with a high content of iron and aluminum (Rivera et al. 2015a; Murgueitio et al. 2015a). *Tithonia diversifolia* has a rapid growth, tolerance to cattle browsing, high yield of DM, and high content of protein, calcium, and phosphorus (Mahecha et al. 2007; Verdecia et al. 2011; Rivera et al. 2015a). Figures 16.3 and 16.4 show ISPSs with *Tithonia diversifolia* and *Cynodon plectostachyus* in San José farm in Ulloa, Colombia and La Pendiente farm in Misiones, Argentina.

In the Amazonian basin of Colombia, a study was carried out to determine the effect of the ISPS with *Tithonia diversifolia* (*ca.* 5000 shrubs ha^{-1}), dispersed trees and a mixture of grasses of the genus *Urochloa* and *Brachiaria* (*Urochloa decumbens, U. brizantha* and *B. humidicola*) in the production of milk. The biomass yield per ha for each rotation in the ISPS was 2.43 Mg ha^{-1} (0.36 Mg of *T diversifolia* and 2.06 Mg of grass), 44% higher than the areas with conventional *Urochloa-Brachiaria* pastures (Rivera et al. 2015a). The production of milk was higher in the ISPS (15.4 kg of milk ha^{-1} day^{-1}) than in the conventional system (9.74 kg of milk ha^{-1} day^{-1}), as a result of the higher carrying capacity (that increased from 1.84 to 2.71 AU ha^{-1}) and individual daily production (from 4.59 to 4.92 kg: $p = 0.01$). Milk quality was

Fig. 16.3 ISPS with *Tithonia diversifolia* and *Cynodon plectostachyus* in San José farm, Ulloa – Valle del Cauca, Colombia (Photo: Fernando Uribe)

Fig. 16.4 ISPS with *Tithonia diversifolia* and *Cynodon plectostachyus* and Braford (Brahman x Hereford) cattle in La Pendiente farm, Misiones, Argentina (Photo: Julián Chará)

also improved as the production of protein, fat, and total solids were 29, 33 and 36% higher respectively in the ISPS ($p < 0.01$). As a result, the income from milk sales increased by 42.1% compared to conventional pastures (Rivera et al. 2015a).

In Minas Gerais, Brazil, Calsavara et al. (2016) evaluated the nutritional value of *T. diversifolia*, harvested in two growing stages (booting and pre-flowering) and its potential as source of forage for ruminants. Fresh and DM production were higher at booting stage (beginning of the reproductive phase) (41.3 and 8.1 Mg ha^{-1} respectively) than at pre-flowering stage (24.7 and 5.6 Mg ha^{-1} respectively). A similar trend was found in Cuba where DM content of *T. diversifolia* grew from 19.7% at 60 days to 29.5% at 180 days although with a drop in crude protein content from 28.9 to 18% (Verdecia et al. 2011).

4 Environmental Aspects

4.1 Carbon Capture

Several studies have demonstrated that tree incorporation in croplands and pastures results in greater net C storage above- and below-ground (Montagnini and Nair 2004; Haile et al. 2010; Montagnini et al. 2013). The estimates of carbon sequestration potential of agroforestry systems are highly variable, ranging from 0.29 to 15.21 Mg ha^{-1} year^{-1} aboveground and 30–300 Mg C ha^{-1} up to 1 m depth in the soil (Nair et al. 2009; Nair 2011). For SPS, the above-ground carbon sequestration potential ranges from 1.5 Mg ha^{-1} year^{-1} (Ibrahim et al. 2010) to 6.55 Mg ha^{-1} year^{-1} (Kumar et al. 1998). These values are a direct manifestation of the ecological production potential of the system, depending on a number of factors, including 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 promote greater plant productivity (Kaye et al. 2000; Resh et al. 2002; Rhoades et al. 1998). According to Radrizzani et al. (2011) leucaena SPS in Queensland accumulated between 79 and 267 kg ha^{-1} year^{-1} more than adjacent pure grass plots. In a study in Colombia, Arias et al. (2015) found that on average aboveground carbon stock was 13.42 Mg of CO_2-eq ha^{-1} in ISPS and 7.55 Mg of CO_2-eq ha^{-1} in control sites with conventional pasture monoculture.

4.2 Reduction of GHG Emissions

In cattle production systems, high GHG emissions are largely caused by increased enteric methane production due to low feed digestibility, low productive parameters such as slow growth rates that cause more emissions per kg of meat and high age at slaughter due to more emissions associated to a longer life (Gerber et al. 2013).

Although agriculture and cattle grazing are viewed as major sources of GHG emissions, they also hold a great potential to contribute to mitigation, by reducing emissions and enhancing carbon sinks (Neely et al. 2009). It is estimated that 89% of potential GHG emission reductions from agriculture up to 2030 will be due to reductions in CO_2 emissions (Smith et al. 2008).

In this context, GHG emissions from cattle in ISPS are reduced as a result of high efficiency and low emissions per kg of metabolizable energy (ME) consumed. As a result of high ME and crude protein (CP) content and less neutral detergent fiber present in ISPS (Barahona et al. 2014) the CH_4 emissions per unit of dry matter consumed and per unit of product are reduced.

According to Archimède et al. (2011) animals fed tropical legumes produced 20% less CH_4 ($p < 0.05$) than those fed C4 grasses. When concentrates and part of the basal diet were replaced by leaves of *Leucaena leucocephala*, Thornton and Herrero (2010) estimated that GHG emissions per unit of milk and meat produced were 43% and 27% of the emissions without the legume respectively. In their study, the mitigation potential of this practice was of 32.9 Mt. CO_2-eq; 28% coming from the reduction in livestock numbers, and 72% contributed from the carbon sequestration effects (Thornton and Herrero 2010).

Several studies have been carried out in Brazil, Colombia, and Australia, to measure the potential of ISPS based on *Leucaena leucocephala* and *Tithonia diversifolia,* to reduce GHG emissions from cattle in relation to conventional systems. CH_4 produced by enteric fermentation has been measured *in vivo* (Molina et al. 2015b, 2016; Ribeiro et al. 2016), *in vitro* (Huang et al. 2011; Molina et al. 2013; Naranjo 2014; Rivera et al. 2015b; Terry et al. 2016), or modelled using the carbon footprint and the GHG balance (Naranjo et al. 2012; Harrison et al. 2015; Rivera et al. 2016).

With regards to enteric emissions, Molina et al. (2016) found that heifers receiving a diet based on *Cynodon plectostachyus* (K.Schum.) Pilg. with 25% inclusion of *L. leucocephala*, had a reduction of 15% in emissions from 30.8 to 26.6 liters of CH_4 kg^{-1} of DM consumed. They also reported a reduction in energy loss due to CH_4 production in the rumen when *L. leucocephala* was included in the diet. Similar results were found by Molina et al. (2015a) with the inclusion of 24% *L. leucocephala* in a diet based on *C. plectostachyus* and *Megathyrsus maximus*. In both cases, animals with *L. leucocephala* had 15–20% higher DM intake than those with the grass-based diet. This increment in dry matter intake and daily gain however was not accompanied by increased methane emissions per unit of weight gain. Thus, in a kg of weight gain basis, steers in ISPS emit at least 33% less methane than steers in grass-only pastures, whereas emissions per liter of milk could be 50% lower in ISPS (Thornton and Herrero 2010). Increases in meat and milk production and reductions in methane emissions are related to improved nutritional fodder quality in the ISPS compared with pastures in monoculture.

These results are explained because the inclusion of *L. leucocephala* reduces the total Neutral Detergent Fiber and this reduces methane emissions (Archimède et al. 2011). The condensed tannin content of *L. leucocephala* can also explain this reduction (Barahona et al. 2003; Naranjo 2014) since these compounds inhibit the growth of some ruminal microorganisms (Archimède et al. 2011; Huang et al. 2011).

Condensed tannins in *L. leucocephala* are known to be smaller than those present in other legumes (Barahona 1999), and their effect on fibrolytic enzymes is not as pronounced (Barahona et al. 2006) and therefore they do not have noticeable effects on DM and fiber digestibility (Barahona et al. 2003). Rivera et al. (2015a) reported that *in vitro,* a 25% inclusion of leucaena in star grass diets, reduced in 13% the production of CH_4 per kg of degraded DM ($p = 0.0016$).

As for *L. leucocephala*, there is a potential to reduce methane emissions with *T. diversifolia* since this species also has low levels of fiber. Molina et al. (2015b) and Donney's et al. (2015) evaluated the effect of the inclusion of *T. diversifolia* on the production of methane in conventional pasture diets. Although there were no differences in the daily emissions of CH_4 per day ($p = 0.351$), the emissions per kg of weight gain were reduced from 22.32 kg of CO_2-eq kg^{-1} in a diet based on *Brachiaria decumbens* to 4.89 kg of CO_2-eq kg^{-1} when *T. diversifolia* was included ($p = 0.002$) (Molina et al. 2015b).

On the other hand, Donney's et al. (2015) found that the dietary inclusion of 20–25% *T. diversifolia* reduced in 10% the *in vitro* production of CH_4 per kg of degraded matter in diets based on *Cenchrus clandestinus* and up to 15% in diets based on *Brachiaria* grasses.

In Brazil, Ribeiro et al. (2016) found that the inclusion of *T. diversifolia* at 15.4% of DM had no effect on intake, milk production and composition, nitrogen balance or enteric methane emissions. The high-nutrition qualities of *T. diversifolia* allowed the replacement of 20.8% of sugar cane and 11.4% of concentrate feed with no significant effect on methane production. From this experiment, it was concluded that *T. diversifolia* could be used as high quality forage to replace concentrate for ruminants without side effects on performance and methane production in tropical crossed-breed dairy cows.

In a study comparing three ISPS, one with *Leucaena* and two with *Tithonia*, and three conventional pasture systems located in contrasting regions of Colombia, Rivera et al. (2016) found that on average, ISPS generated 15% less emissions to produce 1 kg of fat and protein corrected milk (FPCM), 20% less to produce a kg of milk fat and 15% less to produce a kg of milk protein than the conventional pastures. The carbon footprint for an ISPS with *Leucaena* and star grass and for a conventional grass monoculture system was 1.96 *vs*. 2.19 kg of CO_2-eq kg^{-1} of FPCM respectively. In addition, when balancing GHG emissions with the carbon sequestration it was determined that the ISPS had a net capture of 6.1 Mg CO_2-eq ha^{-1} (Rivera et al. 2016).

5 Economic Implications

In order to determine the economic implications of introducing these systems in Colombia, four pioneer farms in establishing ISPS were analyzed (World Animal Protection et al. 2014). As a first step, the baseline situation was determined, specified, and quantified showing the farms' status before ISPS implementation; then, a

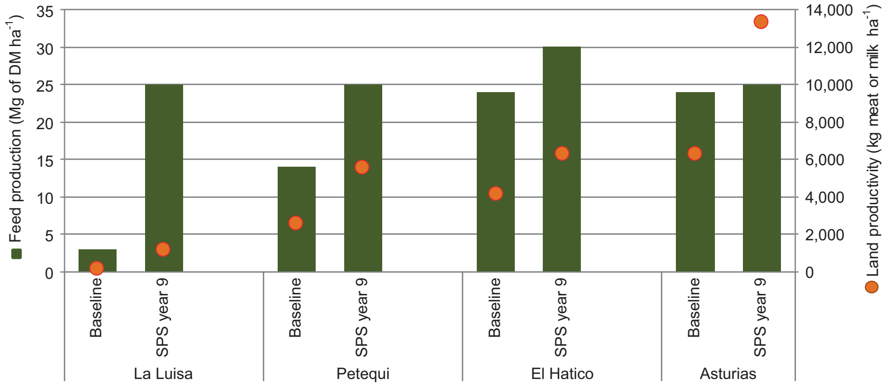

Fig. 16.5 Feed production and land productivity in farms with ISPS in three regions of Colombia. The baseline scenario represents conventional management of pastures without trees, at year 1

detailed pathway of the introduction of the systems and their implications on productivity and farm economics was assessed and modelled for 10 years (World Animal Protection et al. 2014). Although all farms implemented ISPS in 47–70% of the grazing area in less than 10 years, there was an important variation in the history of the farms since one of them started from degraded pastures with very low productivity while the remaining three had improved grasses and a relatively intensive management with high costs before the introduction of ISPSs. Once the systems were fully established, feed production had an eight fold increase in the farm with the degraded baseline scenario (from 3 to 25 Mg of DM ha^{-1} $year^{-1}$) and from 4 to 79% increase in the farms with a more intensive baseline scenario (Reyes et al. 2016).

In addition to the higher amount of DM available, for these farms the quality of the fodder was also improved due to the inclusion of leucaena, but the most important fact was that the increased biomass yield was obtained with the elimination of the need of nitrogen fertilizers and the reduction of protein feed requirement for cattle. As a result of the improved availability and better quality of biomass, farm productivity in milk or beef per ha increased from 52 to 82% after the introduction of ISPS; on average, milk production raised from 4329 to 8390 kg ha^{-1} $year^{-1}$ (Reyes et al. 2016) (Fig. 16.5).

The implementation of ISPS implied higher investment costs as compared with pasture monocultures. The investment and maintenance cost of ISPS ranged from US$ 2692 to $3187 per ha. Further, for La Luisa farm (beef finishing) and Petequi farm (cow-calf), purchases of animals for the growth of the herd, which generate returns in terms of weaner calves and finished animals at a later stage, also constitute investment costs. From a mid-term perspective, the implementation cost is however compensated by an increase in farm returns due to higher productivity. For dairy farms, once the system is installed, maintenance cost is lowered due to the reduction of external inputs such as fertilizers, mineralized salt, and commercial

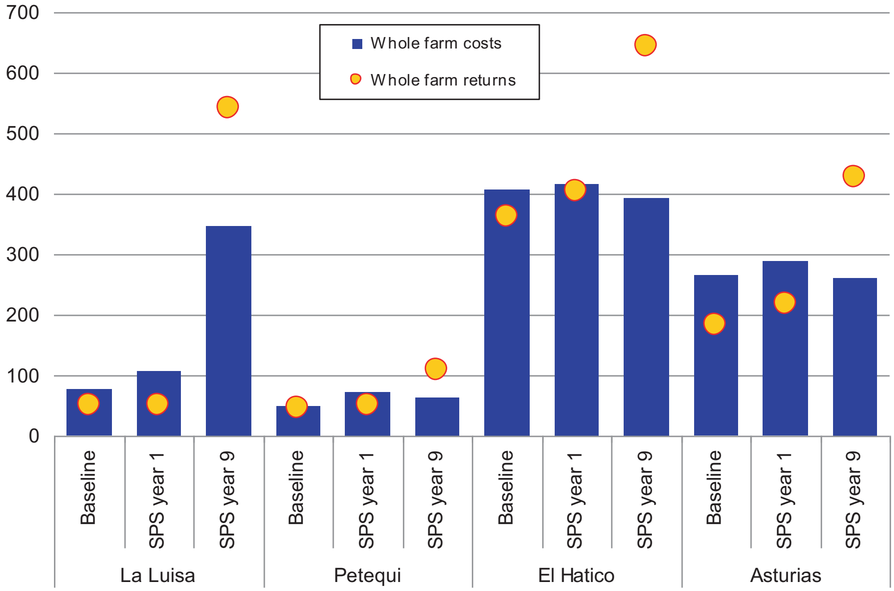

Fig. 16.6 Impact of ISPS on the returns and costs at whole farm level in three regions of Colombia. Whole farm costs and returns: thousands of US dollars (´000 USD). Size of the farms ranged between 30 (Petequí) and 200 has (La Luisa). The baseline scenario represents conventional management of pastures without trees, at year 1. It can be seen from the Figure that in all cases the annual returns at year 9 substantially increase from those of year 1 (56–72% as shown in text)

feed supplements. After the initial investment and a stabilization period, the higher productivity per hectare generates returns that ensure the economic viability of ISPS. Analyzing income values, after the 6th year, they cover the costs and leave a positive balance in the cash flow, achieving situations of large economic surplus. Figure 16.6 shows the impact of the silvopastoral system on the returns and costs at whole farm level. For this study, the farm income and profitability was 56–72% higher than that of the baseline scenarios (Reyes et al. 2016).

The study demonstrated that the introduction of ISPS increased yield and improved farm profitability as it was also demonstrated by Murgueitio et al. (2015a). However, the first years of establishment are characterized by investments in infrastructure and animals, resulting in reduced cash flow and profitability during this initial period.

6 Implications for Public Policy

Despite their on-farm and off-farm benefits, ISPS have not been widely implemented so far due to several barriers, including the lack of technical assistance to farmers that need to adapt the system to local conditions and their high initial cost and technical complexity. According to Calle et al. (2013), ISPS require high initial investment which defies the prevailing view of tropical cattle ranching as a low-investment activity. Additionally, the technical complexity of some ISPS demands a specialized knowledge that is not available among farmers, professionals, conventional academia, or commercial rural extension companies in the field (Calle and Murgueitio 2008b).

Local governments can play a significant role in the access to capital as well as in extension services targeting the management of the systems. The economic analysis provided evidence for the ability of ISPS to create 'triple-win' solutions for sustainable livestock production, productivity and profitability gains, environmental improvements, and animal welfare benefits (Reyes et al. 2016).

To encourage ISPS adoption, it is required to increase technical capacity at local level and to improve the accessibility of farmers to technical and financial resources. This should be pursued from national policies including credit lines and incentives such as payment of environmental services. Policies that promote specialized training for extension workers and technicians are also required.

Specialized market incentives (included in the prices paid for products of ISPSs) are also desirable. Small-scale farmers need access to markets and subsidies throughout the certification process. Larger and entrepreneurial producers need incentives and promotion to enter marketing chains (Calle et al. 2012).

A recent FAO study on policies to encourage sustainable farming in Mesoamerica concluded that in the region there are different types of policy instruments that can be used to encourage the development of SPS. These instruments include the strengthening of institutional capacities for research and training and increased technology transfer especially to the farmer organizations with emphasis on the establishment and management of SPS. It also highlights the application of the methodology of agricultural field schools, the design of financial support instruments linked or not to rural credit, payment for environmental services, as used in Colombia (Zapata et al. 2015), and access to different markets. The success of these processes depends on the simultaneous and coordinated implementation of several of them (Acosta et al. 2014). One aspect that is most important in the dissemination of SPS is the dialogue between scientific knowledge and local expertise, and the farmer to farmer exchange through informal meetings or meetings with producers, technicians and scientists to share experiences between different regions and countries with similar problems.

More research is needed to increase the number of species used as fodder shrubs adapted to different soil and climatic conditions in the tropics and subtropics. More knowledge of native trees and pastures and their interactions is also required. In relation to the tree component, technology for the introduction of forest species in ranchlands is scarce, especially in tropical countries. Development of silvicultural practices, markets, and wood-processing techniques for timber produced in silvopastoral systems is insufficient (Calle et al. 2012). The development of such practices will contribute to improve the profitability of the system and to persuade farmers to introduce timber trees in important regions where the market for forestry products is not yet developed.

7 Conclusions

Due to its lower dependence on external inputs such as fertilizers and concentrates, and to improved animal production ISPS are a valid alternative to increase productivity and lower environmental burdens of livestock production. Cattle production in Latin America can continue contributing to the economy and livelihoods of many countries (rural populations), and at the same time contribute to protect and restore ecosystems and to meet the pledges of the countries in terms of reduction of deforestation and GHG emissions. ISPS can also contribute to the Sustainable Development Goals (SDG), mainly those related to responsible production and consumption, climate action, life on earth, and zero hunger.

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