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Silvopastoral systems with traditional management in southeastern Mexico: a prototype of livestock agroforestry for cleaner production

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A B S T R A C T

Silvopastoral systems are a prototype of agroforestry with a livestock component, which may be characterized as cleaner production as they provide a variety of goods and services to society; one of their functions is to help adapt to and mitigate climate change. In this article, traditional silvopastoral systems with cattle are characterized, and 35 pastures with silvopastoral management in communities of the Lower Grijalva hydrographic region of Chiapas and Tabasco in Southeastern Mexico are evaluated. This article discusses the general context as well as technical and economic aspects of the cattle raising units (CRU). The high frequency (71%) of land use conversion from maize fields to pastures demonstrates that a significant process of increased establishment of cattle raising is under way. Pastures have an average age of 17.9 years, soils are of medium to high quality, and the dominant herbaceous species are grasses. Scattered trees (ST) in pastures are remnants of the original vegetation which has largely disappeared due to change in land use, with 53 species belonging to 24 botanical families and an average density of 12.3 trees ha^{-1}. In living fences (LF), 32 tree species belonging to 18 botanical families were found, with an average density of 45.8 trees per 100 linear m. It is estimated that on average, one hectare of pasture with a dominance of *Cynodon plectostachyus* grass (13.10 Mg C ha^{-1}) surrounded by a living fence (7.28 Mg C ha^{-1}) and containing scattered trees (3.00 Mg C ha^{-1}) has a total accumulation of 23.38 Mg C ha^{-1}. Finally, provision of several environmental services, levels of production or yields, and animal products of the CRU with treeless pastures and with two types of silvopastoral systems are analyzed. In order to be considered a form of sustainable development, traditional silvopastoral systems must gradually be transformed into intensive silvopastoral systems. This requires the commitment and co-responsibility of all social actors involved in order to plan community-based, municipal, state-wide, and national policy related to agroforestry with an animal component.

1. Introduction

Silvopastoral systems are tools for adaptation to and mitigation of climate change due to the fact that they provide a variety of goods and services to society (Steinfeld et al., 2006; Murgueitio and Ibrahim, 2008). According to Nair's (1993) typology for agroforestry systems, in southeastern Mexico, a variety of prototypes of traditional agroforestry systems exist which contribute to cleaner production. These include silvopastoral systems, also known as agroforestry systems with an animal component, or simply agroforestry with an animal component. They include a variety of forms of land use and ordinance to achieve greater productivity of the livestock raising unit (Sanchez, 1999), and are characterized by a combination and interaction of agricultural crops with grasses, shrubs, multiple use trees, and animal husbandry, managed simultaneously or successively in an integrated manner (Ojeda et al., 2003; Murgueitio and Ibrahim, 2008).

In silvopastoral systems, animals graze and/or browse directly among or below trees and/or shrubs of the natural vegetation or which have been planted for construction lumber or to wood for industrial products, for fruit trees, or as multi-purpose trees which directly benefit animal production (Sanchez, 1999). The diverse

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types of silvopastoral systems found in many regions include living fences (LF), which function to delimit pastures, agricultural fields, and properties by establishing trees or shrubs throughout rural landscapes (Avendaño and Acosta, 2000; Harvey et al., 2003; Ojeda et al., 2003; Murgueitio and Ibrahim, 2008) and scattered trees (ST) in pastures, which are favored by selective management of remnant vegetation or by introduction of trees and shrubs in already existing prairies (Esquivel et al., 2003; Ojeda et al., 2003). This study addresses these systems due to the fact that they are widely distributed along the Grijalva cross-border watershed, particularly in Chiapas (Soto et al., 1997; Nahed et al., 2010) and Tabasco (Maldonado et al., 2008; Grande et al., 2010), and because they fulfill important functions but until now have been studied little.

Over the past few decades, the human population has grown at an accelerated rate (INEGI, 2010; SE, 1930a) in the states of Chiapas (1930: 529,983 – 2010: 4,793,406 inhabitants) and Tabasco (1930: 224,023 – 2010: 2,238,603 inhabitants), as well as on the level of the municipalities which make up the Grijalva watershed, including Motozintla (in the upper watershed; 1930: 12,049 – 2010: 69,119 inhabitants), Huitiupan (1930: 2478 – 2010: 21,507 inhabitants), Tecpatan (1930: 2515 – 2010: 41,045 inhabitants), and Tacotalpa (in the mid-watershed; 1930: 7203 – 2010: 46,302 inhabitants). This population growth has exerted great pressure on natural resources, leading to permanent competition for land use for agricultural crops, animal husbandry, and forestry. This process leads to changes in the land use pattern, manifested in a clear tendency toward an increase in areas devoted to agriculture and grasslands at the expense of forested areas (SE, 1930b; INEGI, 2007).

The interaction of these factors has resulted in ecological degradation, observed in: i) severe changes in land use, with loss of up to 50% of forested area in the upper part of the watershed, between Chiapas and Guatemala (De Jong et al., 1999; Cayuela et al., 2006; Flamenco-Sandoval et al., 2007; Sanchez et al., 2008); ii) deterioration of soil and of water quality throughout the entire watershed (Bueno et al., 2007); and iii) low fertility and physical degradation of the land in over half the watershed's territory (College of Postgraduates, 2002).

One of the principal causes of this situation is the population's growing needs, leading to greater demand for food and economic resources in the short term in order to meet these needs. This complex situation has contributed to conversion to livestock raising in the Grijalva cross-border watershed, evident in the clear tendency (SE, 1930b; INEGI, 2007) toward growth of the cattle population (Chiapas: 1930: 362,330 heads – 2007: 1,406,419 heads; Tabasco: 1930: 159,394 heads – 2007: 957,760 heads) and an increase in grazing area (Chiapas: 1930: 422,507 ha – 2007: 1,818,746 ha; Tabasco: 1930: 252,578 ha – 2007: 1,264,337 ha).

Fortunately, expansion of cattle raising in the watershed takes place in pastures with diverse forms of traditional silvopastoral management. These systems are integrated into crop production, and animals feed in pastures with a tree gradient ranging from pastures without trees to pastures with (LF) with shrubs and/or fallows, with (ST) and within forested areas, used alternately throughout the annual cycle (Nahed et al., 2010). In these pastures, living fences and scattered trees in pastures predominate (De Dios, 2001; Lopez et al., 2001; Camara-Cordova, 2008; Maldonado et al., 2008; Grande et al., 2010; Nahed et al., 2010), as is the case in other regions of Chiapas (Jimenez-Ferrer et al., 2008), Mexico (Betancourt et al., 2005) and in The Americas in general (Nepstad et al., 1994; Lok, 2006), in all of which it has been demonstrated that they provide greater ecological, economic, and social benefits than conventional livestock raising systems.

In general, the various types of silvopastoral systems with traditional or innovative management increase productivity of the cattle raising units in terms of meat, milk, fiber, manure, work animals, lumber, firewood and constitute prototypes of cleaner production. They are tools for adaptation to and mitigation of climate change, as they increase tree and shrub cover, provide shade, and regulate climate stress. They increase pasture production and quality, improve nutrient provisioning and efficiency of fodder use, fix atmospheric nitrogen to the soil, and reduce use of chemical fertilizers (Ibrahim et al., 2006; Alonso, 2011). They also provide a variety of environmental services, including climate regulation; regulation of C emissions, nitrous oxide, and methane; nutrient recycling and restoration of degraded soils; biodiversity conservation; protection of watersheds; improvement of water quality; connectivity among ecosystems; and scenic beauty (Harvey and Haber, 1999; Ibrahim and Mora, 2001; Ibrahim et al., 2006; Souza et al., 2000). Thus, these systems benefit society on the local/producer level as well as on the regional/landscape and global levels as compared to conventional pastures dominated by gramineae in monocultures. This is a prototype of livestock agroforestry for cleaner production.

Based on the previous information, the objectives of this study were to evaluate silvopastoral systems with traditional management in the Lower Grijalva hydrograpic region. In particular, this study: i) characterizes the general context and the technical and economic aspects of the cattle raising units; ii) identifies the land use history and dominant grasses in the region; iii) characterizes scattered trees and living fences in the pastures; and iv) estimates the quantity of C stored by the scattered trees, living fences, and grasses present in the pastures.

2. Materials and methods

2.1. Study area

This study was carried out in cattle raising units located in the mid-watershed of the Grijalva River. Particularly, within the micro-watershed of the Almandros River in the muncipalities Huitiupan, Chiapas and Tacotalpa, Tabasco. This micro-watershed is located between 17°12′ and 17°27′ north latitude and 92° 36′ and 92° 46′ west longitude, is made up of twenty six watersheds and includes the Almandros River. The watershed's principal soils are: i) Eutric Fluvisols on both sides of the extreme north of the river, before it joins the Amatan River, ii) Rendzic Leptosols on the eastern slope, and iii) Peli-eutric Vertisols in the western part of the watershed (Palma and Cisneros, 1996).

In general, the landscape is characterized by a steep and craggy relief, with peaks of varying dimensions and presence of structural faults parallel to the river, above all to the west, according to the river's course, where limestone rocks predominate. Also, much runoff occurs, originating in the upper part and feeding the Almandros River. Natural vegetation is evergreen forest, found only in patches in the most abrupt parts of the landscape. A majority of the land is currently used for grazing, with native and exotic species, some coffee groves, very few cocoa groves, and areas devoted to subsistence agriculture.

The climate throughout the year is as follows:

- December, January, and February are the coolest months, while April–September are the hottest.
- Average monthly maximum temperature occurs before the summer solstice (before June 21).
- The "canicula" or "dog-days" (short dry period within the rainy season) occurs during July.
- Precipitation is lowest during March and April, and during the driest month (April, in all cases) precipitation varies from 76.3 to 141.4 mm.

- During September, precipitation varies from 418.9 to 612.4 mm.

Pastures with traditional silvopastoral management were evaluated from November, 2011 to April, 2012 in the municipalities of Huitiupan, Chiapas and Tacotalpa, Tabasco. In Huitiupan, pastures were evaluated in the communities El Remolino, Buen Paso, and Ramos Cubilete, and in Tacotalpa, in La Cumbre, La Pila, Cuviac, Oxolotán, and Tomas Garrido. Altitudes of pastures evaluated were between 70 and 500 m above sea level (masl).

2.2. General context and technical and economic aspects of cattle raising units

Cattle raising units were characterized by certain qualitative and quantitative technical and economic indicators, previously defined by Toussaint (2002); Mena et al. (2004) and Nahed et al. (2006). These indicators were: objectives of production, level of technological development, inputs used, relation of cattle raising with other agricultural systems, producer age and educational level, continuity of cattle raising across generations, type of land tenancy, membership in producer organizations, training, technical support, provision of credit, labor used, infrastructure, total land and grazing surface, herd size in animal units, birth rate, cattle breeds, animal welfare, net profit per cow, stocking rate, production and sale of calves and milk, and difficulties in marketing.

2.3. Characterization of pastures under traditional silvopastoral management

Thirty five pastures under continuous grazing were selected based on data from cattle production units located in the mid-section of the Grijalva cross-border watershed (Nahed and Aguilar, 2011). Selection was based on the most frequent pasture size which the producer devotes to grazing cattle (which varied from 1 to 10 ha). In the municipality Tacotalpa, Tabasco, 25 pastures were selected, and 10 in the municipality Huitiupan, Chiapas.

In order to understand the management dynamics of each pasture, a semi-structured interview was applied to each landowner ($n = 22$) to obtain the following specific information regarding the property: name, surface area, number of years the plot has been used as pasture, and dominant grass type.

2.3.1. Evaluation of scattered trees in pastures

For each pasture, all scattered trees (ST) present with a diameter at breast height (DBH) of 1.30 m greater than 20 cm were measured. For each ST, the following were recorded: i) DBH using a diametric tape, ii) height of clean bole, iii) total height with a clinometer, and iv) greatest crown diameter with a flexometer (West, 2009).

2.3.2. Evaluation of living fences in pastures under traditional silvopastoral management

The evaluation was carried out along the perimeters of 35 pastures in order to characterize trees in the living fences (LF). Four to fourteen 10 m linear transects were carried out. The number of transects varied in function of the homogeneity of the fence and presence and/or absence of trees. In each transect, only those trees with a DBH greater than 10 cm were evaluated. The same data was recorded for each tree in the LF as for the ST, and additionally distance between trees was measured in each transect.

A local guide assisted in identifying the ST and trees of the LF. Botanical collections were carried out and species were later identified through comparison in the herbarium of the College of the South Border, in Chiapas. Later, nomenclature of genera and species was verified using the specialized database of botanical nomenclature administrated by the Missouri Botanical Gardens (MBG, 2012).

In order to calculate basal area of each species recorded for the ST and the LF, the following formula was used (Mueller-Dombois and Ellenberg, 1974):

$$\text{ba} = (1/2\, d)^2 (\pi)$$

where:

ba = basal area
d = diameter at breast height
$\pi = 3.1416$

Alfa and beta diversity (Whittaker, 1977) was calculated from the group of data from the 35 pastures. Alfa diversity was measured as number of species from the community (specific richness). Beta diversity (level of change or replacement in species composition among different communities of a landscape) was calculated using the Whittaker formula (1977) modified by Halffter et al. (2001) in order to compare this diversity with the measure of complementarity (level of difference in composition of species among different communities). The formula used to calculate beta diversity was:

$$\beta = \left(\frac{a_t}{\overline{a}} - 1\right) 100$$

where:

a_t = Total number of species accumulated in the communities compared (those of Tacotalpa and Huitiupan)
$\overline{a}$ = Average number of species of both communities

Also, the amount of carbon (C) fixed by the tree and herbaceous components of each pasture was estimated. For the tree component, the allometric model proposed by Chave et al. (2005) was used:

$$Y = \exp\left(-2.977 + \text{nl}\left(\rho D^2 h\right)\right)$$

where:

Y = biomass (kg/tree)
exp (n) = 2.718 ^{n} (elevate the base $e = 2.718$ to the power n)
nl = natural logrhythm (base $e = 2.71\ldots$)
ρ = density per species (gr/cm^3) taken from the Global Wood Density Database (2012)
D = diameter at breast height (DBH)
h = height (m)

In order to estimate C stored by dominant grasses of the study area (*Cynodon plectostachyus* and *Pennisetum merkeri Lecke*), information from Guzman (2011) was used regarding net annual primary production of pastures (obtained with a 45 day harvest frequency) with a steep slope and low tree coverage (1–10 trees ha^{-1}).

2.4. Data analysis

Data obtained were examined using descriptive statistics (frecuency, average, standard deviation, minimum and maximum values). For this, the Statistical Package for Social Sciences version 15.0 (SPSS, 2006) was used.

3. Results and discussion

3.1. Land use history

Until the 1980s, the principal economic activity in the zone was growing coffee for export, milpa (maize policulture), and management of fallow plots in early successional stages (Camara, 1985; Palma et al., 1985; Camara et al., 1999). Since then, various government economic and agricultural development programs have promoted extensive cattle raising. Such State programs provide the animals, while beneficiaries prepare their land for extensive cattle raising. This has led to elimination of coffee and cocoa groves, as well as patches of original vegetation in order to establish pastures with exotic grasses. According to producers, the most common land use conversion in the plots has been from milpa to pasture (71%), and to a lesser extent (29%) from milpa with small areas of coffee grove to pasture.

On average, pastures evaluated have been used for 17.9 ($\pm$11.2) years. The most recent are an average of 3.5 years old, while the oldest have been used for 35 years. Pastures of the communities of the municipality Tacotalpa have been used for longer (23.2 years, Table 1) than those of Huitiupan (8.4 years).

3.2. General context and technical and economic aspects of the cattle raising units

In the study area, a traditional agrosilvopastoral cattle raising system predominates, and is oriented toward producing weaned calves for sale and milk for self-provisioning and sale. This system is characterized by a low level of technological development, little use of external inputs, diversified resource use, and a management calendar adapted to the variable local environmental conditions. Cattle raising is integrated with crop and forest production through energy flows and circulation of materials by fertilizing crops with manure, feeding crop residues to cattle, and grazing cattle in pastures with a tree gradient ranging from extensive grasslands (without trees) to grasslands with LF, grasslands with shrubs and/or fallows, or grasslands with ST, used in a rotating manner throughout the annual cycle. Such cattle management with low use of external inputs has a lower environmental cost and tends to be more sustainable than conventional systems with high use of external inputs (Nahed-Toral et al., 2013).

Cattle raisers of the municipalities Huitiupan and Tacotalpa have an average age of 49 ($\pm$2) years old. These producers have shown greater openness to receiving advisory and training, and greater interest in experimenting with innovative technologies than older adults; this represents an opportunity to develop agrosilvopastoral systems and organic cattle raising. These producers consider that at least one of their children or another family member will continue to raise cattle due to the fact that cattle raising provides 40% of the family production unit's total income.

Table 1
Average years of pasture use in communities in two municipalities in the mid region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

Municipality	Community	Average years of use as pasture	St. dev.
Huitiupan[a]	Buen Paso	10.6	9.9
	Ramos Cubilete	6.3	1.8
Tacotalpa[a]	Cuviac	21.0	9.6
	La Pila	24.9	11.1
	Oxolotan	23.0	19.7
	Tomas Garrido	24.0	3.6

[a] In El Remolino, in the municipality of Huitiupan, and in La Cumbre, municipality of Tacotalpa, interviews were not carried out with respect to land management.

Land tenancy in all cattle raising units evaluated follows the Mexican *ejido* system (collective landholding). Nevertheless, at the municipal level, private land holdings with cattle production also exist. The majority of producers have a primary and middle-school education; a small proportion is illiterate, and another minority have high school or college education. A similar situation – high level of openness of young adult producers with a low level of education – has been reported by Nahed et al. (2010) for ejido cattle raising in the community Tierra Nueva, in the “El Ocote” Biosphere Reserve in Chiapas, Mexico.

The producers have a low level of participation in agricultural organizations and few receive training, technical assistance, or financial support. The principal source of labor in all cattle raising units is the family. Nevertheless, a significant proportion of producers contract part time workers. Only a small proportion of cattle raising units in both municipalities have an access road in good condition, running water, and electricity. This situation greatly limits implementation of innovations, improvement of facilities and equipment, and development of the production systems in general. Nevertheless, from an environmental point of view, the cattle raising units have a significant diversity of herbaceous, shrub, and tree fodder species, with a high level of potential for intensification and sustainable development of cattle raising.

The cattle raising units have Zebu and creole cattle, crossed with several European breeds, including Swiss and to a lesser extent Simmental. The cattle raising units of Tacotalpa have a greater total land surface area (14.4 $\pm$ 10.9 ha) than those of Huitiupan (6.1 $\pm$ 3.0 ha); the same pattern is true for grazing land (Tacotalpa: 11.3 $\pm$ 10.4 ha; Huitiupan: 4.1 $\pm$ 2.3 ha), herd size (Tacotalpa: 15.0 $\pm$ 15.0 animal units (AU); Huitiupan: 9.0 $\pm$ 4.8 AU), birth rate (Tacotalpa: 75.0 $\pm$ 24.3%; Huitiupan: 42.1 $\pm$ 13.2%) and net margin per cow per year (Tacotalpa: MX$ 2, 383 $\pm$ 1, 468; Huitiupan: MX$ 1, 675 $\pm$ 859). Also, in a favorable manner, cattle raising units of Tacotalpa have a lesser stocking rate (Tacotalpa: 1.4 $\pm$ 0.7 AU ha^{-1}; Huitiupan: 2.2 $\pm$ 1.6 AU ha^{-1}).

All cattle raising units have the objective of selling weaned calves (at 8–10 months of age) to be fattened in other regions, as well as selling discarded cows. In Tacotalpa, 2.3% of cattle raising units are double purpose, with a low volume of milk production (on average 4.7 $\pm$ 0.2 L cow^{-1} day^{-1}), and milking is seasonal (during the rainy season, which typically lasts from May to October). Sale of animals involves passing through several levels of intermediaries in the supply chain, as is common in Mexican tropical regions (Ortíz, 1982; Nahed-Toral et al., 2013) and other regions of the world (Niemeyer and Lombard, 2003; Garcia et al., 2007).

Current tendencies of the cattle raising units point toward gradual diminishing of yields, deterioration of natural resources, and increasing poverty levels. Reversing this tendency requires: i) functional changes such as technological aspects and those related to management of the production system, and ii) structural changes such as reorientation of public policy toward development of cattle raising systems congruent with use, conservation, and holistic management of watersheds, as well as cleaner production. At the same time, adequate public policy requires favoring the transition of the current beef supply chain toward a value chain. The development of cattle raising in the context of intensive, integrated silvopastoral systems constitutes a key instrument of environmental policy for cleaner production, due to the fact that it prevents contamination; improves productivity and competitiveness of cattle raising; increases producers' economic income; promotes efficient use of water, energy, and materials; and enhances natural resource conservation (Verchot et al., 2007; Jose, 2009; Murgueitio et al., 2011). This results in a lesser environmental impact and a lower health risk.

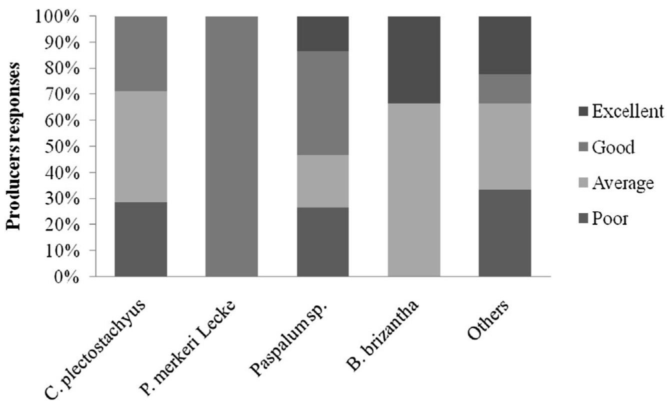

Fig. 1. Classification of the condition of pastures according to type of grass, carried out by producers of the communities of two municipalities in the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

3.3. Soil

Based on the first update of the World Referential Base for Soil Resources (IUSS Working Group WRB, 2007), it was determined that on elevations toward the east of the Almandros River, geological material (lutite) led to formation of mature soils, characterized as Cambisols (soils with evidence of change in color from that of the mother material, translocation of clays, and development of soil structures) or Luvisols (light colored clayish soils). On elevations toward the west of the Almandros River, limestone provided soils with little or intermediate development, characterized as Leptosols (which limit agricultural use due to their continuous rock within 25 cm of the soil surface) in the most abrupt areas, as well as Vertisols (soils which seasonally crack and reseal) in the less steep areas, and Gleysols (soils with excess humidity which has led to a grayish, greenish, or bluish appearance) in some isolated depressions on the slopes. Soils found on both sides of the river originated due to sedimentation of eroded material on the river banks and from these sediments being transported by the river; these soils are characterized as Fluvisols.

Based on the previous information, it is predicted that pastures studied in locations on the right side (when facing down-river) of the Almandros River (the communities La Cumbre, La Pila, Cuviac, Oxolotan and Tomas Garrido) could present Cambisols or Luvisols. These soils are characterized by being deep, consisting of not very expansive clay, and having a medium level of natural fertility. They have a low to medium level of acidity and are moderately susceptible to hydric erosion. Meanwhile, the communities to the left of the river (El Remolino, Buen Paso, and Ramos Cubilete) are predicted to have Leptosols, Vertisols, and Gleysols. Leptisols are very thin soils found over continuous rock and therefore they are often extremely gravelly or rocky. They have a high natural fertility, are very clayish, and crack when drying, forming very hard clumps. Vertisols are clayish, not very deep, very expansive when humid, and when they dry they contract and crack. They have a high natural fertility, are slightly alkaline to slightly acid, and are highly susceptible to hydric erosion due to their thinness. Gleysols are similar to these other two soils, but due to their physiographic position in deep or low relief areas, they form zones of accumulation of eroded sediments in the most elevated parts of the terrain and cause problems of water saturation. As a consequence, the lack of air in soil pores which have filled with water induces chemical reduction, which propitiates ammonification and iron accumulation, giving the soil a greyish, greenish, or bluish color. Nevertheless, they generally have a high level of natural fertility.

3.4. Grass

Grasses most frequently found in the pastures evaluated were: *Paspalum* sp. (Natural grass; 43%), *C. plectostachyus* (African star grass; 20%), *P. merkeri Lecke* (Merkeron; 9%), and *Brachiaria brizantha* (Señal; 9%), followed by combinations of these.

Producers evaluated grass types based on their yield as: a) excellent, b) good, c) average, and d) poor. In general, all grasses were highly qualified (Fig. 1). The majority of evaluations varied from average to excellent in the case of *C. plectostachyus*, *Paspalum* sp., and *B. brizantha*, and good in the case of *P. merkeri Lecke*. This indicates that producers feel that grass yield is not affected by the current average stocking rate (Huitiupan: 2.25 $\pm$ 0.3 AU ha^{-1}; Tacotalpa: 1.43 $\pm$ 0.1 AU ha^{-1}) or by the generally low densities of ST found in the pastures. Another factor which undoubtedly contributes to high grass yield is the shade tolerance of grasses found in the pastures. It should be noted that *Paspalum* sp., *P. merkeri Lecke*, and *B. brizantha* have a median level of shade resistance (Shelton et al., 1987; Wong, 1991), while *C. plectostachyus*, which is not very shade tolerant, is only planted on 20% of the surface area.

3.5. Scattered trees

The majority of ST in pastures of the study area are remnants of original vegetation, and in some cases is a result of secondary succession, although some introduced species are also found (for example *Citrus* spp., *Mangifera indica*, and *Cocos nucifera*).

Table 2 shows the number of ST, density, and average number of species of ST for each community evaluated. As a whole, the 35 pastures of the 8 communities added up to a total of 122.6 ha. The smallest surface area was 1 ha, the greatest 10 ha, and average surface area was 3.5 ha.

Range of variation of tree density was very broad, with pastures with densities from 0.6 to 34 trees per ha, and average number of trees per pasture was 30.9 ($\pm$26.4), with a density of 12.3 ($\pm$10.9) trees ha^{-1}. In the majority of communities studied, average

Table 2
Number of scattered trees, tree density, and average number of tree species in pastures evaluated in communities in two municipalities of the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

Municipality	Community	Number of pastures	[a]Total surface area evaluated, ha	[a]Maximum number of trees	[a]Minimum number of trees	[a]Average number of trees ($\pm$SD)	[a]Average number of species ($\pm$SD)	Average tree density ha^{-1} ($\pm$SD)
Huitiupan	Buen paso	5	8	40.0	1.0	16.4 ($\pm$14.8)	3.6 ($\pm$1.7)	9.2 ($\pm$6.8)
	El Remolino	2	3.5	62.0	33.0	47.5 ($\pm$20.5)	6.5 ($\pm$3.5)	28.9 ($\pm$5.8)
	Ramos Cubilete	3	5.0	35.0	5.0	17.0 ($\pm$15.9)	4.0 ($\pm$0.0)	10.3 ($\pm$7.5)
Tacotalpa	Cuviac	3	6.3	18.0	6.0	13.7 ($\pm$6.7)	5.7 ($\pm$1.5)	7.0 ($\pm$4.6)
	La Cumbre	5	16.4	64.0	37.0	59.8 ($\pm$14.9)	9.6 ($\pm$4.4)	23.7 ($\pm$10.9)
	La Pila	11	69.4	62.0	5.0	20.4 ($\pm$17.7)	6.1 ($\pm$3.5)	3.5 ($\pm$2.8)
	Oxolotan	3	10.0	106.0	18.0	67.7 ($\pm$45.1)	6.7 ($\pm$2.3)	18.8 ($\pm$8.9)
	Tomas Garrido	3	4.0	49.0	3.0	29.3($\pm$23.7)	5.7 ($\pm$2.5)	19.9 ($\pm$15.3)

[a] Based on the number of pastures evaluated and the sum of their surface areas.

densities were less than 20 trees ha^{-1}, which is lower or similar to those reported in other studies (Guevara et al., 1998; Esquivel et al., 2003; Villanueva et al., 2004). Average tree densities greater than 20 trees ha^{-1} in pastures in El Remolino and La Cumbre are greater than those reported in a study in the dry tropics of Costa Rica, where densities of the majority of pastures were less than this (Esquivel et al., 2003). Tree density of the region's pastures is within the average range obtained in other studies carried out in tropical regions (Guevara et al., 1994, 1998; Harvey and Haber, 1999; Souza et al., 2000; Esquivel et al., 2003; Villacis et al., 2003; Villanueva et al., 2004; Harvey et al., 2007), in which densities from 3 to 33 trees ha^{-1} were reported. Nevertheless, this is less than the average tree density of other pastures in the same study area (38 trees ha^{-1}) reported by Grande et al. (2010).

3.5.1. *Species composition of scattered trees*

A total of 1083 ST were counted in 122.6 ha of pasture, of which 1026 individuals from 24 botanical families were identified. Fig. 2 shows that the largest number of tree species found belong to the Fabaceae family, followed by Moraceae and Rutaceae. Botanical families with a lesser number of species were also found (from 1 to 3).

Specific richness was 53 identifiable tree species, and 8 additional species could not be identified. This number of species is similar to the 57 species found in pastures of the region of Los Tuxtlas, in Veracruz, Mexico (Guevara et al., 1994), and the 55 species reported in farms of Guanarito, Venezuela (Solorzano et al., 2006) and the 55 species of the highly technified pastures of the humid tropics of Costa Rica (Villacis et al., 2003). Meanwhile, the 53 species found in this study greatly surpass the 21 species reported in native grasslands with a high tree density in Matagalpa, Nicaragua (Perez et al., 2006), the 20 species on the Coast of Chiapas, Mexico (Otero et al., 1999), and the 16 species in pastures of La Fortuna, in San Carlos, Costa Rica (Souza et al., 2000).

The 53 species present in the pastures evaluated are less than the 72 species reported in a cattle raising landscape in Rivas, Nicaragua (Harvey et al., 2007), the 98 species found in pastures in the region of Los Tuxtlas (Guevara et al., 1998), the 96 species in cattle farms with low levels of technification in the humid tropics of Costa Rica (Villacis et al., 2003), and the 101, 101, and 106 species found in three other cattle raising landscapes of Costa Rica and Nicaragua (Harvey et al., 2007). Number of species in these sites contrasts with the great diversity of tree species observed in pastures in the Monteverde region, in Costa Rica, where 190 species were recorded (Harvey and Haber, 1999).

Table 3 shows the family, species, common name, and frequency with which ST were found in pastures. With respect to their complementarity (Colwell and Coddington, 1994), species composition of pastures in the municipalities Tacotalpa and Huitiupan

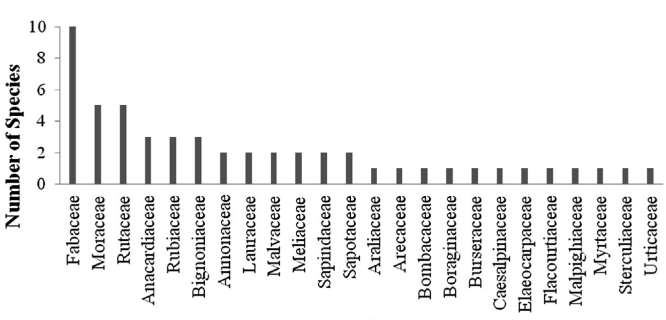

Fig. 2. Tree species and botanical families of scattered trees present in pastures of communities in two municipalities in the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

Table 3
Family, species, common name, and frequency of species of scattered trees in pastures of the communities of two municipalities of the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

Family	Species	Common name	Frequency
Anacardiaceae	*Mangifera indica*	Mango	37
	Spondias mombin	Jobo	4
	Spondias purpurea	Ciruela, Jocote	1
	Total		42
Annonaceae	*Annona purpurea*	Chincuya	3
	Annona reticulata	Anonilla	13
	Total		16
Araliaceae	*Dendropanax arboreus*	Caracolillo	2
Arecaceae	*Cocos nucifera*	Coco	2
Bignoniaceae	*Tabebuia rosea*	Macuilís	20
	Parmentiera edulis	Chanchig, Cuajilote	2
	Tabebuia guayacan	Guayacán	1
	Total		23
Bombacaceae	*Ceiba pentandra*	Ceiba	5
Boraginaceae	*Cordia alliodora*	Bojón	74
Burseraceae	*Bursera simaruba*	Palo mulato	1
Caesalpiniaceae	*Tamarindus indica*	Tamarindo	4
Elaeocarpaceae	*Muntingia calabura*	Capulín	5
Fabaceae	*Dalbergia stevensonii*	Amargoso	1
	Diphysa robinioides	Chipilín	95
	Erythrina sp.	Madre	1
	Gliricidia sepium	Cocoíte	34
	Inga punctata	Zelel	5
	Platymiscium dimorphandrum	Marimba, Cachimbo	2
	Inga spuria	Chelel	20
	Lonchocarpus hondurensis	Palo gusano	7
	Lonchocarpus rugosus	Matabuey, Machiche	2
	Enterolobium cyclocarpum	Guanacaste, Piche	105
	Total		272
Flacourtiaceae	*Zuelania guidonia*	Hule de montaña	6
Lauraceae	*Persea americana*	Aguacate	6
	Persea schiedeana	Chinín	3
	Total		9
Malpighiaceae	*Byrsonima crassifolia*	Nanche, Nance	9
Malvaceae	*Guazuma ulmifolia*	Guácimo	15
	Luehea candida	–	1
	Total		16
Meliaceae	*Cedrela odorata*	Cedro	393
	Swietenia macrophylla	Caoba	16
	Total		409
Moraceae	*Artocarpus altilis*	Castaño	1
	Brosimum alicastrum	Ramón	8
	Ficus padifolia	Matapalo	1
	Ficus sp.	Amate	1
	Poulsenia armata	Carne de pescado	1
	Total		12
Myrtaceae	*Psidium guajava*	Guayaba	2
Rubiaceae	*Blepharidium mexicanum*	Popiste	57
	Genipa americana	Jagua	3
	Genipa sp.	Palo calabaza	2
	Total		61
Rutaceae	*Citrus limon*	Limón	4
	Citrus reticulata	Mandarina	1
	Citrus sinensis	Naranja	30
	Zanthoxylum sp.	Abrojo	2
	Zanthoxylum riedelianum	Cola de lagarto	4
	Total		41
Sapindaceae	*Cupania glabra*	Quebracho cimarrón, Quiebrahacha	7
	Sapindus saponaria	Jaboncillo, Bolchiche	1
	Total		8
Sapotaceae	*Manilkara zapota*	Chicozapote	2
	Pouteria sapota	Zapote, Zapote mamey	3
	Total		5
Sterculiaceae	*Theobroma bicolor*	Pataste	1
Urticaceae	*Cecropia obtusifolia*	Guarumbo	1

differ by 69.8% and by 53.6% according to the Whittaker index (1977), indicating that several species identified are present in pastures in both municipalities. These phytogenetic resources are valuable for developing more intensive silvopastoral systems.

Species most frequently found were *Cedrela odorata* (393 individuals), *Enterolobium cyclocarpum* (105), *Diphysa robinioides* (95), *Cordia alliodora* (74), and *Blepharidium mexicanum* (57). The tallest species in the pastures (mean ± SD) were *Genipa americana* (25 ± 25.9 m), *Lonchocarpus hondurensis* (22.4 ± 9.9 m), and *Platymiscium dimorphandrum* (18.0 ± 1.4 m). The species with the greatest crown diameter were *Lonchocarpus rugosus* (25 ± 7.1 m), *Ceiba pentandra* (12.2 ± 4.8 m) and *P. dimorphandrum* (12.0 ± 2.8 m), while the ST with the greatest commercial height of clean bole were *P. dimorphandrum* (9.8 ± 0.4 m), *Pouteria sapota* (9.0 ± 1.7 m), and *E. cyclocarpum* (7.5 ± 2.5). Finally, the tree species which most contributed to basal area of the ST were *C. odorada* with 32.0 m^2, *E. cyclocarpum* with 8.7 m^2, and *M. indica* and *D. robinioides* with 5.3 m^2 each (Table 4).

3.6. Living fences

329 transects (3290 linear m) were carried out, and on average 45.8 ± 15.8 trees were recorded per 100 linear m of LF. The minimum average was recorded in the community El Remolino (9.5 individuals) and the maximum in Tomas Garrido (70.0 individuals; Table 5). Greater tree densities were observed in LF of the pastures of communities of Tacotalpa than in those of Huitiupan. Tree densities observed in LF of both municipalities (15.1–51.6 trees/100 linear m) approximate that of a cattle farm with a high level of intensification (30.8 trees/100 linear m; Villacis et al., 2003).

Of 35 pastures evaluated, 54% have LF comprised of several tree species, and the remaining 46% contained only the species *Gliricidia sepium* (Cocoite). This species is widely used by producers to delimit their pastures; it is frequently pruned to control its height, and prunings are used as vegetative matter for propagating the plant (Villacis et al., 2003).

Ranchers' preference for *G. sepium* – the principal species in many LF in the communities studied and which is also found in other parts of the state of Chiapas and above all in Tabasco – is largely explained by its agronomic versatility, its functionality, and by the products obtained from it. *G. sepium* is easy to plant by cuttings, is durable, and has rapid initial growth. Each individual has an average useful life of 12 years, and fulfills multiple functions, principally for small landholders. Pruning is generally carried out in January or every eight or nine months, and the principal trunk is maintained at a height of 2–2.5 m (Elgueta and Perez, 2001).

From the branches, firewood is obtained, with a minimum dry weight of 80–90 kg in a year and a half at a density of 60–75 plants per 100 linear m of LF (Ruiz, 2000). Furthermore, *G. sepium*'s foliage is used as fodder during the dry season, or as organic fertilizer, according to demand. Producer management of *G. sepium* demonstrates the importance of the species in the LF, as well as their broad knowledge and experience with this plant.

3.6.1. Species composition of living fences

In 3290 linear m of LF, 1464 trees were recorded, of which it was only possible to identify 1427, which belong to 32 species and18 botanical families (Table 6). In terms of number of species, the most representative tree in the LF is Fabacea, followed by Anacardiaceae and Meliaceae (Fig. 3). The most numerous species in the LF were *G. sepium* (1194 individuals), *C. odorata* (50), *Erythrina folkersii* (50), *Bursera simaruba* (36), and *Jatropha curcas* (26). Specific richness was 32 species, not including 37 trees which could not be identified.

The tallest species recorded in the LF (mean ± SD) were *Dalbergia stevensonii* (11.5 ± 0.7 m), *D. robinioides* (11.0 ± 5.7 m), and *E. cyclocarpum* (11.0 ± 0.0) (Table 7). Those with the greatest crown diameter were *E. cyclocarpum* (10 ± 0.0 m), *D. stevensonii* (8.0 ± 0.0 m), and *Byrsonima crassifolia* (6.0 ± 2.0 m), while the species with the greatest commercial height of clean bole were *D. stevensonii* (6.0 ± 2.8 m), *D. robinioides* (5.7 ± 6.0 m) and *E. cyclocarpum* (5.5 ± 2.1 m). Those species which most greatly contributed to the LF' basal height were *G. sepium* (29.3 m^2), *C. odorata* (2.1 m^2), and *E. folkersii* (1.1 m^2).

3.7. Carbon storage

Cattle raisers in the study area base animal feeding on grazing in pastures with a predominance of *Paspalum* sp., *C. plectostachyus*, and *P. merkeri Lecke*, and with varying densities of ST (Table 2) and/or LF (Table 5). With this type of livestock management, the producer: i) obtains a variety of products and services such as meat, milk, fiber, manure, animal labor, lumber, and firewood for self-provisioning or for sale; and ii) provides diverse environmental services on a local, regional, and global level.

One of the environmental services provided by silvopastoral systems which contributes to cleaner production is mitigation of effects of climate change through capture and storage of carbon (C) in biomass, leaf litter, roots, and soil by preserving or planting trees in pastures, which also leads to increased soil organic matter (Andrade and Ibrahim, 2003).

Estimations for C storage in pastures in the study area show that in the 122.6 ha sampled, the 1083 trees recorded have stored approximately 105 Mg of C.

For ST, based on average tree density of the pastures (12.3 trees ha^{-1}), average storage is calculated to be 3 (±4) Mg of C ha^{-1}. These pastures have a minimum storage of 0.04 and a maximum of 18.65 Mg of C ha^{-1} in above ground tree biomass alone. Average C storage of ST in this study (3 ± 4 Mg ha^{-1}) is greater than C stored in tree biomass (1.6 Mg ha^{-1}) of improved pastures with a low tree density (less than 30 trees ha^{-1}) in Costa Rica (Ibrahim et al., 2007), and less than C stored (7.1 Mg ha^{-1}) in the tree biomass of natural grasslands with a high tree density (more than 30 trees ha^{-1}) in that country, and than the 9.0 Mg of C ha^{-1} of improved pastures with a high tree density (more than 30 trees ha^{-1}) and the 11.9 Mg ha^{-1} of C of natural grasslands with a low tree density (less than 30 trees ha^{-1}) in Nicaragua (Ibrahim et al., 2007). Despite the fact that average tree density is low in our case study, C stored could be up to 18.6 Mg ha^{-1} if we consider the maximum value of tree density observed (34 trees ha^{-1}). This surpasses quantities of C stored in the different land use systems previously mentioned for Costa Rica and Nicaragua.

A variety of studies of tropical zones have demonstrated that the quantity of C stored in the soil is much greater than that stored in tree biomass (Callo-concha et al., 2002; Ibrahim et al., 2007). Given that this study does not consider C stored in the soil, the potential for C capture in pastures evaluated is even greater than that reported.

Based on data from net above ground primary production in pastures with steep slopes and little tree coverage – reported by Guzman (2011), it is estimated that pastures of the species *C. plectostachyus* evaluated store 13.1 Mg ha^{-1} of C per year. By contrast, grasslands of *P. merkeri Lecke* store 11.1 Mg ha^{-1} of C per year.

With respect to LF, it is estimated that for every 100 linear m of multi-species LF (±32 species), with an average distance of 2.1 m between trees and an average of 23.3 (±15.9) cm of DBH, 1.82 (±1.41) Mg of C ha^{-1} is accumulated. Pastures with LF along their entire perimeter (400 linear m) accumulate 7.28 (±5.66) Mg of C ha^{-1} in above ground tree biomass alone.

Table 4
Averages of diameter at breast height (DBH), total height, height of clean bole, greatest diameter of crown, and contribution to basal area of scattered trees in pastures with traditional silvopastoral management in communities of two municipalities in the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

Species	*N*	Average DBH, cm. (±SD)	Average total height, m. (±SD)	Average height of clean bole, m	Average greatest diameter crown, m	Basal area, m^2 ha^{-1}
Annona purpurea	3	21.3 (±1.5)	10.7 (±5.7)	1.6 (±0.5)	8.7 (±3.2)	0.11
Annona reticulata	13	31.7 (±13.7)	10.3 (±4.0)	2.6 (±2.3)	8.0 (±3.5)	1.20
Artocarpus altilis	1	43.3	11.0	5.0	6.0	0.01
Blepharidium mexicanum	57	26.3 (±6.3)	10.5 (±3.3)	4.2 (±2.2)	3.8 (±1.1)	3.27
Brosimum alicastrum	8	61.7 (±24.2)	14.3 (±2.9)	7.3 (±2.7)	7.2 (±3.3)	2.71
Bursera simaruba	1	22.9	14.0	4.0	8.0	0.04
Byrsonima crassifolia	9	31.1 ((±7.6)	7.5 (±1.9)	2.1 (±0.9)	5.4 (±1.9)	0.72
Cecropia obtusifolia	1	22.3	7.5	6.0	6.0	0.04
Cedrela odorata	392	36.0 (±10.3)	15.0 (±12.2)	5.3 (±3.8)	5.5 (±2.0)	43.22
Ceiba pentandra	5	88.6 (±53.0)	13.0 (±3.4)	4.5 (±3.3)	12.2 (±4.8)	3.96
Citrus limon	4	23.6 (±4.4)	5.4 (±0.75)	2.3 (±1.2)	4.0 (±2.0)	0.18
Citrus reticulate	1	33.0	9.9	2.5	8.9	0.09
Citrus sinensis	30	27.1 (±5.1)	7.4 (±6.2)	1.4 (±0.5)	5.2 (±1.2)	1.79
Cocos nucifera	2	25.1 (±7.2)	7.8 (±1.8)	5.5 (±0.7)	5.5 (±0.7)	0.10
Cordia alliodora	74	27.0 (±6.0)	11.7 (±7.9)	5.8 (±2.4)	4.4 (±1.5)	4.45
Cupania glabra	7	35.0 (±4.7)	7.1 (±1.2)	2.5 (±0.5)	4.9 (±0.4)	0.68
Dalbergia stevensonii	1	25.5	12.0	1.0	10.5	0.05
Dendropanax arboreus	2	24.5 (±3.2)	–	–	–	0.10
Diphysa robinioides	95	28.5 (±6.2)	11.1 (±3.7)	3.0 (±2.2)	7.7 (±2.9)	6.33
Erythrina sp.	1	25.5	4.0	1.5	4.0	0.05
Ficus padifolia	1	25.8	–	–	–	0.05
Ficus sp.	1	111.0	16.0	3.0	19.0	0.97
Genipa americana	3	43.8 (±8.1)	10.2 (±5.3)	6.5 (±4.3)	8.5 (±3.3)	0.46
Genipa sp.	2	67.0 (±1.4)	11.5 (±0.7)	3.5 (±2.1)	11.5 (±4.9)	0.71
Gliricidia sepium	34	33.9 (±10.0)	5.8 (±2.2)	2.1 (±0.5)	5.0 (±1.9)	3.33
Guazuma ulmifolia	15	42.4 (±20.4)	7.5 (±2.8)	1.7 (±0.7)	6.8 (±2.7)	2.58
Inga punctata	5	27.7 (±4.2)	14.1 (±6.0)	6.7 (±3.9)	5.4 (±1.8)	0.31
Inga spuria	20	24.0 (±3.2)	9.7 (±1.8)	2.0 (±1.2)	6.2 (±2.2)	0.92
Lonchocarpus hondurensis	7	45.2 (±14.2)	22.4 (±9.9)	4.1 (±3.0)	15.4 (±8.9)	1.22
Lonchocarpus rugosus	2	65.0 (±25.5)	17.5 (±3.5)	3.8 (±3.2)	25.0 (±7.1)	0.71
Luehea candida	1	67.5	9.5	1.7	6.5	0.36
Mangifera indica	37	43.6 (±22.2)	12.7 (±11.5)	2.2 (±1.6)	6.8 (±2.2)	6.33
Manilkara zapota	2	29.5 (±6.4)	16.9	2.2	8.0	0.14
Muntingia calabura	5	26.1 (±4.1)	6.8 (±2.0)	2.4 (±1.5)	7.2 (±1.6)	0.27
Parmentiera edulis	2	40.4 (±6.4)	13.3 (±4.8)	1.4 (±0.6)	10.5 (±0.7)	0.17
Persea americana	6	32.5 (±10.2)	10.5 (±3.0)	4.0 (±1.6)	6.4 (±2.3)	0.66
Persea schiedeana	3	36.3 (±15.0)	7.8 (±1.3)	2.0	7.3 (±1.5)	0.37
Platymiscium dimorphandrum	2	37.5 (±4.6)	18.0 (±1.4)	9.8 (±0.4)	12.0 (±2.8)	0.81
Poulsenia armata	1	71.7	30.2	12.3	17.0	0.50
Pouteria sapota	3	80.0 (±25.4)	14.3 (±1.5)	9.0 (±1.7)	6.8 (±2.8)	1.24
Psidium guajava	2	69.6 (±13.3)	6.8 (±3.2)	1.1 (±0.8)	7.0 (±2.8)	0.15
Sapindus saponaria	1	29.4	2.1	7.0	4.0	0.06
Enterolobium cyclocarpum	105	27.7 (±9.6)	13.0 (±3.1)	7.5 (±2.5)	5.8 (±1.8)	10.46
Spondias mombin	4	32.3 (±28.4)	8.6 (±6.6)	4.0 (±2.8)	5.8 (±5.2)	0.99
Spondias purpurea	1	28.0	2.5	1.7	5.0	0.06
Swietenia macrophylla	16	28.0 (±11.6)	9.6 (±2.4)	3.9 (±1.8)	4.0 (±1.4)	1.13
Tabebuia rosea	20	27.8 (±7.5)	9.7 (±1.2)	3.3 (±1.2)	4.6 (±1.3)	1.41
Tabebuia guayacan	1	29.0	12.0	6.0	10.0	0.06
Tamarindus indica	4	28.0 (±8.8)	5.4 (±2.4)	3.7 (±2.9)	5.6 (±1.5)	0.33
Theobroma bicolor	1	31.6	7.0	2.5	3.0	0.04
Zanthoxylum sp.	2	23.6 (±0.0)	6.7	2.7	10.0	0.14
Zanthoxylum riedelianum	4	30.0 (±26.6)	11.8 (±3.1)	4.0 (±2.7)	7.9 (±4.3)	0.56
Zuelania guidonia	6	35.2 (±18.7)	11.3 (±2.0)	6.6 (±3.5)	7.8 (±1.7)	1.20
Other trees	57	47.5 (±17.5)	11.7 (±7.8)	4.9 (±3.8)	6.2 (±3.1)	8.66
					Total	116.46

Table 5
Average density (trees per 100 linear meters) of living fences and average distance between each tree in communities of two municipalities in the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

Municipality	Community	Maximum no. of trees	Minimum no. of trees	Average number of trees (±SD)	Average distance between trees, m (±SD)
Huitiupan	Buen Paso	62.2	38.8	47.1 (±9.4)	2.2 (±1.4)
	El Remolino	20.7	9.5	15.1 (±7.9)	2.6 (±0.1)
	Ramos Cubilete	47.5	36.6	42.1 (±5.4)	1.7 (±0.2)
Tacotalpa	Cuviac	62.5	46.0	51.6 (±9.5)	2.0 (±0.6)
	La Cumbre	67.7	38.4	50.4 (±10.9)	2.4 (±0.3)
	La Pila	62.5	20.0	48.5 (±15.1)	2.8 (±1.6)
	Oxolotán	54.2	42.5	49.8 (±6.4)	1.9 (±0.5)
	Tomas Garrido	70.0	52.8	61.4 (±12.1)	1.6 (±1.0)

Table 6
Family, species, common name, and frequency of tree species in living fences of pastures in communities of two municipalities of the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

Family	Species	Common name	Frequency
Anacardiaceae	*Mangifera indica*	Mango	1
	Spondias mombin	Jobo	10
	Spondias purpurea	Ciruela, Jocote	4
	Total		15
Annonaceae	*Annona muricata*	Guanábana	1
	Annona reticulata	Anonilla	4
	Total		5
Bignoniaceae	*Tabebuia rosea*	Macuilís	4
Bixaceae	*Bixa orellana*	Achiote	1
Bombacaceae	*Ceiba pentandra*	Ceiba	1
Boraginaceae	*Cordia alliodora*	Bojón	3
Burseraceae	*Bursera simaruba*	Palo mulato	36
Elaeocarpaceae	*Muntingia calabura*	Capulín	2
Euphorbiaceae	*Jatropha curcas*	Piñón	26
Fabaceae	*Dalbergia stevensonii*	Amargoso	2
	Diphysa robinioides	Chipilín	2
	Erythrina folkersii	Madre	50
	Gliricidia sepium	Cocoíte	1194
	Inga punctata	Zelel	3
	Inga spuria	Chelel	2
	Lonchocarpus hondurensis	Palo gusano	1
	Enterolobium cyclocarpum	Guanacaste, Piche	2
	Total		1257
Flacourtiaceae	*Zuelania guidonia*	Hule de montaña	2
Lauraceae	*Persea americana*	Aguacate	2
Malpighiaceae	*Byrsonima crassifolia*	Nanche, Nance	3
Malvaceae	*Guazuma ulmifolia*	Guácimo	7
Meliaceae	*Cedrela odorata*	Cedro	50
	Swietenia macrophylla	Caoba	3
	Trichilia havanensis	Castarrica	3
	Total		56
Moraceae	*Brosimum alicastrum*	Ramón	1
	Ficus sp.	Amate	1
	Total		2
Rubiaceae	*Blepharidium mexicanum*	Popiste	1
Rutaceae	*Citrus reticulata*	Mandarina	3
	Citrus sinensis	Naranja	1
	Total		4

Considering the entire tree component of the pastures (ST + LF), it is estimated that one hectare of pasture with a tree density of 12.3 trees completely delimited by LF (400 linear m), with an average of 45.8 trees per 100 linear m, without taking into account C stored in the grass, stores 10.28 Mg ha^{-1} of C, with a minimum of 1.6 Mg ha^{-1} and a maximum of 41.97 Mg of C ha^{-1}. When C stored by herbaceous plants is added to this hectare, considering dominance by

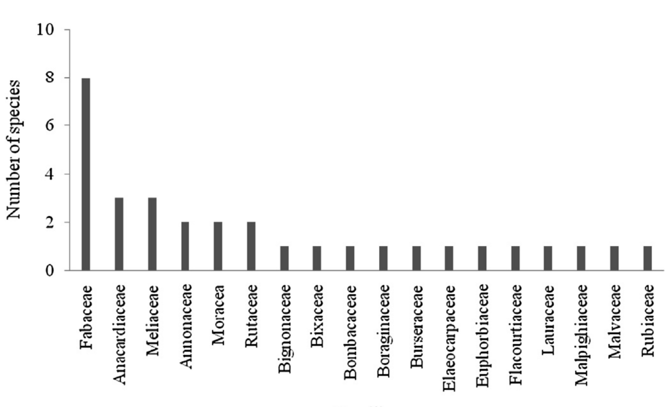

Fig. 3. Tree species and botanical families found in the living fences of pastures with traditional silvopastoral management in communities of two municipalities in the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

C. plectostachyus (ST + LF + grass), a total average accumulation of 23.38 Mg of C ha^{-1} is estimated. On the other hand, when *P. merkeri Lecke* predominates, a total average C accumulation of 21.38 Mg of C ha^{-1} is estimated.

Results of this study surpass the storage of 8.18 Mg of C ha^{-1} by grasslands with native grass and ST, and the 12.54 Mg ha^{-1} of C fixed by improved grasses in silvopastoral systems in Matiguas, Nicaragua (Ruiz, 2002). Nevertheless, it approaches the 22.80 ± 8.34 Mg of C ha^{-1} reported by Morales-Coutiño (2010) for live biomass (mature and young trees, grass, and roots) of pastures with ST in the Lacandon Jungle region.

On the contrary, maximum accumulation of C (23.38 Mg of C ha^{-1}; ST + LF + *C. plectostachyus* grass) was greatly inferior to findings for carbon capture by the Scolel'te Project in the Tzeltal and Tzotzil Maya regions of the Mexican state of Chiapas, which show that agroforestry systems' potential for carbon capture may vary from 40 to 140 Mg of C ha^{-1} (De Jong et al., 1997).

Using local phytogenetic resources, a good option for increasing C capture in the study area is implementation of protein banks, due to the fact that they benefit meat and milk production, and furthermore provide a variety of environmental services. For this reason, in communities in Huitiupan, Tacotalpa, and Tecpatan, fodder banks were established, such as those reported by Gomez-Castro et al. (2010) and Morales-Diaz (2011). These authors have estimated that the tree component alone of a fodder bank of *G. sepium* with a density of 1600 trees per hectare (planted at 2.5 × 2.5 m distances) may store up to 15.3 Mg of C ha^{-1}. Also, a protein bank of *Leucaena leucocephala* with a density of 4444 trees ha^{-1} (planted at 0.5 × 1.5 m distances) in an open grassland with *Hyparrhenia rufa* (jaragua grass) may store up to 19.6 Mg of C ha^{-1} (Chave et al., 2005; Gomez-Castro et al., 2010).

3.8. Environmental services and cattle production in treeless pastures, and with two types of silvopastoral systems

Table 8 compares several environmental and other indicators related to cattle production with three forms of management. The table shows that C stored in one hectare of pasture in monoculture (without trees) of *C. plectostachyus* grass is less than that stored in one hectare of pasture with LF and ST. Both prove to be less than C stored in a pasture with LF and ST which was improved by planting 1600 additional *G. sepium* trees as a protein bank. These results confirm the significant contribution of trees in pastures to cleaner production.

A similar tendency was found with respect to symbiotic fixation of atmospheric nitrogen to the soil by leguminous trees present in the management systems compared in Table 8. The quantity of fixed nitrogen provides a valuable contribution to cleaner cattle production as its presence allows for avoiding use of chemically synthesized fertilizers which, aside from being costly, are produced using energy intensive processes, and they contain nitrogen in a form which may be harmful to soil microorganisms and contaminate soil, plants, and groundwater due to lixiviation (Rodríguez, 1993; Elevitch and Wilkinson, 1999; Urzua, 2000; Steinfeld et al., 2006). Another advantage is that the efficiency of use of N fixed to the soil by leguminous trees is close to 100%, as compared to 50–60% for soil application of nitrogen fertilizers (Rodríguez, 1993; Urzua, 2000).

Based on data from several reports (Liyanage et al., 1994; Jayasundara et al., 1997; Dulormne et al., 2003), leguminous trees in pastures fix approximately 32 g N tree^{-1} year^{-1}, and therefore it is estimated that as a whole, the total of all leguminous trees (1529 individuals) present in the 35 pastures evaluated (122.6 ha) fix a total of 48.9 kg N year^{-1}. The majority of this fixed N (40.2 kg N year^{-1}) is attributable to LF, which contain a large majority (82%)

Table 7
Average of diameter at breast height (DBH), total height, greatest crown diameter, height of clean bole, and average contribution at basal area of trees in living fences in pastures of communities in two municipalities in the mid-region (Chiapas–Tabasco, in southeastern Mexico) of the Grijalva cross-border watershed.

Species	N	Average DBH, cm. (±SD)	Height, m. (±SD)	Average height of clean bole, m. (±SD)	Average greatest diameter crown, m. (±SD)	Basal area, m^2 ha^{-1}
Annona muricata	1	12.0	4.0	1.5	2.0	0.01
Annona reticulata	4	16.0 (±2.9)	5.0 (±2.7)	2.8 (±2.4)	2.3 (±1.3)	0.07
Bixa orellana	1	11.0	3.0	1.0	2.0	0.01
Blepharidium mexicanum	1	17.0	5.0	1.5	4.0	0.02
Brosimum alicastrum	1	90.0	8.0	5.0	4.0	0.64
Bursera simaruba	36	19.9 (±7.1)	7.2 (±2.8)	3.7 (±1.8)	4.5 (±2.2)	0.54
Byrsonima crassifolia	3	22.7 (±9.5)	7.3 (±1.5)	2.3 (±0.6)	6.0 (±2.0)	0.16
Cedrela odorata	50	23.2 (±10.5)	6.6 (±2.8)	3.5 (±2.2)	4.3 (±2.2)	1.96
Ceiba pentandra	1	28.0	8.0	4.0	4.0	0.06
Citrus reticulata	3	16.0 (±4.4)	5.0 (±0.0)	0.5 (±0.0)	4.0 (±0.0)	0.06
Citrus sinensis	1	12.0	4.0	1.6	4.0	0.01
Cordia alliodora	3	25.0 (±13.7)	8.0 (±1.0)	3.8 (±1.9)	5.0 (±1.4)	0.33
Dalbergia stevensonii	2	60.9 (±83.6)	11.5 (±0.7)	6.0 (±2.8)	8.0	1.17
Diphysa robinioides	2	23.0 (±0.0)	11.0 (±5.7)	5.8 (±4.3)	3.5 (±0.7)	0.08
Erythrina folkersii	50	17.0 (±6.9)	5.6 (±2.7)	2.4 (±1.2)	3.1 (±1.8)	2.12
Ficus sp.	1	10.5	12.6	1.8	2.0	0.01
Gliricidia sepium	1193	17.1 (±9.0)	5.1 (±2.1)	2.1 (±0.7)	3.6 (±1.6)	36.99
Guazuma ulmifolia	7	24.1 (±6.7)	6.7 (±2.0)	3.1 (±2.8)	4.8 (±1.1)	0.18
Inga punctata	3	23.0 (±14.7)	5.7 (±2.1)	1.7 (±0.2)	5.7 (±1.5)	0.14
Inga spuria	2	35.0 (±25.4)	6.0 (±2.8)	3.3 (±1.1)	5.5 (±2.1)	0.29
Jatropha curcas	26	15.9 (±5.5)	4.6 (±1.0)	1.9 (±0.5)	4.0 (±1.3)	1.18
Lonchocarpus hondurensis	1	14.0	6.0	4.0	6.0	0.02
Mangifera indica	1	22.0	15.0	10.8	4.2	0.04
Muntingia calabura	2	17.5 (±3.5)	6.5 (±4.9)	2.5 (±1.0)	4.4 (±0.6)	0.04
Persea americana	2	20.0 (±5.7)	4.9 (±4.5)	3.3 (±2.5)	2.7 (±3.3)	0.16
Enterolobium cyclocarpum	2	47.5 (±17.7)	11.0	5.5 (±2.1)	10.0	0.13
Spondias mombin	10	19.5 (±6.9)	7.9 (±3.2)	2.8 (±0.8)	2.9 (±1.2)	0.37
Spondias purpurea	4	18.3 (±2.1)	4.0 (±1.4)	1.7 (±0.2)	2.8 (±1.0)	0.11
Swietenia macrophylla	3	21.3 (±9.6)	6.2 (±3.2)	3.0 (±1.1)	4.0 (±2.6)	0.12
Tabebuia rosea	4	20.3 (±7.3)	6.5 (±1.7)	2.1 (±1.0)	4.5 (±1.9)	0.14
Trichilia havanensis	3	14.7 (±1.5)	6.0 (±2.6)	0.9 (±0.8)	4.0 (±1.7	0.04
Zuelania guidonia	2	12.5 (±3.5)	7.0 (±1.4)	3.5 (±2.1)	6.0 (±0.0)	0.07
					Total	47.29

of the leguminous trees and in which *G. sepium* is the most common species. Meanwhile, association of leguminous trees with grasses in pastures has positive effects on yield of grasses, which are nourished with part of the nitrogen biologically fixed by the leguminous trees (Jayasundara et al., 1997; Rao and Giller, 1993). In this manner, traditional silvopastoral systems help reduce environmental contamination while also enhancing production.

Animal welfare is also favored by silvopastoral systems due to the fact that cattle are managed in pastures with a high tree density and the trees protect the animals from inclement weather (Matthews, 1996; Souza et al., 2004). This leads to improvement of environmental conditions required by the animals to develop their productive and reproductive functions and in general satisfy their physiological needs (Nahed-Toral et al., 2013).

Similarly, milk production during the rainy season (May–October) as well as production of weaned calves per year increased when animals were managed in pastures with a greater tree density. In this manner, sustainable pasture management is achieved due to avoidance of overgrazing, erosion, and loss of soil humidity. Furthermore, biodiversity is increased, forage production is enhanced, and animal feeding is improved throughout the year.

The rate of the Organic Livestock Proximity Index (OLPI; Nahed-Toral et al., 2013) increases when pastures are managed so as to have a greater tree density (Table 8). This index is an indicator of: i)

Table 8
Comparison of several environmental indicators, as well as indicators for production and quality of animal products of cattle raising units managed with treeless pastures and with two types of silvopastoral systems with a predominance of African star grass (*Cynodon plectostachyus*) in the mid-watershed of the Grijalva River in Mexico.

Indicator	[a]Pasture with *C. plectostachyus* as a monoculture	[a]Pasture with living fence, scattered trees, and *C. plectostachyus*	[b]Pasture with living fence, scattered trees, [c]protein bank, and *C. plectostachyus*
C Storage, Mg ha^{-1}	13.1 (±6.8)	23.4 (±12.4)	27.1 (±12.4)
N Fixation, kg N ha^{-1} $year^{-1}$	–	0.40 (±0.25)	51.6 (±12.8)
[e]Animal welfare, %	65.9 (±9.2)	75.9 (±10.6)	86.0 (±12.0)
Milk during rainy season, l cow day^{-1}	4.0 (±0.1)	4.75 (±0.2)	5.0 (±0.2)
Calves, no. ha^{-1} $year^{-1}$	0.47 (±0.2)	0.56 (±0.3)	0.63 (±0.3)
[d]OLPI, %	48.4 (±5.3)	54.0 (±5.9)	63.4 (±6.9)

[a] Pasture with 1 ha surface evaluated in this study.
[b] Pasture with 1 ha surface, with traditional silvopastoral management, improved with 1600 *G. sepium* trees as a protein bank (Guzman, 2011; Nahed-Toral et al., 2013).
[c] C stored by the 1600 trees (3.7 Mg ha^{-1}) during the first year of establishment, when tree trunks had an average diameter at breast height of 5 cm (estimated according to Gomez-Castro et al., 2010).
[d] Organic Livestock Proximity Index (estimated according to methodology proposed by Nahed-Toral et al. (2013)).
[e] This indicator is composed of five variables which is one of the ten OLPI indicators (Nahed-Toral et al., 2013; Mena et al., 2011).

the level of use of agroecological technologies, which are environmentally friendly, ii) the extent to which producers respect the list of permitted, prohibited, and restricted substances stipulated by organic production standards, and iii) the quality of animal products obtained in the cattle raising units. The higher rate of OLPI in the two systems of pastures with trees is principally due to the fact that indicators for sustainable pasture management, animal welfare, and feed management – included among OLPI's ten indicators – have a high rate of approximation to organic production standards (IFOAM, 2009). It is necessary to implement corrective measures for the OLPI indicators and variables which limit organic certification (also known as green-seal, eco-labeled, or ecological seal) of animal products in order to differentiate them from conventional products and thus guarantee authenticity of producers' environmental efforts (Abarca and Sepúlveda, 2001).

On an international level, silvopastoral systems is a prototype agroforestry for cleaner production, because are currently considered to be tools for adaptation to and mitigation of climate change, and therefore their producers have the possibility of receiving payment for environmental services, due to the fact that these systems allow for (Gobbi and Casasola, 2003; Ibrahim et al., 2006; Steinfeld et al., 2006; Murgueitio, 2009): i) mitigating effects of climate change through C capture and storage, principally by planting trees and increasing organic soil matter; ii) reducing CO^2 emissions by avoiding slash and burn and deforestation due to reduced pressure on forests and jungles; iii) reducing nitrous oxide emissions by reducing nitrogen fertilizer use; iv) reducing methane gas emissions by offering animals a variety of fodders with greater nutritional quality, greater digestibility, and a better pattern of ruminal fermentation; and iv) reducing the impact of rain on the soil, thus increasing the soil's capacity for water infiltration and retention and diminishing surface runoff (Rios et al., 2007).

Unlike treeless pastures, silvopastoral systems increase a property's plant coverage, improve connectivity among forest fragments, and have a greater genetic diversity of trees, shrubs, grasses, weeds, wild animals, ants, spiders, and dung beetles (Harvey and Haber, 1999). The increase in species and number of birds in pastures with trees enhances environmental services related to pollination, seed dispersion, and biological control of insect pests Crespo, 2008; Harvey and Haber, 1999; Alonso, 2011).

In silvopastoral systems with rotational grazing (Ibrahim et al., 2006; Steinfeld et al., 2006; Murgueitio, 2009): i) better conditions are provided for nutrient recycling in the soil, which depends on the activity of a large number of organisms which decompose organic matter (feces, leaf litter, dead plants); ii) favorable soil conditions are recovered upon diminishing soil compaction, principally due to recuperation of beneficial organisms, production of leaf litter, and reduction of agrochemical use; iii) a large quantity of biological controllers naturally regulate pests without the need for frequent application of chemical insecticides. These beneficial organisms are highly dependent on plant cover, shade, and humidity, and require specific sites for feeding and nesting, such as those offered by silvopastoral systems (Crespo, 2008).

Trees associated with pastures contribute to reducing erosion through their root systems. The variety of species is very important, as variation in lengths and structures of the root system helps to more effectively retain soil (Ibrahim et al., 2006; Young, 1997). Furthermore, use of leguminous trees reduces the need for nitrogen fertilizers, thus avoiding contamination resulting from application of nitrogen to the pastures (Steinfeld et al., 2006).

An important aspect of silvopastoral systems is that they improve the hydric balance, since, when woody plants and grasses share the same space, the lesser temperature of the herbaceous strata under the tree crown leads to a diminished transpiration rate and less evaporation (Wilson and Ludlow, 1991). This may retard or avoid hydric stress during the dry period. Perennial woody plants affect the water dynamic (Young, 1997; Rios et al., 2007) by: i) acting as barriers which reduce runoff; ii) reducing the impact of raindrops, and iii) improving the soil by increasing water infiltration and retention. These impacts depend on tree size, principally height and crown cover.

Due to greater ecological, economic, and social benefits of silvopastoral systems as compared to conventional livestock raising systems, we recommend that producer capabilities be strengthened in the context of intensive, integrated silvopastoral systems. This prototype of alternative livestock raising provides a tool for adaptation to and mitigation of climate change, as well as for achieving cleaner production, and the development of this prototype through local resources involves commitment and co-responsibility by the various social actors involved, as well as tangible changes in state and national livestock policy.

Results presented in this study show that traditionally managed silvopastoral systems undoubtedly contribute to cleaner cattle production. Nevertheless, the following actions may be taken which increase benefits provided by these systems. Aside from the topics analyzed, it is recommended that further scientific studies be carried out regarding greenhouse gas emissions, particularly with respect to diminishing nitrous oxide emissions as a result of reduced use of chemically synthesized nitrogen fertilizers and reduced processing of manure, as well as reduction of enteric methane emissions of ruminants managed with different types of silvopastoral systems. Also, it is necessary to evaluate the socio-economic benefits of silvopastoral systems.

Currently, agricultural producers of the region do not receive any recognition or economic benefit for environmental services provided by their traditional silvopastoral systems. Therefore, government institutions – such as the Mexican National Forestry Commission (CONAFOR according to its Spanish initials) - should provide cattle raisers with traditionally managed silvopastoral systems with an economic incentive for their contributions to this type of production, as has been achieved in some countries for environmental services of silvopastoral and other agricultural systems (Montagnini, 2009; Pagiola et al., 2004).

4. Conclusions

- Technical and economic characteristics of the cattle raising units show limits and potentials which should be addressed so that farms may advance toward sustainable development.
- In the study area, extensive cattle raising, promoted by governmental institutions, has strongly impacted vegetation and modified original landscapes, and maize fields are being converted to pastures at an accelerating rate.
- Scattered trees in pastures and living fences fulfill multiple functions in the cattle raising units. The majority of scattered trees are remnants of original vegetation deliberately conserved as a result of producer preferences, and living fences are planted and cared for by producers.
- Fifty three species of scattered trees from 24 botanical families were identified, with a predominance of the species *C. odorata*, *E. cyclocarpum*, and *D. robinioides*.
- In the living fences, 32 tree species belonging to 18 botanical families were identified, with a predominance of *G. sepium*.
- Average density of scattered trees in the pastures studied is low (12.3 trees ha^{-1}), and that of living fences (45.8 trees/100 linear m) is similar to other densities reported for the study area.
- Predominant herbaceous species in pastures were the grasses *Paspalum* sp. and *C. plectostachyus*
- Considering the average tree density found in this study, it is estimated that one hectare of pasture with a dominance of

C. plectostachyus grass (13.10 Mg C ha^{-1}) surrounded by a living fence (7.28 Mg C ha^{-1}) and containing scattered trees (3.00 Mg C ha^{-1}) has a total accumulation of 23.38 Mg C ha^{-1}.
- The total of the leguminous trees (1529 individuals) found in the 35 pastures evaluated (122.6 ha) fix 48.9 kg N $year^{-1}$; the majority of this fixed N (40.2 kg N $year^{-1}$) comes from living fences, in which the large majority of the leguminous trees (82%) are found and in which *G. sepium* is the most common species.
- Carbon storage, symbiotic fixation of atmospheric nitrogen to the soil by leguminous trees, animal welfare, production of milk and calves, and the Organic Livestock Proximity Index are all increased to the extent that pastures are managed with a greater tree density.

Cattle raising with silvopastoral management provides a variety of goods and services to society, is a means of adaptation to and mitigation of climate change, and is a prototypical form of agroforestry which may be classified as cleaner production. Increasing intensification and integration of silvopastoral systems by using local resources depends on development of producers' capabilities and implies commitment and co-responsibility by the various social actors involved, as well as significant changes in state and national livestock raising policies.

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