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AGRO-ECOSYSTEM SERVICES ASSESSMENT OF SILVOPASTORAL EXPERIENCES IN CHIAPAS, MEXICO: TOWARDS A METHODOLOGICAL PROPOSAL

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SUMMARY

In response to the current needs of humanity with regard to food production, environmental disasters and climate change, it is important to define (livestock) production systems and management practices that are both productive and ecologically sustainable. We qualitatively assessed advanced silvopastoral experiences in five ecologically and culturally distinct regions in Chiapas, Mexico, given their ability to provide key services: internal (productivity and productive resiliency) and external (climate change mitigation and biodiversity conservation). We propose 20 indicators that reflect management, resources, use of external inputs, availability of food, commercial products and animal feed and trees in grazing and forest areas. Sets of some indicators form criteria for dependence on external inputs, productive diversification with emphasis on food security, soil conservation, tree cover and landscape connectivity, among others. Indicators and thresholds were adjusted to critical (traffic light) levels, based on field data. Comparing the levels reached by the studied experiences, we found that most of the resulting services go hand in hand; so 'win–win' situations are possible to be achieved. The elements and practices that affect both internal and external services were explored. The red light critical points in each production unit were identified so that they could be attended. Experiences that presented higher levels in assessment criteria could serve as examples to enable the improvement of livestock systems under similar conditions. We propose this assessment as a tool for rapid intervention that can be widely applied to livestock systems, from conventional to organic or diversified, because of the criteria used. However, it can be more flexible, as new criteria can be added and thresholds can be adjusted for other types of production systems, always reflecting local and desired conditions. The proposed indicators can be also used as a basis for a quantitative agroecosystem assessment.

INTRODUCTION

In south-eastern Mexico, as in most Latin American countries, extensive livestock systems have become increasingly important at the expense of forests and agricultural land uses. During the last few decades, to counteract the damage caused by extensive ranching, silvopastoral systems – which are areas of livestock management diversified with arboreal – were re-evaluated and began to be promoted (Herrero *et al.*, 2009). Furthermore, practices that respect and enhance the natural processes and functions

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of soil and living species as well as good practices for livestock feeding, gained importance (see: Morales *et al.*, 2011; Niggli *et al.*, 2009). Throughout this text, the term silvopastoral experiences (SPE) refers to livestock systems of small-medium size (10–120 ha) that include, to a greater or lesser degree, the management of trees and other good practices.

Diverse approaches, criteria and methods to assess livestock systems have focused on productivity, sustainability, resilience, greenhouse gases (GHG) emissions or balance, mitigation and adaptation to climate change, biodiversity and ecosystem services in general. For this study, we distinguish Agro-Ecosystem Services (AES), according to the principal type of beneficiary, in two types: (i) internal, those that benefit the agroecosystem and/or the producer, and () external, those that benefit the environment and society outside the production system boundaries, without apparent direct internal benefit.

The objective of this study is to comparatively assess advanced SPE[1] in different regions-contexts in the state of Chiapas, in order to know the best levels reached in AES. To this end, we propose qualitative indicators that facilitate the rapid evaluation of livestock systems by researchers or by their owners. Moreover, we explore the elements and management practices in the different regions, which benefit both the agroecosystem-producer and the environment.

MATERIALS AND METHODS

Study area: advanced silvopastoral experiences

The advanced experiences were selected following a snowball sampling strategy (Atkinson and Flint, 2001); first through consultations with Chiapas-based silvopastoral experts and producers participating in the 'Red de Ganadería Sostenible y Cambio Climático de Chiapas' (Network for Sustainable Livestock and Climate Change CATIE-ECOSUR), and then through proposals of local silvopastoral producers.

These were 13 SPE in eight locations, in five ecologically and culturally distinct regions in Chiapas, Mexico: Taniperlas and San Caralampio in the Lacandon jungle; Tierra y Libertad and California in 'Sepultura' Biosphere Reserve in the Sierra Madre; Unión Pijijiapan and Salto de Agua, municipality of Pijijiapan, on the Pacific coastal plain and Sierra Madre's foothills; San Vicente in the Frailesca region, in the central valleys, and Raudales Malpaso, municipality of Mezcalapa, in the northern region (Figure S1, available online at https://doi.org/10.1017/S0014479717000539). Advanced SPE have an altitude that ranges from 10 to 1140 masl, and original vegetation from high evergreen to deciduous tropical forest and pine-oak forest, on different levels of conservation-fragmentation. Type of producers and system management also differ (Table 1).

[1]Advanced silvopastoral experiences refers to production units that are considered locally as the best livestock systems with the highest tree cover.

Table 1. Main agro-ecological features of the studied silvopastoral experiences in the five cattle regions, in Chiapas State, Mexico.

Physiographic regions	Lacandon Jungle*	Sepultura BR†	Pijijiapan municipality‡	Frailesca region‡	Mezcalapa xmunicipality‡
Altitude (masl)§	600–800	900–1140	10–250	500–700	200–400
Annual average temp °C	25	22	27	24	25
Precipitation (mm/year)	2000–2500	1500–2000	1500–2000	800–1200	1700–2200
Primary vegetation type	Evergreen tropical forest	Pine-oak forest	(Semi) evergreen tropical forest	Dry deciduous tropical forest	(Semi) evergreen tropical forest
Landscape state§, ¶	Variegated-fragmented	Fragmented	Fragmented	Relictual	Relictual
Producer type	Indigenous	Mestizos	Mestizos	Mestizos	Mestizos
Management type	Traditional	Traditional	Traditional	Holistic	Organic
Average farms' size (has)§	17	32	53	93	110

Sources: *INE (2000); †INE (1999); ‡(INEGI, 2016); § field data; ¶ landscape categories: variegated 60–90%, fragmented 10–60%, relictual <10% of original forest cover (McIntyre and Hobbs, 1999).

Criteria and indicators to assess agro-ecosystem services provided by silvopastoral experiences

SPE were assessed upon four indicative AES. We considered two internal services: (i) productivity and (ii) productive resilience, because we recognize productivity as the obvious aim of livestock systems, along with the importance to ensure this function against deterioration and sudden changes (Koohafkan *et al.*, 2011).

We took into account two external services: (iii) climate change mitigation and (iv) biodiversity conservation because we consider that both combined reveal overall system potential to provide environmental services. This is because the tree cover (TC) and soil conservation criteria used to assess the potential for GHG sequestration can also indicate hydrological services provision because they increase infiltration, reduce runoff and sediments, and improve water physical–chemical quality (Ríos *et al.*, 2007). Meanwhile, efforts on biodiversity conservation affect ecosystem functions, scenic beauty, and recreational and cultural activities (Cardinale *et al.*, 2012).

We used 20 local indicators to assess SPE for the AES provided (Table 2). Initially, the indicators were selected through literature revision and consultation with experts, and then these and thresholds were adjusted after consultation with producers, semi-structured interviews, analysis of production unit maps and field observations. Based on a traffic light evaluation, ordinal values 1, 3 and 5 are assigned to indicators; where 1 represents a red light, 3 a yellow light that means a can-be-better or a not-to-worry situation, and 5 a green light or the highest level (Table 3). In some cases, a value of three indicates a situation, which cannot be evaluated under certain criteria; for example, in evaluating the state of riparian areas, it could mean that there is no visible erosion and that there is a moderate TC protection, but could also mean that there is no water stream. Some sets of indicators integrate useful

Table 2. Criteria and indicators used to assess internal and external services of silvopastoral experiences.

Indicators and criteria	Agroecosystem services	*Productivity*	*Productive resilience*	*Climate change mitigation*	*Biodiversity conservation*
Livestock system purpose		+			
Calves survival (less mortality)		+			
Less fattening time		+			
Infrastructure		+			
Less fossil fuels	*Reduced use of external inputs*		+	+	
Less agrochemicals	*Reduced use of external inputs*		+	+	
Less purchased animal feed products	*Reduced use of external inputs*		+	+	
Food tree species	*Food security*; *Production diversification*		+		
Food products	*Food security*; *Production diversification*		+		
Trade products and activities	*Trade*; *Production diversification*		+		
Animal breeds	*Livestock system*; *Trade*; *Production diversification*		+		
Fodder tree spp.	*Livestock system*; *Trade*; *Production diversification*		+	+	
Energy forage spp. and products	*Livestock system*; *Trade*; *Production diversification*		+		
State of slopes	*Soil conservation*		+	+	
State of riparian areas*	*Soil conservation*		+	+	+*
Tree cover in grazing areas	*Tree cover*			+	+
Size (%) of forest areas	*Tree cover*			+	+
Tree richness in grazing areas					+
State of forest areas					+
State of live fences	*Connectivity**				+

*It is an indicator of connectivity and of the biodiversity conservation service.

criteria for assessing independence from external inputs, production diversification with emphasis on food security, soil conservation, TC and landscape connectivity, among others. All indicators have equal importance for being qualitative and for being based on different types of necessities and decision. The potential of SPE to provide each AES was the result of the unweighted mean of these indicators, taking values from 1 to 5 (very low, low, medium, high and very high).

Productivity indicators

To evaluate the productivity potential of SPEs four criteria were considered: (A.1) purpose of livestock system (with bimodal high and low values: 1 and 5), (A.2) calf survival, (A.3) less fattening time and (A.4) infrastructure, as indicators of productivity and efficiency of the livestock system.

On a dual-purpose livestock system: milk and meat, productivity is improved by long-term sales and short-term day to day sales, as interviewed producers and others stated (e.g. Waithaka *et al.*, 2006). Calf survival or its opposite, mortality rate, is an important indicator of animal welfare as well as of productivity (Uetake, 2013). Shortening breeding or fattening time – from calves to steers (250 kg or more) – to a year or less, also improves productivity. The use of tools and machinery, either individually

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Table 3. Criteria and thresholds for the agro-ecosystem services assessment of livestock systems (based on advanced silvopastoral experiences in Chiapas, México).

Indicators Levels	Red (1)	Yellow (3)	Green (5)
Livestock system purpose	Breeding, fattening	–	Dual purpose*
Calves mortality	>10%	5–10%	≤5%
Fattening time	>1 year	9–12 months	<9 months
Infrastructure	Barbed wire fence, chute, extensive paddocks	Forage mill, silos, fodder banks with cut and carry	Milk machine, electric fence, rotational graz. small paddocks
Fossil fuels	Frequent use	Occasional	No use
Agrochemicals	Frequent use	Occasional	No use
Purchased animal feed products	Frequent use	Occasional	No use
Food tree species	<3	3–6	≥7
Food products	<2	2–3	≥4
Trade products and activities	<3	3–4	≥5
Animal breeds	Non-adapted	Adapted or creole	Crosses, reproductive management
Fodder tree species	<3	3–4	≥5
Energy forage species and products	<4	4–6	≥7
State of slopes	Without or sparse Tree Cover (TC), erosion	No slope or with moderate TC, without erosion	Dense TC, appropriate management practices
State of riparian areas	Without or sparse TC, erosion	No water streams or with moderate TC, without erosion	Dense TC, appropriate management practices
Tree cover in grazing areas	≤5%	5–15%	>15%
Proportional size of forest areas†	≤10% of total area	10–25% of total area	>25% of total area
Tree richness in grazing areas	<10 species	10– 19 species	≥20 species
State of forest areas‡	Fallows, swampy areas	Forest fragments of low relative diversity	Conserved or reforested
State of live fences	Without TC	Sparse or moderate TC	Closed canopy or multi-strata

*Dual-purpose: milk and meat production.
†Forest areas on farms are considered as forest fragments, fallows and forest around water bodies.
‡The diversity of forest fragments should be evaluated in comparison to the natural state of forests in each region.

or in a group, is considered the same level. Infrastructure and practices that are implemented but abandoned by some producers for others, were not valued as high level. The stocking rate was not taken into account given that it varied, depending on site and seasonal forage production, as well as on producers' strategies regarding production diversification and market change on milk/beef demand (e.g. Naylor, 2009).

Criteria to assess productive resilience

To evaluate the livestock systems' resilience potential, we considered: (B.1) the reduced use or independence from external inputs because it can show their response

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capacity to any socio-political and market changes (Nicholls and Altieri, 2013); (B.2) productive diversification because it acts as a buffer against climatic or any adverse circumstances (Koohafkan *et al.*, 2011) and (B.3) soil conservation because of its importance to biophysical resilience and against disturbances that occur through time (several authors in Nicholls and Altieri, 2013).

(B.1) External inputs include (B.1.1) fossil fuels, (B.1.2) agrochemicals (fertilizers, herbicides and pesticides) (Koohafkan *et al.*, 2011) and (B.1.3) animal feed (Cortez-Arriola *et al.*, 2016). Regarding fossil fuels, occasional use (mid-level) stands for a low-recurrence use of tillage machinery, achieved when it is shared among a group of producers or rented for specific field sites and occasions. For agrochemicals, a yellow light signifies that they are applied in a discriminatory or in a spot-specific way. For animal feed, salt or other basic needs were not considered. Occasional use means that animal diet does not include purchased feed at all times and ages. Green light stands for the elimination of external inputs, or their scarce use during extreme need situations.

(B.2) For production diversification, food for self-consumption, trade products and activities, and livestock system were taken into account. (B.2.1) Diversity of food for self-consumption is one of the most important criteria for achieving resilience, due to its relevance regarding food sovereignty (FAO, 2013). Each food tree species and food product or by-product used for self-consumption counts. (B.2.2) The diversity of trade products and activities offers more opportunities to switch between income sources when faced with socio-economic and market changes (e.g. Waithaka *et al.*, 2006). The livestock system's diversity, due to its importance in the SPE, was assessed separately from the rest of activities, taking into account: (i) animal breeds and species, (ii) fodder-tree species and (iii) energy-forage species and products (e.g. molasses, stubble). It is considered that Creole breeds are more resistant under local conditions than non-adapted purebreds such as Holstein, Jersey and Swiss; but crossbreds have even better production response under the same conditions (De Alba and Kennedy, 1985). Foliage, seeds and fruits of trees provide high quality forage (protein and energy), even during the dry-season (Murgueitio *et al.*, 2011) thus supporting livestock system's resilience, and can respond to unfavourable changes in availability and prices of off-farm feed (Cortez-Arriola *et al.*, 2016).

(B.3) For soil conservation, the states of: (B.3.1) slopes and (B.3.2) riparian areas were taken into account, as these are the most susceptible sites to soil erosion and loss of fertility. Red light indicates visible deterioration of soil, such as gully erosion and compaction in any site's circumstances (slope percentage, soil type or cover and environmental conditions) (Pimentel and Kounang, 1998). High tree density indicates good level, because it has the ability to reduce runoff and soil erosion, and supports in coping with extreme weather events, more than other vegetation strata, especially in sites with more precipitation (McIvor *et al.*, 1995). Moreover, the use of soil conservation practices was considered, such as living barriers, contour planting, as well as the prevention of negative management practices. These practices, on European arable land, help to reduce soil erosion by an average of 19% (Panagos *et al.*, 2015).

Criteria to assess silvopastoral experiences' potential to mitigate climate change

The potential of SPE in mitigating climate change was evaluated considering both reduction and sequestration of GHG emissions.

(C.1) For reduction of GHG emissions, we took into account: (C.1.1) reduced use of external inputs; as the use of fossil fuels for machinery and irrigation, agrochemicals, and animal feed (production and transportation) increases CO_2 and NO_X and (C.1.2) fodder tree species, provided their potential to reduce enteric CH_4 and improve animal diet, which can result in fewer animal units for the same yield, and thus less GHG emissions (Herrero *et al.*, 2016).

(C.2) For GHG sequestration, carbon sequestration in three components was considered: (C.2.1) TC in grazing areas, (C.2.2) forest areas and (C.2.3) soil conservation in slopes and riparian areas as these are the more susceptible areas to loose soil and carbon (FAO, 2010). Trees in grazing and forest areas in production units present the greatest potential in carbon sequestration (FAO, 2010). Trees in grazing areas can be dispersed or in a line, in low to high density. Forest areas can be conserved fragments, fallows, riparian or surrounding water bodies.

Criteria to assess silvopastoral experiences' potential in biodiversity conservation

To assess the potential of a SPE in biodiversity conservation, we considered the following landscape criteria: matrix quality, habitat patches and connectivity (Bennett, 1998).

(D.1) For grazing areas (matrix), the following are considered: (D.1.1) TC, since in grazing areas with higher TC ($>$15%) species richness can be similar to the one found in forest fallows and riparian forests (Harvey *et al.*, 2006) and (D.1.2) tree richness, using trees as a taxonomic group predictive of overall biodiversity.

(D.2) For forest areas (D.2.1) the proportional size of all fragments and (D.2.2) their state of conservation were considered. The first indicator because both the presence of sets of small forest patches on productive land and their size are essentials for the conservation of biodiversity (Bodin *et al.*, 2006; Oertli *et al.*, 2002). The second is related to TC age and structure, as well as its density and diversity, compared to the natural state of forests in each region (Schulze *et al.*, 2004).

(D.3) For connectivity, the states of (D.3.1) riparian areas and (D.3.2) live fences were considered. An increased TC on these elements enhances lineal connectivity among forest patches, although riparian forests may support more biodiversity (Harvey *et al.*, 2006). SPE potential to connectivity was evaluated supposing that surrounding conditions do not vary.

RESULTS AND DISCUSSION

Productivity levels of advanced silvopastoral experiences

The small-medium sized, traditional SPE in the Lacandon jungle and in the Sepultura regions showed comparatively the lowest productivity levels. There, livestock grazed freely on extensive paddocks, as reported for most livestock systems in several 'developing countries' (Herrero *et al.*, 2009). Milking was uncommon and calves mortality was high, reflecting minimum sanity control. Livestock was used mostly as a 'bank' investment, as it was sold within a year and a half or when there was a need, presenting the lowest levels in fattening time. Pijijiapan's advanced SPE had medium infrastructure level, including private or common grinders and silages, and managed several paddocks. Most of them were engaged in dual-purpose production: milk and breeding, and few in fattening, and showed medium calves' mortality and low fattening-time levels. On the other extreme, the large sized advanced experiences in the Frailesca and Mezcalapa regions displayed the highest levels. They managed dual purpose systems on small paddocks with rotational grazing, showing the lowest mortality rates, and high and medium fattening time levels, respectively (Figure 1b). Collaborating producers considered that they could manage well systems ranging from 10 to 100 ha, depending on conditions and resources, but larger areas became less efficient.

To face the problem of extensive ranching, which not only decreases productivity but also the other services, would require a change in producers' culture-vision on the use of livestock (Herrero *et al.*, 2009). Once this occurs, less animal energy waste and better weight could be achieved by improving forage management and infrastructure for greater livestock control. Taking advantage of the milk and dairy products could be a next step. In the regions, where advanced SPE presented low levels of livestock productivity, promoting land-use change in parts of the grasslands to agroforestry systems such as *Chamaedorea* palms (field data), cacao or coffee (e.g. Soto-Pinto *et al.*, 2017) could constitute another consideration.

Productive resilience and external services of advanced silvopastoral experiences

The advanced SPE in Sepultura region persistently displayed the lowest levels in the three other services. With respect to resilience, this was primarily due to the low diversification; in climate change mitigation this was due to the low TC in grazing areas and the lowest fodder-tree richness, among others (Figure 1c ande). Although these SPE maintained relatively large forest areas, biodiversity conservation was also affected due to the grazing areas' low TC and low connectivity (Figure 1f).

In the Lacandon and Pijijiapan regions, SPE compensated low and medium productivity, respectively, by presenting best resilience levels (Figure 1a). However, these levels could be improved; in the first case by diversifying trade products and activities, as well as food trees, and by protecting hillsides from erosion (Figure 1d). The Lacandon's advanced SPE were comparatively the best at mitigating climate change, although they could improve their potential by emphasizing slopes protection (Figure 1a, d and e). To enhance their medium biodiversity conservation capacity they could primarily increase live fences as proposed by Jimenez-Ferrer *et al.* (2008) and enrich TC (Figure 1f). Pijijiapan's experiences could improve productive resilience by generating more trade products, by maintaining more fodder-tree species and by reducing dependence on external inputs (Figure 1d). Attending the previous two elements could improve climate change mitigation capacity (Figure 1e). Their high

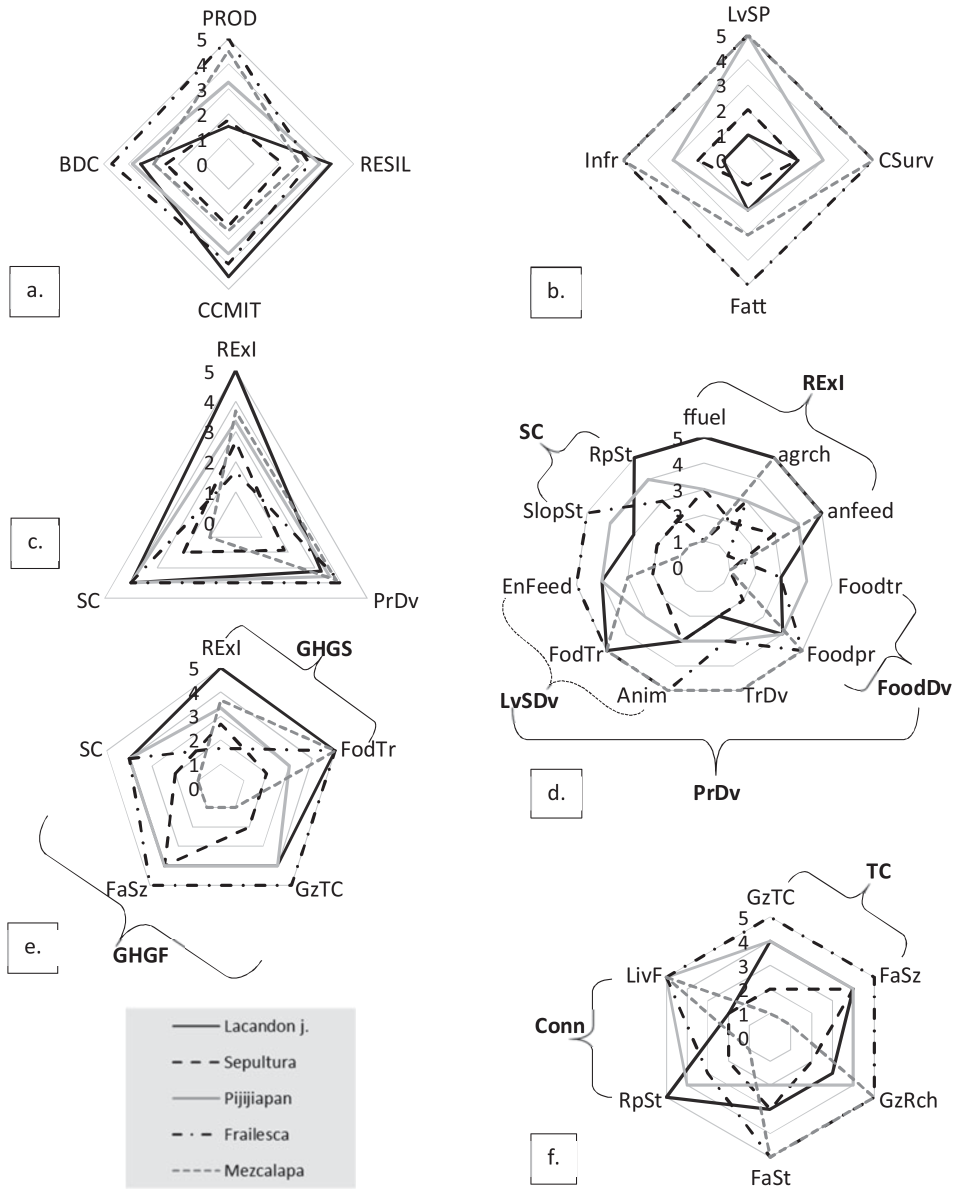

Figure 1. Average level reached by advanced silvopastoral experiences in five Chiapas regions (1–5: very low–very high) for the agro-ecosystem services provided, their indicators and criteria. (a) Agro-ecosystem services; PROD: productivity, RESIL: productive resilience, CCMIT: climate change mitigation, BDC: biodiversity conservation. (b) PROD indicators; LvSP: livestock system purpose, CSurv: Calves survival, Fatt: fattening time, Infr: infrastructure. (c and d) RESIL criteria and indicators; RExI: reduction of external inputs, f-fuel: fossil fuels, agrch: agrochemicals, anfeed: animal feed; PrDv: production diversification, FoodDv: overall food diversity, Foodtr: food-trees, Foodpr: food products; TrDv: trade products and activities diversification; LvSDv: overall livestock systems' diversity, Anim: breeds and species, FodTr: fodder-tree species, Enfeed: energy forage and feed products; SC: soil conservation, SlopSt: state of slopes, RpSt: state of riparian areas. (e) CCMIT criteria and indicators; GHGR: GHG reduction, GHGS: sequestration, GzTC: tree cover (TC) in grazing areas (Gz), FaSz: % size of forest areas (Fa). (f) BDC criteria and indicators; GzRch: tree richness in Gz, FaSt; state of Fa; Conn: connectivity capacity, LivF: live fences.

biodiversity conservation potential only declined due to forest areas' deterioration (Figure 1f).

In the case of Mezcalapa organic SPE, though the productivity level was high, the remaining three services were of intermediate levels. They were highly independent from external inputs. Nevertheless, to improve both resilience and GHG fixing capacity they need to increase TC, including on slopes and riparian areas (Figure 1d). The low TC on forest and grazing areas also undermined biodiversity conservation, and the unprotected riparian areas, in particular, affected connectivity capacity (Figure 1f).

The most productive Frailescaś holistic SPE showed medium resilience level and high levels on the two external services. They had the highest levels of dependence on external inputs that directly harms both productive resilience and climate change mitigation capacity. By improving the protection of riparian areas, productive resilience, CO_2 sequestration capacity, connectivity and so biodiversity conservation could be enhanced (Figure 1d). In the last aspect, these SPE exhibited the best levels due to proportionally larger conserved natural areas, and high TC and richness in grazing areas (Figure 1f).

Implications derived from the agro-ecosystem services assessment of advanced silvopastoral experiences

Comparing the advanced SPE in the five regions, we found that the positive internalities and externalities results were on par. Sepulturaś experiences exemplified that low internal services are not translated as more external services. At the other extreme, Frailescaś example demonstrated that it is possible to maintain higher levels in both internal and external services (see Ferguson *et al.*, 2013) (Figure 1a).

Three of the AES were directly associated to some same criteria, such as reduced use of external inputs, TC and its specified diversity, and soil conservation which is intimately related to TC. It is possibly that productivity results were also influenced by these criteria and related management practices. While services and criteria to be attained were determined by the interests of the producer, taking care of the components and functions that affect both the production unit and the environment would lead to the achievement of multi-directional benefits. Therefore, we proceeded to analyse two of the most important criteria for the AES assessment: reduced use of external inputs and TC.

External inputs reduction, related components and practices

Independence from external inputs provided numerous benefits, such as an increase in both a production system's resilience and its climate change mitigation capacity. Opinions differ over whether the use of external inputs increases productivity, particularly under the conditions shared by the majority of production systems in tropical regions (Naylor, 2009; Niggli *et al.*, 2009). In Frailesca, the productivity level, as well as the use of external inputs, was high. On the other hand, the small Lacandon's SPE ($\leq$ 20 ha) presented the least dependence on external inputs but also the lowest productivity level. Moreover, the reduced use of external inputs did not reveal low productivity. The example of Mezcalapa's organic SPE, as can be assumed of other low-external input farms (e.g. conservationist, sustainable, agroecologic, permaculturist, etc), showed that high productivity levels can also be maintained. This achievement was related to SPE elements and good management practices.

There was a tendency to use more fossil fuels in larger production units (>50 ha), primarily for machinery, as in Frailesca and Mezcalapa experiences (producers' comments). In Sepultura, an advanced traditional producer utilized animal traction (oxen), although this practice is becoming scarcer. To reduce fossil fuels, FAO (2010) recommends the use of alternative type of energies, such as the aforementioned one, as well as a more efficient use of energy based on reduced or no-till methods in conjunction with soil conservation practices (e.g. cover crops, mulch) and pastures-livestock management (FAO, 2010), although none of these recommendations were registered on the studied sites.

The most advanced SPE exhibited a relatively reduced agrochemical use. Mezcalapa's organic SPE used no agrochemicals and neither purchased feed, although they maintained high productivity levels. In the buffer zones of Lacandon and Sepultura natural reserves, as well as in Pijijiapan, producers keep an informal agreement within their social networks to decrease agrochemical use. In most of the regions producers practiced manual weeding and in Sepultura and Pijijiapan they used herbicides in a spot-specific way. None of the producers used pesticides; their common comment was that TC and shade control in grazing areas along with some pest control practices, reduced pests incidence, as confirmed by other authors (e.g. Poveda *et al.*, 2008). Producers specifically used *Acacia* spp. to avoid the presence of pasture looper, *Guazuma ulmifolia* as animal dewormer, and lime sulphur acid with *Azadirachta indica* extract as tickicide. In Lacandon and Sepultura, no practice was performed to maintain pasture productivity, which could explain low productivity levels. In Pijijiapan, producers maintained pasture productivity using agricultural residues; in Mezcalapa they used N-fixing plants on rows and live fences, rotational grazing and returned the manure from corral to pastures; practices recommended by several authors (e.g. Lin *et al.*, 2011; Niggli *et al.*, 2009). Producers in Frailesca shared many of the practices utilized in Mezcalapa, although they also applied fertilizers. According to Niggli *et al.* (2009), preventing industrial nitrogen fertilizer use could reduce 20% of agricultural GHG. In addition, decreasing the agrochemical use reduces soil and water pollution (Wimalawansa and Wimalawansa, 2014), and supports producers' and consumers' health (Sekhotha *et al.*, 2016; Wimalawansa and Wimalawansa, 2014), even though these benefits were not of interest in the present study.

In Frailesca, producers permanently purchased animal feed (fodder, grains and concentrates), even if they had high quality on-farm forages. In Sepultura, producers occasionally did the same to cope with pasture shortages, caused probably by the low forage diversification, among other reasons. However, dependence on external feeds produces GHG emissions; for example, in North America, for each 10 ha of grains for livestock feed, approximately 1 Mg CO_2 year^{-1} is generated, principally because of synthetic fertilization (calculated by data in Lin *et al.*, 2011). A common practice of advanced SPE – used to reduce dependence on purchased feed and also to improve productivity – is the management of fodder banks recommended by several authors (e.g. Calle *et al.*, 2012). Forage banks required little initial investment and provided high quality forage. In these, there were mainly diverse types of sugarcane, tall grasses like *Pennisetum* species and varieties, *Sorghum* sp., and fodder trees and herbaceous legumes like *Canavalia* sp. The practice of silage did not result a good investment because it required much labour for cut-and-carry and could be easily destroyed as repeatedly happened in Sepultura and other regions. Both practices in Frailesca and Mezcalapa have been replaced by rotational grazing of tall grasses like CT115 (*P. purpureum*), which some producers called 'standing silages'. Rotational grazing had productive and ecological benefits, as reported also in several studies (e.g. Fischer *et al.*, 2009). Producers commented that it helped to control animal density and to improve pastures management, as well as reduce fattening time and/or need for purchased feed; additionally, it helped to control pests, such as nematodes and spittlebugs, and improved the potential of pastoral areas in trees natural regeneration. Unfortunately, rotational grazing requires knowledge for management, and a high initial investment for paddocks' division that not all producers can afford (field data).

Increasing tree cover and quality-richness on small-medium SPE

Growing trees constituted one of the main strategies of the advanced SPE for generating both external and internal services. TC and diversification could serve as direct criteria of AES provision, but they also had an indirect influence on more indicators. For example, trees shade created favourable microclimates that reduced heat stress, thereby increasing animal reproduction and production rates; it also reduces requirement for weeding (Murgueitio *et al.*, 2011) and thus of herbicide use.

By initial choice, the documented experiences exhibited greater TC compared to the rest of SPE in their region. All advanced SPE presented high coverage of forest areas, except Mezcalapa's (one-eighth of the total area). Although, in this region and in Frailesca did we find relatively large conserved forest; the majority in the remaining regions were fallows. Trees in grazing areas were dispersed or systematically planted in rows and alleys, in compact areas of constantly pruned forage banks and in other configurations, such as pastured fallows. TC was usually maintained on slopes and along rivers, supporting soil conservation (Amy and Robertson, 2001; Pimentel and Kounang, 1998), carbon accumulation (FAO, 2010) and connectivity; but in Sepultura and Mezcalapa these sites lacked TC and presented visible erosion. The same occurs on the hillsides of the Lacandon region. The high TC in live fences and riparian areas, as in Pijijiapan's advanced SPE, improved connectivity capacity (Harvey *et al.*, 2006). In Sepultura, TC in grazing areas and live fences was the lowest, while in the Lacandon region had few live fences. In Mezcalapa SPE there was not a great deal of TC, but there was a large presence of live fences and high tree diversity in a system of 'grazing banks between fallow strips' although within a restricted area. Frailesca's SPE with large conserved forest areas and the highest TC in grazing areas

(25%) had the highest GHG sequestration capacity. A study by Ibrahim *et al.* (2013), showed that net GHG balance of livestock systems can be 8.6–221 Mg CO_{2}-eq ha^{-1}, depending on the size of areas dedicated to forest and pastures with trees. Soto-Pinto *et al.* (2010) found that scattered trees or live fences in grazing areas present 20 times more capacity in living biomass carbon sinks compared to treeless pastures. Depending on environmental conditions, some silvopastoral systems combined with well-managed pastures can exhibit similar values to native forests (FAO, 2010). Frailesca's SPE were also good examples of tree richness in grazing areas. Note that in high TC pastures (>15%), a greater diversity of species could be found, similar to that found in forest fallows and riparian forests (Harvey *et al.*, 2006). Producers in Pijijiapan and Frailesca regions, for example, commented that in recent years they had seen iguanas again, several turtle species, badgers, bobcats, deer, wild pigs and crocodiles.

Different tree types can improve productivity and production system's resilience (Solorio *et al.*, 2017) because they provide quality forage, as well as food and products for self-consumption or trade. The tree types maintained in production systems can express preferences of livelihood strategies in diversification versus intensification of efforts in few products. The documented SPE in Pijijiapan had the highest food-tree level and in Frailesca and Lacandon regions a medium level, thus improving family's food security (FAO, 2013). In Mezcalapa, producers compensated their food-tree level deficit with high levels of productivity, trade and food products diversity. In all regions producers took advantage of a variety of firewood species and of some wood species, and in Sepultura they produced resin from pines. Maintaining different tree types in production units was an alternative for regions with high forest degradation, such as Frailesca; in regions with less fragmentation, such as the Lacandon jungle, this maintenance buffered the impact of extractive (destructive) activities (producers' comments; FAO, 2013). The advanced SPE in four regions presented medium-high richness of fodder-trees in grazing areas. Note that in all studied regions there was pastures' shortage, mainly in the dry season, although all advanced producers have resolved this issue. In two of these regions, Frailesca and Mezcalapa, the productivity levels were high, although in Frailesca extra feed was also purchased. The most abundant fodder-tree species were *Gliricidia sepium*, *G. ulmifolia*, *Leucaena leucocephala*, *Erythrina* spp. and in some regions *Brosimum alicastrum*. Diversifying livestock systems with high nutritive value tree species, such as those mentioned, can benefit the productivity and resilience of the livestock system (Koohafkan *et al.*, 2011; Murgueitio *et al.*, 2011). The use of fodder trees can also reduce CH_4 emissions of livestock, accounting for 44% of the total CH_4. (FAO, 2013). In southeast México, Albores-Moreno *et al.* (2017) and Piñeiro-Vázquez *et al.* (2017) estimated that trees' fruits and foliage (*Bursera Simaruba, Enterolobium cyclocarpum, G. sepium, L. Leucaena*) in optimal doses can mitigate between 21–37% of ruminal CH_4. Indirectly, these fruits and foliage helped to reduce the use of off-farm fodder (previous chapter) and consequently also reduced GHG emissions. Regarding this, Herrero *et al.* (2016) estimated that the livestock sector could represent up to 50% of the global mitigation potential of the agriculture and forestry land use sector, *via* management practices, intensification, as well as moderating the demand for livestock products.

Future efforts in forest areas on small-medium SPE could be focused on improving their state (enriched, conserved or better managed) rather than their size, as it is more likely that current productive areas will continue to be used. Therefore, to increase a production system's contribution to AES and improve the agricultural matrix, it is crucial to focus on maximizing TC and diversity in grazing areas. All pasturelands, even those of Frailesca's, could support more TC without harming productivity. TC can be increased as much as 20–25% without a negative effect on grass growth (e.g. *Braquiaria brizantha* spp.) (Esquivel, 2007). Moreover, it can increase fodder productivity and quality if combined with broad leaves forage species, either woody or herbaceous in mixed pastures (Congdon and Addison, 2003). When SPE's strategy means to diversify production, as in Pijijiapan, then TC can be increased up to 30%, including fodder, fruit and multipurpose trees – while keeping individual shade <40% – helping to improve livestock and overall productivity (Esquivel, 2007).

CONCLUSIONS

This assessment approach was useful as a tool that allowed producers to easily locate red light critical points of their livestock systems, which require work in order to achieve better results in one or more AES, according to their interests and livelihood strategies. On the other hand, the high (green light) levels of criteria, taken from current advanced experiences, could serve as examples for improving livestock systems in the same or another region with similar characteristics. The suggested criteria and sets of indicators open the possibility of rapid intervention to improve management so that livestock systems can be more productive, resilient and environmental friendly.

For a balanced development of SPE, more attention should be paid to the criteria that affect both internal and external services; such as reduced use of external inputs in Frailesca; TC in grazing areas and soil conservation in Sepultura and Mezcalapa. TC can be increased in grazing areas in all SPE studied, which would directly benefit the three AES and indirectly productivity. Tree richness should be in line with producers' subjective targets. These targets could aim towards improving quality forage as would be required in the case of Sepultura's livestock systems, or towards food, self-consume or trade products diversification. The smart promotion of silvopastoral systems and good management practices that help achieve high levels in the aforementioned criteria combined with maintaining productivity and/or other aims, can lead in 'win–win' situations.

To apply this methodological approach in other regions, the same thresholds could be used or could be modified to better suit the conditions of the SPE to study. For particular types of livestock production systems, such as dairy or intensified, new criteria and indicators may be added to cover more features. Finally, the proposed criteria constitute a basis for building a quantitative assessment methodology.

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SUPPLEMENTARY MATERIAL

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