# Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico

**Lorena Soto-Pinto · Manuel Anzueto ·
Jorge Mendoza · Guillermo Jimenez Ferrer ·
Ben de Jong**

**Abstract** The importance of agroforestry systems as carbon sinks has recently been recognized due to the need of climate change mitigation. The objective of this study was to compare the carbon content in living biomass, soil (0–10, 10–20, 20–30 cm in depth), dead organic matter between a set of non-agroforestry and agroforestry prototypes in Chiapas, Mexico where the carbon sequestration programme called Scolel'te has been carried out. The prototypes compared were: traditional maize (rotational prototype with pioneer native trees evaluated in the crop period), Taungya (maize with timber trees), improved fallow, traditional fallow (the last three rotational prototypes in the crop-free period), Inga-shade-organic coffee, polyculture-shade organic coffee, polyculture-non-organic coffee, pasture without trees, pasture with live fences, and pasture with scattered trees. Taungya and improved fallow were designed agroforestry prototypes, while the others were reproduced traditional systems. Seventy-nine plots were selected in three agro-climatic zones. Carbon in living biomass, dead biomass, and soil organic matter was measured in each plot. Results showed that carbon in living biomass and dead organic matter were different according to prototype; while soil organic carbon and total carbon were influenced mostly by the agro-climatic zone ($P < 0.01$). Carbon density in the high tropical agro-climatic zone (1,000 m) was higher compared to the intermediate and low tropical agro-climatic zones (600 and 200 m, respectively, $P < 0.01$). All the systems contained more carbon than traditional maize and pastures without trees. Silvopastoral systems, improved fallow, Taungya and coffee systems (especially polyculture-shade coffee and organic coffee) have the potential to sequester carbon via growing trees. Agroforestry systems could also contribute to carbon sequestration and reducing emissions when burning is avoided. The potential of organic coffee to maintain carbon in soil and to reduce emissions from deforestation and ecosystem degradation (REDD) is discussed.

L. Soto-Pinto (✉) · M. Anzueto · G. J. Ferrer
El Colegio de la Frontera Sur, Unidad San Cristóbal,
Carretera Panamericana y Periférico Sur S/N,
29290 Chiapas, Mexico
e-mail: lsoto@ecosur.mx

J. Mendoza
El Colegio de la Frontera Sur, Unidad Campeche,
Calle 10 × 61 264 Col. Centro, 24000 Campeche,
Campeche, Mexico

B. de Jong
El Colegio de la Frontera Sur, Unidad Villahermosa,
Carretera Villahermosa/Reforma Km 15.5 Rancheria
Guineo 2a. Seccion, 86280 Villahermosa, Tabasco,
Mexico

# Introduction

A growing interest in the role of different types of land use in reducing atmospheric $CO_2$ ($CO_{2atm}$) concentration and lowering the emissions rate of this greenhouse gas (GHG), has led to an increased research on the function of forestry and agroforestry systems as carbon sinks. Tropical deforestation and forest degradation are considered to be an important source of GHG contributing to 17.4% of the global emissions (IPCC 2007); the use of fire in agriculture is also an important driver of climate change, especially in the tropics (Canadell and Raupach 2008). Undoubtedly, forests are the main land-based $CO_2$ sinks (Houghton et al. 2001). However, it is difficult to determine how and to what extent forest carbon sinks and reservoirs may be managed to mitigate $CO_{2atm}$ (Canadell and Raupach 2008). In this context, further research is needed to be able to select areas of priority and adequate land-use practices in order to reduce effectively emissions caused by deforestation and at the same time that could provide additional benefits (Miles and Kapos 2008).

Land-use practices such as afforestation, reforestation, natural regeneration of forests, silvicultural systems and agroforestry can help reducing $CO_{2atm}$ concentrations (Brown 1996; Canadell and Raupach 2008). Agroforestry systems (AFS) are very important given the area currently destined for agriculture, the number of people who depend on land for their livelihoods, and the need for integrating food production with environmental services (Soto-Pinto et al. 2001; Garrity 2004; Makundi and Sathaye 2004). The potential of AFS to accumulate carbon (C) is estimated to be 12–228 Mg ha$^{-1}$, with an average of 95 Mg ha$^{-1}$. However, the amount of C in any AFS depends on the structure and function of the different component within the systems put into practice (Schroeder 1994; Albrecht and Kandji 2003). Besides the potential of AFS to accumulate and sequester carbon, these systems could evolve into a technological alternative for reducing deforestation rates in tropical zones while also offering a wide variety of products and services to rural communities (de Jong et al. 1995).

Masera et al. (2001) developed a baseline and mitigation scenario for Mexico. The mitigation scenario assumes that current efforts will continue in the future and that native forest management,

forest protection, plantations for industrial use and restoration purposes as well as agroforestry systems will increase. However, trends and figures on carbon to be stored in each AFS component with locally adapted practices is still unknown.

Agrosilvicultural systems consist in planting trees in croplands (Nair 1993). These systems such as coffee plantations, improved fallow, and taungya systems could offer other environmental services (ES) than carbon sequestration (Montagnini 2007). A prediction of the potential of Carbon in AFS using the model $CO_2$ FIX showed that taungya systems, improved tropical fallows, and coffee plantations may, in 25 years, store approximately 130–181 Mg C ha$^{-1}$ in above ground biomass (de Jong et al. 1995). Other studies report that natural fallow systems could store from 14 to 191 Mg C ha$^{-1}$ in 2 and 25 years, respectively (Kotto-Same et al. 1997; Acosta 2003; Callo-Concha 2001; Esquivel 2005), while enriched fallow may store up to 60 Mg C ha$^{-1}$ in 5 years (Kotto-Same et al. 1997). Studies attribute the quantity of carbon accumulated in an ecosystem to several factors: system age (Acosta 2003; Albrecht and Kandji 2003), structure and function (Albrecht and Kandji 2003), silvicultural management (Vogt et al. 1996; Albrecht and Kandji 2003; Scott et al. 2004; Peichl et al. 2006), climate (Rao and Nair 1998), soil conditions such as texture and clay properties (Batjes 1999), and land-use history (Esquivel 2005; Tian et al. 2005; FAO 2006). Although there is a great potential for implementation, silvopasture land use practices are not widely adopted in neotropics. Nevertheless these practices could contribute to a significant long-term reduction in atmospheric GHG (carbon and methane) levels, particularly in tropical areas, while also improving animal welfare in general (Murgueitio 2005). Estimations of carbon in cattle farming landscapes in degraded pastures, natural pastures, improved pastures with trees, fodder banks and secondary forest, are recorded to be at 72.5, 97.3, 115.13, 130.6 and 162.17 Mg C ha$^{-1}$ respectively (Ibrahim et al. 2007).

Since 1997 the Scolel'te project (Chiapas, Mexico), which means in the Tzeltal language "the tree that grows", has been actively participating in the voluntary market through carbon sales under the Payment for Environmental Services (PES) scheme (Soto-Pinto et al. 2004; Montoya et al. 1995). This programme is one of the first initiatives in Latin America that developed a technical/social model for

carbon sequestration through forestry and agroforestry systems. Scolel'Te originated from a collaboration between AMBIO, The Plan Vivo Foundation formerly Plan Vivo (both nongovernmental organizations), several farmer organizations, and ECOSUR (El Colegio de la Frontera Sur, research institution). This programme was first implemented in Chiapas and then expanded its operation to Oaxaca, Mexico (Soto-Pinto et al. 2007). Farmers, together with researchers and NGO-technicians, designed the most viable land-use options in order to adapt the systems according to their needs and interests, following D&D methods (Raintree 1987). Participating farmers have been involved in the Carbon Voluntary Market (VCM) since 1997. Currently, the environmental service has been paid to farmers under the VCM scheme (de Jong et al. 1995; Soto-Pinto et al. 2004). The carbon sequestration potential of the project was estimated *ex-ante*, with secondary and locally collected data (de Jong et al. 1995).

The present study compares the carbon content between a set of non-agroforestry and agroforestry prototypes in Chiapas (Mexico) in plots of farmers involved in the Scolel'te programme.

## Materials and methods

### Study area

This study was carried out in eight locations in Chiapas (the southernmost state of Mexico): Alan Kantajal, Muquenal, Segundo Cololteel, Jolkacuala and Chapuyil in the municipality of Chilon; Arroyo Palenque, municipality of Salto de Agua, La Corona and Reforma Agraria, municipality of Marques de Comillas (Fig. 1). The locations have an altitudinal gradient with three climatic zones: (1) the low-tropical zone at 160–250 m a.s.l., with a warm-humid climate, tropical rainforest as the natural vegetation, and predominantly Luvisol as the main soil type; (2) the intermediate tropical zone at 700–900 m a.s.l., with a warm climate and abundant summer rains, with tropical rainforest the natural vegetation, and Regosol, Leptosol, and Cambisol as the main soil types; (3) the high tropical zone >1,000 m a.s.l., with a semi-warm humid climate, a mountainous rainforest, and Regosol, Leptosol and Cambisol as the main soil types (INEGI 1984).

The main economic activity in Chilon and Salto de Agua municipalities is agriculture, based on maize and coffee, whereas in Marques de Comillas cattle breeding is the main land-use related economic activity. In general, landscape is characterized by a mosaic of primary and secondary forests, agricultural plots, pastures, shaded coffee, and rural settlements.

The most common land use change in Lacandon area is from forest to pastures for cattle farming purposes which is the most profitable activity in the area. Although people are aware of the importance of conserving forests, crop and cattle farming activities in use are exerting pressure and threatening the remaining conserved areas. The practices evaluated were: traditional maize with pioneer trees, Taungya (rotational maize with trees), improved fallow, traditional fallow (these three last, rotational prototypes in
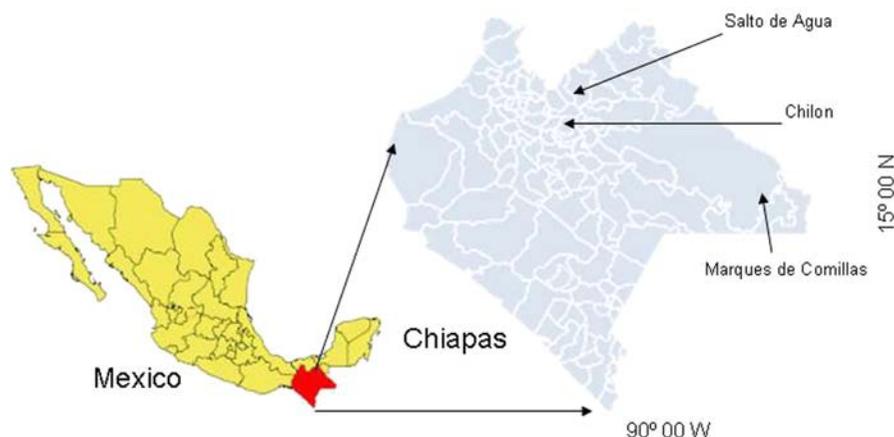


**Fig. 1** The study area

the crop-free period), Inga-shade organic coffee plantations, polyculture-shade organic coffee plantations, polyculture-shade-non-organic coffee plantations, pasture without trees, pasture with live fences, and pasture with scattered trees (Nair 1993). These, except Taungya and improved fallow which were designed by producers and scientist through the Scolel'te are traditional practices in the region.

Description of prototypes

*Maize and Taungya*

Maize with pioneer trees corresponds to the Mayan traditional system for self-consumption, associated to beans (*Phaseolus vulgaris* L.), chili (*Capsicum annum* L.) and squash (*Cucurbita pepo* L.) called "milpa" as described by Nations and Nigh (1980). Producers tolerate some pioneer trees with average density of 210 trees ha$^{-1}$, height of 2.90 m and diameter of 14.1 cm.

Taungya corresponds to the above-mentioned maize system enriched with timber and multipurpose trees. Maize is intercropped in the first 3–7 years between trees, which are arranged in lines with a density of 425 trees ha$^{-1}$, of the following species: *Swietenia macrophylla* King, *Cedrela odorata* L. and *Bombacopsis quinatum* (Jacq.) Dugand as cultivated trees, and other native spontaneoulsy-grown species such as *Acacia angustissima* (Mill.) Kuntze, *Brosimum alicastrum* Sw., *Bursera simaruba* (L.) Sarg., *Cecropia obtusifolia* Bertol., *Chrysophyllum mexicanum* Brandegee, *Cinnamomum grisebachii* Lorea-Hern and *Clibadium arboretum* Donn. Sm., among others. The studied plots averaged 3 and 7 years of establishment.

*Traditional and improved fallow*

Traditional fallow refers to the abandoned agricultural phase in which secondary vegetation develops with an average density of 938 trees ha$^{-1}$ and it is mainly composed of native trees belonging to 36 species (among them, the most important were *Hedyosmum mexicanum* Cordemoy, *Blepharidium mexicanum* Standl., *Inga pavoniana* G.Don, *Lonchocarpus guatemalensis* Benth, *Leucaena macrophylla* Benth., *Lippia myriocephala* Schltdl., *Persea Americana* Mill, and *Saurauia scabrida* Hemsl). This phase lasts a variable period of 10 to more than 50 years, depending on land availability. The studied plots averaged 23.4 years old.

Improved fallow is a set of plots similar to the traditional fallow but it is enriched with timber trees in lines with a final density of 1,058 trees ha$^{-1}$ of the native spontaneous-tree species previously mentioned as well as timber species: *Swietenia macrophyla*, *Cedrela odorata* and *Pinus oocarpa* Sch. The studied plots averaged 6.9 years since the enrichment.

*Coffee systems*

These prototypes are characterized by the level of inputs as well as the shade composition (Moguel and Toledo 1999); Inga-shade-organic coffee refers to the organic coffee plantation with shade composed mainly of Inga species and high level of organic inputs, often coffee-pulp compost (Romero-Alvarado et al. 2002); polyculture-shade-organic coffee is the organic coffee plantation with a shade composed by a variety of species including fruit species and several strata (Peeters et al. 2003); and polyculture-shade-non-organic coffee is the "natural" no-input, low-management plantation with a shade composed by a variety of species and several strata. The age of coffee plantations is unknown by producers but it is generally longer than 20 years.

*Pasture without trees, live fences and scattered trees*

These prototypes refer to pastures of *Cynodon nlemfuensis* Vanderyst, *Andropogon gayanus* Kunth., *Brachiaria decumbens* Stapf, and *B. brizantha* Hochst. Stapf., grazed by cattle with or without trees. Live fences are mainly composed of *Gliricidia sepium* (Jacq.) Steud. while pasture with scattered densely-forested patches composed of native self-grown trees of the species *B. mexicanum* Sw., *Sabal mexicana* Mart., *Vatairea lundelli* (*Stand.*) Killip ex Record, *Guarea glabra* Vahl, *Albizia adinocephala* (Donn. Sm.) Brit. & Rose, *B. simaruba*, *Spondias mombin* L., and *Swietenia macrophylla*. The studied plots have been established for more than 15 years.

Plot selection and forest inventory

Seventy-nine plots under different prototypes were randomly selected. In each plot, a forest inventory

was carried out in 1,000 m$^2$ circle plots (Lamprecht 1990; Richards 1996; Melo Cruz and Vargas 2003). Diameters at breast height (DBH at 1.3 m) and heights (H) were measured for all trees >10 cm in diameter. All juvenile trees of 5–10 cm in diameter and all coffee plants were measured in 100 m$^2$ circle plots within each larger circle (Hairiah et al. 2001). All dead trees above 10 cm DBH were recorded, and their heights measured (Lamprecht 1990; MacDicken 1997; Penman et al. 2003). Species were collected and processed for botanical identification. Specimens were located in the El Colegio de la Frontera Sur herbarium.

Estimation of carbon reservoirs

For each plot, the amount of organic carbon present in each reservoir was estimated (Penman et al. 2003): living biomass contained in trees, small plants, and roots (coarse and fine); litter (fallen branches and surface litter); and soil organic matter. In order to estimate trees and coarse root carbon reservoirs allometric formulas were used. In the case of palms, citric trees, and banana, specific allometric models were employed (Table 1). In general, these models use the following variables: average diameter at a height of 1.3 m (DBH), height (H), and wood density ($\rho$). Data for wood density was obtained from previous studies (Brown 1997; Cordero and Boshier 2003; Penman et al. 2003). A value of 0.5 was assumed as a carbon factor in order to calculate carbon density present in living biomass (Penman et al. 2003).

Understorey biomass was collected randomly from sixteen 0.5 × 0.5 m quadrates assigned within each 1,000 m$^2$ plot (in coffee plantations, 8 quadrates were used). Understorey vegetation, roots, and litter were air dried, weighed, sub-sampled, oven dried for 24 h at 70°C and corrected for moisture content.

Fine roots ($\leq$5 mm in diameter) were collected using a soil sampler (4.21 cm internal diameter) in four soil nuclei (30 cm deep) randomly distributed in the 1,000 m$^2$ plot (Castellanos et al. 1991). These were carefully separated from the soil, washed with deionised water, oven dried for 24 h at 60°C and weighed. The biomass of coarse roots was estimated by an allometric equation proposed by Cairns et al. (1997).

$$Y = \exp[-1.3267 + 0.8877(\ln \text{ABD}) + 0.1045(\ln B)]$$

where:
$Y$ = Root biomass density (Mg ha$^{-1}$)
ABD = Aboveground biomass density (Mg ha$^{-1}$)
$B$ = Tree age
The surface litter was collected from four circular rings (radius of 0.13 m$^2$) and classified into three decomposition categories: fresh, intermediate and humus. This litter was ground and analyzed for total carbon (Anderson and Ingram 1993).

A soil sample was excavated from each 1,000 m$^2$ circle from three depths: 0–10, 10–20, and 20–30 cm. Additional soil samples were collected using a Hoffer sampler in order to determine bulk density at the same points for each of the three depths. The soil sample was air dried and passed through a 2 mm sieve. Soil organic carbon (SOC) contents at three depths were adjusted using soil bulk density and their respective field volumes.

Additionally, in the maize system, 10 randomly selected samples including leaves, stems, and roots from maize plants were collected and processed as described for understorey vegetation.

The baseline was calculated regarding the scenario without trees as the baseline (IPCC 2000). The additionality or accumulated carbon was calculated as the difference between carbon content in aboveground biomass in the traditional maize or pasture

**Table 1** Allometric equations used to estimate above-ground biomass in AFS

| Type of biomass | Allometric equation | $R^2$ | Source |
|---|---|---|---|
| Above ground biomass for trees | $Y = \exp[-2.977 + \text{Ln}(\rho D^2 H)]$ | 0.99 | Chave et al. (2005) |
| Palms | $Y = 10 + 6.4(H)$ | 0.96 | Frangi and Lugo (1985) |
| *Musa* sp. | $Y = 0.0303 D^{2.1345}$ | 0.99 | Hairiah et al. (2001) |
| *Citrus sinensis* | $Y = -6.64 + 0.279(\text{BA}) + 0.000514(\text{BA})^2$ | 0.94 | Penman et al. (2003) |
| *Coffea arabica* | $Y = 0.2811 D^{2.0635}$ | 0.94 | Hairiah et al. (2001) |

$Y$ above ground biomass density (Mg ha$^{-1}$), $D$ diameter in cm, $H$ height in m, $\rho$ wood density in g cm$^{-3}$, $BA$ basal area in cm$^2$

without trees. Therefore, the carbon in aboveground biomass in traditional maize was the baseline for taungya, fallows and coffee; and by the other hand, carbon in aboveground biomass in pasture without trees was the baseline for silvopastoral prototypes.

## Laboratory analysis

Plant matter and soil samples were processed in the Bromatology and Soil Laboratories in El Colegio de la Frontera Sur. Subsequently, carbon was determined using an elemental autoanalyzer LECO CHN 1000[®] (Anderson and Ingram 1993). The Walkley-Black method for wet combustion was used for soil samples with pH > 7 in order to determine the fraction of organic C, (MacDicken 1997). The pH was determined in water with an ORION/RESERCH potentiometer model 301, and texture was determined using the Bouyocos method.

## Statistical analysis

An analysis of variance by prototype and zone was carried out (GLM procedure SAS 2000). As the interactions between zone and prototype were not significant, the single effect of prototype was tested in each zone (Steel and Torrie 1992). Data were pooled

between climate zones and Duncan's multiple range test was run in order to compare variables between zone and systems. Variables tested were: soil organic carbon (SOC: 0–10, 10–20 and 20–30 cm in depth), total SOC, dead organic matter (DOM), carbon in living biomass (LBC), accumulated carbon above the baseline (ACC) and total carbon (TC). Correlation analysis for the selected variables was conducted (SAS 2000).

## Results

SOC showed significant differences between agro-climatic zones and prototypes ($P < 0.01$; Table 2), while LBC and DOC showed significant differences between prototypes ($P < 0.01$; Table 2). Carbon content in the three depth-soil layers was higher in the high tropical agro-climatic zone (1,000 m) in comparison with intermediate and low tropical agro-climatic zones (600 and 200 m, respectively, $P < 0.01$; Table 3).

In the low agro-climatic zone, the prototype differed significantly in SOC, DOM, TC and LBC ($P < 0.001$). In general, SOC and DOM were higher in Taungya and improved fallow than in silvopastoral and pastures without trees (Table 4). Silvopastoral

Table 2 Analysis of variance for SOC, DOM, and LBC by agro-climatic zone, prototype and the interaction of both variables, in Chiapas Mexico

| Source | Stock | DF | Type III SS | Mean square | $F$ | Pr > $F$ |
|---|---|---|---|---|---|---|
| Zone | SOC | 2 | 11,965.80614 | 5,982.90307 | 10.82 | <0.0001 |
| | DOM | 2 | 72.207427 | 36.103713 | 1.07 | 0.3504 |
| | LBC | 2 | 1,066.27710 | 533.13855 | 1.33 | 0.2704 |
| Prototype | SOC | 9 | 15,269.84306 | 1,696.64923 | 3.07 | 0.0040 |
| | DOM | 9 | 1,673.291932 | 185.921326 | 5.49 | <0.0001 |
| | LBC | 9 | 36,937.33801 | 4,104.14867 | 10.28 | <0.0001 |
| Zone × prototype | SOC | 3 | 2,150.00356 | 716.66785 | 1.30 | 0.2832 |
| | DOM | 3 | 89.938969 | 29.979656 | 0.89 | 0.4536 |
| | LBC | 3 | 409.92988 | 136.64329 | 0.34 | 0.7949 |

Table 3 Comparisons of SOC at three depth layers and total SOC (Mg ha$^{-1}$) in three agro-climatic zones of Chiapas, Mexico ($n = 79$)

| Zone | 0–10 cm | 10–20 cm | 20–30 cm | Total SOC |
|---|---|---|---|---|
| Low tropical zone ($n = 23$) | 39.7b | 23.2b | 18.1b | 77.4b |
| Intermediate tropical zone ($n = 17$) | 34.56b | 20.58b | 17.14b | 73.87b |
| High tropical zone ($n = 39$) | 51.5a | 39.0a | 30.54a | 120.7a |

Different letters between rows mean statistical significance at $P < 0.01$

**Table 4** Comparison among prototypes for total SOC, DOM, LBC, TC and ACC in Mg C ha$^{-1}$ in the low-tropical agro-climatic zone of Chiapas, Mexico ($n = 23$)

| Prototypes | Total SOC | DOM | LBC | TC | ACC |
|---|---|---|---|---|---|
| Improved fallow | 104.0ab | 4.8b | 46.4b | 155.2a | 47.6b |
| Taungya | 112.7a | 7.5a | 35.3b | 155.5a | 39.2b |
| Pastures with scattered trees | 68.5c | 0.0c | 74.0a | 142.5a | 70.4a |
| Pastures with live fences | 60.6c | 0.0c | 70.1a | 130.7a | 66.5a |
| Pastures without trees | 75.1bc | 0.0c | 3.6c | 78.8b | 0.0 |

Different letters between rows refer to a statistical significance ($P < 0.01$)

systems had higher LBC than improved fallow and taungya prototypes; whereas, pastures without trees showed the lowest LBC (Table 4). Coffee sytems and traditional maize were not present in this zone.

Land use change from traditional fallow to maize caused a total living biomass carbon loss of 94%, shifting from traditional fallow to improved fallow, taungya or coffee prototypes maintains carbon in living biomass (50 Mg C ha$^{-1}$ in average); whereas changing from pasture without trees to pastures with live fences or scattered trees augment living biomass carbon by 20 times (Tables 3, 4).

In the low agro-climatic zone the baseline (aboveground carbon in pasture without trees) was 3.63 Mg C ha$^{-1}$; while in the high and intermediate tropical agro-climatic zones the baseline (aboveground carbon in traditional maize) was 11.1 Mg C ha$^{-1}$. Further, the additionality or accumulated carbon (ACC) in both live fences or scattered trees was higher than improved fallow and taungya in the low agro-climatic zone (Table 4). In the high agro-climatic zones ACC was similar in AF prototypes (Table 5). Comparing maize and pasture without trees to AF

prototypes, ACC amounted approximately 47.66 and 68.5 Mg C ha$^{-1}$ respectively.

In the high tropical zone (1,000 m), SOC dropped sharply in all prototypes, except in Inga-shade organic coffee where SOC maintained more constant with depth (Fig. 2). Soil is the largest sink of carbon, averaging 66.2% in taungya, improved and traditional fallow; and 69.6% in coffee prototypes. In the maize systems the soil accounted for 90.7% of the total carbon.

In the high agro-climatic zone, living biomass was higher in Taungya, traditional and improved fallow and coffee prototypes than in traditional maize ($P < 0.001$; Fig. 3; Table 5), although this last includes a small proportion of short and thin pioneer trees. However, the post-harvest residues of maize seem to contribute significantly to DOM; nevertheless, this did not occur in the Taungya and improved fallow prototypes. Coffee doubled the quantity of DOM of traditional maize, but it was not statistically significant ($P > 0.05$).

It is important to note that in this agro-climatic zone, the amount of LBC in the agroforestry systems,

**Table 5** Comparison among prototypes for SOC, DOM, LBC, TC and ACC, in Mg C ha$^{-1}$, in the high-agro-climatic zone, Chiapas, Mexico ($n = 39$)

| Prototypes | 0–10 cm SOC | 10–20 cm SOC | 20–30 cm SOC | Total SOC | LBC | DOM | TC | ACC |
|---|---|---|---|---|---|---|---|---|
| Taungya | 62.8ab | 39.5ab | 27.9b | 130.2ab | 58.5a | 2.7c | 191.7a | 50.1a |
| Improved fallow | 42.0c | 33.4b | 22.9b | 98.3b | 59.9a | 5.3bc | 163.5ab | 54.1a |
| Traditional fallow | 56.1abc | 36.5ab | 28.1b | 120.7ab | 39.8a | 13.1ab | 173.6ab | 41.8a |
| Inga-shade organic coffee | 50.5bc | 53.4a | 47.1a | 151.0a | 46.3a | 16.5a | 213.8a | 51.7a |
| Polyculture-shade organic coffee | 45.1bc | 37.4a | 30.3b | 112.8ab | 39.4a | 15.2a | 167.4ab | 43.5a |
| Polyculture-shade non organic coffee | 64.8a | 43.2ab | 27.0b | 135.0ab | 39.4a | 16.5a | 190.9a | 44.7a |
| Traditional Maize | 53.0abc | 32.1b | 24.7b | 109.8ab | 2.4b | 8.7abc | 120.9b | 0.0 |

Different letters between rows refers to a statistical significance ($P < 0.01$)

Fig. 2 Carbon in soil organic matter in relation to depth for AF prototypes in high tropical zone, in Chiapas, Mexico
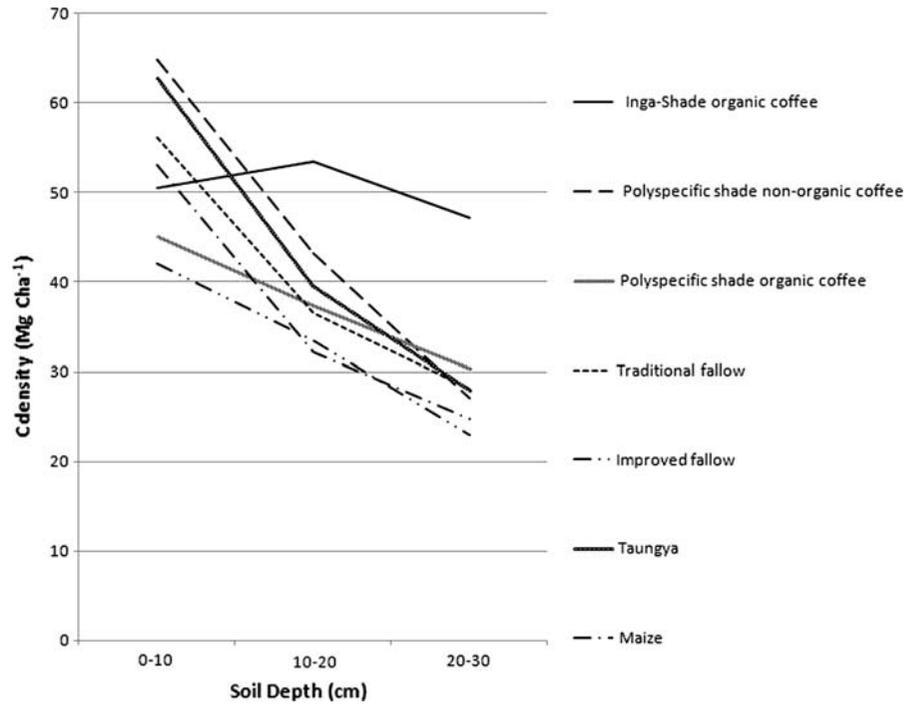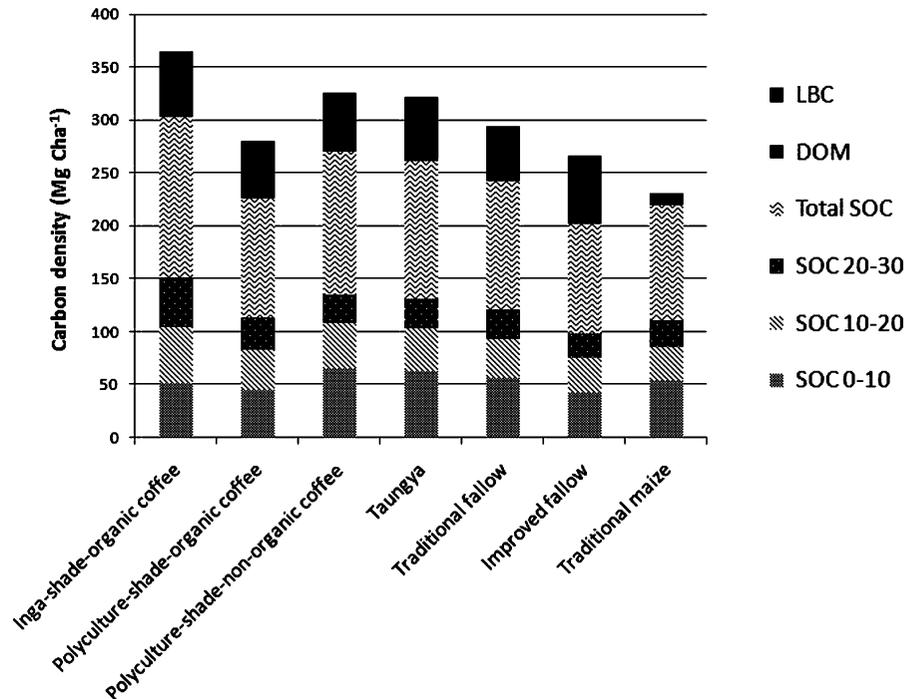


Fig. 3 Carbon components of AF prototypes in high tropical zone (1,000 m) in Chiapas, Mexico



which averaged $184.2 \pm 16.5$ Mg C ha$^{-1}$, was several times higher than in the traditional maize system ($2.4 \pm 2.3$ Mg C ha$^{-1}$). In the low tropical zone the

baseline is proposed as the difference between pasture without trees and AF prototypes (3.6 Mg C ha$^{-1}$); therefore ACC was in average 68.5 Mg C ha$^{-1}$ for

silvopastoral prototypes and 43.4 Mg C ha$^{-1}$ for rotational prototypes.

No significant differences resulted by comparing 0–10 cm-depth soil carbon; nevertheless, 10–20 and 20–30 cm-depth soil carbon differed between prototypes, showing that Inga-shade organic coffee plantations had the highest amounts of carbon in comparison with polyculture-shade organic- and non-organic coffee plantations (Table 5). No silvopastoral systems were present in this agro-climatic zone.

In general, land use change from traditional fallow to maize caused a total living biomass carbon loss of 94%, shifting from traditional fallow to improved fallow, taungya or coffee prototypes maintains carbon in living biomass (50 Mg C ha$^{-1}$ in average). Whereas changing from pasture without trees to pastures with live fences or scattered trees increase living biomass carbon to 20 times (Tables 4, 5). Additionally, producers who establish timber trees do not use burning in their land.

In the intermediate zone soil variables and accumulated carbon above the baseline did not differ between prototypes ($P > 0.05$). However dead organic matter was higher in polyculture-shade-non-organic coffee (26.2 Mg ha$^{-1}$) than improved fallow (6.3 Mg ha$^{-1}$) and taungya (6.7 Mg ha$^{-1}$) ($P < 0.01$); additionally, carbon in living biomass was higher in improved fallow than polyculture-non-organic coffee, meanwhile Taungya did not differed from them. No other systems were studied in this agro-climatic zone.

Figure 4 shows the percentage for each component in every zone. It highlights the percentage of carbon in SOM in the high tropical zone, which gets to 71%.

Dead organic matter correlated to carbon in SOM, especially to layers 10–20 cm and 20–30 cm in depth ($P < 0.05$).

## Discussion

It is generally known that a land-use change from forested systems to others with less coverage results in C loss, especially in living biomass. This study contributes to the knowledge of carbon stocks in AF prototype with locally adapted practices. In the future, disappearance of a large proportion of forests at all latitudes could lead to an increase in GHG emissions if sustained management and conservation policies are not employed (Dixon et al. 1999), this applies especially in Mexico where 35% of C emissions occur due to land-use change from forest to livestock or agriculture using slash and burn practice (Masera et al. 1997), which is no longer operative (Kotto-Same et al. 1997). Results showed that shifting from traditional fallow to traditional maize caused a loss of about 94%. However establishing AF prototypes maintains carbon in living biomass and increases by 22 times living biomass in comparison to traditional maize in a period of approximately 7 years. Furthermore, reconverting pastures without trees to silvopastoral systems increased carbon in living biomass on the order of 20 times.

As has been established previously, carbon sequestration in aboveground biomass and mitigation of GHG emissions associated with avoided deforestation are the benefits expected from agroforestry systems (Dixon 1995; Mutuo et al. 2005; Kiyono et al. 2007). The establishment of improved fallow, taungya systems, coffee plantations and silvopastoral prototypes in the study communities resulted in significant carbon accumulation in above ground biomass. In addition, as farmers do not longer practice burning establishing it is assumed that AF prototypes contribute to reducing emissions.



Fig. 4 Percentages of SOC, DOM and LBC in three agro-climatic zones in Chiapas, Mexico
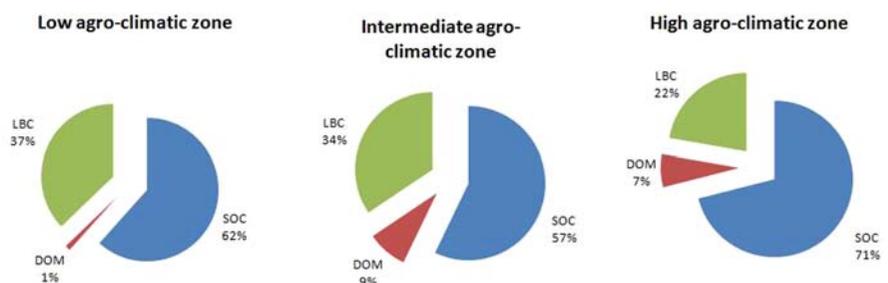
Results showed that agro-climatic zone determined significantly the content of carbon in soil component; this is due to properties of the soil itself, and on climate (Albrecht et al. 2004). However, in this study, carbon in dead organic matter and living biomass were affected by AF prototypes. It has been reported that carbon in plant biomass depends on structure of the agroforestry system among other factors (Albrecht and Kandji 2003).

Nonetheless, coffee plantations with densely growing trees resembling the forest structure store high amount of carbon in above ground biomass and soil. Surprisingly, Inga shade organic coffee is the only prototype which maintains carbon in SOM almost without changes through differences in depths; this can probably be associated to applied organic amendments (Palm et al. 2001). It has to be noted that among the three coffee systems, the latter prototype is the most intensive system, in relation to inputs and labor applied. This support the suggestion that coffee may be considered as an appropriate practice for reduction emissions by deforestation and degradation (REDD). These perennial systems have the comparative advantage in relation to rotational systems that carbon sequestration remains for a longer period. It is interesting to note that some producers from the study area have established coffee under Taungya and improved fallows canopies once trees have grown enough to shade crop, contributing to maintain SOM by litter and root residues (Albrecht and Kandji 2003). This fact guarantees the permanence of carbon sequestration, highlighting the role of coffee in soil conservation (Grewal et al. 1994; Young 1997).

The higher content of carbon in 20–30 cm soil layer in Inga-shade organic coffee in relation to the polyculture-shade organic prototype may be due to the high diversity of species of this last, since many of the species are useful as fruits (Soto-Pinto et al. 2001, 2007) or related to the contribution of the roots of Inga to SOC in this layer (Nygren Com Pers.).

On the other hand, throughout a 7-year period taungya and improved fallows have accumulated one-third of the carbon previously predicted to be reached in 25 years (de Jong et al. 2000; Roncal-García et al. 2008). Results validate the scientific and technical basis of the Scolel'te Programme related to projection of carbon sequestration in AF practices in the lifetime span. Despite the short time period in which establishment of improved fallow and taungya were studied

(7 years of establishment), carbon stocks accumulated above the baseline demonstrate that the potential of these prototypes have rapidly reached carbon amounts similar to those contained in natural fallows (average of 23 years old) (Kotto-Same et al. 1997). Although their ages are unknown, coffee and silvopastoral systems also demonstrated the same potential. In improved fallows, even though biomass accumulation apparently depends on fallow age, species, and amount of rainfall during the first years of establishment (Kass et al. 1993; Mafongoya and Dzowela 1999), management seems to be crucial for carbon sequestration. For instance, results of this study showed that only 40% of C supplied by trees in improved fallows comes from the enrichment as timber trees; the remaining 60% represented trees naturally grown through secondary succession as other authors reported recently (Nyamadzawo et al. 2008). The role of species is of crucial importance (Albrecht and Kandji 2003); hence this issue will require more research.

The importance of fallow increases given the existing land area dedicated to this type of land use. This may be mainly due to the fact that from 1970 to 1990, land use shifted mainly from mature forest ecosystems toward secondary shrub and forest vegetation and, to a lesser degree, to open areas (de Jong et al. 2000). Fire suppression by means of enriching fallows and maize through taungya prototype may reduce C emissions, as it has been suggested other agricultural practices (Canadell and Raupach 2008).

Furthermore, soil organic carbon sequestration is attributed to those management systems which, among other functions, minimize soil disturbance and erosion (Paustian 2000). Results from the upper soil layer were much variable and in the latter differences between prototypes did not occur. Power (2004) has previously stated that most marked differences in SOC occur in the upper soil layer. However the deeper soil layers seemed to be more stable. Soil carbon sequestration seems to respond to a long term process. Therefore, in the context of ES, the conservation of forest soil carbon through deforestation reduction practices is desirable (Miles and Kapos 2008).

The challenge in marginal areas inhabited by small-scale farmers relates to food production along with processing products derived from forests, reduce pressure on forest areas, and diversify incomes. It has been confirmed that payment for ES responds to these needs (Wise and Cacho 2005). Through the

establishment of AF prototypes with high-quality timber trees, not only C sequestration may be achieved but emissions may be reduced as farmers do not longer practice burning.

AF prototypes could provide additional benefits to farmers through payments for other ecosystem services such as biodiversity and watershed protection (Perfecto et al. 1996, 2007; McNeely and Schroth 2006; Schoeneberger 2008).

In coming years developing countries will develop capabilities for establishing AF prototypes which offer environmental services and additional benefits to farmers given that there is a significant potential area to be covered by AF (estimated in $317 \times 10^6$; Jarecki and Lal 2003).

Moreover one of the main land use changes experienced in south of México has been the transformation of forests into pasture for cattle breeding. The inclusion of trees in pastures is a strategy which is currently being implemented in order to reverse the trend towards extensive cattle farming. Additionally, this strategy enables production units' diversification and offer environmental services (BSAS 2008). Evidence from this study suggests that a high complexity in livestock systems results in higher C accumulation as reported in other regions of Chiapas. This provides an opportunity for producers to implement silvopastoral projects and design plans in order to sell ecosystem services related to carbon and methane market (Tennigkeit and Wilkes 2008).

## Conclusions

Agroforestry systems show significant carbon accumulation in living biomass when it is compared with the baseline. This demonstrates the additionality and the potential of AFS to offer the environmental service of carbon sequestration. Furthermore, AF prototypes contribute to reducing emissions by avoiding burning and conserving soil, which is the greatest carbon sink. Inga-shade organic coffee plantations have a potential for conserving carbon and may be considered as a good practice to be included in reduction emissions for deforestation and degradation. This system along with polyculture organic coffee represents adapted prototypes due to the need for a more permanent-land use, in addition to economic added-value.

Shifting from traditional fallow to traditional maize caused a total living biomass carbon loss of 94%, shifting from traditional fallow to improved fallow, taungya or coffee prototypes maintains carbon in living biomass (50 Mg C ha$^{-1}$ in average). Whereas changing from pasture toward silvopastoral systems increased carbon in living biomass by 20 times. Pastures with trees as important carbon sinks can act as carbon sequestration pools with potential to offering ecosystem services.

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