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Abstract Litterfall and its subsequent decomposition in the soil are two essential ecosystem processes. In order to determine the biological potential of a species to aid soil restoration, it is necessary to evaluate litter production, its temporal variation, and rates of decomposition and nutrient cycling. In this study, we examined patterns of litterfall production, quality, and decomposition of two slow-growing (*Crescentia alata* and *Eysenhardtia polystachya*) and two fast-growing (*Leucaena leucocephala* and *Pithecellobium dulce*), multi-purpose indigenous species from seasonally dry tropical forest, in a 10-year-old plantation in Morelos, Mexico. Average litterfall was 7.82 ± 2.69 Mg ha^{-1} year^{-1} and varied significantly among species as follows: *P. dulce* > *L. leucocephala* > *C. alata* = *E. polstachya*. Leaf litter comprised the highest fraction in all species studied. In a litterbag experiment, all species had fast mass loss in the first 183 days of decomposition, coinciding with the rainy season. *L. leucocephala* had significantly higher decomposition than the other species. Nitrogen percentages increased significantly as decomposition progressed for all species except for *E. polystachya* while Carbon percentages during decomposition significantly decreased only in *C. alata* and *L. leucocephala*. *C. alata* had the highest average C/N ratio and *L. leucocephala* the lowest. We recommended for soil biological restoration, *P. dulce* because it is a fast-growing tree, with a rapid canopy closure and a high litter production and *L. Leucocephala*, which produces large amounts of rapidly decomposing mulch with high amount of nutrients, which can be rapidly released into the soil.

Keywords Multi-purpose species · Decomposition rate · Litterfall · Agroforestry systems · Carbon · Nitrogen

E. Ceccon (✉)
Centro Regional de Investigaciones Multidisciplinárias, UNAM, Av. Universidad s/n, Circuito 2, Col. Chamilpa, 62210 Cuernavaca, Morelos, Mexico
e-mail: ececcon61@gmail.com

I. Sánchez
Facultad de Ciencias, UNAM, Mexico, Mexico

J. S. Powers
Department of Ecology, Evolution & Behavior and Plant Biology, University of Minnesota, Saint Paul, MN, USA

Introduction

Seasonally dry tropical forest (SDTF) is regarded as the most altered and threatened tropical ecosystem in the world (Jaramillo and Sandford 1995). Because of its high diversity, SDTF should be a high priority for conservation and ecological or productive restoration (Miles et al. 2006; Ceccon 2011). In order to facilitate these activities, it is important to carry out studies to characterize the original species of this ecosystem, know their role in forest dynamics, and use this

knowledge to inform sustainable management of these species or their potential use in agroforestry or restoration projects in degraded landscapes (Ceccon 2013).

Central issues in the study of ecosystem structure and function are understanding the dynamics of organic matter and how it contributes to energy flow and nutrient cycling (Bourlière and Hadley 1970), which in turn are essential for the continuity and stability of living systems (Pomeroy 1970). At the same time, restoration of degraded habitats requires the establishment of a self-sustaining soil–plant system. Vegetation management is often essential to combat soil erosion, restore soil fertility and accelerate natural recovery processes (Dobson et al. 1997; Holl 1999; Leitão et al. 2010; Ceccon et al. 2012).

The present study was conducted to understand the dynamics of litter production, leaf decomposition, and C and N concentration in four SDTF indigenous tree species growing in a 10 year experimental plantation. These species are commonly used by local people and are considered among the most important 20 multi-purpose tree species in the State of Morelos, Mexico (SAGARPA-INIFAP 2001). Two of these, are very abundant and fast -growing (*Pithecellobium dulce* and *Leucaena leucocephala*) and two less common and slow-growing (*Eysenhardtia polystachya* and *Crescentia alata*; SAGARPA-INIFAP 2001) within the State of Morelos. Our study is one of a handful of experiments to quantify the litter production, decomposition dynamics and its effects on the return of some nutrients in forest plantations, with the specific goal of producing useful information for the restoration of degraded soils and the potentially successful establishment of productive or agroforestry systems (Montagnini et al. 1993; Byard et al. 1996; Montagnini 2000).

Materials and methods

Study site

The study was carried out in the experimental field of the Center for Agricultural and Forestry Research (CIFAP in Spanish) in Zacatepec, Morelos, Mexico (18°92′N lat. and 99°12′W long., 920 m of altitude; Ornelas et al. 1997), belonging to National Institute for Agricultural and Forestry Research (INIFAP in Spanish).

The climate of the area is characterized as Awo (w) (i′) gw″ (Koppen, modified by García 1987), considered the driest of the warm sub-humid, with rain in summer and winter precipitation percentage of less than 5 % of the annual total rainfall. Total annual precipitation is $\sim$919 mm. The driest period is from November to April (39 mm) and the wettest, from May to October (880 mm). The average annual temperature is 24.1 °C. The soil is a vertisol with clay texture (48.8 %), with high montmorillonite clay content expandable (2:1), and a neutral pH (7.3; FAO–UNESCO 1988). The vegetation is tropical deciduous forest and the majority of the trees lose their leaves during the dry season. The most abundant tree families are Fabaceae, Burseraceae and Euphorbiaceae (Trejo and Dirzo 2000).

Methods

Species distribution in the plantation

The trees were 10 years at the beginning of the study and were distributed in 8 blocks (replicates). Each block had 4 rows, with 10 trees of one species each. The spacing used among trees was 3×2 m corresponding to 1,666 trees per ha. In total, there were 80 individuals of each species in the plantation. Species characteristics are found in the Table 1.

Litterfall production

To measure litterfall production, 64 square traps 60×60 cm (0.36 m^2) and 1 m high were used. The traps were placed randomly in the row corresponding to the species of study (16 traps per species). Litterfall was collected monthly during one year (December to November). Subsequently, the collected material was separated by species and components: leaves, reproductive structures (flowers, fruits and seeds) and twigs (fragments with a diameter >1 cm and bark). The material was dried and moved to a desiccator (Pyrex) with silica gel (dried) and weighed.

Organic matter decomposition

We used the litterbag method to determine the decomposition rate of leaves of each species (Wieder and Lang 1982). We focused on leaf litter rather than twigs because it represented a substantial portion

Table 1 Some characteristics of species used in this study (Batis et al. 1999 and Cervantes-Sánchez 1994)

Species/family	Growth rate	Ecological characteristics	Uses
Crescentia alata Kunth (1819)[a,b] Bignonaceae	Slow	Deciduous, tree or shrub (4–18 m tall). Anemochorous and zoocorous[d]. Drought and fire resistant, tolerant to poor soils	Fuel, construction, agricultural implements, saddles, food, foraging, shade, ornamental, traditional medicine, crafts, household items
Eysenhardtia polystachya (Ortega) Sarg. (1892) Leguminosae	Slow	Deciduous, nitrogen-fixing, tree or shrub (6–9 m tall). Anemochorous. Can grow on eroded soils, stony and shallow soil. High tolerance to drought, saline and alkaline soils	Fuel, construction, foraging, medicinal, craft, household items
Leucaena leucocephala (Lam) de Wit subsp. *glabrata* (Rose) S. Zárate (1987)[a,b,c] Leguminosae	Fast	Semi-deciduous, pioneer, nitrogen-fixing tree or shrub (3 to 6 m tall). Zoochorous. It grows best on fertile, neutral to slightly alkaline, well drained soils. Tolerates air pollution and drought. Useful to restoration of eroded soils for their well-developed taproot and deep. Resistant to pruning and grazing	Fuel, paper, construction, food, crafts, medicinal, shade, ornamental, forage, livestock, melliferous, agroforestry, organic fertilizer, land reclamation and reforestation
Pithecellobium dulce (Roxb) Benth. (1844)[a], Leguminosae	Fast	Evergreen, pioneer, nitrogen-fixing and spiny tree or shrub (5–22 m tall). Zoochorous. Resistant to drought and fire. Tolerant to very clay, shallow, saline, flooded limestone rock, poor and eroded soils	Fuel, construction, timber, tanning, agricultural implements, food, fodder, flavoring, coloring, cosmetics, medicinal, melliferous, ornamental, shade, reforestation and living fence

[a] Parrotta (1991), [b] Parrotta (1992), [c] Pérez-Negron and Casas (2007), [d] Janzen (1983)

(50–80 %) of total litter in terms of biomass produced (Sundarapandian and Swamy 1999), it has higher nutrient concentrations (Álvarez-Sánchez 2001) and decomposes faster than twigs and other wood materials (Anderson and Swift 1983), thus accelerating the cycling of nutrients in the soil. Freshly senesced leaves of each species were gathered and placed in decomposition bags (30 × 30 cm). Leaves of *P. dulce* and *C. alata*, with large leaflets, were collected directly from the plantation floor and were dried at room temperature. Leaves of *E. polystachya* and *L. leucocephala* were collected directly from trees of multiple individuals in the same period as the others, just before to abscission in order to avoid an overestimation in the nutrients content (Xuluc-Tolosa et al. 2003) because during senescence a decrease of nutrient content is observed in the leaves (Addicott 1978). Leaves of all species were dried at 60 °C for 72 h (Xuluc-Tolosa et al. 2003). The main reason for the different collections among species is that the latter two species have leaves with small leaflets, which are falling off, making it almost impossible to collect ground. Once dried, sub-samples of 15 g (dry weight) of *L.*

leucocephala, 12 g of *C. alata* and *P. dulce* and 7 g of *E. polystachya* (Palm and Sanchez 1990) were placed in bags. The lower amount of E. *polystachya* in the bags, was due to the fact that this tree produced the smallest sized leaves and the lowest amount of leaves (Fig. 1) and there was few biomass of leaves just before the abscission in the collection periods. A total of 48 bags for 12 collections (one per month) with four replicates of each species were randomly placed and set in the ground by a metal stake under trees of each species. Four randomly selected mesh bags of each species were collected monthly for 12 months. After collection, the material was removed manually, including plant material (leaves, seeds, grasses, roots) and fauna, if present. Then they were sieved in mesh of 0.25 mm pore size to remove the smaller fragments and soil particles. The material was dried in an oven at 80 °C until reaching constant weight.

Remaining weight (RW) for each collection date was expressed as a percentage of initial weight as follows:
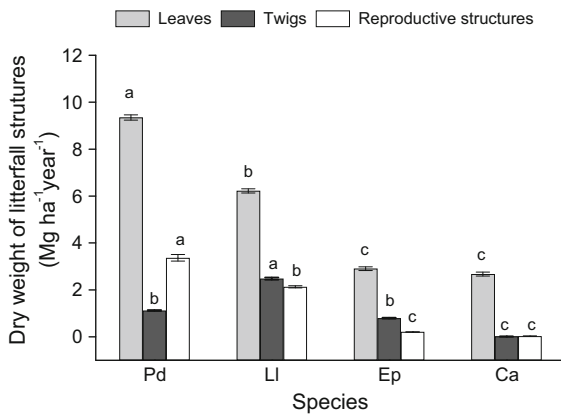
$$RW = (Wt_1/WT_0) \times 100,$$

Fig. 1 Dry weight of litterfall structures produced in one year by *Pithecellobium dulce* (Pd), *Leucaena leucocephala* (Ll), *Eysenhardtia polystachya* (Ep), *Crescentia alata* (Ca) tree species in a 10 year old plantation. *Vertical bars* represent standard errors. *Different letters* represent significant differences by the Duncan test (P < 0.05)

where RW = remaining weight; WT_0 = weight at time 0; WT_1 = weight after a given period.

The decomposition rate constant (K) was estimated for each collection date following the exponential model (Olson 1963) that characterizes the weight loss during the decomposition.

$$K = -[\ln(X_t/X_0)]/t,$$

where X_0 = weight (g) of litter at time 0; X_t = weight (g) of litter at time t (days); K = decomposition rate constant.

From K it was possible to obtain the average lifespan of the material sampled, in terms of time of decomposition, using the following equation (Olson 1963): $t_{(0.5)} = -\ln_{(0.5)}/k_{t(0.5)} = 0.6931/k$.

The time (t) necessary for 99 % organic matter loss was obtained by using the following equation (Olson 1963): $t_{(0.99)} = \ln_{(1-0.99)}/k$.

According to Wieder and Lang (1982), time (t) and average lifespan of litterfall return is expressed as: $t = 1/k$.

Chemical quality of leaf litter

Approximately 30 g of leaf material per species was taken in a bulked sample of leaf litter to estimate initial litter quality. Three of the four bags of decomposed litter (29, 122, 212, 302 and 398 days after decomposition) of each species were selected and dried. The mixed samples of each species were analyzed by a NC 2500 model elemental auto analyzer to quantify carbon (C) and nitrogen (N).

The percentage of nutrients remaining in the decomposing material was determined by the following formula:

$$C \text{ or total } N = (C \text{ or } N_{t_1}/C \text{ or } N_{t_0}) \times RW \times 100,$$

where C or N_{t0} = initial concentration of C or N in the leaf litter; C or N_{t1} = concentration after a t period; RW = remaining weight.

The C/N ratio was obtained by dividing the concentration of C by N (%) for each species at different times of decomposition of the material.

Statistical analysis

The data were transformed when was necessary and were subjected to a one-way ANOVA or to a *t* test. Differences in means were tested using a Duncan test. A Kruskal–Wallis test was made to compare N and C concentrations of species through the time of decomposition. A Pearson correlation was used to correlate the monthly remaining percentages of dry weight of each species with monthly precipitation.

Results

Annual litterfall production

Average litterfall production for all species after 12 months was 7.82 ± 2.69 Mg ha^{-1} year^{-1}. However, litterfall production differed significantly among species (F = 150.30, p < 0.0001). *P. dulce* had the highest litterfall production and *C. alata* had the lowest amount; Table 2).

Litterfall fractions

Leaf litter comprised the highest fraction in all species studied, being more than half of the total litterfall. The smallest fractions were twigs or reproductive structures. *C. alata* showed the highest percentage of leaf litter (98.41 %), while *L. leucocephala* the lowest percentage (57.43 %). *L. leucocephala* had the highest percentage of fallen twigs (20.90 %) while *C. alata* had the lowest percentage (0.52 %). The species with the highest percentage of reproductive structures was *P. dulce* (24.34 %) while *C. alata* had the lowest

Table 2 Annual litterfall production of tree species in a 10 year old plantation

Species	Litterfall (Mg ha^{-1} year^{-1})	SD
P. dulce	13.83616[a]	0.15081
L. leucocephala	10.83275[b]	0.08387
E. polystachia	3.90747[c]	0.07815
C. alata	2.71905[d]	0.08429

SD is standard error. Different letters represent significant differences by the Duncan test (P < 0.05)

(1.06 %). The total annual amount of leaves in the litterfall was significantly different among species (F = 111.08, p = 0.000). *P. dulce* had significantly greater amount of leaf litter, followed by *L. leucocephala* compared to the two other species. The quantities of leaf litter for *C. alata* and *E. polystachya* did not differ from one another statistically (Fig. 1).

The amount of fallen twigs was significantly different among all species (F = 49.10, p < 0.0001, Fig. 1). *L. leucocephala* had the largest amount of twigs (56.36 % of total) and *C. alata* dropped the lowest amount of twigs (0.23 % of total). *E. polystachya* (17.95 % of total) and *P. dulce* (25.45 % of total) dropped similar amounts (Fig. 1).

The species also differed significantly from each other in the total amount of reproductive structures fallen along the year (F = 60.47, p = 0.0001, Fig. 1). *P. dulce* stood out as having the significantly highest amount of reproductive structures than the other species, followed by *L. leucocephala*, which both differed from the other species. *C. alata* and *E. polystachya* dropped a small amount of reproductive structures and showed no significant differences between them (Fig. 1). Most of species increased the production of reproductive structures in the dry period (Fig. 2): *L. leucocephala* from February to April (59.73 %), *P. dulce* from March to May (79.60 %) and *E. polystachya* from December to March (76.02 %). By contrast, *C. alata* produced more reproductive structures at the onset of the rainy season (from May to June, 92.23 % of total).

Temporal dynamics of leaf litterfall production

Leaf litterfall production in *C. alata* followed a unimodal distribution, with increased production in the driest period (December to April, 80.72 % of total) and the lowest production from June to November (rainy season; 6.81 % of the total; Fig. 3). *E. polystachya* showed fluctuations, with a low production from December to August (19.54 % of total) and high production only in September and October (rainy season, 80.47 % of the total, Fig. 3). *L. leucocephala* leaf litterfall production was relatively constant through the year, with two small peaks of production in April (13.03 % of total) and October (11.86 %) and two lowest productions in January (4.99 %) and July (4.50 %; Fig. 3). *P. dulce* showed a maximum peak in May (the month in which the rain season begins, 16.89 %), a minimum in July (wettest month of the year; 2.53 %) and maintained a constant litterfall production along the year.

Organic matter decomposition

After 398 days in the plantation ground, the percentage of average dry weight remaining differed significantly among species (F = 19.90, p = 0.000). In all species mass loss in the first 183 days was rapid, coinciding with the rainy season (May to November). After this period, the mass loss stabilized showing small losses that were similar and continuous (Fig. 4). In fact, remaining percentages of dry weight of *C. alata* (R = 0.87, p = 0.000), *L. leucocephala* (R = 0.75, p = 0.005) and *P. dulce* (R = 0.66, p = 0.020) were significantly and positively correlated with precipitation, but *E. polystachya* did not show a significant correlation (R = 0.48, p = 0.110). *L. leucocephala* had the significantly lowest percentage of material remaining after 398 days (16.75 %) and consequently had the fastest decomposition rate (F = 9.73, p < 0.0001), losing approximately half of litter mass after 59 days (Fig. 4).

The decomposition rate constant K differed significantly among species (F = 21.90, P = 0.000). *L. leucocephala* had the highest value of $k_{(3.06)}$ and was significantly different from the other species (*C. alata*, *P. dulce* y *E. polystachya*), which did not differ from one another. The average lifespan and the time to lose 99 % of leaf fall suggest the same pattern. *C. alata* was the species with the lowest rate of decomposition (Table 3).

Quality of leaf litter after decomposition

The C and N concentrations in the leaf litter

The average of N and C concentrations along the time of decomposition was significantly different among

Fig. 2 Monthly reproductive structures production of *Pithecellobium dulce* (Pd), *Leucaena leucocephala* (Ll), *Eysenhardtia polystachya* (Ep), *Crescentia alata* (Ca) tree species and monthly precipitation (Pp) in a 10 years old plantation. *Vertical bars* represent standard errors
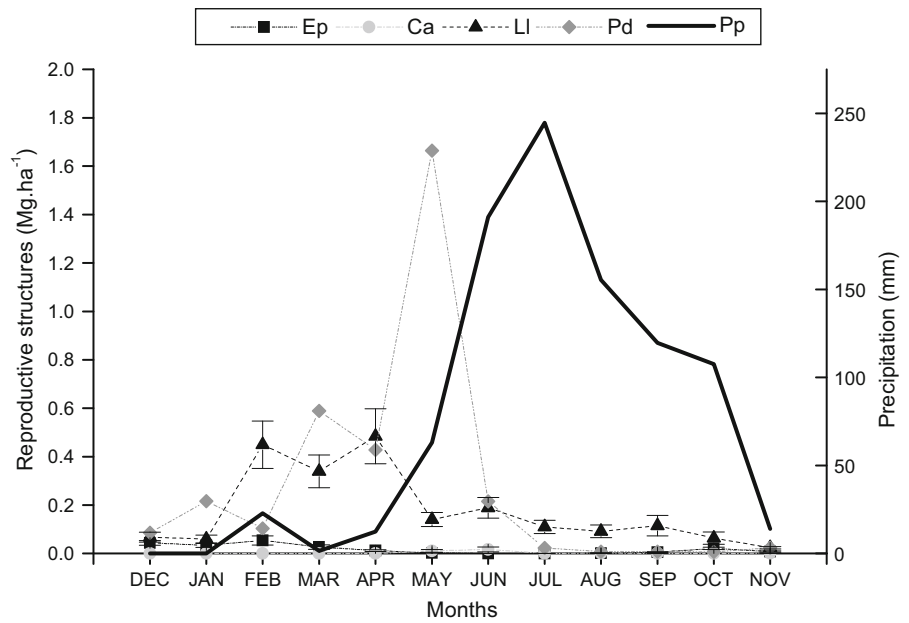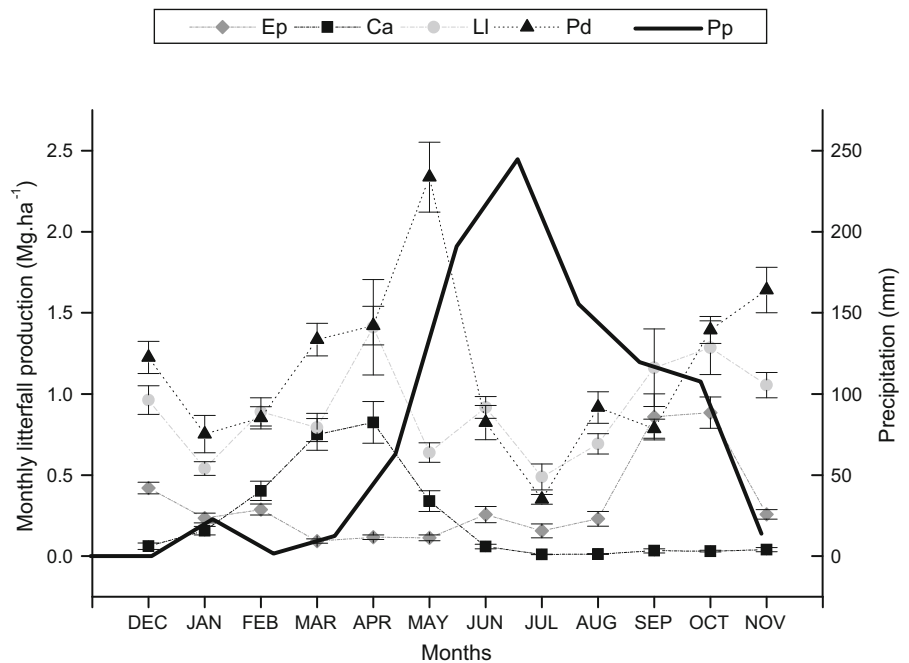

Fig. 3 Monthly leaf litterfall production of *Pithecellobium dulce* (Pd), *Leucaena leucocephala* (Ll), *Eysenhardtia polystachya* (Ep), *Crescentia alata* (Ca) tree species and monthly precipitation (Pp) in a 10 year old plantations. *Vertical bars* represent standard errors

species according to Kruskal–Wallis test ($H_N 38.52$, p = 0.0001; H_C = 11.09, p = 0.011). *C. alata* increased significantly N % through time (H = 13.05, p = 0.023). N percentage was 1.72 % ± 0.11 after 29 days exposure and 2.84 % ± 0.1 after 302 days of exposure. On the other hand, C percentages

significantly decreased (H = 13.47, p = 0.019) through decomposition time (43.36 % ± 0.22 in the first day of exposure and 34.55 % ± 2.86 after 122 days of exposure). *L. leucocephala* showed the same pattern, increasing significantly in N % through time (H = 11.92, p = 0.036), had the lowest N

Fig. 4 Percentage of dry mass remaining of leaves as a function of the exposure time (days) in the soil of *Pithecellobium dulce* (Pd), *Leucaena leucocephala* (Ll), *Eysenhardtia polystachya* (Ep) and *Crescentia alata* (Ca) tree species in a 10 years old plantation. *Vertical bars* represent standard errors
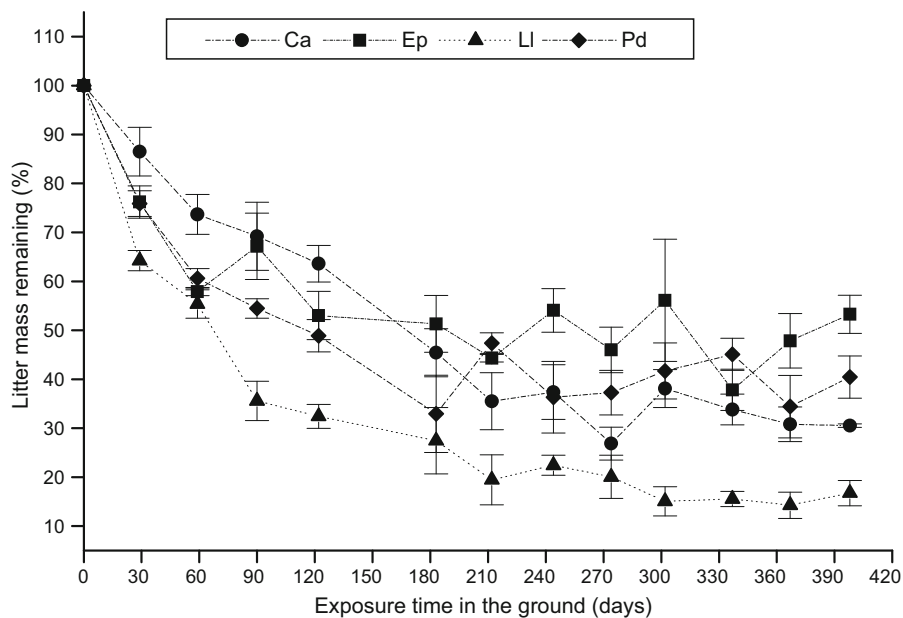

Table 3 Decomposition rate (k, year^{-1}), time necessary (years) to disappear 50 % and 99 % of leaf litterfall (lifespan average in years), initial Carbon (N), initial Nitrogen (N) and initial C/N ratio of tree species in a 10 years plantation

Species	k (year^{-1})	Lifespan average (50 % of loss) (years)	99 % of loss (years)	C (%)	N (%)	C/N
Crescentia alata	1.51[b]	0.60	3.97	43.36	1.81	24.01[a]
Eysenhardtia polystachya	1.61[b]	0.98	6.51	48.02	3.19	15.07[c]
Leucaena leucocephala	3.06[a]	0.36	2.37	46.20	3.19	14.50[c]
Pithecellobium dulce	1.91[b]	0.68	4.51	45.84	2.46	18.68[b]

Different letters represent significant differences by the Duncan test (P < 0.05)

percentage (3.19 % ± 0.07) at the start of the decomposition process (0 days exposure) and the highest (3.78 % ± 0.2) after 212 days of exposure. C percentage significantly decreased in relation to time (H = 12.74, p = 0.026), had the lowest percentage (38.89 % ± 1.11) after 398 days of exposure and the highest (46.87 % ± 0.4) at 29 days of exposure. Also *P. dulce* increased significantly in N percentages over time of exposure (H$_)$ = 11.93, p = 0.0357), showed the lowest N percentage (2.46 % ± 0.12) at the start of the decomposition process and the highest (3.5 % ± 0.05) at 302 days after exposure. However, in terms of C percentage there was no significant differences through the time of decomposition (H = 9.25, p = 0.0856). Meanwhile, *E. polystachya* showed no significant differences in N and C percentages (H = 4.77, p = 0.445; H = 8.48, p = 0.131 respectively) among days of exposure (Fig. 5).

The C/N ratio of the leaf litter along the decomposition time

The C/N ratio differed significantly among species (F = 10.87, p = 0.000) and time (F = 10.50, p = 0.000). The average ratio of *C. alata* was significantly higher from other species, the ratio of *E. Polystachya* and *P. dulce* followed in magnitude and were significantly similar, *L. leucocephala* was the species with the lowest C/N ratio and similar to *P. dulce* (and was significantly different from *E. polystachya*, that was similar to *P. dulce* (Table 4). In average, species showed a significantly higher C/N ratio in the beginning of decomposition (18.06 and 17.51 for 0 and 29 days, respectively) than in subsequent times, that were significantly similar to each other (12.74, 13.55, 12.81 and 13.26 for 122, 212, 302 and 398 days respectively).
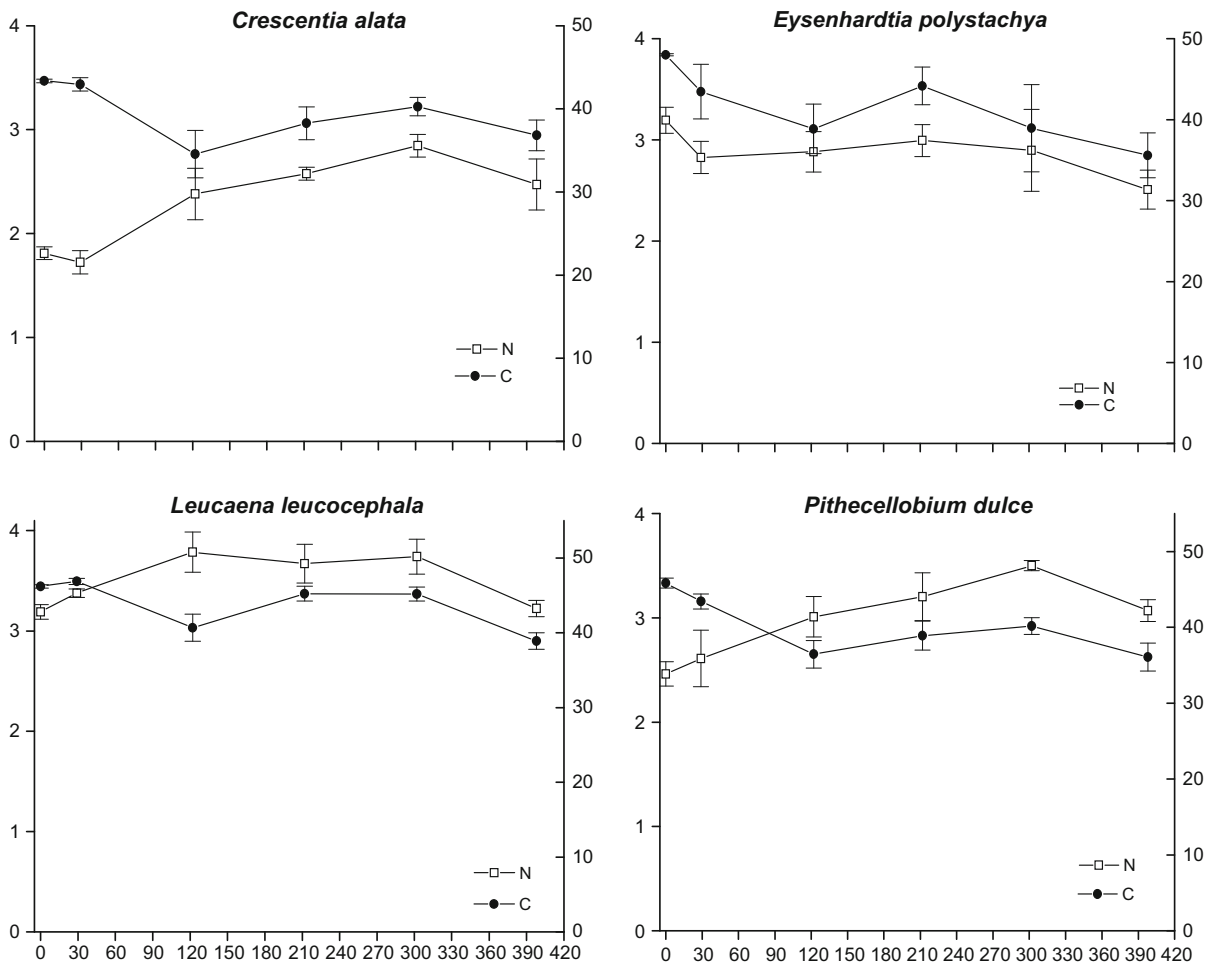
Fig. 5 Nitrogen (N; *left axis*) and Carbon (C, *right axis*) percentages along the time of decomposition of tree native species in a 10 years old plantation. *Vertical bars* represent standard errors

Discussion and conclusion

The quantity of biomass per unit area over time constitutes the primary data needed to understand the flow of nutrients and water through terrestrial ecosystems. The average of productivity in terms of litterfall (7.82 ± 2.69) of the 10 year-old plantations of four species from SDTF in Morelos, Mexico was not too much lower than the productivity of a secondary SDTF in Yucatán, also in Mexico (9.2 ± 0.6 Mg ha^{-1} year^{-1}, Campo and Vázquez-Yanes 2004).

  P. dulce and *L. leucocephala* produced the highest annual litterfall, possibly because both are fast-growing species, and after 10 years they had the highest basal area, cover and crown volume; which correlate with litterfall production (Álvarez-Sánchez 2001;

Table 4 C/N ratio average of 390 days of decomposing leaf litter of tree species, in a 10 years old plantation

Species	C/N Ratio	SD
C. alata	17.97512[a]	2.08554
E. polystachia	14.38012[b]	0.3324
P. dulce	13.85882[bc]	1.27166
L. leucocephala	12.61304[c]	0.55506

SD is standard error. Different letters represent significant differences by the Duncan test ($P < 0.05$)

Descheemaeker et al. 2006). The annual litterfall production of *L. leucocephala* in this study was similar to reported by Parrotta (1999) for this species in a mixed plantation in Puerto Rico (9.7 Mg ha^{-1} year^{-1}).

In this study, leaves constituted the largest proportion of total litterfall (57.4–98.4 %) similar to other studies in SDTF: in upland forests of Ethiopia (57–77 %; Lisanework and Michelsen 1994), in Chamela (70 %; Martínez-Yrízar 1995) and in Tigray uplands in Ethiopia (68–86 %; Descheemaeker et al. 2006). Regarding the small proportion of reproductive structures found in this study, according to Vitousek and Hooper (1998), in SDTF, plants generally produce more structures responsible for photosynthesis than reproductive structures. The zoochorous species *P. dulce* and *L. leucocephala* showed the highest production of reproductive structures because they are fast growing species and at 10 years, they already reached the reproductive age. The early reproduction and zoochory are two characteristic potentially important for restoration ecology projects, since these species shortly after implantation will be attracting the fauna to eat their fruits and increasing the seed dispersion by defecation, catalyzing the regeneration of other species in the restoration area (Holl 1999; Leitão et al. 2010, among others).

Most of reproductive structures of the species was produced in the dry season, in all SDTF, seed dispersal occurs mainly in this season (Bullock and Solis-Magallanes 1990). Seeds remain on the forest floor until the next rainfall season when they encounter more favorable conditions for germination and growth (Ceccon et al. 2006).

There was a marked effect of precipitation seasonality in the leaf litterfall of *P. dulce* and *C. alata*, while *E. polystachya* and *L. leucocephala* did not show this effect, because they are evergreen species. *P. dulce* produced the highest amount of leaf litterfall followed by *L. leucocephala*. Both species have a great potential to recuperate the organic matter of degraded soils.

All species of the study had significantly faster mass loss in the first 183 days of exposure, which coincided with the rainy season (May to November), then stabilizing with smaller but continuous mass loss. This behavior was similar to what happened in others SDTF (Nuñez-Quevedo 1998, Sundarapandian and Swamy 1999; Goma-Tchimbakala and Bernhard-Reversat 2006). At same time, decomposition rates of this study were similar to those of other species in plantations with similar climatic conditions (Lisanework and Michelsen 1994; Attignon et al. 2004; Goma-Tchimbakala and Bernhard-Reversat 2006).

Leaucaena leucocephala was the species that decomposed faster (lost 83.25 % of its leaf litter in 398 days) and the lifespan average of leaf litter was only 4.3 months, because this species contains much water that is lost at the beginning, and makes its weight greatly reduced, water-soluble compounds are released as carbohydrates and proteins, which creates a moist and nutrient rich environment for microbial activity and decomposition (Parrotta 1999). Furthermore, its N fixing status, its smooth, small and thin leaflets with cell walls that have high concentrations of N, Ca, Mg and K in the tissues, a low C/N ratio and a high initial N contents, as in this study, that make its leaf litter much more palatable (Heal et al. 1997; Parrotta 1999). Due to these characteristics, *L. leucocephala* is commonly used in alley cropping systems in tropical zones (Shelton and Brewbaker 1994) and it is recognized as a very efficient species in reclamation of physical properties of the soil, particularly porosity and bulk density, due to the rapid incorporation of humus in mineral soil.

P. dulce had less rapid decomposition rates than *L. leucocephala* presumably due to the morphology of their more rigid and thick leaves, but its decomposition rate depended on the quality of the resource expressed as a similar *to L. leucocephala* C/N ratio. Therefore, this species presents high biological potential for soil restoration.

The low rate of decomposition in *E. polystachya* certainly does not derive from its leaf litter quality (its initial C/N ratio was similar to *L. leucocephala*). This low rate probably resulted from the existence of a sunny, hot and dry microclimate under its open tree canopy (Byard et al. 1996; Barlow et al. 2007) that affected dynamic population of the microorganisms responsible for the decomposition (Valle-Arango 2003). Moreover, some authors (Singh 1969; Ewel 1976; Palm and Sanchez 1990; Byard et al. 1996) found that species with high nitrogen content in the leaves not always decompose faster than those with low concentrations, lignin and polyphenols can be important factors in determining the rate of decomposition and release retard decomposition of N, joining N compounds of the plant tissues.

C. alata was the species presenting the highest initial ratio C/N and lowest initial N concentration in the leaves, but its decomposition rate was not significantly different from that of *P. dulce* and *E. polystachya*, possibly due to decomposition depended

not only on the quality of litter, but also of the microclimate condition of the soil microorganisms. It is likely that it decomposed faster by the shade provided by neighboring species (*P. dulce* and *L. leucocephala*) that afford an optimal microclimate for decomposition and mineralization of humus, as also reported by Attignon et al. (2004) for a species of lower quality leaves.

Remaining mass correlated significantly with precipitation in all species except for *E. polystachya*, probably because its decomposition was more influenced by microenvironmental conditions under its canopy, an open canopy allows greater exposure to solar radiation and therefore there is less moisture in the soil. While in other species, rainfall keeps the leaf litter in wet conditions to their decay (Aerts 1997).

The release of deposited nutrients depends on the rate of decomposition. In this study, the only species that showed a rate similar to a natural seasonally dry tropical forest in India [among 4–4.5 months for 50 % decomposition; Roy and Singh 1994)] was *L. Leucocephala*. In this case, mixing leaves from species with differing resource quality and leaf structure may change the chemical environment and physically alter the total litter surface where decomposition is occurring (Kaneko and Salamanca 1999; Hector et al. 2000) and these alterations can also affect decomposer abundance and activity (Wardle 2002). Thus, chemical and physical changes in leaf mixes can influence decomposition rates. At same time, the relatively slow leaf litter decomposition of other tree species in this study should lead to soil organic matter build up in the long run and is expected to provide benefits of mulching such as preventing soil erosion and conserving soil moisture (Yadav 1963).

The analysis of quality of leaf litter coupled with mulch decomposition is of great importance for the understanding of energy flow, primary production and nutrient cycling in forest ecosystems (Vitousek 1984; Sundarapandian and Swamy 1999). Mulch with a high concentration of N tends to decompose faster and much of the N released is taken by microorganisms for the synthesis of cells and only a small part of it is removed from the soil by denitrification and uptake by plants (Singh 1969). Nitrogen is one of the most limiting factors in litter decomposition because it determines the growth and transfer of microbial biomass to organic C mineralized; therefore, mulch with a high concentration of N tends to decompose

faster (Heal et al. 1997). In this study N percentage increased significantly with the time of decomposition for *C. alata, L. leucocephala* and *P. dulce* except for *E. polystachya*. An increasing of N along the decomposition also happens for the most species in other studies (Montagnini et al. 1993; Xuluc-Tolosa et al. 2003; Berg and Mc Claugherty 2008). Some possible reasons for this accumulation of nitrogen were due nitrogen fixation, atmospheric ammonia absorption, caulinar flow, dust, fungal translocation and/or immobilization (Melillo et al. 1989; Xuluc-Tolosa et al. 2003) and microbial growth (Berg and Mc Claugherty 2008). Concentration of C during the decomposition process decreased in *C. alata* and *L. leucocephala* leaf litter, because during the decomposition, possibly C was the source of energy for decomposers, N fixation and denitrification (Berg and Mc Claugherty 2008).

C. alata had the highest annual average C/N ratio and *L. leucocephala* the lowest and similar to reported by Tian et al. (1992). *L. leucocephala* by its low C/N ratio can be considered the species with the best quality leaf litter, additionally it is a legume that fixes N. Meanwhile, *C. alata* is a slow-growing species that has thick leaves, leathery texture and low concentration of nutrients per unit of dry weight, by the accumulation of carbon compounds, resulting in a high C/N ratio in their leaves, which are long-lived and are decomposed very slowly (Chapin 1980). The C/N ratios of all studied species were higher at the beginning of the decomposition process (at 0 and 29 days) and lowest in the following days as happened with the species studied by Singh (1969). The C/N ratio decreases along the degradation process, because the concentration of N in the residual matter incrementing along the process and is immobilized in the microbial structure while organic C is respired as CO_2, in this way towards the end of the process, much of this tissue is the microbial residue that has replaced the original substrate (Waring and Schleslnger 1985 in Sachman 2004).

When the goal of restoration is the soil protection and nutrients recuperation, *P. dulce* is recommended, because it is a fast-growing tree, with a rapid canopy closure and a high litter production, which contributes to the establishment of mulch that protects against erosion and reduces the soil compaction, while slowly releasing nutrients, mainly N. This mulch could retain moisture preventing water loss and low soil temperature; it also prevents (due the mulch thick) the growth

of weeds, promoting the regeneration of tree shade species.

When the objective is to increase soil fertility as soon as possible, the appropriate species according to the results of the study is *L. leucocephala*, which produces large amounts of rapidly decomposing mulch with high amount of nutrients, which can be rapidly released into the soil. This mulch can be used as fertilizer in N deficient soils due to the rapid biological fixation of its N content, favoring the growth of crops and plants associated with this species. Therefore, for fast STDF biological soil restoration, the combination of both species is recommended.

Although the study was conducted on a plantation and may have somewhat limited correspondence with the natural dynamics of the species used, it can provide support for studies in natural ecosystems and also provide basic information necessary for the selection of species in restoration projects of degraded areas and agroforestry systems.

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