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Leucaena macrophylla: An ecosystem services provider?

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Abstract *Leucaena macrophylla*, a tree native to southern Mexico's tropical dry forest, belongs to a genus that is popular worldwide as a component of agroforestry systems. However, despite appreciation by local communities, this species is poorly studied and has not been evaluated as a multipurpose tree in its native range. This work evaluated whether *L. macrophylla* has the qualities necessary to serve as a multipurpose tree for agroforestry systems and a provider of ecosystem services in its original distribution, specifically, in soil nutrient amelioration and recovery, fuelwood production, and provision of quality livestock fodder. Leaves contained high values of nitrogen and calcium, and litter decomposition was relatively rapid ($\sim$50 % of mass lost over first 6 months). Despite somewhat low wood density, this species' high calorific value and low ash and moisture contents yielded a relatively high firewood value index (FVI = 2,594.65), suggesting high potential as a fuelwood. In terms of fodder quality, protein and digestible fiber contents were high and in vitro digestibility was adequate, as was condensed tannin concentration. It is important to mention, however, that *L. macrophylla* showed higher-than-ideal contents of lignin, both in fresh leaves and in litter. However, this apparently does not drastically reduce overall quality (i.e. decomposition rate and in vitro digestibility), and appropriate management techniques such as composting can mitigate its effects. Given its potential for providing a variety of ecosystem services, we recommend that *L. macrophylla* be installed in agroforestry systems in its native range to evaluate its effect on crop productivity.

Keywords Ecosystem services · Fuelwood · Fodder · Leaf litter · Alley cropping · *Leucaena macrophylla*

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Introduction

Around 60 % of "ecosystem services" evaluated by the Millennium Ecosystem Assessment around the world, are being degraded or used unsustainably and we don't yet know with certainty the extent of consequences for human welfare (MEA 2005). Agricultural production of food and fibers is one of the principal contributors to the degradation of natural

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ecosystems and the subsequent loss of the goods and services they provide (Tilman et al. 2011). The main consequence of this loss is decreasing biodiversity, which impairs ecosystem function and hence reduces goods and services available for human wellbeing (Foley et al. 2005; Tilman et al. 2011).

Clearly there exists a trade-off between satisfying the high demand for some ecosystem services like food and fibers, and sacrificing other services like fresh water and soil fertility (Foley et al. 2005). Therefore, the challenge is to improve the productivity of ecosystems or agro-ecosystems for immediate human needs, while reducing the environmental impacts of agriculture through sustainable ecosystem management over time (Foley et al. 2011; Tilman et al. 2011).

In this sense, many authors have proposed agroforestry and silvopastoral systems as a strategy to meet dietary, economic, and other immediate human needs with sustainable ecosystem services management and conservation (Lamb et al. 2005; Jose 2009; Vieira et al. 2009; Perfecto and Vandermeer 2008; Ceccon 2013). These land use systems were developed centuries ago by farmers and scientists, and take advantage of interactions between trees, crops, and/or livestock to optimize productivity and offer a set of ecosystem services, provided they are based on strong ecological principles (Jose 2009; Vieira et al. 2009; Ceccon 2013). The main ecosystem services offered by agroforestry systems include; carbon sequestration, biodiversity conservation, soil enrichment, and air and water purification, as well as a number of derived products (Jose 2009).

Seasonally dry tropical forest (SDTF) is one the most widely distributed and biodiverse tropical ecosystems (Murphy and Lugo 1986; Miles et al. 2006; Dirzo et al. 2011) and possesses high levels of endemism due to special adaptations to highly seasonal water availability (Murphy and Lugo 1986). The SDTF also offers a large number of ecosystem services, but it is one of the most threatened ecosystems, primarily due to human action (Trejo and Dirzo 2000; Miles et al. 2006; Dirzo et al. 2011). According to Miles et al. (2006), Latin America was the region that experienced the highest rate of deforestation between 1980 and 2000 (12 %), and the SDTFs of Mexico and Central America are especially at risk.

In Mexican SDTF, agro-pastoral activities and policies have been the main drivers of forest transformation (Maass et al. 2005; Castillo et al. 2005). Also, biophysical factors (e.g. environmental fragility) and socioeconomic factors (e.g. lack of productive options), influence the SDTF transformation dynamic (Maass et al. 2005). In addition, stakeholders are not aware of the dependence of ecosystem services on ecosystem functionality, and therefore unknowingly sacrifice long-term benefits for immediate ones (e.g. long-term soil fertility and clean water for immediate intensive crop production, Maass et al. 2005). Solving the SDTF degradation problem and achieving successful restoration will require sustainable management that accounts for the wellbeing of the human populations that depend on them (Maass et al. 2005; Miles et al. 2006).

The La Montaña region is located in the southeastern Mexican state of Guerrero and is comprised of three ethnic groups: Tlapanecos, Nahuas, and Mixtecos. Like many other rural regions in Mexico, it presents strong ecological deterioration and social problems such as lack of health and security, resulting in poverty traps (Sachs and McArthur 2005; Landa and Carabias 2009). The Human Development Index (HDI) of the Metlatonoc and Acatepec municipalities (0.36 and 0.48 respectively) are similar to those of African nations like Mali and Malawi (CONAPO 2000; Taniguchi 2011). These socio-ecological problems are strongly influenced by the loss of many ecosystem services, but also by environmental fragility, cultural marginalization, population growth and the lack of support and effective policies from the government (Bawa et al. 2004; Landa and Carabias 2009).

Some studies have suggested that the main environmental problems in the La Montaña region are in large part due to transformation of forest areas (mostly of SDTF) into productive fields, despite being steeply sloped and unsuitable for agriculture (Landa et al. 1997; Cervantes-Gutiérrez et al. 2001). The tools offered by agroforestry and agroecology are therefore particularly relevant for potential productive restoration strategies for alleviating La Montaña's economic and social problems. In addition, integrating traditional knowledge and practices into new systems accelerates the adoption process and keeps alive this important part of indigenous culture (Berkes et al. 2000).

The New world, mostly Mexico and Central America, is the native distribution of the *Leucaena* genus (Hughes 1998; Argel et al. 1998). Species from this genus have been studied around the world and are popular components of agroforestry systems (Argel et al. 1998; Hughes 1998). *Leucaena leucocephala* is one of the most used multipurpose trees, and despite some limitations presents many positive qualities such as fast growth, ease of propagation, exceptional quality of forage, and adequate wood density (Hughes 1998). The intense study of *L. leucocephala* makes it a useful point of comparison for evaluating the potential of other *Leucaena* species (Hughes 1998).

Leucaena macrophylla subsp. *macrophylla Benth,* is native to the Mexican SDTF and is highly valued by the communities of La Montaña for several services it provides, including timber, fuelwood, food and forage. Because of its ease of propagation, nitrogen fixing capacity, and fast growth, Cervantes-Gutiérrez (2001) considered *L. macrophylla* a promising multipurpose species for agroforestry and reforestation. However, studies of *L. macrophylla*'s potential to provide ecosystem services address only biomass and forage (Pottinger et al. 1996; Stewart and Dunsdon 1998; García and Medina 2006).

The aim of this study is to evaluate whether *L. macrophylla* in its native distribution has the qualities necessary to serve as a multipurpose tree for agroforestry systems, providing ecosystem services such as soil nutrient amelioration and recovery, fuelwood production, and provision of quality livestock fodder. In particular, we assessed leaf litter quality, fuelwood quality, and forage. Favorable qualities in these aspects would make this species a strong candidate for use in alternative production and restoration systems within its native distribution in Mexico and other tropical regions.

Methods

Study sites

Leaf litter and fuelwood quality analyses were carried out on samples obtained from an experimental *L. macrophylla* alley cropping plot installed in the municipality of Ayutla de los Libres in the foothills of the La Montaña region of the state of Guerrero in southeastern Mexico (16°59′21″N, 99°05′48″W, elevation: 400 m). Samples for fodder analyses were obtained from wild-growing *L. macrophylla* trees in the municipalities of Ayutla (17°02′40″N, 99°05′31″W, elevation: 913 m) and Acatepec (17°07′18″N, 99°06′08″W, elevation: 546 m). The region's climate is hot and sub-humid with rain in summer and a total annual precipitation of ~1,800 mm. The rainy season lasts from April to November, with highest rainfall in September (434 mm). The mean annual temperature is 25.7 °C; May is the warmest month (mean temperature 27.2 °C) and January the coldest (mean temperature 24.7 °C; SMN 2013).

The experimental alley cropping system from which we obtained samples and data for leaf litter quality and fuelwood evaluations was installed in 2009 using *L. macrophylla* and maize in a random block design. *L. macrophylla* was planted every 2 × 5 m (a density of 1,000 trees ha^{-1}) and maize in rows every 0.7 m between alleys of trees. According to the World reference base for soil resources (WRB 2007), the soil in the alley cropped area is classified as *Umbric Stagnic Fluvisol (Episkeletic, clayic)*. These are soils formed by alluvial materials deposited in terraces, with high gravel content and weak stratification but with at list two differentiated horizons. The surface horizon (0–35 cm) is dark with moderate to high content of organic matter (3.3 %), with low pH (around 4.8) and low base saturation. A second horizon (>35 cm) presents high clay content with poor water drainage and reducing conditions with a stagnic color pattern (WRB 2007). These features result in low nutrient availability, and therefore low soil productivity in the experimental plots.

Leaf samples for fodder analyses were taken from wild-growing adult *L. macrophylla* in natural stands of SDTF. Soils in these areas are mainly Regosols and Leptosols (INEGI 2010). These are young and not very developed mineral soils, sometimes rich in gravels from the parental materials and common in mountainous areas. These soils are also a signal of erosion, and are frequently used for animal grazing as well as rainfed agriculture (WRB 2007).

Leaf litter quality

Nutrient cycling is one of most important ecosystem functions, as it maintains soil fertility and productivity of ecosystems and agro-ecosystems (Nair et al. 1998). The rate of litter decomposition by soil biota and subsequent release and cycling of nutrients are largely determined by the leaves' secondary chemistry (Lambers et al. 2008). Therefore, high-quality litter, characterized by high N but low C/N ratio, lignin and polyphenol contents (e.g. tannins), is expected to release nutrients quickly (Mafongoya et al. 1997).

In order to evaluate the leaf litter quality of *L. macrophylla*, a litterbag decomposition experiment was installed within the experimental alley cropping plot in April 2012 (Anderson and Ingram 1993). A compound sample of leaves was harvested directly from 3-year-old *L. macrophylla* trees and air-dried for 48 h. 30 g of leaf litter was placed in 25 × 25 cm nylon mesh bags with 1.5 mm mesh. The bags were staked to the ground next to randomly selected *L. macrophylla* trees. Two bags were reserved to determine the initial dry weight and for initial chemical analyses (time zero). Approximately every 30 days for 6 months, four litterbags were collected and soil particles and other organic debris were manually cleaned with 1.0 and 0.5 mm sieves. Once clean, the samples were oven dried (48 h at 60 °C), milled and mixed to generate a compound sample for each month. All analyses of the remaining mass were carried out in duplicate. Total nitrogen was analyzed by the Kjeldahl method (AOAC 1990). Total carbon of the samples was converted by dry digestion at 950 °C to CO_2 and quantified by infrared detection with a 5050A TOC analyzer (Shimadzu Scientific Instruments, Columbia MD, USA). Crude lignin (lignin + cutin) content was quantified by 72 % sulfuric acid digestion of the acid detergent fiber (Goering and Van Soest 1970; Van Soest 1982; Anderson and Ingram 1993). Because this method does not differentiate cutin from lignin, it may overestimate lignin content by 0.3–1.2 % compared to the Klasson method, in which cutin is eliminated (Robbins et al. 1987).

The proportion of remaining mass after decomposition was expressed as percentage of dry weight, and of organic matter (dry weight—ash content), and the carbon/nitrogen (C/N) ratio, as well as lignin/nitrogen (L/N) ratio was calculated on a dry weight basis for each sample.

A simple exponential model was applied to calculate the annual decay constant, "k" (Olson 1963), which expresses the rate of mass lost as a function of time. Mineral particles that we were unable to exclude from the samples may have introduced error into our calculations of mass lost. In order to correct for this underestimation of mass lost (and therefore, decay rate), we utilized an alternative decay constant based on the ash-free dry matter (k_{af}), calculated by subtracting the ash content from the remaining dry mass at each collection time. The decay constant k was calculated as follows:

$$k_{af} = \frac{\left[\ln\left(\frac{x_t}{x_0}\right)\right]}{t}$$

where x_t is the remaining mass at time t (days) and x_0 is the initial mass. "Half life" ($t_{0.5}$) of mass decay was calculated using the decay constant, k, and solving the exponential model formula as follows (Olson 1963):

$$t_{(0.5)} = \frac{\ln(0.5)}{k} = \frac{0.6931}{k}$$

In order to evaluate the content and release dynamic of some of the main nutrients in the leaf material, subsamples were collected from initial, 4, and 6 month samples and were analyzed in duplicate for phosphorus (P), potassium (K) and calcium (Ca) content. The subsamples were digested with an acid mixture, and then each nutrient was determined in independent analyses. The steam stripping method was employed to determinate P. On the other hand, K was determinate by flame photometry and Ca by atomic absorption spectrophotometry in accordance with Mexican government standards for soil analysis (NOM-021-SEMARNAT 2002; Álvarez-Sánchez and Marín-Campos 2011).

Finally, a table was constructed in order to compare the main predictor parameters of decomposition for *L. macrophylla* with the ideal values proposed by Mafongoya et al. (1997), and the values found in the literature for *L. leucocephala,* one of the most popular species for agroforestry and a congener of *L. macrophylla* (see Table 1).

Fuelwood value

In order to evaluate the fuelwood quality of *L. macrophylla,* seventeen sticks from 3-year-old trees were collected from the alley cropping experiment mentioned above. All samples were taken at breast high (1.3 m aboveground) and their diameters ranged from 12 to 24 mm. Sample lengths were between 17 and 30 cm. The samples were weighed within 5 h of being cut and brought to the laboratory in paper bags. The calorific or energy value (kJ/g), moisture content

Table 1 Results of analyses of chemical parameters associated with leaf litter decomposition

Decomposition predictors.	*L. macrophylla*	*L. leucocephala*	Ideal values (Mafongoya et al. 1997)	Reference
N (%)	**3.52 ± 0.02**	4.21–5.33	≥2	(Vanlauwe et al. 1997)
C/N ratio	**14.46 ± 0.14**	10–16	≤20	(Mafongoya et al. 1997)
Lignin (%)	29.57 ± 0.02	5.85–10.53	<15	(Vanlauwe et al. 1997)
P (%)	0.095 ± 0.005		>0.2	–
k_{af} (yr^{-1})	**1.8**	3.06	–	(Ceccon et al. *In review*)
Half time (yr^{-1})	**0.38**	0.36	–	

In addition to results from our study of *Leucaena macrophylla,* values from a closely species, *Leucaena leucocephala* and those proposed by Mafongoya et al. 1997 as ideal values are provided for comparison

Bolded values are those that fulfill standards set by Mafongoya et al. 1997

(g/g), ash content (g/g), biomass/ash ratio, and density were used to calculate the fuelwood value index (FVI, Purohit and Nautiyal 1987). Duplicate sub-samples 5 cm long were taken from each stick and oven dried at 70 °C for 48 h until reaching constant weight (Chettri and Sharma 2009). A subset of the dried samples was used to determine density by the water displacement method. Another set of the samples was weighed and burned in a muffle furnace at 550 °C to determine their ash content and the biomass/ash ratio, obtained by dividing dry weight by ash weight (Bhatt and Todaria 1990; Chettri and Sharma 2009). Finally, 0.5 g of each dried sample was burned in an oxygen bomb calorimeter (Parr© 1266 Bomb Calorimeter; Moline, Illinois USA) to obtain the energy value of each sample. This type of calorimeter is common for energetic studies in animal feeding (Leeson and Summers 2001). Calorimeter measurements were calibrated using Benzoic acid, for which precise heat of combustion is known (Good et al. 1956). The calculation of the complete FVI was based in the following formula (Purohit and Nautiyal 1987):

$$FVI_C = \frac{Energy\ Value(kJ/g) \times Density(g/cm^3)}{Ash(g/g) \times Moisture(g/g)}$$

According to some authors, energy value and ash content are relatively uniform among species and are highly correlated with density and moisture content, which vary more widely (Abbot and Lowore 1999; Alves Ramos et al. 2008). They propose the use of a simplified FVI index calculated as follows:

$$FVI_S = \frac{Density(kg/m^3)}{Moisture(g/g)}$$

We characterized the suitability of *L. macrophylla* for use as fuelwood by comparing the result of fuelwood value analysis against other species found in the literature recommended for this application (Table 2).

Fodder quality

Samples of mature leaves and twigs for fodder analysis were collected from ten adult *L. macrophylla* trees growing wild in two stands (see Study Sites). All samples were air dried and saved in paper bags until they were brought to the laboratory the next day. They were then oven dried for 72 h at 50 °C and ground to pass through a 1 mm sieve. To assess the fodder quality of *L. macrophylla*, we performed, in duplicate, a proximal analysis according to AOAC (1990) methods, consisting of a set of laboratory procedures to calculate the dry matter (at 100 °C), crude protein content (Kjeldahl Nitrogen X 6.25), ether extract, crude fiber, ash content (with muffle at 550 °C) and organic matter content (See Van Soest 1982 for comprehensive methods). Dietary fiber, divided into neutral detergent and acid detergent fibers, as well as cellulose, hemicellulose and crude lignin, were calculated by the detergent system (Goering and Van Soest 1970; Van Soest 1982; Anderson and Ingram 1993).

Tables 1, 2 and 3 compare our results with literature values for other species commonly used in agroforestry systems and/or "ideal values". Data were not suitable for formal statistical analysis but comparisons are intended as a guide and to put our results in context.

Table 2 Wood quality parameters of *L. macrophylla* compared to literature values of trees recommended for use as fuelwood

Study (# species)	Calorific value (kJ/g)	Density (g/cm^3)	Ash content (g/g)	Moisture (g/g)	Complete FVI	Simplified FVI
Nirmal Kumar et al. (2011) (5)	25.34 ± 0.69	0.90 ± 0.020	0.022 ± 0.003	0.41 ± 0.039	2,945.73 ± 610.63	2.27 ± 0.19
Alves Ramos et al. (2008) (3)	–	0.72 ± 0.008	–	0.26 ± 0.016	–	2.77 ± 0.15
Abbot and Lowore (1999) (3)	–	0.72 ± 0.026	–	0.41 ± 0.022	–	1.74 ± 0.09
Bhatt and Todaria (1990) (5)	19.54 ± 0.30	0.80 ± 0.029	0.013 ± 0.001	0.48 ± 0.024	2,506.62 ± 158.01	1.68 ± 0.11
Mainoo and Ulzen-Appiah (1996) (3)	18.07 ± 0.14	0.67 ± 0.015	–	0.49 ± 0.068	–	1.41 ± 0.20
Puri et al. (1994) (5)	18.89 ± 0.42	0.76 ± 0.050	0.025 ± 0.004	0.48 ± 0.016	1,342.26 ± 316.85	1.57 ± 0.11
Literature median ± IQR	19.56 ± 3.91	0.74 ± 0.18	0.019 ± 0.011	0.44 ± 0.118	2,358.77 ± 1,121.11	1.79 ± 0.48
L. macrophylla	**19.15 ± 0.05**	0.55 ± 0.020	**0.013 ± 0.007**	**0.35 ± 0.013**	**2,594.65 ± 289.00**	**1.627 ± 0.08**

Values are given as mean ± SE, except for literature medians, which are given ± the inter-quartile range (IQR)

The complete fuelwood value index (FVI) is calculated using all four parameters (calorific value, density, ash, and moisture content), while the simplified index considers only density and moisture (see methods)

Bolded values are those that are equally or more favorable than recommended species

Table 3 Results of fodder quality analysis of *L. macrophylla* compared with the literature values from the same species and two of the most commonly used legume forage species, *Medicago sativa* (Alfalfa) and *L. leucocephala*

	L. macrophylla		*L. macrophylla Literature*		*Medicago sativa*		*L. leucocephala*	
	Mean ± SE	Range	Mean	Range	Mean	Range	Mean	Range
Dry matter	**95.29 ± 0.19**	94.6–96.2	42.13	–	90.78	90–93	–	–
Crude protein	**15.93 ± 1.12**	12.0–22.5	20.58	–	19.01	15–23	23.8	23.6–24.1
Ash	8.26 ± 0.45	6.25–11.1	6.22	–	10.0	8.9–11.3	–	–
Organic matter	**91.74 ± 0.45**	88.8–93.4	92.1	–	–	–	92.15	92.3–92.0
Crude fiber	**26.48 ± 0.46**	24.0–29.0	–	–	24.27	19.8–29.4	–	–
Neutral detergent fiber	**55.63 ± 0.62**	53.4–56.8	44.13	–	43.67	38.0–51.0	37.25	35.5–39.0
Acid detergent fiber	46.24 ± 1.2	40.8–52.5	21.16	–	32. 78	28.0–41.0	27.0	26.2–27.8
Lignin	22.8 ± 1.04	19.8–26.0	12.07	8.46–14.67	8.67	5.0–12.0	–	–
Condensed tannins	**1.54 ± 0.15**	0.7–2.0	3.45	–	–	–	–	–
Dry matter digestibility	**57.76 ± 1.15**	51.6–63.0	42.6	–	–	–	46.8	46.6–47.0
References			(García and Medina 2006; García et al. 2008)		(National Research Council 2000)		(Stewart and Dunsdon 1998)	

Values are given as dry base percentages

Bolded values are those that are equally or more favorable than recommended values for forage from literature

Results

Leaf litter quality evaluation

Initial concentration of C, N and P in collected litter material was 50.97 ± 0.88, 3.54 ± 0.03, and 0.095 ± 0.005 % respectively, while initial Ca and K content were 7.39 ± 0.06 and 0.88 ± 0.02 %. Initial C/N ratio was 14.39 ± 0.13, while crude lignin content was 29.72 ± 0.02 %, and the L/N ratio was 8.39 ± 0.06. See Table 1 for comparison with *L. leucocephala* and "ideal values" (from Mafongoya et al. 1997).

Figures 1 and 2 show the dynamic of mass loss and nutrient release. Over 6 months, around 46 % of litter mass was lost. The annual decay constant for remaining dry mass was $k_{af} = 1.8$. Half-life ($t_{0.5}$) of mass decay was 138 days for ash-free value of k_{af}. Over

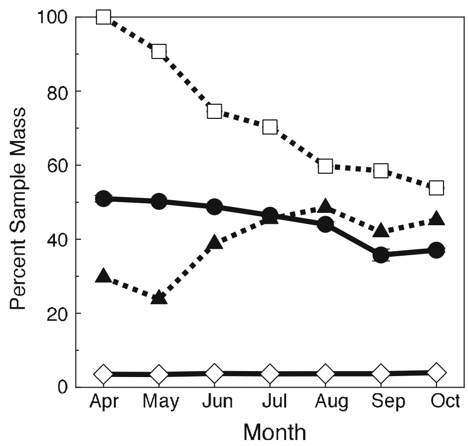

Fig. 1 Percent remaining mass (*empty squares*), and relative nitrogen (*empty diamonds*), carbon (*filled circles*) and crude lignin (*filled triangles*) contents as a function of decomposition time (months)

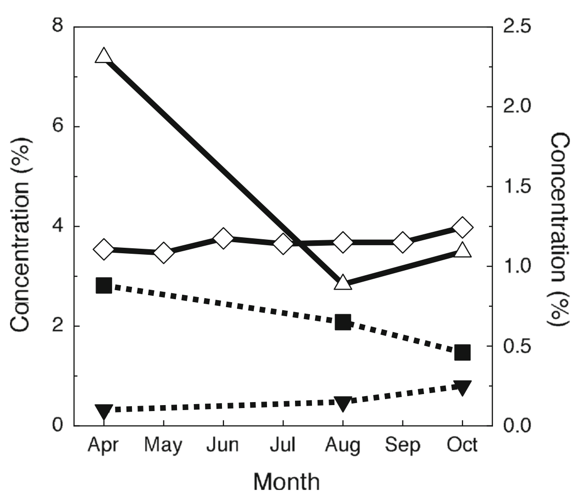

Fig. 2 The *left axis* shows nitrogen (*empty diamonds*) and calcium (*empty triangles*) concentration, and the *right axis* show phosphorus (*filled inverse triangles*) and potassium (*filled squares*) concentration, as a function of decomposition time (months)

6 months of decomposition, the relative carbon content declined with the remaining mass while crude lignin content increased. Stable N content (3.54–3.98 % relative concentration, see Fig. 1), meant that C/N and L/N ratios showed similar patterns to C and lignin, respectively. Through time, relative P content rose from 0.095 to 0.25 %, while Ca and K contents declined, losing 77 and 56 % of their respective initial concentrations during the first 4 months (see Fig. 2).

Fuelwood value analysis

The average calorific value was 19.15 ± 0.05 kJ/g, and density was 0.55 ± 0.02 g/cm^3. The average ash content was 1.30 ± 0.07 % and samples contained 35 ± 1.3 % moisture. The complete fuelwood value index obtain for *L. macrophylla* from 17 tree samples was 2,594.65 ± 289, and the simplified index (density/moisture) yielded a value of 16.27 ± 0.81.

Fodder quality analysis

L. macrophylla fodder was 91.74 ± 0.45 % organic matter, 15.93 ± 1.12 % crude protein, 8.26 ± 0.45 % ash content, and 26.48 ± 0.46 % crude fiber. In the analysis of fiber fractions, 55.63 ± 0.62 % was neutral detergent fiber, while 46.26 ± 1.2 % was and acid detergent fiber and crude lignin content was 22.8 ± 1.04 %. The in vitro digestibility was 57.76 ± 1.15 %, and the content of condensed tannins was 1.54 ± 0.15 %.

Discussion

Leaf litter quality

L. macrophylla had a high initial concentration of nutrients, particularly N (3.5 %) and Ca (7.3 %) and low C/N ratio (13.6), which are correlated with faster decomposition (Table 1), and fall within ideal values (Mafongoya et al. 1997). Initial lignin content (29.72 %) was nearly double the ideal values, which is generally thought to slow decomposition (Rahman et al. 2013). While in this case high lignin content did not reduce the decomposition rate to below ideal values, it may have inhibited nutrient liberation (Rahman et al. 2013).

The decay rate ($k_{af} = 1.8$) was slower than *L. leucocephala* (Ceccon et al. *in review*), but faster than most forest species, and similar to other agroforestry multipurpose trees (Swift et al. 1979; Jamaludheen and Kumar 1999). *L. macroplylla* lost most mass quickly during the first 4 months, then the decomposition was slower during the last 2 months (Fig. 1). A similar dynamic of decomposition has been observed in other important agroforestry species like *Gliricidia sepium*, which virtually stops decomposing after 4 months, when relative lignin content are elevated, exceeding 18 % (Hartemink and O'Sullivan 2001). In alley cropping systems, where litter from rows of leguminous trees serves as a main source of fertilizer for crops, synchronization of litter decomposition with crop N requirements is important for efficient nutrient use (Sanginga et al. 1995). In contrast to the rapid decomposition of *L. leucocephala* prunings, which tends to liberate more N than young maize plants can absorb after the first post-dry season pruning (Sanginga et al. 1995), the steady decomposition of *L. macrophylla* litter over the first 4 months is potentially well synchronized with the 14 week growing season of maize, though this remains to be tested.

Similar to the decomposition dynamics for mass, Ca and K were quickly released, losing 77 and 56 % respectively in 4 months. The high initial concentration and fast release of Ca and K may be particularly advantageous in acidic soils, potentially improving pH conditions and cation exchange capacity and increasing soil nutrient availability (Anderson and Ingram 1993; Young 1989). Important amounts of alkaline nutrients like K or Ca supplied by litter, can change the soil conditions as fast as 24 weeks, which is important for the growth of some crops (Hartemink and O'Sullivan 2001).

N was less labile, reducing its concentration by 39 %. P was quite stable, decreasing by only 12 %, making it the nutrient with the highest relative concentration at the end of decomposition tests (Fig. 2). This reduction in release rate of N and virtual immobilization of P is likely due to *L. macrophyllá*s high lignin concentration. It has been suggested that, at least in tropical ecosystems, the decomposition process can initially be controlled by nutrient concentration, but over time high lignin concentration may become limiting (Hobbie 2000; Rahman et al. 2013).

Lignin is a complex carbon polymer that is virtually impossible to degrade by most organisms due to its aromatic structure and strong bonds (Lambers et al. 2008; Rahman et al. 2013). Large N and P-rich compounds, such as proteins, can become trapped within a matrix of lignin (Rahman et al. 2013). Though this high lignin concentration might be an intrinsic property of *L. macrophylla*, lignin content is phenotypically plastic, and the poor soil in which individuals used for these analyses were grown may contribute to higher lignin concentration (Lambers et al. 2008; Rahman et al. 2013). Lignin content also tends to be higher in areas with high amounts of precipitation (Santiago et al. 2005), a potentially important consideration in wetter or highly seasonal areas. There are many relatively simple, low-cost options for reducing the effects of high lignin content, including milling the litter, incorporating it into the soil, and composting, which all promote bacterial and fugal activity and thus aid in the breakdown of lignin and release of trapped nutrients (Mafongoya et al. 1997). On the other hand, lignin can be a valuable addition to degraded soil, as it is an important part of humus and other complex compounds that may ameliorate soil quality and aid in carbon sequestration (Mafongoya et al. 1997; Rahman et al. 2013; Nair et al. 2009), which are frequently main goals of agroforestry systems (Nair et al. 2009).

The high concentration and release rate of Ca and K, as well as its N content make *L. macrophylla* a particularly strong candidate for agroforestry systems and restoration projects in thin, degraded, acidic soils. The main limitation of *L. macrophylla* as a provider of green manure is its lignin content; however, management techniques to improve decomposition and nutrient liberation are relatively simple and inexpensive. Alternatively, using *L. macrophylla* at different developmental phases (e.g. using both budding and mature leaves) or in conjunction with lower lignin multipurpose species could be used to address specific restoration and productivity goals (Mafongoya et al. 1997).

Fuelwood quality

Ideal fuelwood has high density and calorific value, but low ash and moisture content (Nirmal Kumar et al. 2011). *L. macrophylla* had calorific value, ash content, moisture content, and complete and simplified FVI close to the median of those of fuelwood recommended species (Table 2). Wood density was substantially lower than the reported value for recommended species (Table 2), however, it is important to note that samples used in this study were of young trees (3 years old) and density may increase with age (Goel and Behl 1996). In addition, the fact that both the complete and simplified FVI are similar between *L. macrophylla* and recommended species suggests that high calorific value and low ash and moisture content were sufficient to compensate for low density in overall quality.

Fuelwood is practically the sole household energy source in La Montaña (Salgado and Ceccon 2013) and the region has been identified as a fuelwood consumption "hot spot" within Mexico (Ghilardi et al. 2007). Due to depletion of this resource in areas surrounding communities, fuelwood collection is time and energy consuming; searchers must travel increasingly long distances on foot and have relatively low success rates, and are limited by their capacity to carry wood back to their communities (Miramontes et al. 2012). Finding alternative sources of fuelwood that both reduce the environmental impact and improve the quality of life of local people is thus of high priority in this region. Though *L. macrophylla* may not have all the ideal intrinsic qualities for fuelwood-providing species, agroforestry systems integrating this species could offer a possible solution to the problems of overexploitation of already degraded ecosystems. In addition, cultivation within a single plot near communities would greatly reduce the time and energy necessary to gather fuelwood (Miramontes et al. 2012). Fast growth, resistance to local conditions, and cheap implementation are all important considerations for fuelwood-providing species (Abbot and Lowore 1999), and native trees tend to perform better than exotics (Puri et al. 1994), all of which are characteristics of *L. macrophylla* in the La Montaña region. *L. macrophylla* is also already highly appreciated by local communities as a fuelwood species, which is a potential advantage for implementation of this species in restoration projects.

Fodder quality

High quality fodder provides livestock with both energy and protein (Van Soest 1982). Leguminous trees are a significant source of quality fodder, especially in arid or seasonally dry areas where other types of forage are limited (Buck et al. 1999). *L. macrophylla* has high proportions of crude protein, crude fiber, and neutral detergent fiber (the most digestible class of fiber), which are signals of high quality fodder (Table 3). However, because of its high content of secondary metabolites (e.g. tannins) and high concentrations of indigestible fibers (e.g. lignin) which can impede digestion, it is important to quantify in vitro digestibility as well to have a more complete picture of fodder quality (Van Soest et al. 1991). *L. macrophylla* also had a low content of condensed tannins (Table 3), which is important because these compounds can impede enzyme action and protein digestion (Robbins et al. 1987). However, we found very high levels of acid detergent fiber and crude lignin both of which are forms of indigestible fiber and are detrimental to fodder quality (Robbins et al. 1987; Van Soest 1982). Overall, *L. macrophylla* presents acceptable values for fodder quality. As in our decomposition experiment, lignin contents are higher than the ideal, however in vitro digestibility remains high (57.76 %; see Table 3). Taken together with other studies that have demonstrated high palatability and favorable nutrient content values (García and Medina 2006), *L. macrophyllá*s characteristics lead us to conclude that it is a promising fodder-provider species for livestock and as a potential secondary product of agroforestry systems.

Conclusions

Our results suggest that *L. macrophylla* may provide high quality leaf litter, a sustainable source of fuelwood, and a source of nutritive livestock fodder. Though lignin concentration is higher than ideal for both leaf litter decomposition and livestock fodder, this apparently does not drastically reduce overall quality (i.e. decomposition rate and in vitro digestibility), and appropriate management techniques can mitigate its effects. Similar analyses could be applied as a screening step to identify and initially evaluate other indigenous species as potential agroforestry systems components and ecosystem service providers. However, further analyses including direct comparisons with other species and evaluating management techniques will be important for exploring real-world potential. Given its potential for providing a variety of ecosystem services, we suggest that *L. macrophylla* be installed in agroforestry systems in La Montaña to evaluate its effect on crop productivity in its native habitat.

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