UNIVERSIDAD NACIONAL AUTÓNOMA DE MÉXICO
POSGRADO EN CIENCIAS BIOLÓGICAS
FACULTAD DE CIENCIAS
Manejo Integral de Ecosistemas

Evaluación del papel potencial *de Leucaena macrophylla* para proyectos de restauración productiva

TESIS

QUE PARA OPTAR POR EL GRADO DE:

DOCTOR EN CIENCIAS

PRESENTA:

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CIUDAD UNIVERSITARIA, CD. MX. ENERO 2018

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AGRADECIMIENTOS

El autor de este trabajo de tesis doctoral agradece especialmente al Posgrado en Ciencias Biológicas de la Universidad Nacional Autónoma de México el apoyo recibido para la realización de la misma. Además, agradece al Consejo Nacional de Ciencia y Tecnología (CONACyT) la beca de manutención recibida durante los periodos de agosto del 2009 a julio 2014, y el apoyo económico recibido por parte de Proyectos de Investigación e Innovación Tecnológica (PAPIIT) UNAM, Numero IN300615 e IN105015, para la realización de las actividades de campo. Asimismo, agradece a la OSC Xuajin Me'Phaa A.C. el apoyo logístico, económico y de personal brindado a este trabajo de tesis.

AGRADECIMIENTOS A TÍTULO PERSONAL

Agradezco a mi comité tutor: la Dra. Eliane Ceccon, la Dra. Cristina Martínez Garza y el Dr. Miguel Martínez Ramos, su apoyo académico, sin el cual no hubiese podido realizar este trabajo. Agradezco también a mis padres quienes aportaron al desarrollo de esta tesis. Y finalmente, agradezco a Daniel, Isaac y a mi querida Mónica, quienes me ayudaron tanto en la tesis como en mi formación académica y humana.

DEDICATORIA

Porque en cada proyecto consumado hay siempre apoyo y amor…

Dedico esta tesis a mis padres y abuelos, que son mis pilares, y a todos los seres queridos que han caminado a mi lado.

Índice

Resumen

A medida que la transformación de los ecosistemas naturales avanza en el planeta, se torna evidente la compleja integración entre los sistemas sociales y los naturales. Por tal motivo, es prioritario desarrollar estrategias de restauración ecológica que fortalezcan la capacidad de dichos socioecosistemas para resistir y adaptarse a los cambios; especialmente en paisajes rurales, donde imperan condiciones de pobreza y vulnerabilidad. En este trabajo se explora el papel de *Leucaena macrophylla,* leguminosa nativa de Mesoamérica, como proveedora de servicios ecosistémicos para ser incorporada en nuevos agroecosistemas como estrategia de restauración en paisajes dominados por el hombre. Aunque las especies del género Leucaena son de las más utilizadas en sistemas agroforestales alrededor del mundo (principalmente *L. leucocephala*), poco se ha estudio sobre las cualidades y el potencial de *L. macrophylla* en asociación con cultivos tradicionales, así como su papel para promover el rendimiento de los cultivos y mejorar los ingresos económicos de los campesinos. Considerando tales carencias de información, esta tesis tuvo como objetivos evaluar a) el potencial de *L. macrophylla* para proporcionar hojarasca, leña y forraje de alta calidad; b) la productividad y viabilidad económica de un sistema alternativo de cultivos en callejones con *L. macrophylla* y maíz criollo, comparado con un monocultivo de maíz en la región de La Montaña de Guerrero, México (uno de los lugares más pobres del país). Los resultados indican que *L. macrophylla* posee alta calidad como hojarasca, leña y forraje, según varios indicadores relevantes, como la tasa de descomposición de hojarasca (tasa media = 0.38), el valor calorífico de la leña (19.5 kJ/g) y la concentración de nutrientes en las hojas (% N = 3.52 %), aun cuando presenta un alto contenido de lignina (22.8 %). En cuanto al cultivo que combina *L. macrophylla* y maíz en callejones, los resultados prueban que obtuvo un mayor rendimiento de grano de maíz (~10% los tres últimos años) y mayor productividad por unidad de área en comparación con los monocultivos (RET > 2). Además, con el aumento de la productividad y la reducción en los costos de fertilización, aumentaron los rendimientos económicos a lo largo del periodo de estudio. Por último, una vez demostrado en este estudio el potencial de *L. macrophylla* como especie agroforestal, recomendamos esta especie para que sea ampliamente diseminada, especialmente en agroecosistemas tradicionales de Mesoamérica.

Abstract

As world's natural ecosystems transformation moves forward, the complex integration between social and natural systems becomes clearer. For this reason, it is a priority to develop ecological restoration strategies that improve the capacity of such socio-ecosystems to resist and adapt to changes, especially in rural landscapes, where conditions of poverty and vulnerability prevail. This work explores the role of *Leucaena macrophylla*, a leguminous tree native from Mesoamerica, as an ecosystem services provider, to be incorporated in new agroecosystems as a restoration strategy in human-dominated landscapes. Although the species belonging to Leucaena genre which are used worldwide in agroforestry systems (predominantly *L. leucocephala*), very little is know about the qualities and potential performance of *L. macrophyla* in association with traditional crops, as well as its role to foster crops yield and improve the monetary incomes of peasants. With this purpose in mind, this work has the aims to a) evaluate the potential of *L. macrophylla* to provide litter, fuelwood and fodder of high quality, as well as b) assess its productivity, and economic viability within an alley cropping alternative system with *L. macrophylla* and creole maize in comparison with a maize monoculture in “La Montaña” region of Guerrero, Mexico (one of the poorest places in the country). According to the results of several relevant indicators, such as leaf-litter decomposition rates (half time decay =0.38), calorific value (19.5 kJ/g), and nutrient concentration in leaves (% N = 3.52 %), among others, *L. macrophylla* possess a high quality as leaf litter, fuelwood and fodder, despite its high lignin content (22.8%). Regarding the alley cropping system of *L. macrophylla* with maize, the results prove that it has a better maize grain yield (~ 10% last three years) and more productivity per unit of area than its monocultures (LER > 2). In addition, along with the increase in productivity and the reduction in fertilization costs, the economic incomes also increased during the study period. Finally, considering the potential of *L. macrophylla* as an agroforestry species demonstrated in this study, we highly encourage the use of this species to be disseminated in many traditional agroecosystems particularly from Mesoamerica.

Introducción

La crisis ambiental global es resultado en gran medida de las acciones humanas entre las cuales se incluye: la transformación de los ecosistemas naturales, la alteración de los ciclos biogeoquímicos, la disminución de la biodiversidad del planeta y el calentamiento global, todo lo cual constituye la dimensión ecológica del denominado cambio global (Vitousek *et al.* 1997; Chapin III *et al*. 2000). Parte de estos impactos son resultado de la agricultura intensiva, que desde hace décadas ha dejado de brindar bienestar humano y responde principalmente a los intereses de grandes corporaciones y monopolios trasnacionales, promoviendo patrones de consumo dañinos, la degradación ambiental, desigualdad y pobreza en el mundo (Foley *et al.* 2011; Tilman *et al.* 2011; Chappell *et al*. 2013).

La rápida transformación de los ecosistemas naturales y sus efectos sobre el bienestar humano han provocado que la restauración de los bosques, la conservación de la biodiversidad y seguridad alimentaria, se vuelvan objetivos centrales de la agenda internacional (Holl 2017). Ciencias como la biología de la conservación, la restauración ecológica, , la economía ecológica y la ciencia para la sustentabilidad, entre otras disciplinas emergentes, han modificado sus paradigmas para afrontar estos nuevos retos (Chazdon 2008; Hobbs y Cramer 2008; Chazdon *et al*. 2009; Holl 2017). En el caso de la restauración ecológica, se está abandonando la idea de regresar a los ecosistemas a un determinado estado previo –a sus condiciones "primigenias"–, priorizando en cambio el restablecimiento de funciones claves para la provisión de bienes y servicios ecosistémicos; además de favorecer ciertas cualidades intrínsecas a los ecosistemas, como su resiliencia (Hobbs y Cramer 2008).

Asimismo, se plantea la necesidad de desarrollar estrategias a una mayor escala, como la de paisaje, lo que implica no solo reconocer una matriz con un mosaico de opciones de manejo, sino además considerar a las comunidades y actores locales como los principales responsables de su éxito (Laestadius *et al*. 2015; Brancalion y Chazdon 2017; Holl 2017). Por tal motivo, la restauración requiere cada vez más de herramientas e ideas provenientes de otras áreas del conocimiento, como la sociología, la ecología del paisaje, ingeniería forestal, y la agroecología (Vieira *et al.* 2009; Perfecto y Vandermeer 2010; Brancalion *et al.* 2013; Ceccon y Pérez 2016).

Debido a que las características ecológicas, socioeconómicas y políticas suelen variar de forma muy importante de una región a otra, un punto clave para el éxito de la restauración es conocer las acciones y objetivos requeridos en cada contexto (Hobbs y Cramer 2008; Brancalion y Chazdon 2017; Holl 2017). Por ejemplo, en países desarrollados, hay áreas con baja densidad poblacional, o regiones con baja aptitud agrícola, donde es posible destinar grandes áreas a la protección y regeneración natural (Fischer *et al*. 2014; Holl 2017). Sin embargo, en regiones económicamente menos favorecidas, con alta densidad poblacional y paisajes sometidos a degradación y disturbios crónicos –como sucede en gran parte de Latinoamérica– es necesario desarrollar estrategias de restauración con base en la participación comunitaria y plantear objetivos sociales más definidos (Ceccon *et al*. 2015; Meli *et al*. 2017).

En regiones tropicales rurales –donde se concentra gran parte de la biodiversidad del planeta (Cincotta *et al.* 2000; Dirzo and Raven 2003)– una estrategia viable es el manejo integral del paisaje agrícola (Perfecto y Vandermeer 2008); se trata de que las comunidades puedan ser partícipes de la conservación y recuperación de los bosques y otros ecosistemas dentro de la matriz agrícola, usando técnicas agroecológicas y agroforestales para actividades de restauración productiva *sensu* Ceccon, (2013), creando así paisajes más biodiversos, resilientes y sustentables (Melo *et al.* 2013). En México, un área de oportunidad para la implementación de este enfoque es la región de la Montaña alta de Guerrero, conformada por 19 municipios mayoritariamente indígenas; se trata de una de las regiones más pobres y marginadas del país, según diversos índices a nivel nacional (CONAPO 2000; CONEVAL 2010). De acuerdo con los estudios realizados en la región, la alta fragilidad ecológica, la degradación crónica y la falta de opciones productivas son en gran medida causantes de las trampas de pobreza que aquejan a su población (Landa y Carabias 2009; Hernández-Muciño *et al*. 2016).

Desde el 2009, un grupo de investigación de la UNAM ha trabajado en colaboración con la organización de la sociedad civil (OSC) Xuajin Me'Phaa A.C. para identificar los problemas socioecológicos más importantes en la región y tratar de desarrollar estrategias de restauración, con un enfoque participativo, *ad hoc* a la región (Ceccon *et al*. 2015). Como resultado de dichas investigaciones, se hizo la caracterización de la dinámica del paisaje, y se identificaron conflictos relativos a los patrones de manejo de recursos forestales y actividades productivas (Ceccon 2016; Borda-Niño *et al*. 2017). Además, se generó información sobre las especies nativas con alto valor socioecológico (especies importantes ecológica, económica y culturalmente), que podrían ser incorporadas en los agroecosistemas de la región con propósitos tanto ecológicos como productivos (Hernández-Muciño *et al*. 2016; Borda-Niño *et al*. 2017).

Considerando el contexto de degradación y pobreza en la región de la Montaña, el cual es semejante a muchas a otras regiones rurales de Latinoamérica y el mundo, se vuelve prioritario proponer nuevas formas de manejo de la matriz agrícola degradada, que permitan la restauración de ciertos servicios ecosistémicos clave (como la fertilidad del suelo, ciclaje de nutrientes e infiltración del agua), así como la conservación y manejo de la biodiversidad local; así, en lugar de vulnerar los medios de subsistencia, se contribuiría a mejor la calidad de vida de los habitantes de esta región. Esto se puede alcanzar en cierta medida, a través del diseño de nuevos sistemas de cultivo más productivos y sostenibles que combinen las bases tradicionales de manejo de los ecosistemas con los conocimientos recientes en el campo de agroforestería y la agroecología. Para ello, se evaluó la incorporación de un sistema agroforestal con una leguminosa nativa, valorada por las comunidades, al sistema tradicional de cultivo de maíz, con la intención de mejorar las condiciones de fertilidad del cultivo, y en consecuencia, aumentar la productividad del sistema en contraste con el monocultivo de maíz estándar.

Leucaena macrophylla subsp. *macrophylla* Benth fue elegida como especie de estudio. Leguminosa nativa de México y Mesoamérica, habita principalmente en bosques tropicales estacionalmente secos y es manejada generalmente *in situ* por comunidades indígenas a lo largo de su distribución (Casas *et al.* 1993; Hughes 1998; Cervantes-Gutiérrez *et al*. 2001). Se eligió esta especie por ser sumamente valorada por las comunidades indígenas de la Montaña alta de Guerrero como parte de su alimentación, ya que se aprovechan sus hojas, flores y vainas tiernas, así como sus semillas (Casas *et al.* 1993); pero también por ser parte de uno de los géneros más estudiados en el mundo como especies multipropósito, en virtud de los beneficios que ofrecen: como mantillo, forraje y leña que (Hughes 1998; Cervantes-Gutiérrez *et al.* 2001; Hernández-Muciño *et al*. 2016).

Por su parte, *L. macrophylla* se considera promisoria como especie multipropósito, debido a algunas características ecofisiológicas, como alto contenido nutricional, rápida nodulación y capacidad para fijar nitrógeno; su fácil propagación y rápido crecimiento, así como su capacidad de rebrotar, producir biomasa y madera (Stewart and Dunsdon 1998; Cervantes-Gutiérrez *et al*. 2001; García *et al*. 2008). Pese a que existen algunos estudios que subrayan el potencial de *L. macrophylla* como especie multipropósito, aún se conoce poco sobre sus cualidades y los beneficios que puede ofrecer en asociación con otras especies o cultivos, además es prácticamente ignorada en los sistemas agroforestales actuales. Finalmente, por ser una especie nativa de Mesoamérica, puede ser más fácilmente adoptada en los sistemas de cultivo tradicionales en dicha región. Por lo tanto, es necesario evaluar si *L. macrophylla* cuenta con las características necesarias para proveer bienes y servicios ecosistémicos, y de ser así, probar su desempeño cuando se incorpora, junto con tecnologías agroecológicas y agroforestales, a los sistemas tradicionales de producción en la Montaña de Guerrero y otros pasajes rurales semejantes. Esto, a fin de proponer este sistema como estrategia de restauración productiva *ad hoc* a la región, y que contribuya a lograr los objetivos de restauración y bienestar social que dichos socioecosistemas requieren.

Para el presente trabajo se plantearon los siguientes objetivos generales, de los que posteriormente derivaron los capítulos de tesis: 1) Evaluar la capacidad de *L. macrophylla* como proveedora de servicios ecosistémicos, específicamente de hojarasca, forraje y leña de buena calidad (comparable a otras especies agroforestales), y de ser así, proponerla como especie multipropósito, para ser incorporada dentro de nuevos agroecosistemas culturales; 2) Evaluar a lo largo de cinco años la productividad en términos de biomasa y grano, de un sistema de cultivo en callejones con *L. macrophylla* y maíz criollo, en dónde la hojarasca es incorporada a dicho cultivo con el propósito de aumentar los rendimientos de grano, mantener la productividad del cultivo por un periodo largo de tiempo, e incrementar los ingresos; 3) Finalmente, destacar la importancia que tiene la creación de nuevos agroecosistemas culturales para la restauración ecológica, el manejo sostenible y la adaptación al cambio climático en paisajes rurales vulnerables, como la Montaña de Guerrero.

El capítulo uno, titulado "*Leucaena macrophylla*: ¿Una proveedora de servicios ecosistémicos? (En inglés)", que se encuentra publicado en el tomo 85 de la revista *Agroforestry systems (2015),* expone los resultados de la evaluación realizada a *L. macrophylla* como árbol multipropósito, en específico, su capacidad para proveer hojarasca, forraje y leña de buena calidad; por tanto, plantea la posibilidad de que forme parte de actividades de restauración, así como de nuevos agroecosistemas culturales. Como principales hallazgos de este capítulo, destacan: La hojarasca de buena calidad, pues aun cuando posee algunas características que podrían ser detrimentales, la tasa de descomposición, el contenido de nutrientes y la concentración de taninos son adecuados; buena calidad de leña, con un valor calorífico, humedad y densidad adecuados de acuerdo con los rangos reportados en la literatura para otras especies; así como una buena calidad como forraje, pues tiene altos contenidos de proteína, fibras digestibles y digestibilidad in vitro; aunque también posee alta concentración de lignina, esto no afecta de modo importante su calidad.

El segundo capítulo de la tesis, titulado "Resiliencia socioecológica para comunidades indígenas: Evaluación de cinco años de productividad a un agroecosistema cultural con *Leucaena macrophylla* en México" (versión en inglés) –en formato de artículo para ser enviado a una revista *Agricultural Systems*– , busca responder si es productivo, y económicamente favorable, incorporar a *L. macrophylla* a los sistemas de cultivo tradicionales en la Montaña de Guerrero, a través de un método agroforestal de cultivo en callejones. En este capítulo, se resumen los principales resultados obtenidos, a lo largo de cinco años, con un sistema alternativo de fertilización, así como de un cultivo en callejones, compuesto de *L. macrophylla* y maíz; en contraste con el método tradicional de cultivo de maíz en la región. También se realizó un breve análisis de la viabilidad económica para estos dos sistemas. Como principales resultados de este capítulo, destacan: que el método alternativo de fertilización, que representa una reducción del 25% en los fertilizantes aplicados, sustituyó adecuadamente el método estándar de fertilización; asimismo, se registró durante los últimos tres años (que fue el tiempo que se aplicó la biomasa de *L. macrophylla*) un mayor rendimiento de grano dentro del cultivo en callejones (aproximadamente 10 % más los últimos tres años); igualmente, una productividad mayor por unidad de área de dicho sistema a lo largo de los cinco años (RET > 2) y una mayor viabilidad económica de este sistema en callejones. Estos resultados en conjunto sugieren una mayor sostenibilidad del cultivo en callejones con *L. macrophylla* y maíz al cabo de cinco años de experimento.

Por su parte, el capítulo tres de esta tesis, titulado "Agroecosistemas culturales para la restauración de paisajes rurales: el estudio de *Leucaena macrophylla* en La Montaña de Guerrero, México (versión en inglés)", hace hincapié en la creación de agroecosistemas culturales biodiversos, *ad hoc* a las condiciones locales, basados en el manejo tradicional de los recursos naturales y en la transferencia de nuevas tecnologías. Asimismo, resume las primeras lecciones obtenidas durante cuatro años de investigación con *L. macrophylla* como proveedora de servicios ecosistémicos y los primeros resultados obtenidos con su incorporación en un sistema tradicional de producción de maíz en la región. Este capítulo esta publicado en el libro *Más allá de la ecología de la restauración: perspectivas sociales en América Latina y el Caribe*, que recopila experiencias de restauración con un enfoque social y participativo a lo largo de 11 países de Latinoamérica y el Caribe; primera publicación en su tipo, que deja patente el crecimiento que ha tenido la restauración ecológica en esta parte del mundo y plantea la necesidad de seguir actuando coordinada y colaborativamente en una región con gran afinidad socioecológica, cultural y lingüística (Ceccon y Pérez 2016).

Por último, en la sección de discusión y conclusiones de la tesis se hace un recuento detallado de los principales resultados y lecciones obtenidas a partir de este trabajo de investigación, así como una reflexión sobre la importancia de realizar investigación en relación estrecha con comunidades y organizaciones de la sociedad civil, lo que puede permitir una mayor difusión y alcance de los resultados. Cabe mencionar que el presente trabajo de tesis sentó las bases de un convenio de colaboración entre el CRIM-UNAM y la OSC Xuajín Me'Phaa A.C., del cual se han desprendido varios trabajos de tesis, proyectos financiados con enfoque de restauración y varias publicaciones (Detalles en; Ceccon 2016).

Como parte de las actividades de investigación complementarias de esta tesis, otros trabajos fueron publicados, de los cuales se destacan: un artículo sobre el análisis de patrones de movilidad de las comunidades indígenas en su búsqueda por leña (Miramontes *et al.* 2012); un artículo de análisis a escala local y de paisaje sobre las trayectorias ecológicas y dinámicas sociales que afectan al paisaje de la Montaña, y cómo pueden ser consideradas en las actividades de restauración (Borda-Niño *et al.* 2017); un capítulo sobre la colaboración entre investigadores y OSC para desarrollar el proyecto de "traspatio cultural Me'Phaa" (Borda-Niño *et al.* 2016); así como el capítulo "La comunidad Me'Phaa construye su futuro: Agroecología y restauración como herramientas de desarrollo social sustentable (Hernández-Muciño *et al.* 2017)" sobre la colaboración transdisciplinaria para el desarrollo del programa agroecológico en la Montaña de Guerrero, en el libro titulado *Construyendo lo común desde las diferencias. I. Experiencias de colaboración transdisciplinaria para la sustentabilidad*. Estos trabajos son importantes, pues complementaron significativamente la experiencia de investigación durante el desarrollo de la tesis.

Finalmente, como individuos y como equipo de trabajo, creemos firmemente que en un país donde la pobreza tiene sexo, edad, tono de piel y origen étnico definidos, no será posible recuperar un metro cuadrado de tierra si no incorporamos a las comunidades, a partir de su territorio y sus necesidades, y no asumimos la lucha por la igualdad y el bienestar humano como parte de nuestro quehacer cotidiano.

Capítulo 1

Leucaena macrophylla: An ecosystem services provider?

Agroforest Syst (2015) 89:163–174
DOI 10.1007/s10457-014-9751-0

Leucaena macrophylla: An ecosystem services provider?

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Eliane Ceccon**

Received: 12 February 2014 / Accepted: 29 September 2014 / Published online: 8 October 2014

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 (~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*

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

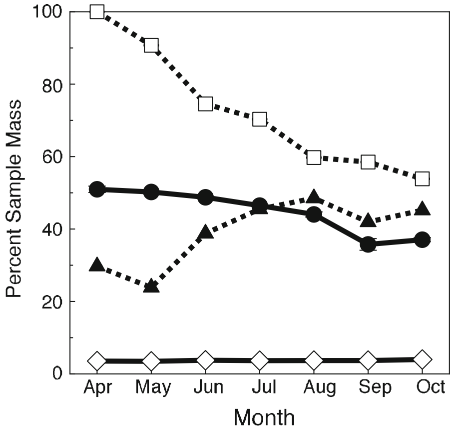

Fig. 1 Percent remaining mass (*empty squares*), and relative nitrogen (*empty diamonds*), carbon (*filled circles*) and crude lignin (*filled triangles*) contents as a function of decomposition time (months)

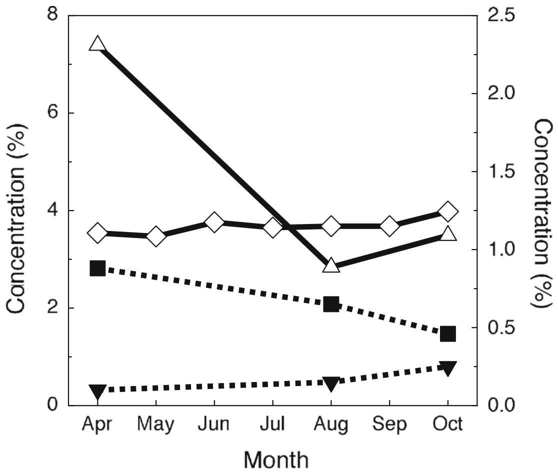

Fig. 2 The *left axis* shows nitrogen (*empty diamonds*) and calcium (*empty triangles*) concentration, and the *right axis* show phosphorus (*filled inverse triangles*) and potassium (*filled squares*) concentration, as a function of decomposition time (months)

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. macrophylla*́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.

Acknowledgments We thank members of the Xuajin Me'Phaa organization and Monica Borda Niño for help with logistics and fieldwork and Lynna Marie Kiere for thoughtful discussion and help with the manuscript. This work constitutes partial fulfillment of DHM's doctoral thesis in the Posgrado en Ciencias Biológicas at the Universidad Nacional Autónoma de México (UNAM), and DHM was supported by a doctoral grant from Consejo Nacional de Ciencia y Tecnología (CONACyT).

Funding for this project was provided by the Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT) UNAM, projects #IN-300112 and #IN-304409.

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Capítulo 2

Socio-ecological resilience for indigenous communities: A five-years evaluation of productivity from a cultural agroecosystem with *Leucaena macrophylla* in Mexico

Socio-ecological resilience for indigenous communities: A five-years evaluation of productivity from a cultural agroecosystem with *Leucaena macrophylla* in Mexico

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Abstract

While modern agriculture is partly responsible for the current environmental crisis reflected in loss of biodiversity, transformation of ecosystems, and alteration biogeochemical cycles, agro-markets also contribute to important socioeconomic and ecological conflicts in rural regions of the world. Therefore, it is a priority to propose new strategies to stop the current degradation trends and build more resilient agroecosystems that contribute to restoring ecosystem services at a landscape level, promoting food security in poor rural regions. *Leucaena macrophylla* is an indigenous legume species with potential to provide many ecosystem services and goods within its native distribution. However, this species is currently unappreciated in modern agriculture and little is known about its performance within agricultural systems or in association with traditional crops, as well as its role promoting crops yield and the incomes provided by this systems to farmers. The goal of this study was to assess the productivity, and economic viability of a new agroecosystem: alley cropping with *L. macrophylla* adapted to the traditional method of maize cultivation in “La Montaña” communities, and an alternative bio-fertilization protocol. A five years evaluation of maize grain yield and *L. macrophylla* biomass were performed in an experimental area from the “La Montaña” region southern Mexico. As well as, through a "Land Equivalent Ratio" analysis and a cost-benefit analysis, the productive and economic viability of the whole systems were valuated. Our results demonstrate that *L. macrophylla*/maize alley cropping system had a better yield with 10-12% higher maize grain, more than double the total productivity by area (LER >2), and generated both economic benefits (by reducing fertilization costs) and better incomes over the five years of the study (e.g. 4.8 USD returned per USD invested last year). While not directly evaluated here, this system may offer important ecosystem services such as nutrient cycling, soil conservation and fertility, water infiltration, landscape connectivity, and biodiversity, which a future work should include in the viability equation.

With some adjustments in tree's density and pruning to increases *L. macrophylla* productivity, the use of this new cultural agroecosystem, could be highly recommended, as well as assessing in similar way other highly valued native species, to contribute to overcome poverty traps in the "La Montaña" and in other poor rural regions.

Introduction

The main environmental consequences of the intensive agriculture model are the degradation of natural ecosystems, habitat fragmentation, the emission of greenhouse gases (about a quarter of total emissions), eutrophication of aquatic ecosystems from agricultural nutrient runoff, and negative human and wildlife health effects from exposure to pesticides and antibiotics (Tilman *et al.* 2002; Ceccon 2008). If the current trajectory of agricultural production continues, it is estimated that by 2050, the demand for crops will have doubled, causing the clearing of ~1 billion ha of forest, release of ~3Gt y^{-1} of CO_2, and application of 250 Mt y^{-1} of nitrogenous fertilizers, with catastrophic environmental consequences (Tilman *et al.* 2011). At same time, there are at least three major issues that contribute to the global environmental crisis and its impacts on human welfare for near future. First, the increasing demand for goods and services from the growing world population is also linked to a food distribution crisis (Tilman *et al.* 2011). Second, an alarming loss of biodiversity, reflected in the biggest extinction event of the earth's history, is driven mainly by a land use change, habitats loss and fragmentation (Dirzo and Raven 2003). Third, the widespread alteration of biogeochemical cycles is driving global climate change that affects the dynamics of all ecosystems (Vitousek *et al.* 1997; Foley *et al.* 2011). Due agriculture contributes at least in part to gases emission, transformation and pollution of ecosystems, it is important addressing this issues within agricultural activities, since these actions also have the potential to ameliorate the global environmental crisis and satisfy at same time the human needs (Perfecto and Vandermeer 2010; Foley *et al.* 2011; Tilman *et al.* 2011). Recently, the Food and Agriculture Organization (FAO) and other international organizations, aware of these increasing threats, have emphasized the need to develop a resilience strategy for both agriculture and rural communities that are mostly dependent on it. This means to develop the socio-ecosystems ability to prevent, anticipate and recover from crises in a sustainable manner, which includes protecting, restoring and improving livelihoods systems in the face of threats that impact agriculture and food security among others (Hegney *et al.* 2008; Folke *et al.* 2010; Meybeck and Lankoski 2012; FAO 2017).

One popular option for satisfying the 2050-level food demand while minimizing the environmental costs is through " sustainable agriculture intensification" were already-cultivated lands are improved, and new technologies are transferred to developing countries; increasing food production, reducing forest clearing, and allowing conservation of biodiversity (Green *et al.* 2005; Tilman *et al.* 2011). This can be suitable in some geopolitical contexts (e.g. developed countries, with low rural population), however this approach fails when it assumes that the food problem is only about productivity and technology gaps, and not a food security problem, which involves the entire food production system and myriad economic, geopolitical, and ecological factors (Chappell and LaValle 2011; Fischer *et al.* 2014). Paradoxically, in most developing countries in tropics, biodiversity hotspots coexist with food insecurity (Cincotta *et al.* 2000; Dirzo and Raven 2003; Godfray *et al.* 2010). More that 70 percent of the poorest people in the world are settled in rural tropical areas, and are dependent on small-scale agriculture, live with food insecurity, and are most vulnerable to the effects of climate change (Nelson *et al.* 2009; Heinemann *et al.* 2011). One alternative option for rural heterogeneous landscapes is the "quality matrix" approach (Perfecto and Vandermeer 2010; Fischer *et al.* 2011). In this model, biodiversity conservation and food security are achieve through a high quality agricultural matrix which is capable of promoting fauna migration, preserving metapopulation structure, and avoiding local extinction (Perfecto and Vandermeer 2010). It is suggested that the ideal way to create this matrix is through small-scale agriculture, which fosters biodiversity-friendly agroecosystems that maintain high-biodiversity fragments of native vegetation while encouraging food security (Perfecto and Vandermeer 2008; Perfecto and Vandermeer 2010).

Therefore, new agricultural management approaches based on more sustainable rural livelihoods are necessary to conserve and to restore ecosystem services and ensure food security in rural tropical regions with diverse land use mosaics and complex socio-ecological contexts (e.g. in Latin America; Armesto *et al.* 2007; Ceccon *et al.* 2015; Ceccon and Pérez 2016). Alternative agricultural systems (e.g. traditional homegardens) are promising tools to build resilience, since they offer more biodiverse, safe and sustainable ways to produce goods, and are easily adapted to climate change (Perfecto and Vandermeer 2008; Koohafkan *et al.* 2012; Melo *et al.* 2013). In this context, productive restoration proposed by Ceccon (2013), employs agroecological and agroforestry techniques to recover some ecosystem elements and functions, prioritizing functions that ensure food sovereignty and human well-being, such as connectivity, nutrient cycling, water infiltration, and pest regulation. A goal shared with the agroecological movement, is to create new cultural agroecosystems that combine traditional ecological knowledge with suitable new technologies, and incorporate native and creole species to promote resilience and maximize social, ecological, and economic benefits (Altieri and Toledo 2011; Hernández-Muciño *et al.* 2016).

Particularly in a country as complex as Mexico with more that 50 million people living in poverty, and where more than 50% of ecosystems are degraded (Bollo Manet *et al.* 2014), deforestation rates continues increasing, and adequate legal instruments for biodiversity conservation do not exist, restoration options become very limited (Ceccon *et al.* 2015). In this context the study and design of this new management practices in rural landscapes, could be essential to abating food insecurity, ecosystems degradation and biodiversity loss (Armesto *et al*. 2007; Ceccon *et al.* 2015; Meli *et al.* 2016). The research group from National University of México (UNAM), in collaboration with indigenous Me'Phaa communities, are using these strategies to restore the rural landscape from "La Montaña" region in Mexico (Ceccon 2016).

The La Montaña region, locate in the state of Guerrero in southeastern Mexico, is comprised of 19 municipalities, with a predominantly indigenous population including the Tlapaneco (Me'Phaa), Nahua, and Mixteco ethnic groups (Landa and Carabias 2009; Hernández-Muciño *et al.* 2016; Hernández-Muciño *et al.* 2017). This region is one the poorest in the country, with nearly 60 percent of its population living in extreme poverty (217, 721 inhabitants; CONEVAL 2010), and it has one of the highest levels of environmental degradation in Mexico (Bollo Manent *et al.* 2014). Most socio-ecological problems of this region are attributed to isolation, environmental fragility, strong dependence on ecosystems resources, and lack of support and adequate policies from government (Landa and Carabias 2009). A recent study in the region (Acatepec municipality), showed a spatial pattern typical of highly human-modified landscapes, with many small, irregular forest remnants (< 21 ha) and intense edge effect, which is confirmed by forest structure and composition characteristic of plant communities disturbed by logging or in early successional phases (Borda-Niño *et al.* 2017). Studies of search patterns and consumption of species used for fuel-wood support these conclusions (Miramontes *et al.* 2012; Salgado and Ceccon 2013). Finally, an analysis of possible sceneries of restoration concluded that productive restoration in agricultural areas can contribute as much as the enrichment of open forests to total landscape connectivity (Borda-Niño *et al.* 2017).

The traditional method of cultivation in the La Montaña region is a local version of the “Milpa”, an indigenous form of rain-fed agriculture where local maize (here, the “tuxpeño” race; Ortega-Paczca; personal communication), is combined with other local crops, semi-domesticated herbs, and some tolerated wild trees (Toledo *et al.* 2003). Also, some traditional techniques and tools are adapted to steeply sloped areas; for example, a non-tillage system using a planting stick called a "Coa", in a quincunx arrangement to reduce erosion (Landa Ordaz 2000). There are still traditional fertility management strategies with periods of three to eight years fallow and the use of mulches and green manures, such as wild beans (e.g. *Mucuna sp.*). Nevertheless, these cultural practices are disappearing due in part to subsidized fertilizers and herbicides. The restoration of agricultural lands with new cultural agroecosystems based on traditional indigenous knowledge and proper technologies to assure food security, improve landscape connectivity, and reduce environmental damage is therefore urgent (Altieri 2002; Hernández-Muciño *et al.* 2016).

One important option to restore agricultural lands, increase the matrix quality, and recover ecosystem services is through agroforestry systems using native species (Jose 2009; Ceccon 2013). Some native species of this region have been proposed as multipurpose trees (MPT): *Hymenaea courbaril*, *Pterocarpus acapulcensis*, *Acacia farnesiana*, *Leucaena esculenta*, *Lysiloma acapulcensis*, and *Leucaena macrophylla*, among others (Cervantes-Gutiérrez *et al.* 2001; Borda-Niño *et al.* 2017). Alley cropping in particular, is an agroforestry system that integrates crops with legume trees and shrubs to contribute to nutrient cycling, reduction of nutrient leaching, increase soil fauna, soil erosion control, and sustain levels of productivity (Kang 1997). In alley cropping, the trees are planted in alternating rows with crops and are periodically pruned to avoid light and water competition, form mulch, hold moisture, limit weed growth, incorporate nutrients into soil, and increase soil fauna (Kang 1997). At the same time, the tree's roots avoid nutrient leaching, reduce soil erosion, and increase water use efficiency (Kang 1997). In addition, the biological nitrogen (N) fixation from leguminous trees is an important and sustainable source of N that may reduce the amount of synthetic fertilizer required for crops, promoting N-use efficiency through formation of more stable compounds and increasing N held in soil (Crews and Peoples 2004; Badgley *et al.* 2007). *Leucaena macrophylla* subsp. *macrophylla* Benth, is a N-fixing species that may provide many ecosystem services (Hernández-Muciño *et al.* 2015). The genus *Leucaena* is native to Mexico and Mesoamerica and is popular worldwide as a component of agroforestry systems, especially *Leucaena leucocephala* (Argel *et al.* 1998; Hughes 1998) and *Leucaena esculenta* (Casas, 1992; Casas and Caballero 1996; Casas *et al.* 2007; Moreno-Calle *et al.* 2013).. *L. macrophylla*, while less studied, is valued by local communities as source of fuel-wood, food, and forage, however most of its management is done *in situ*, that means that trees of this species are collected in the forest or tolerated as lonely trees within agricultural areas (Casas y Caballero 1996). Also some early studies point out advantages including ease of propagation, N-fixing capacity, fast growth and high biomass production (Hughes 1998; Cervantes-Gutiérrez *et al.* 2001; Mullen and Gutteridge 2002).

A recent evaluation of *L. macrophylla* as ecosystem services provider within its native distribution showed high litter quality (high N; 3.5%, Calcium Ca; 7.3%, and fast decomposition), adequate fuel-wood quality compared with other species (fuel-wood value index = 2,594.65), and good fodder quality (high protein; 16%, and *in vitro* digestibility; 58%). These features suggest that *L. macrophylla* may be useful in agroforestry and restoration projects (Hernández-Muciño *et al.* 2015).

Based in current information available for *L. macrophylla* qualities as multipurpose tree and ecosystem services provider, the present study aims to evaluate the performance and economic viability of *L. macrophylla* as part of an agroforestry system, to be later included as productive restoration strategy into the cultivation systems of the La Montaña region and other similar regions. With this purpose, an experiment was carried out over the course of five years comparing an alley cropping system of *L. macrophylla* and maize (the "tuxpeño" creole variety) to each this species in monoculture, in order to evaluate the effect of intercropping on maize grain yield and N content, compare the total productivity per area of maize (grain yield) and *L. macrophylla* (biomass), also evaluate an alternative method of fertilization (first two years), and access the economic viability of each production system. Since the alley cropping was composed of living components, we did not expect immediate differences between cultivation systems (Alley cropping *vs.* monoculture), but rather, predicted differences to emerge once the leaves of *L. macrophylla* began to be incorporated into the system some years after planting (after second year). We therefore expected increased grain yield and N content, higher total productivity per area from intercropping system, and higher benefits and incomes in the alley cropping compared to the monoculture systems in the later three years of production.

Methods

Study area

This experiment was conducted in an abandoned pasture from the CSO Xuajin Me'Phaa; locate at the foothill of La Montaña region, in the municipality of Ayutla de los Libres Guerrero, Mexico (16°590 2100 N, 99°050 4800 W), with 400 m of altitude. The region's climate is hot and sub-humid with summer rain. The rainy season lasts from April to November, with highest rainfall in September (434 mm), and total annual precipitation is about 1,800 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 soil in this area is classified as Umbric Stagnic Fluvisol (Episkeletic, clayic), according to the World reference base for soil resources (WRB 2007). This is a shallow and not very developed soil, 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 (~ 4.8) and low base saturation, follow by a second horizon (>35 cm) with high clay content, poor water drainage and reducing conditions, with a stagnic colour pattern (WRB 2007).

Study design

In May 2010 an Alley cropping experiment in random block design were installed (see figure 1(A)). This experiment was initially conformed by 20 plots, five treatment with four replicates; eight plots in intercropping with two different fertilization treatments (four and four), other eight with maize monocultures, and four more with *L. macrophylla* monocultures, as is explained in table 1. This with the purpose of evaluates two different fertilization treatments and to be able of compare the total productivity by area of intercropping *vs.* monoculture systems. After the second year of experiment evaluation of fertilizers stop and the experiment was reduced to three treatments (see table 1), with the intention of increase the number of replicates of maize monoculture and intercropping and observe better the effect of *L. macrophylla* biomass application on maize grain yields. The implantation of each element into the system was as follow:

L. macrophylla plantation (2010-2011)

After an initial calcium dolomite application (1.5 T ha^{-1}) to counteract soil acidity, seedlings of *L. macrophylla* (six months old) from a local greenhouse were planted in May of 2010, using 5 x 2 m spacing (1,000 trees ha^{-1}), on 12 of 20 plots. Each plot occupied an area of 20 x 12 m (240 m^2). In eight plots *L. macrophylla* were planted intercropped with maize (intercropping), and in more four plots were planted alone (monoculture). The first two years (2010-2011) biomass yield was calculated as volume per hectare ($m^3 * ha^{-1}$) according with the following formula (Ceccon 2005):

$$V\ ha^{-1} = \frac{(\pi * D^2 * H * 1000)}{4}$$

Were V= volume (m^3), D = diameter (m), and H = height (m)

Leucaena macrophylla management (2012-2014)

In the last three years of the experiment, foliage and small branches above 1.5 m of *L. macrophylla*'s stems were pruned twice, in June and September, to obtain the biomass, and its yield was measured by biomass production in Kg ha^{-1} harvested. Also this biomass was spread uniformly over intercropped treatments.

Maize cultivation (2010-2011)

Over five consecutive years, a local maize variety (Tuxpeño race) was planted in 16 of 20 plots (eight in monoculture and eight intercropped with *L. macrophylla*). In the intercropping systems, the maize occupied six rows lines between *L. macrophylla* rows (18 lines by plot; Fig. 1A). In the monoculture systems, the same spacing between rows was used in order to compare the same production resulting from the monoculture and the intercropping systems (Fig. 1A). Also, to an initial assessment of fertilization protocols, the maize received two different treatments: four plots in monoculture and four more intercropped with *L. macrophylla* received a standard chemical fertilization (100-30-50 Kg ha^{-1} of NPK), and other four monoculture and four intercropped plots received a reduction of 25% in chemical fertilization plus a commercial bio-fertilizer, composed of two microorganisms cultures; *Glomus intraradices*, an arbuscular mycorrhiza (MicorrizaFer®; 1X10^{5} spores kg), and *Azospirillum brasilense* a N-fixer bacteria living freely in the rhizome area (Azofer®; 5X10^{8} ufc g), called hereafter as bio-fertilized treatment (table 1).

Maize cultivation (2012-2014)

After 2012 until 2014 (last three years), the maize treatments were changed (table 1). The *L. macrophylla* biomass was applied within the intercropping treatments in June and September. Also, bio-fertilized treatment was employed as general method of fertilization, since no significant differences were found among methods of fertilization over the first two years of experiment (2010 and 2011; see results). Data from those last three years of maize production were statistically analyzed separately. The maize yield was also expressed in Kg ha^{-1} year^{-1}.

N content in maize grain

In 2013, N content (N %) was analyzed in the maize grain in each treatment, for which corncobs were collected in nine of the 18 lines of maize per plot. These corncobs were dried, threshed and milled to subsequently determine its N content by the Kjeldahl method (AOAC 1990).

Table 1. Treatments over five years of *L. macrophylla* and maize alley cropping experiment

Treatments from 2010-2011	**Treatments from 2012-2014**
Intercropping + chemical fertilizer (**ML:Q**)	Intercropping + bio-fertilizer + leaf litter (**Inter-C**)
Intercropping + bio-fertilizer (**ML:B**)	
Monoculture of maize + chemical fertilizer (**M:Q**)	Monoculture of maize + bio-fertilizer (**Mono-C**)
Monoculture of maize + bio-fertilizer (**M:B**)	
L. macrophylla monoculture (**L**)	*L. macrophylla* monoculture (**L**)

Land Equivalent Ratio (LER)

Land equivalent ratio has been used to evaluate the intercropping yield by area, in relation to its components apart (Mead and Willey 1980). To calculate the LER is necessary to sum up the resulting ratios of divide the yield of each element growing in intercropping by their yield in monoculture as follows:

$$LER = ERM + ERL = \frac{Mi}{Mm} + \frac{Li}{Lm}$$

Where: EMR = equivalent ratio of maize, ERL = equivalent ratio of *L. macrophylla*, *Mi* = maize yield in intercropping, *Mm* = maize yield in monoculture, *Li* = *L. macrophylla* yield in intercropping and *Lm* = *L. macrophylla* yield in monoculture (Ceccon 2008).

Statistical Analysis

To compare the productivity between Alley cropping system and maize and *L. macrophylla* monocultures, as well as between fertilization protocols, Maize grain yield, N content in gain, and *L. macrophylla* biomass yields were statistically tested. Base on the experiment design (randomized block design), Linear Mixed-Effect Models (LMM) with the R package mle4, were suitable option to analyze the data (Crawley 2012; Fox and Weisberg 2012). A selection of models was performed for each of the explanatory variables, employing as predictor variables; fertilization protocols (chemical fertilization *vs.* bio-fertilization), cultivation system (monoculture *vs.* intercropping), and years (2010 and 2011, and 2012 to 2014), with block as random factor, considering the important yield variation due to spatial heterogeneity. For selection of the minimum adequate model, a likelihood-ratio test using deviance was employed, while to determine the significance of predictor variables a deviance analysis with type II Wald F test was employed (Fox and Weisberg 2012). In order to comply with the LMM normality assumptions, log transformations were performed for grain yield data from 2012 to 2014, and biomass yield data from 2010 and 2011, and a square root transformation for biomass yield data from 2012 to 2014, to eliminate the zero values. As was mentioned before, statistical analyses were conducted separately the first two years (2010 and 2011) and last three years (2012 to 2014), due to changes as reduction in the fertilization protocol, biomass pruning and its incorporation on intercropping treatment.

Economic viability analysis

A cost-benefit analysis was performed after five years of cropping, for this purpose it was obtained the cost by cropped hectare (Cost ha^{-1}), for each treatment every year. This calculation was based on two scenarios: The first one included supplies, as well as the whole labor involved in cropping an experimental hectare (preparation, planting, harvesting, and post-harvest), adjusted to the local labor payment in communities. On the other hand, in the second scenario only supplies was included in cost of cropped hectare, since in family-based agriculture, the required labor to cropping comes from family members and it is mostly unpaid, which is generally the case in La Montaña and in most of rural regions from Latin America (Berdegué and Fuentealba 2011). Also, “Gross Income” of maize in USD was obtained by calculating the income from maize grain yield by treatment, according to maize national price each year from 2010 to 2014 (CEDRSSA 2014). As well to assign gross income from *L. macrophylla*, nutrients contribution were considered, by multiply biomass yields (T. ha^{-1}), N content in fresh litter (3.5%; Hernandez-Muciño *et al.* 2105), and Calcium Nitrates’ regional price from 2012 to 2014 (SAGARPA 2015). Finally the “Net Income” was calculated by subtracting the cost of hectare planted (Cost ha^{-1}) from either two scenarios mentioned above, to gross income, while the “Returned per USD” was calculated by dividing the gross income by the cost per planted hectare (Akhtar *et al.* 2000).

Figure 1.

1 A. 1 B.

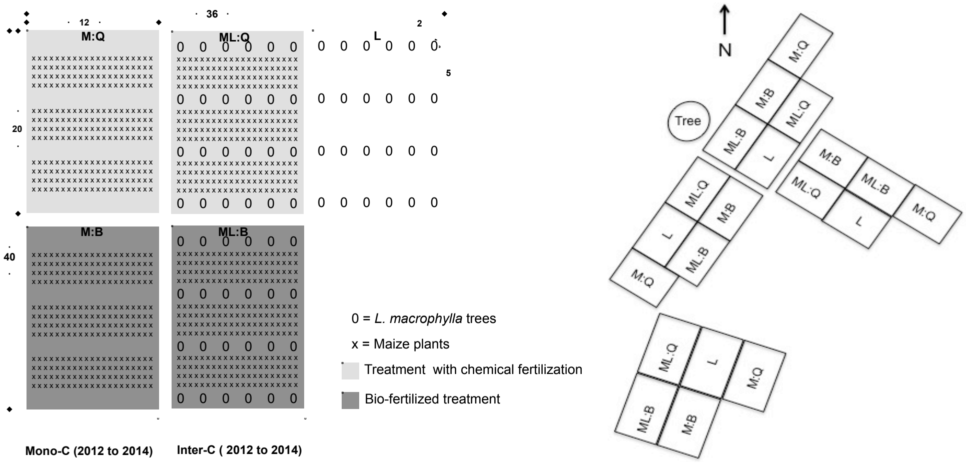

Figure 1 A. Schematic figure of a block of *L. macrophylla* alley cropping experiment design in 2010. From left to right, the special arrangement of maize monoculture plots with both fertilization protocols; bio-fertilization (M:B) and chemical fertilization (M:Q), followed by the corresponding intercropping plots (ML:B and ML:Q), and finally the monoculture of *L. macrophylla* (L). Also, at the bottom of the plots, the reduction to three treatments after 2012 is showed.

Figure 1 B. is the spatial distribution of four blocks (20 plots), in the random block design for 2010-2011. Eight bio-fertilized plots, four maize monocultures (M:B), and four intercropped with *L. macrophylla* (ML:B), and eight plots more under chemical fertilization, four maize monocultures (M:Q), and four intercropped with *L. macrophylla* (ML:Q), and finally four plots with *L. macrophylla* monocultures (L).

Results

L. macrophylla productivity (2010-2011)

To evaluate *L. macrophylla* yield the first two years of experiment (2010-2011), the minimum adequate model employed were: (log (Volume) ~ Year + (1|Block)), in this case only the factor "year" resulted to be significant to explicate timber volume yield ($F_{1, 19} = 49.27$, ***P*< 0.001**), and according with estimate values, 2011 was the more productive year (2010: -4.92±0.63, 2011: -2.52±0.63). On the other hand, no significant differences among treatments were found, both monoculture and intercropping, nor between fertilization protocols (chemical fertilization *vs.* bio-fertilization).

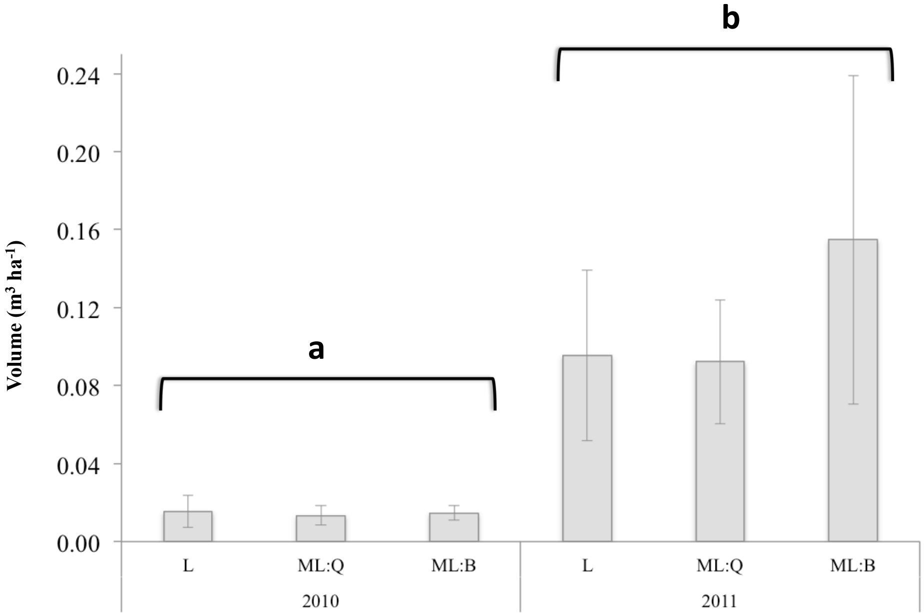

Figure 2. *L. macrophylla* timber volume (m^3 ha^{-1}) yielded by treatment from 2010 and 2011. From left to right; monoculture of *L. macrophylla* (L), and intercropping of *L. macrophylla*/ maize with both fertilization protocols: chemical fertilization (ML:Q), and bio-fertilization (ML:B).

L. macrophylla productivity (2012-2014)

After three years of *L. macrophylla* pruning, about 30% of trees died, and the total biomass added to the intercropping treatments (Inter-C), were 5696 Kg. ha^{-1}, an average of 1899 ± 125 Kg. ha^{-1} $year^{-1}$ of biomass, which represents an addition of around 33.4 Kg of N in the soil each year. On the other hand, there was a great variation of biomass produced within treatments and years (Fig. 3, see error bars), and according with LMM analysis no model differed from null model, indicating no significant effects from explanatory variables (treatments or years).

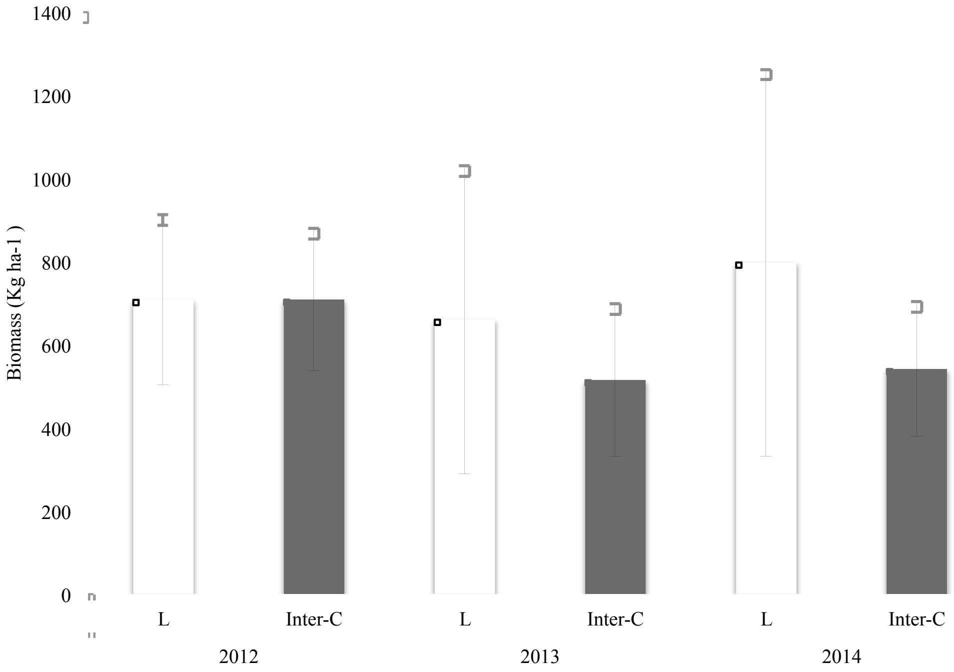

Figure 3. Biomass of *L. macrophylla* pruned, in (Kg ha^{-1}) from 2012, 2013, and 2014. White bars: monoculture of *L. macrophylla* (L), and black bars: intercropping of *L. macrophylla*/maize (Inter-C). Vertical lines are standard errors.

Maize productivity (2010-2011)

The first year of maize harvest (2010), all treatments showed a very low productivity in contrast with consecutive years (Figure 4). According to minimum adequate model (Kg of grain ~ Year + (1|Block)), only “years” were a significant factor ($F_{1,\,27} = 69.12$, ***P*< 0.001**), and 2011 was the most productive year according with model’s estimate values (2010: 8.27±4.27 Kg. ha^{-1}, 2011: 18.59±4.27 Kg. ha^{-1}). As well, no significant differences were found according to fertilization protocols or treatments. In consequence, as has been mentioned before, since 2012 bio-fertilizer treatment was employed as general method of fertilization, and the experiment design was reduced to intercropping (Inter-C) and monoculture (Mono-C) system.

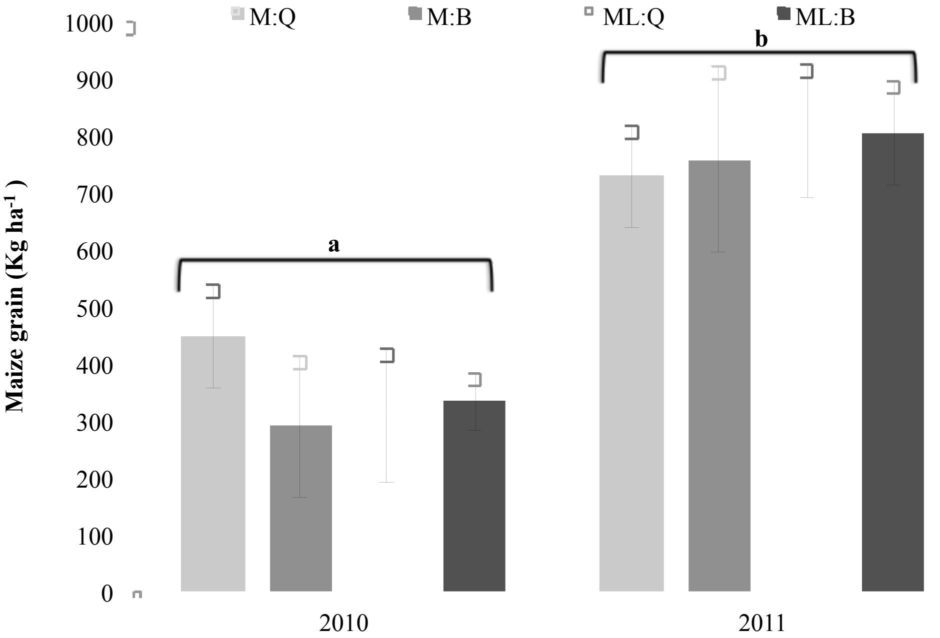

Figure 4. Maize grain yields in 2010 and 2011 by treatment. From left to right, maize monocultures with both fertilization protocols; bio-fertilization (M:B) and chemical fertilization (M:Q), followed by the corresponding intercropping plots with bio-fertilization and chemical fertilization (ML:B and ML:Q).

Maize productivity (2012-2014)

According to LMM analysis the minimum adequate model (log (Kg of grain~ Crop system + Year + (1|Block)), both the crop systems (monoculture *vs.* intercropping; $F_{1, 41}$ = 4.655, ***P*< 0.05**) and years (2012 to 2014; $F_{2, 41}$ = 42.96, ***P*< 0.001**) were significant factor to explicate grain yield, and according with estimate values the intercropping system was more productive than monoculture (intercropping = 4.09±0.23, monoculture = 3.97±0.23), and 2014 was the most productive year (2012 = 3.70±0.23, 2013 = 4.03±0.23, 2014 = 4.35±0.23). In general, the maize yield from intercropping was about 10 to 12% higher than monoculture over the last three years of experiment, however analyzing the data block by block, is in the less productive one (block 1), where the differences were more clear (Fig. 5).

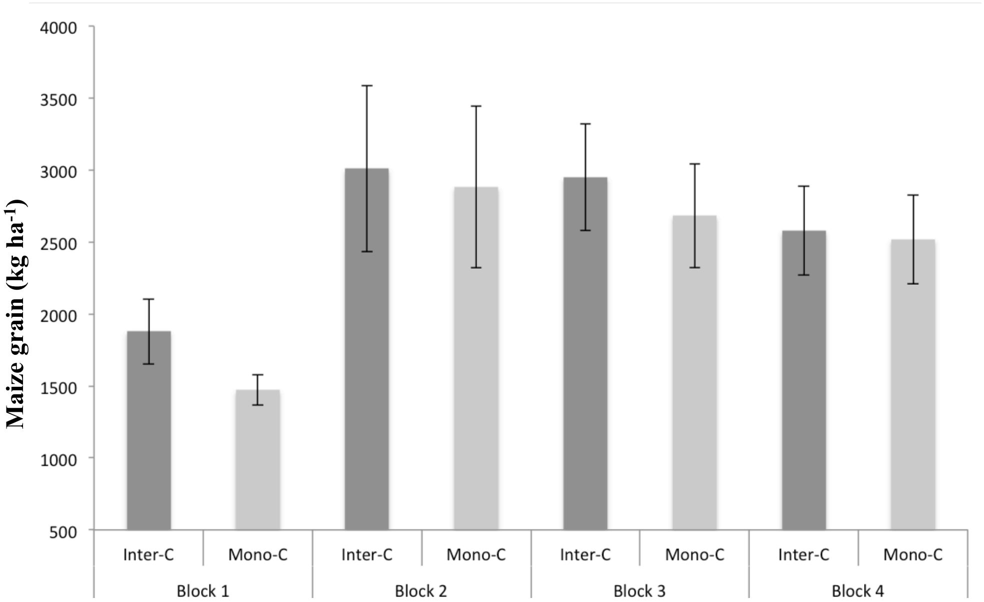

Figure 5. Maize yields from 2012 to 2014 by block. Dark gray bars correspond to *L. macrophylla*/ maize intercropping (Inter-C), and light gray bars to maize monoculture (Mono-C). Vertical lines are standard errors.

N content in maize grain (2013)

According to LMM analysis of N contents in grain for 2013, no model differed significantly from null model, which means no significant differences in N percentage in maize grain between intercropping and monoculture, even though the data show a slight increase in N content in intercropped maize grain.

Land equivalent ratio (LER)

LER analyses of experiment over five years are shown in Table 2. All LER values for intercropping systems were very similar between fertilization protocols and years, and always above two, confirming its feasibility. This means that more than one hectare of maize monoculture and one of *L. macrophylla* monoculture are required to reach the yield of an hectare of *L. macrophylla*/ maize intercropping. The highest values of LER were found in the bio-fertilized treatments in 2010 and 2014, the first was due to a general low productivity in bio-fertilized maize monocultures, and the last one because the high mortality in two plots of *L. macrophylla* monocultures. It is important to mention that no statistical test was conducted because the goal of LER analysis, is to observe if intercropping system is affecting the components yield (LER <1), or if the intercropping favors the total yield of the system, and if it is a viable option in terms of productivity by unit of area (LER ≥1).

Table 2. Land equivalent ratio (LER) by year and fertilization protocol. *L. macrophylla* yield expressed as volume ($m^3 ha^{-1}$) for 2010 and 2011, and biomass pruned ($Kg ha^{-1}$) for 2012 to 2014, as well as maize grain yield (Kg. ha^{-1}), over five years. Total LER is the sum of equivalent ratio of maize (ERM), and equivalent ratio of *L. macrophylla* (ERL), obtained dividing the yield of each element in intercropping by their yields in monoculture.

Year	**Fertilization**	**Equivalent Ratio for maize (ERM) and *L. macrophylla* (ERL)**		**Total LER**
2010	Bio-fertilization	ERM	4.19	5.73
		ERL	1.54	
	Chemical fertilization	ERM	0.75	2.05
		ERL	1.30	
2011	Bio-fertilization	ERM	1.15	2.55
		ERL	1.40	
	Chemical fertilization	ERM	1.13	2.74
		ERL	1.61	
2012	Bio-fertilization	ERM	1.16	2.20
		ERL	1.04	
2013	Bio-fertilization	ERM	1.19	2.22
		ERL	1.03	
2014	Bio-fertilization	ERM	1.22	5.69
		ERL	4.47	

Economic viability analysis

The results from cost-benefit analysis under two scenarios are showed in tables 4 and 5. In the first scenario which considers full labor payment, both net income and returned per USD invested, indicated an important deficit for almost all treatments and years, however this deficit was reduced from around 90 % in the first year (2010) to 0 % in the fifth year (2014), especially for the intercropped treatment, which achieved a gain of 10 % the last year (Table 3). In the second scenario, which considers only the supplies' cost, an income deficit was found only the first year, and intercropping systems showed better returned per USD invested (4.8 *vs.* 3.7 USD) values than monoculture the last three years (Table 4).

Table 3. Economic analysis for first scenario (full labor payment): Gross income of maize = grain yield * national price, and Gross income of *L. macrophylla* = biomass yield * N content * N-fertilizer local cost. Net income= Gross income – Cost ha^{-1} in USD, and Returned per USD = Gross income / Cost ha^{-1}. The treatments are as follows: Intercropping (ML:Q), and monoculture (M:Q) with chemical fertilization, and intercropping (ML:B), and monoculture (M: B) with bio-fertilization, for 2010 and 2011. For 2012 to 2014, the treatments were only intercropping (Inter-C) and monoculture (Mono-C), both under bio-fertilization.

Year	**Treatment**	***L. macrophylla* yield (T. ha^{-1})**	**Grain yield (T. ha^{-1})**	**Cost ha^{-1} (USD)**	**Gross Income (USD)**	**Net Income (USD)**	**Returned per USD**
2010	ML:Q		0.31	$761.15	$67.10	$-694.05	0.09
	M:Q		0.45	$721.31	$97.48	$-623.83	0.14
	ML:B		0.33	$736.29	$72.55	$-663.74	0.10
	M:B		0.29	$696.45	$63.02	$-633.43	0.09
2011	ML:Q		0.81	$828.68	$281.16	$-547.52	0.34
	M:Q		0.73	$828.68	$253.59	$-575.09	0.31
	ML:B		0.81	$793.31	$280.44	$-512.87	0.35
	M:B		0.76	$793.31	$264.11	$-529.20	0.33
2012	Inter-C	2.13	1.83	$721.60	$553.15	$-168.45	0.77
	Mono-C		1.65	$721.60	$495.77	$-225.83	0.69
2013	Inter-C	1.69	2.54	$803.77	$665.76	$-138.01	0.83

	Mono-C		2.33	$803.77	$605.47	$-198.30	0.75
2014	Inter-C	1.88	3.57	$776.32	**$861.68**	**$85.36**	**1.11**
	Mono-C		3.19	$776.32	$766.88	$-9.44	0.99

Table 5. Economic analysis for second scenario (only supplies with internalized labor costs): Gross income of maize = grain yield * national price, and Gross income of *L. macrophylla* = biomass yield * N content * N-fertilizer. Net income= Gross income – Supplies' Cost ha^{-1} in USD, and Returned per USD = Gross income / Supplies' Cost ha^{-1}. The treatments are as follows: Intercropping (ML:Q), and monoculture (M:Q) with chemical fertilization, and intercropping (ML:B), and monoculture (M: B) with bio-fertilization, for 2010 and 2011. For 2012 to 2014, the treatments were only intercropping (Inter-C) and monoculture (Mono-C), both under bio-fertilization

Year	**Treatment**	***L. macrophylla* yield (T. ha^{-1})**	**Grain yield (T. ha^{-1})**	**Cost ha^{-1} (USD)**	**Gross Income (USD)**	**Net Income (USD)**	**Returned per USD**
2010	ML:Q		0.31	$176.72	$67.10	$-109.62	0.38
	M:Q		0.45	$176.72	$97.48	$-79.24	0.55
	ML:B		0.33	$151.86	$72.55	$-79.31	0.48
	M:B		0.29	$151.86	$63.02	$-88.84	0.42
2011	ML:Q		0.81	$226.89	$281.16	$54.27	1.24
	M:Q		0.73	$226.89	$253.59	$26.70	1.12
	ML:B		0.81	$191.52	$280.44	$88.92	1.46
	M:B		0.76	$191.52	$264.11	$72.59	1.38
2012	Inter-C	2.13	1.83	$167.99	$553.15	**$385.16**	**3.29**
	Mono-C		1.65	$167.99	$495.77	$327.78	2.95
2013	Inter-C	1.69	2.54	$232.62	$665.76	**$433.14**	**2.86**
	Mono-C		2.33	$232.62	$605.47	$372.85	2.60
2014	Inter-C	1.88	3.57	$206.05	$861.68	**$655.63**	**4.18**
	Mono-C		3.19	$206.05	$766.88	$560.83	3.72

Discussion

The results of maize grain yield, LER and cost-benefit analyses, presented in this study strongly support the integration of *L. macrophylla* as part of the maize cultivation systems in the La Montaña region, as well as the benefits of using an alternative method of bio-fertilization more economically and environmentally advantageous. However as was expected, the general productivity conditions in the beginning of the experiment were low, as can be observed in maize grain and *L. macrophylla* biomass yields, this probably linked to the growth stage from the leguminous tree and the harsh soil fertility conditions in the plots, in this sense, it is important to remember that the experimental area previously was an abandoned pasture. However, these conditions improved with the course of time, which is reflected in the increase of maize grain yields, probably due to the incorporation of *L. macrophylla* biomass into the soil, and crop management practices. Also it is possible to observe in the economic incomes a positive trend of productivity over the years, especially in intercropping treatments, which indicates sustainability of the cultivation system.

L. macrophylla productivity

In the first and second year (2010 and 2011), there were no significant differences in *L. macrophylla* volume of timber between treatments, only between years (table 2).

The general low yields for all treatments the first year, strongly suggest a common factor affecting such yields. A possible explanation is the initial low fertility conditions caused by the acidity of soil (pH 4.8). It is well established that legume growth can be limited by acidity and other harsh soil conditions, by affecting the *Rhizobium*-legume symbioses and N-fixation (Graham 1992; Tang and Thomson 1996; Zahran 1999), unfortunately there was not a second pH assessment after the first dolomite application to corroborate this. Also other studies found similar initial results (Kang *et al.* 1981; Ceccon 2005; Ceccon 2008), the poor initial soil conditions and a period of adaptation (slow growth) are indicated as possible reasons for low productivity (Kang *et al.* 1981).

From 2012 to 2014, there were no significant differences in *L. macrophylla´s* biomass among cultivation systems or years, due possibly to high yield variability among them (Figure 3). However, every year about 33 Kg ha^{-1} of N was added to the alley cropping system. According to other studies, the best multipurpose tree species as *L. leucocephala* and *Gliricidia sepium* in similar weather conditions, produce around three times the amount of biomass and N reported here (Kang 1997; Okogun *et al*. 2001), however it is important to mention that the density of trees and events of pruning reported in those works are around twice than this study. For this reason it is recommendable to increase the density of trees, and gradually the pruning events to achieve the maize nutrient needs. According to Mullen and Gutteridge (2002), *L. macrophylla* has the potential to produce between 7.9 to 13.2 Kg of dry matter by tree, over two-year, which is comparable with more commercial species of *Leucaena* genus. Nevertheless, some sensitivity to drought, pruning, and harsh soil conditions, could be some problems for this species, since an important fraction of the mortality reported here (30% over last three years), possibly involved this two cases.

Also *L. macrophylla* could be an important provider of other nutrients. For example, the high concentration of Ca in *L. macrophylla* litter (7.3%), represent about 138 Kg. ha^{-1} translocated into the system, besides, according a previous analysis of litter quality (Hernández-Muciño *et al.* 2015), Ca and Potassium (K; 0.88%) are fast released to the soil (77% and 56% respectively in four months), and could be particularly advantageous in acidic soils, as the case of this study (soil pH; 4.8). These nutrients may potentially improve pH soil conditions, cation exchange capacity and increase soil nutrient availability and fertility (Tang and Yu 1999; Hartemink and O'Sullivan 2001).

Maize productivity

There were no significant differences in maize yield among treatments, neither according to fertilization protocol (chemical fertilization or bio-fertilization), nor cultivation system (monoculture or intercropping). The harsh initial soil conditions, especially the pH conditions, also could be a suitable explanation of the low maize grain yield found in the first season in all treatments (Ceccon 2008; Fageria and Baligar 2008; Allen *et al.* 2011). Based on this results, and considering an unlikely beneficial or detrimental effect from young *L. macrophylla* trees, it is reasonable to assume that the bio-fertilized treatment, which is conformed of 75% of standard fertilization plus a commercial bio-fertilizer (*Glomus intraradices* and *Azospirillum brasilences*), at least compensates the reduction on chemical fertilizers. Indeed, it is well documented the positive effect on plants growth and grain yield from inoculation of these microorganisms, and even a synergistic interaction among them (Bashan and Levanony 1990; Okon and Labandera-Gonzalez

1994; Bashan and de-Bashan 2010). *Azospirillum brasilences* colonizes the rizosphere and increase the root biomass and number of root hairs, fixing N, and synthesizing phytohormones, that promote the absorption of nutrients and water (Okon and Labandera-Gonzalez 1994; Perrig *et al.* 2007). Some studies had reported that *Azospirillum* inoculation increase the biomass and grain yield between 5-30 %, depending on soil and environmental conditions, and had around 60 to 70% of colonization success (Bashan and Levanony 1990; Okon and Labandera-Gonzalez 1994). In similar way, arbuscular mycorrhiza (AM) as *Glomus intraradices*, acts in the rizosphere increasing the mineral phosphate mobilization, solubilisation, and plant intake with positive effects in plant growth and phosphorus (P) content in tissues, which is probably the less available and one of most limiting nutrients for plants (Duponnois *et al.* 2005; Smith *et al.* 2011). Finally a synergistic positive effect has been report for interaction between *Azospirillum* and AM species, resulting in significant increase in growth and P content in plants (Bashan and Levanony 1990). It is important to mention that even when both organisms show the biggest benefits under low nutrient condition, do not replace other nutrient sources (e.g. green manure or chemical fertilizers), but improve its uptake, and contribute to a more sustainable, environmental-friendly, and economically advantageous method of fertilization (Okon and Labandera-Gonzalez 1994; Smith *et al.* 2011).

On the other hand, the global statistical analysis of last three years (2012 to 2014), showed a higher maize grain yield in intercropping (Inter-C) than in the monoculture (Mono-C; $p<0.05$), indicating a benefit to maize by growing together with *L. macrophylla*, from which received fresh litter. According to Hernández-Muciño *et al.* (2015), the fresh litter of *L. macrophylla* has 3.5 % of N , therefore maize could receiving around 33 kg ha^{-1} of N (regarding to biomass amount produced by *L. macrophylla* in one year*)* Nevertheless, despite the positive effects observed in intercropped maize yield (about 10 to 12 % higher than the monoculture yield each season), the analysis of N content in grain did not show differences between treatments. These contrasting results could be related to low maize N uptake efficiency. According to some authors, maize N uptake efficiency is generally lower that 20 %, regardless of the N source, N-fertilizer or pruning (Palm 1995; Mafongoya *et al.* 1997; Okogun *et al.* 2001), however the N uptake can be higher (around 49 to 59 %; Okogun *et al.* 2001) when comes from some legume species, but it depends a lot of the pruning quality and N release synchronization (Mafongoya *et al.* 1997; Sanginga 2003). On the other hand, many authors refer that an important N fraction is not uptaken by the crop, but stays in the system and contribute to soil fertility in the long term (Palm 1995; Kang 1997; Mafongoya *et al.* 1997; Sanginga 2003). This idea can be supported in this study by the fact that maize yield increased every year, especially in the intercropping system (See Figures 4 y 5), indicating an improvement in soil fertility conditions probably due to biomass accumulation. Also, this could be possible for maize monoculture because as was above mentioned, in the traditional method of maize cultivation used here, organic matter is not removed from the system. The differences in maize yield between treatments (monoculture *vs.* intercrop) could be due to *L. macrophylla* litter quality, and this is supported by the marked differences between intercropping and monoculture observed in block 1, which exhibited the worst soil conditions (figure 5). According with a *L. macrophylla* litter quality analysis, about 40% of N is released in the first five months before start to be immobilized by lignin and could be available for crops, the litter that remains probably stays longer in soil or turns slowly into soil fauna biomass (Hernández-Muciño *et al.* 2015). Likewise, it should be mentioned that this data came from a litterbag experiment, which tends to underestimate the decomposition and therefore nutrient release rates (Huhta 2007). However, even considering the best case scenario for maize N uptake efficiency from fresh pruning (around 49 to 59%; Okogun e*t al.* 2001), the amount of total N recovered by maize would not be higher than 19.5 Kg ha^{-1}, enough to be reflected in yield but not in N content in the grain, which is generally a small fraction (13–14 g kg^{-1} of grain; Cassman *et al.* 2002). For this reason, once again, is recommendable increase the density of trees and pruning, to maximize the benefits of *L. macrophylla* biomass application.

Land equivalent ratio (LER)

Between 2010 to 2014, every year the total LER value of alley cropping was >2, regardless the type of fertilization received, which mean that is necessary more than two hectares of land of both monocultures to produce the same amount of grain and tree biomass yielded by one hectare of intercropping (see table 2). This result also reveals the aptitude of both; maize and *L. macrophylla* to growing in association. For example, with an exception the first year, every season maize equivalent ratio (ERM) was >1, indicating a better performance of maize in intercropping, and a probable positive effect of fresh litter on grain yield (See Table 2). The positive association of maize varieties and legumes has been found in several works employing LER analysis, but less frequently has been found so good performance from intercropped maize (Wahua *et al.* 1981, Long Li *et al*. 1999, Akhtar *et al.* 2000, Dahmardeh *et al.* 2009). *L. macrophylla* also showed positive equivalent ratios (ERL >1) indicating a good performance of this specie in intercropping, which is important because its appreciated benefits as pruning, forage and fuel-wood (Cervantes-Gutiérrez *et al.* 2001; Hernández-Muciño *et al. 2015*). The high values of LER suggest the absence of competition between both components, when grow together regardless the quality of fertilization. Along five years the productivity of intercropping was markedly advantageous over the monocultures.

Economic viability analysis

It is possible to observe in cost-benefit analysis an important initial deficit of incomes (beginning with 90 %), when full labor payment scenario was considered for cultivated hectare cost, which is consistent with the initial investment and low general productivity the first two years of experiment, however as biomass was accumulate in soil, productivity increased within treatments and economic deficit was reduced, especially for the intercropping treatment which achieved a slight gain of 11 % in the fifth year (Table 4). In this context it is important to recognize that many agroforestry systems requires extra time and labor investment to produces economic and ecological benefits (e.g. soil fertility restoration), however, in long-run, they may be the most sustainable option (Ngambeki 1985; Ehui *et al.* 1990; Kang 1997). On the other hand, in the second scenario where labor is unpaid and only supplies are considered for cultivated hectare cost (the real case of the “La Montaña” region), incomes deficit was found only the in first year, besides the bio-fertilized intercropping showed better profits since the second year and achieving a return of 4.18 USD by each dollar invested the last year. However, it is clear that most initial incomes obtained under second scenario are actually resulted of externalization costs of labor, which along with environment deterioration are part of the hidden costs imposed by agro-markets (Altieri 2002; Chappell and LaValle 2011). Still for local peasants, the productivity and incomes increases year by year instead of reducing as commonly occurs with loss of soil fertility in conventional agriculture (Blanco-Canqui and Lal 2009), and in fact after five years, labor investment start to be compensated by incomes, making the intercropping system a suitable option in long term. Additionally, this analysis does not consider other economic advantages from these alternative systems, for instance, the diversification of commodities (wood, food, forage, etc.), and risks reduction of production losses (Altieri 2002). Actually this last advantage can be especially important for the La Montaña productive systems, because this region is highly vulnerable to storms and hurricanes, as recently happened (2013) with the tropical storms Ingrid and Manuel, which caused great human, and economic losses (Kimberlain 2014).

Alley cropping, possible adoption by communities

Regarding *L. macrophylla* alley cropping adoption, it is well documented that indigenous communities traditionally use diverse species of native legumes including *Leucaena* species, which involves a selection process and traditional management (Zárate Pedroche 1994; Hughes 1998). For example, a study conducted by Casas and Caballero (1996), with traditional management of *Leucaena esculenta* in the mixtec portion of the "La Montaña" region, evaluated phenotypic variation among populations under different managements, and found marked differences between managed and unmanaged wild populations, with high frequency of the phenotypes preferred by people within wild populations, even more than in cultivated populations. This means a long *in situ* domestication process, and artificial selection, which involves a profound knowledge of *L. esculenta* biology from ethnic groups, that is supported by some archaeological findings from more than 8000 years (Casas and Caballero 1996). *L. macrophylla* on the other hand, also has been managed manly *in situ* within the seasonal dry tropical forest, and tolerated in productive lands, by indigenous communities, all over its native distribution (Zárate Pedroche 1994; Casas and Caballero 1996). However, this species still has an important potential to be introduced in home gardens and agricultural lands, not only in the region but throughout Mesoamerica where *Leucaena* species are traditional and widely used by local communities (Hughes 1998; Cervantes-Gutiérrez *et al.* 2001). The incorporation of indigenous trees in productive areas could be a significant strategy to improve resilience in a landscape level – for example, increase biodiversity and restoring some ecological functions –, likewise their diversity and complexity of associations from traditional systems are a refection of knowledge and deep connection with nature from indigenous communities (Backes 2001; Toledo 2001). Under these circumstances, it is highly expected that a cultural system *L. macrophylla*/ maize be widely adopted by rural peasants in the "La Montaña" region and in similar socio-ecological contexts, considering that it has proven to be productively and economically suitable and part of the biodiversity managed by communities for a long time.

Finally, the implementation of this new cultural agroecosystem with *L. macrophylla* and maize is just a small step to achieve more resilient and sustainable landscapes in rural regions as the quality matrix model proposes (Perfecto and Vandermeer 2010), and to achieve a greater impact of these landscapes, it would be essential to influence other ecological management activities carried out by communities, such as pastures and forests management (Salgado-Terrones *et al.* 2017). In this context, the study of forest native species of great socio-ecological interest takes paramount importance, because these can be incorporated into different management activities in rural communities.

Conclusions

In general, even the traditional method of maize cultivation alone, showed increase in yield over time, however considering the conditions of fragility and degradation of the "La Montaña" region, this traditional management method is not enough to keep soil fertility and productivity in a sustainable way. On the other hand, *L. macrophylla*/ maize alley cropping showed advantages in maize grain yield (especially under harsh soil conditions), also around the double than monocultures in the total productivity by area (RET>2; table 2), and provided higher economic benefits in terms of fertilization costs, as well as more commodities and better incomes.

Although it has not been evaluated in this study, there are important evidences that *L. macrophylla*/ maize alley cropping could offers the amelioration of important ecosystem

services as nutrient cycling, soil conservation and fertility, water infiltration, landscape connectivity, and biodiversity, and this should be added in the final viability equation.
It is important to highlight that this work has been developed with the collaboration of the CSO Xuajin Me'Phaa A.C., which seek a more resilient satisfactory and sustainable way of life for the communities of La Montaña region, by promoting food security, hydric security, and overcoming poverty, through programs of landscape restoration with productive focus, highly biodiverse home gardens, water sustainable management, and an organic and fare-trade program with almost 400 farmers (Hernández-Muciño *et al.* 2017). The idea of this work is to contribute to Xiajin Me'phaa labor providing new ideas and technologies that can help communities to increase resilience overcome poverty and achieve food security and welfare.

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Capítulo 3

Cultural agroecosystems for the restoration of rural landscapes: The study of *Leucaena macrophylla* in “La Montaña” of Guerrero, Mexico

CHAPTER 16

Cultural agroecosystems for the restoration of rural landscapes: the study of *Leucaena macrophylla* in “La Montaña” of Guerrero, Mexico

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INTRODUCTION

Agriculture, although not the only one, is the main anthropogenic activity that results in the transformation of ecosystems, favoring both the loss of ecosystem services and their associated biodiversity as well as inducing global climate change due to crop intensification and alteration of biogeochemical cycles (Foley *et al.*, 2011; Tilman *et al.*, 2011). However, the expansion of the agricultural frontier itself is the result of various social and economic factors, such as population growth, market speculation and changes in consumption patterns as well as poor application of technologies in areas with low agricultural potential (Foley *et al.*, 2011). If these patterns do not change, it is expected that in 40 years the demand for products will be doubled and, thus, the negative effects on ecosystems will also be increasingly noticeable (Tilman *et al.*, 2011).

Another important aspect to consider is that rural populations in countries with low economic development and higher dependency on ecosystem goods and services (e.g., indigenous groups) are the most vulnerable to the global environmental crisis: these are the so-called poverty traps, where a population is too busy trying to subsist to adequately address the environmental and cultural degradation problems in which it is immersed (Sachs & McArthur, 2005).

Due to this complex and colossal scenario, experts from different areas of knowledge have called to design a simultaneous strategy of conservation and restoration of ecosystems and their services to ensure the livelihood of those who depend on them (SER, 2004; Lal *et al.*, 2004; Lamb *et al.*, 2005; Chazdon, 2008; Tilman *et al.*, 2011; Foley *et al.*, 2011). This strategy necessarily includes several aspects, such as the incorporation of involved social actors, design and transfer of new technologies, design of new more resilient and adaptable ecosystems (if necessary) as well as the recovery of traditional knowledge for managing ecosystems (Hobbs *et al.*, 2009; Kimmerer, 2011; Egan *et al.*, 2011; Foley *et al.*, 2011).

Areas of knowledge, such as restoration ecology, have had to adopt, in recent years, new objectives to match current circumstances when trying to ensure that human beings assume their role as main agents of ecosystem transformation and to recognize their ability to generate reciprocal relationships with ecosystems, through sustainable management activities that reinforce ecological processes. These new systems are known as 'cultural ecosystems' (SER, 2004).

In this context, productive restoration seeks to recover some functions and components of ecosystems in human-dominated landscapes, prioritizing those functions that guarantee food sovereignty and human well-being as well as integrating nutrient cycling, water purification, pest regulation and increased soil fertility for food production. To achieve this goal, agroforestry and agroecological techniques as well as traditional knowledge in landscape management are used. In addition, this approach seeks to include local populations into the practice of long-term and adaptive restoration (Ceccon, 2013).

A proposal of productive restoration, also shared by the agroecological approach, is the creation of new cultural agroecosystems that combine the benefits of traditional management with the transfer of new technologies as well as the incorporation of native and multipurpose creole species to promote biodiversity and productivity within the systems (Altieri & Toledo, 2011; Ceccon, 2013). The benefit of this proposal lies in the adaptation of the system components and cultural management practices to the particular conditions of each landscape. This scheme, together with new technologies suitable for these conditions, confers stability, resilience, adaptability and sustainability to such agroecosystems (Altieri & Toledo, 2011). These cultural agroecosystems can provide, in addition to food security, several ecosystem services by increasing the connectivity and permeability of the landscape. This outcome together with marketing strategies, such as processing, commercialization of products and/or organic certification can generate further economic benefits, which increase the social viability of these systems (Altieri & Toledo, 2011; Foley *et al*., 2011).

Here, is presented the case of "La Montaña", in the state of Guerrero, southern Mexico. It is a predominantly indigenous region, where four ethnic groups live: Tlapanecos, Mixtecos, Nahuas and Amuzgos. In addition, the region has 19 municipalities, of which several are considered among the poorest in the country (Landa-Ordaz & Carabias, 2009). Social problems in the region, such as poverty, marginalization, insecurity and migration are strongly linked to environmental problems such as ecological fragility or expansion of the agricultural frontier, but also by phenomena such as acculturation and loss of knowledge about the traditional management of ecosystems. Furthermore, the governmental abandonment and poor rural development policies in the region have contributed to this situation (Landa-Ordaz & Carabias, 2009).

Several studies indicate that the most important environmental problems in "La Montaña" are due to the transformation of forest areas into productive areas, considering that most of the region has steep slopes and low agricultural aptitude (Landa-Ordaz *et al*., 1997; Cervantes-Gutiérrez *et al*., 2001). In addition, its geographical location, opposite to Guerrero, makes this region vulnerable to tropical storms and hurricanes, as recently seen (2013) with the tropical storms Ingrid and Manuel, which caused great human and material losses (Kimberlain, 2014).

Furthermore, most fragments of seasonally dry tropical forest (SDTF) in the region have less than 10 ha; these forests are threatened throughout the world (Miles *et al*., 2006) and are mostly degraded and open as a result of selective logging in search for firewood (Miramontes *et al*., 2012; Salgado *et al*., 2016; Ceccon, 2016), which strongly compromise their biodiversity (Borda-Niño *et al*., 2017).

In "La Montaña" of Guerrero, as in many other rural areas of the tropics, there is an urgent need to protect SDTF and their biodiversity. However, this will only be possible if there is combined strategies for forest conservation and restoration, supporting community livelihoods, promoting sustainable agroecological and agroforestry practices, incorporating traditional knowledge and policy-making to foster the adoption of these forms of management in human-dominated landscapes.

Due to the characteristics of the socio-environmental conflict in "La Montaña" of Guerrero, the productive restoration approach seems to be the ideal; however, this task requires the synergy between academic institutions, government agencies and/or the civil society and, of course, the indigenous communities that inhabit the region.

In "La Montaña", the work carried out by Xuajín Me' Phaa A.C. should be highlighted. This non-governmental organization was founded in 2006 by prominent members of 14 Tlapaneco communities (Me' Phaa), from the municipality of Acatepec and Ayutla de los Libres, in the highlands of Guerrero. This organization seeks to promote a more satisfactory and sustainable way of life for the communities, through the Human Promotion program in "La Montaña" of Guerrero, which uses the methodology of 'organized common work', based on knowledge, organization and collective indigenous work. Thus, the development of communities is promoted in three areas: social, economic and ecological.

According to the diagnosis made by Xuajín Me' Phaa A.C., in the 14 communities of the region, one of the most urgent needs for farmers is to find a way to maintain soil fertility over a longer period of time, since most of the plots are abandoned after three years because of their low productivity, even under more sustainable management, such as the organic agriculture program (Xuajin Me' Phaa A.C., personal communication). Therefore, it is necessary to establish productive restoration projects to increase the land productivity and use indigenous native species that have the potential to increase the connectivity among fragments and the productivity of agroecosystems.

Borda-Niño *et al.* (2017) performed a phytosociological analysis in the SDTF of "La Montaña"' and highlighted a list of species with potential for productive restoration, such as *Byrsonima crassifolia, Hymenaea courbaril, Pterocarpus acapulcensis* and *Spondias purpuria*, most of them nitrogen-fixing plants or attractive to the fauna for its flowers or fruits. Likewise, Cervantes-Gutiérrez *et al.* (2001) propose several species with multipurpose potential for "La Montaña" region, among which they emphasize *Acacia farnesiana*, *Leucaena esculenta*, *Lysiloma acapulcensis* and *Leucaena macrophylla*.

CASE STUDY OF *LEUCAENA MACROPHYLLA*

Native to the New World, species of the genus *Leucaena* have been extensively studied and have become a common component of agroforestry systems throughout the planet (Hughes 1998, Argel *et al.*, 1998). In particular, *Leucaena leucocephala* is recognized as one of the most widely used multipurpose species on the planet. Despite a few strong limitations, *Leucaena leucocephala* has numerous qualities, such as easy propagation, rapid growth, high quality leaves and leaf litter, and acceptable wood density (Hughes, 1998). Due to the large number of studies on this species and its incorporation into agroforestry systems, it constitutes a good benchmark for assessing the potential of other members of the genus or other multipurpose species (Hughes, 1998).

Leucaena macrophylla subsp. *macrophylla* Benth is native to SDTF of Mexico and is a highly valued species by the indigenous communities of "La Montaña" of Guerrero for its firewood, fruits and forage; therefore, it is common in the cultivated lands of the re-

Figure 1. Two-and-a-half-year-old trees of *L. macrophylla*, freshly pruned for the experiment of alley cropping.

gion. Moreover, it is an easy-to-propagate and fast growing species; its seeds are small and abundant and do not require germination treatments; also, nitrogen-fixing nodules are formed at an early age; thus, it is considered a promising multipurpose species (Cervantes-Gutiérrez *et al*., 2001).

Despite its qualities, there are few studies that address the potential of *L. macrophylla* to provide ecosystem services, except for some related to biomass and forage quality (Pottinger *et al*., 1996; Stewart & Dunsdon, 1998; García & Medina, 2006).

The traditional cultivation method in "La Montaña" is the 'milpa', which is an ancient crop system in Mesoamerica and the basis of subsistence for a large number of rural communities (Altieri & Toledo, 2011). This polyculture consists of the simultaneous planting of several varieties of corn, beans and squash, occasionally accompanied by other cultivated creole species and semi-domesticated herbs (Benítez *et al*., 2014). In addition, a variant of 'milpa' is accompanied by a series of tools and techniques of cultural management, adapted during hundreds of years to the particular conditions of "La Montaña" (Landa-Ordaz, 2000).

Figure 2. Alley cropping experiment with *L. macrophylla* trees and corn. (Archive Xuajin Me´ Phaa A.C.).

Therefore, it is essential to evaluate whether *L. macrophylla* has the necessary qualities as a multipurpose tree and if, by incorporating this species to traditional farming systems in "La Montaña", it is possible to observe effects on the productivity of these agroecosystems.

For this purpose, the potential of *L. macrophylla* to provide leaf litter, firewood and high quality fodder was evaluated (Hernández-Muciño *et al*., 2015); subsequently, an alley cultivation experiment (2010-2013) with *L. macrophylla* and native maize of the Tuxpeño breed (a simplified version of a 'milpa') was designed to test the productivity of intercropping with the productivity of each component in monoculture. In addition, the performance of each of the treatments under two different methods of fertilization (chemical fertilization and biofertilization with *Azospirillum brasilense* and mycorrhizae of the genus *Glomus*) was tested; the latter was tested to search for more economical and sustainable alternatives to conventional fertilization (article in preparation).

As for the potential of *L. macrophylla* as a multipurpose species, there was found contrasting decomposition predictors: for example, a low Carbon/Nitrogen coefficient (14.39), but a lignin content (29.72%) almost twice as high as an ideal value (Mafongoya *et al.*, 1997). However, when decomposition of leaf litter were analyzed: a rapid decomposition rate was found (1.8) and a short half-life (135 days) as well as a release of almost 50% of mass during the first six months (Hernández-Muciño *et al.*, 2015).

In relation to its quality as firewood, it is expected to have high density and high calorific value, but low moisture and ash content. The calorific value (19.15 kJ/g) and moisture content (35%) of *L. macrophylla* are good and, although the wood density is not so high (0.55 g/cm^3), it is adequate considering that only 3-year-old logs were collected. In contrast, the ash content (1.30%) is higher than values reported in other studies, which indicate that the combustion was not complete. However, the firewood value indexes (complete: 2594.65, and simplified: 16.27) are high, which reflect the firewood quality when compared to other studies using similar methods (See Hernández-Muciño *et al.*, 2015).

Regarding its quality as fodder, *L. macrophylla* has a large amount of organic matter (91.74%), crude protein (15.93%) and digestible fiber (FDN 46.26%). In contrast, non-digestible fiber (FDA 46.26) and lignin content (22.8%) are relatively high. However, these characteristics do not appear to significantly affect its *in vitro* digestibility (57.76%), which is good (Hernández-Muciño *et al.*, 2015).

As for the field productivity of *L. macrophylla* associated with corn, a mixed model statistical analysis revealed that, after two years, there were no significant differences based on the type of fertilization applied. However, there was an additive effect of the biofertilizer with *Azospirillum* and *Glomus* over four years because, in combination with the intercropping, it was significantly more productive (in the same period of time) than the corn monoculture, which was initially only chemically fertilized (P <0.01). Instead, after four years, there were no significant differences in grain productivity when mixed culture and corn monoculture were compared without considering the history of fertilization, (P> 0.3). This result indicates that the incorporation of *L. macrophylla* into the traditional crop system does not affect the corn productivity and that, in combination with other technologies, it could generate higher corn yields (article in preparation).

Figure 3. Me′ Phaa indigenous people collecting and growing ‘quelites’ (wild edible herbs; Photo: Archive Xuajin Me′ Phaa A.C.).

In relation to the overall productivity analysis, there was found that the land equivalent ratio (LER; Mead & Willey, 1980), which compares the productivity per hectare of the mixed crop versus the productivity of each monoculture, was positive (>1) throughout the four years, especially under the biofertilization method, which remained close to a value of 2. This means that two hectares of each monoculture (corn and *L. macrophylla*) are required to equal the productivity of one hectare of the mixed crop.

CONCLUSIONS

Finally, *L. macrophylla* provides high quality leaf litter as well as firewood and fodder, and although it presents some limitations, such as its high lignin content, those do not seem to significantly affect its quality. This type of analysis is a good starting point because it allows to have a general idea of the capacity of multipurpose species to provide ecosystem services. Future analyzes should include direct comparisons of performance with other tested species and management techniques to improve their performance in agroecosystems.

It is important to highlight that the field productivity of *L. macrophylla* associated with corn after two years showed no differences in relation to the type of fertilization applied; however, there was an additive effect of the biofertilizer with *Azospirillum* and *Glomus* over four years, and in conjunction with the intercropping was significantly more productive than the corn monoculture initially only fertilized with chemicals.

In contrast, there were no differences in grain yield after four years between the intercropping and the corn monoculture without considering the fertilization history. Thus, the incorporation of *L. macrophylla* into the traditional crop system does not affect corn productivity and, in combination with other technologies, could generate higher yields.

Likewise, the overall productivity analysis found that, based on the land equivalent ratio, two hectares of each monoculture (corn and *L. macrophylla*) are required to match the productivity of one hectare of mixed crop.

This study with *L. macrophylla* can help lay the foundations to explore new native species with potential to be introduced into cultural agroecosystems. In addition, it allows exploring new, more sustainable and satisfying forms of production to help communities meet the challenges of the new millennium in terms of biodiversity, food security, economy and climate change. Furthermore, coupling the use of traditional species and management practices as an integral part of research can facilitate the adoption of new technologies and their adaptation to particular environmental conditions, such as alley crops and the use of biofertilizers. In this sense, it should be mentioned that several of the lessons learned during the course of this research have been considered in the management plans for the organic agriculture program and the Me' Phaa cultural 'traspatios' project managed by Xuajín Me' Phaa A.C. with support from the Walmart de México foundation.

ACKNOWLEDGEMENTS

The authors are grateful for the support received in the field by members of Xuajín Me' Phaa A.C. The funding for this project was provided by 'Programa de Apoyo a Proyectos de Investigación e Innovación Tecnológica (PAPIIT) UNAM (Number IN300615 and IN105015). In addition, this work is part of the PhD thesis of Diego Hernandez-Muciño in the Graduate Program of Biological Sciences at Universidad Nacional Autónoma de México, who also received a PhD scholarship from the National Council of Science and Technology (CONACyT, in Spanish).

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Discusión y conclusiones

Leucaena macrophylla, especie nativa de Mesoamérica, forma parte de un grupo muy amplio de árboles nativos, cultivados o manejados *in situ* por las pueblos indígenas durante cientos o posiblemente miles años; por tal motivo estos árboles, además de representar un alto valor cultural para las comunidades, gracias a sus múltiples propósitos, pueden contribuir de forma muy importante a la restauración del capital natural, especialmente en paisajes rurales altamente modificados por el hombre, como es el caso de la Montaña de Guerrero. Sin embargo, con los conflictos socioambientales, como la degradación de los ecosistemas y las trampas de pobreza asociadas, no solo se pone en riesgo la existencia de estas especies, también la cultura de manejo tradicional que se realiza con ellas. Por lo tanto, es nuestro deber rescatar, revalorar y estudiar el papel que juegan dichas especies como proveedoras de bienes y servicios ecosistémicos, y su potencial para ser introducidas en sistemas productivos tradicionales o culturales (nuevos agroecosistemas), así como hacerlos más resilientes, sostenibles y socialmente satisfactorios.

En este sentido, *L. macrophylla,* como proveedora de servicios ecosistémicos, posee hojarasca de buena calidad, tanto para fertilización del suelo como para forraje. Entre sus principales características, destacan un alto contenido de nitrógeno (3.5 %), buena relación C/N en hojas (14) y adecuada digestibilidad *in vitro* (57 %). Pese a que tiene un alto contenido de lignina, esto no parece afectar drásticamente su calidad. Por otra parte, esta especie presenta características adecuadas para ser usada como leña, tales como una densidad de madera de 0.55 g/ cm^3 y un índice de valor de la leña completo de 2594.65.

En cuanto al uso de *L. macrophylla* y maíz en un sistema de cultivo en callejones en la Montaña de Guerrero, se concluye que en un análisis global, en los últimos tres años el cultivo en callejones presentó visibles ventajas sobre el monocultivo de maíz en términos de rendimiento de grano (aproximadamente entre un 10 y 12 % más), especialmente en el área con suelo más pobre; asimismo, una mayor productividad por unidad de área (RET >2), ya que sería necesario más de una hectárea de cada monocultivo, tanto de maíz como de *L. macrophylla*, para alcanzar la productividad de una hectárea de cultivo en callejones. Además, desde el comienzo del experimento el protocolo con biofertilizante demostró ser un sustituto adecuado de la fertilización estándar. Sin embargo, para cubrir los requerimientos de N por parte del cultivo y alcanzar el máximo potencial productivo, es necesario aumentar al menos al doble tanto la densidad como el número de podas de *L. macrophylla*, lo cual es factible, puesto que el cultivo de maíz es de temporal y no existe una limitante considerable de agua. Asimismo, este agroecosistema cultural mostró ventajas en términos socioeconómicos, pues no solo incrementó el número de bienes que pueden ser obtenidos de la parcela, sino que produjo mejores rendimientos económicos, especialmente en los último tres años; ello significa que el sistema puede contribuir de forma muy importante a terminar con algunas externalidades económicas que los agromercados imponen a los campesinos, así como a generar modos de producción más sustentables a largo plazo.

Por último, este tipo de agroecosistemas contribuye al mejoramiento de algunos servicios ecosistémicos, como pudo observarse en el reciclado de nutrientes y la conservación de la fertilidad del suelo; también reduce los riesgos en la producción de bienes, lo cual es un punto clave para superar la pobreza, y por tanto debería ser añadido a la ecuación para determinar la viabilidad de estos sistemas de producción alternativos.
El estudio realizado a *L. macrophylla* permite sentar las bases de la investigación y exploración sobre nuevas especies indígenas y/o nativas y sobre sus métodos tradicionales de manejo, a fin de proponer nuevas especies con potencial para ser introducidas en agroecosistemas culturales alternativos. Se trata de generar nuevas formas de producción más sostenibles, resilientes y satisfactorias, que ayuden a superar los diversos retos que enfrentan las comunidades en áreas rurales pobres del mundo, como son la pérdida de la biodiversidad, las trampas de pobreza, la inseguridad alimentaria y los efectos del cambio climático.

Asimismo, se concluye que la investigación participativa con el rescate de los saberes y prácticas de manejo tradicionales, además de generar nuevo conocimiento transversal, puede ayudar a facilitar la adopción y adaptación de nuevas tecnologías adecuadas a cada contexto, así como contribuir a generar una conciencia colectiva en las comunidades sobre el uso y manejo sostenible de los recursos naturales.

Finalmente, es muy importante resaltar que cada avance durante la investigación se logró en colaboración con la organización de la sociedad civil Xuajin Me’Phaa A.C., la cual trabaja arduamente en proyectos de manejo integral del paisaje y agricultura orgánica, y busca generar bienestar social en la Montaña de Guerrero. Dado que compartimos totalmente este propósito, tenemos la firme esperanza de que el presente trabajo de investigación alcance la mayor difusión posible, para que contribuya a impulsar formas de vida más resilientes y dignas en una de las regiones más pobres y olvidadas de México.

Recomendaciones

Debido a las cualidades de *L. macrophylla* como especie proveedora de servicios ecosistémicos (específicamente, hojarasca, leña y forraje), así como al valor que tiene esta y otras especies de *Leucaena* para los pueblos indígenas en Mesoamérica, se recomienda la utilización intensiva de esta especie tanto en agroecosistémas culturales, como en otras actividades de restauración con enfoque productivo; por ejemplo, en actividades de enriquecimiento de bosques y rehabilitación de bordes riparios con especies nativas multipropósito. Por otro lado, en sistemas de cultivo, se recomiendan algunas actividades para el mejoramiento de calidad de la hojarasca, como el picado de las hojas o su incorporación al suelo.

Por otro lado, para su implantación dentro de sistemas agroforestales como el cultivo en callejones, es recomendable una densidad de 2000 árboles por hectárea, aproximadamente el doble de lo empleado en esta tesis, así como una frecuencia de 3 a 4 podas por temporada de cultivo. Esto, con el propósito de cubrir de la mejor manera las necesidades nutricionales de los cultivos.

Finalmente, se recomienda retomar los distintos métodos empleados aquí, ya que pueden ayudar a evaluar otras especies nativas multipropósito y a diseñar nuevos agroecosistemas culturales, adecuados a distintas regiones que presenten contextos socioecológicos semejantes.

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