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The use of farmers' knowledge in coffee agroforestry management: implications for the conservation of tree biodiversity

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Abstract. In agroforestry systems, the survival of shade trees is often the result of farmers' deliberate selection. Therefore, how communities generate knowledge and apply it to resource management practices influence the potential for biodiversity conservation of agroforestry systems. In this study, we investigated the use of knowledge by farmers to manage coffee (*Coffea arabica*) agroforests and the consequences for the conservation of tree biodiversity and composition of surrounding forests. We interviewed 50 coffee farmers to investigate their shade tree preferences and sources of knowledge of the properties of shade trees and coffee management practices; we also conducted tree inventories in 31 coffee farms and 10 forest sites in La Sepultura Biosphere Reserve in Chiapas, Mexico. Our results showed that farmers are modifying agroforests according to their knowledge and tree preferences, and that the resulting agroforest is lower in tree diversity and dominated by pioneer and farmers' preferred tree species as compared to forests. The principal sources of knowledge of management practices are external sources, such as governmental and non-governmental organizations, whereas the primary source of tree specific knowledge is empirical knowledge. We found that the higher proportion of pioneer trees relative to forest is mostly explained by farmers' tree selection decisions (63%) rather than as a byproduct of management practices (37%) that disturb the soil and open the canopy, altering light penetration and microclimate conditions. Based on interviews and tree inventories, we found that farmers gradually replace canopy trees of neutral and disliked species by preferred species, in particular *Inga* spp. We found that external sources continue to promote the idea that *Inga* spp. trees bring significant benefits to coffee production in spite of a lack of scientific evidence to support this claim. This indicates that farmers are receptive to incorporate outside knowledge into their knowledge systems and adapt their resource management practices accordingly. Our findings highlight the importance of disseminating sound and clear scientific information to practitioners who work directly with farming communities to ensure that accurate and up-to-date information is being contributed to local knowledge systems.

Key words: agroforestry; biodiversity; Chiapas; *Coffea arabica*; farmers' knowledge; Latin America; local knowledge; Mexico; tree conservation.

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Introduction

In agroforestry systems, where crops such as coffee and cacao are cultivated beneath the forest canopy, the survival of shade trees is often the result of farmers' deliberate selection. Farmers' decisions to tolerate, foster, plant, transplant or eliminate shade trees influence patterns of vegetation richness and structure, resulting in a wide array of agroforestry systems characterized by varying vegetation and structural complexities and under different management intensities (Moguel and Toledo 1999). Therefore, how communities generate knowledge and apply it to management practices influences the potential for biodiversity conservation of agroforests.

By knowledge we refer to an understanding of the world that is acquired by perceiving, experimenting, and learning. Philosophers distinguish between a posteriori knowledge, or knowledge that is gained by experience, and a priori knowledge, or knowledge that is gained independently of experience. A posteriori knowledge, also known as empirical knowledge, includes learning by observation and experimentation, such as observing the forest and experimenting in crop fields. A priori knowledge includes knowledge gained from myths, family members, agricultural extension agents, and conservation organizations, for example.

The study of people's knowledge of nature may be found in the literature under the terms indigenous knowledge (IK), local ecological knowledge (LEK), or traditional ecological knowledge (TEK). Many studies in this field have focused on validating the accuracy of IK/LEK/TEK vis-á-vis western knowledge and argued for its greater integration in natural resources management schemes (Berkes et al. 1998, Huntington 2000, Pierotti and Wildcat 2000, Mackinson 2001, Gilchrist et al. 2005, Anadón et al. 2009, Gratani et al. 2011). Other studies have moved away from the validation approach and recognized the complementarily of IK/LEK/TEK and scientific knowledge systems in advancing our understanding of ecosystem and biodiversity management (e.g., multiple evidence approach; Chalmers and Fabricius 2007, Brondizio 2008, Tengö et al. 2014). Literature in this field has also centered on demonstrating that natural resource management based on IK/LEK/TEK contributes to the conservation of biodiversity (Gadgil et al. 1993, Becker and Ghimire 2003, Kajembe et al. 2003, Charnley et al. 2007, Diemont and Martin 2009, Luo et al. 2009, Rist et al. 2010, Ruiz-Mallén and Corbera 2013); however, many of these studies have omitted systematic biodiversity assessments to evaluate the actual consequences of IK/LEK/TEK-based management on biodiversity.

Studies that have investigated farmers' knowledge of shade trees in agroforestry systems have evaluated farmers' shade tree preferences and knowledge about ecosystem services, the benefits that humans derive from ecosystem functioning (Cardinale et al. 2012). These studies have found that farmers select shade trees based on their compatibility with crops by assessing traits such as crown shape, shade production, deciduousness, foliage density, root system attributes, and allelopathic effects (Albertin and Nair 2004, Soto-Pinto et al. 2007, Souza et al. 2010, Anglaaere et al. 2011, Cerdán et al. 2012). Farmers also demonstrate detailed knowledge about the effects of tree cover on ecosystem services (Cerdán et al. 2012), such as soil fertility (Grossman 2003, Pauli et al. 2012) and pest control (Segura et al. 2004). The limitation of these studies is that the consequences of findings in the social system (i.e., farmers' knowledge, shade tree preferences) on the ecological system (i.e., changes in tree species abundance) are seldom investigated.

On the other hand, studies that have examined tree biodiversity in agroforestry systems have found higher levels of tree biodiversity in the more rustic, less intensively managed agroforests (Moguel and Toledo 1999, Reynoso 2004, López-Gómez et al. 2008, Asase et al. 2010) and shifts in tree species community composition in agroforests as compared to forests (Ambinakudige and Sathish 2008, Anglaaere et al. 2011, Valencia et al. 2014). Studies have also found that pioneer trees tend to dominate agroforestry systems (Rolim and Chiarello 2004, Bandeira et al. 2005, Valencia et al. 2014). However, it remains unclear to what degree pioneer proliferation in agroforestry systems is due to farmers' direct and conscious modification of tree community composition or an indirect and unintentional consequence of management practices. Although informative, these studies contribute a limited understanding of how management based on farmer's knowledge may be generating patterns of biodiversity in agroforests.

The degree to which farmers' knowledge and preferences for shade trees modifies agroforests when compared with surrounding forests merits clarification. Understanding the degree to which coffee agroforests may serve as reservoirs of forest biodiversity is particularly important since some of the major coffee growing regions in the world overlap with biodiversity hotspots (Hardner and Rice 2002). In this study, we investigated the use of certain forms of enduring knowledge, or understandings that have long-lasting value, by farmers to manage coffee (*Coffea arabica*) agroforests and the consequences for the conservation of tree biodiversity and composition of surrounding forests. We hypothesize that farmer's selection for tree "utilitarian" functional traits (sensu Brown et al. 2011) results in a shift in tree species community composition and lower tree species diversity compared to surrounding forests. We propose that farmers attempt to maximize the provisioning (i.e., coffee production) and supporting (i.e., soil fertility) ecosystem services of interest by modifying associated tree species richness, abundance, and composition by means of favoring trees with the utilitarian functional traits that farmers associate with enhanced crop production (e.g., nitrogen fixation, light tree crown) and eliminating species whose functional traits are detrimental to the crop (e.g., allelopathic effects).

To achieve this, we interviewed coffee farmers and conducted floristic inventories in farms and forests. First, we investigated farmers' knowledge of shade trees and their role in coffee agroforestry; we identified local coffee management practices, which included the establishment of coffee agroforests and cyclical practices, such as weeding and shade management; and we investigated the mechanisms by which knowledge specific to coffee agroforestry was being generated. Finally, we evaluated the outcomes of farmer's knowledge choices on tree species diversity and composition in agroforests and compared it to surrounding forests. We also disentangled the effects of management practices and farmers' tree selection on pioneer abundance.

Methods

Study area

This study was conducted in Los Angeles and Tres Picos communities in the Upper Tablon river basin in the buffer zone of La Sepultura Biosphere Reserve (SBR) in Chiapas, Mexico (16°00′18″–16°29′01″ N and 93°24′34″–94°07′35″ W; Fig. 1). SBR encompasses an area of 167,309 ha, of which 8% is designated as core area, destined for the protection of biodiversity and educational and research activities, and 92% as buffer zone restricted to human activities compatible with "sound ecological practices" (INE 1999). The degree of forest disturbance by human activities (e.g., occasional subtraction of firewood or timber wood, seasonal cattle grazing) vary from none or very low to high, depending on the location of the forest or the time of the year. Anthropogenic disturbances of forest include cattle grazing, especially during the wintertime when fodder is scarce, and extraction of secondary products, such as firewood and timber, from forested areas near homes. Approximately 77 communities are found in the buffer zone, comprising a demographically young and fast-growing population of 24,564 people (CONANP 2013). The local population speaks Spanish and fewer than 4% also speak an indigenous language (INE 1999). Catholicism is the dominant religion followed by Jehovah's Witnesses, Seventh Day Adventists, and Pentecostalism (INE 1999). Among households, 63% have electricity (INE 1999), 89% rudimentary sewage and 77.3% running water (CONANP 2013). Households depend primarily on agriculture to support their livelihoods. The majority of households cultivate maize and beans for household consumption, although for some households these crops also represent a source of monetary income. Livestock raising and organic coffee cultivation are the most significant economic activities in the area. In the 1960s, landless peasants from other regions founded Los Angeles and, a few years later, other migrant peasants established Tres Picos (Cruz-Morales 2014).

This area is located in the Mesoamerica hotspot (Myers et al. 2000) and considered a global conservation priority (Conservation International 2014). SBR encompasses multiple ecosystems, including evergreen pine forest, evergreen forest,

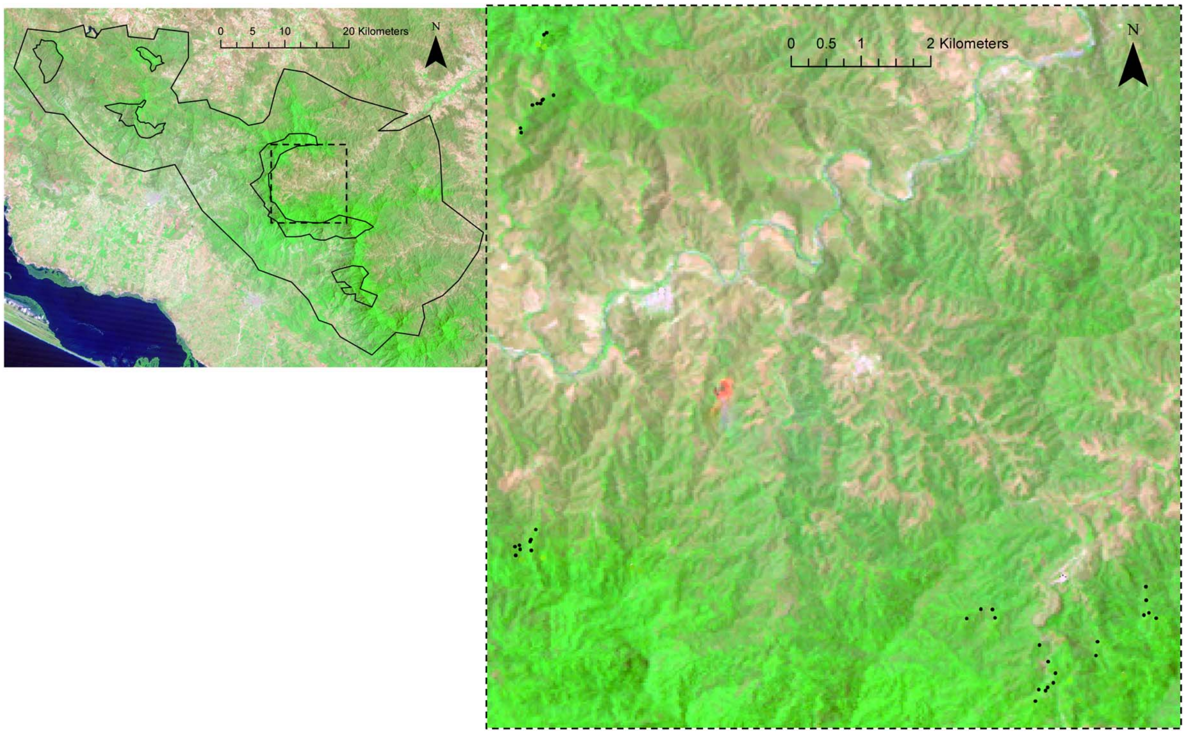


Fig. 1. Map of La Sepultura Biosphere Reserve (left), where core areas are indicated by inner polygons and study area by a dotted square. Enlargement of study area (right) shows the location of sampled coffee farms ($n = 31$) with black dots. Maps were created using Landsat satellite data.

montane forest, low deciduous tropical forest, medium semievergreen and semideciduous tropical forest, foggy chaparral and savannas (INE 1999). Coffee agroforests are located at an elevation between 800 and 1500 m a.s.l. Mean annual temperature ranges from 20° to 22°C at altitudes between 970 and 1500 m a.s.l. (INE 1999). The rainy season lasts from May to October; mean annual precipitation ranges between 2000 and 2500 mm.

Surveys of farmers' tree preferences and management practices

In February 2012, we conducted structured interviews among 50 coffee farmers in the two communities. We identified participating coffee farmers through a snowball sampling method (Goodman 1961), which started with the coffee representative in each community and thereafter grew through a network of nominated acquaintances. The primary researcher conducted interviews in farmers' homes in Spanish and recorded answers by hand. Interviews were composed of open- and closed-ended questions. During interviews, which lasted between 45 and 60 minutes, farmers openly discussed which trees they preferred and disliked in their coffee farms, the rationale for their preferences, management practices, and the sources of knowledge of tree uses and attributes and of coffee management practices. We also collected data on farm characteristics such as farm size and number of years under management.

We classified a particular tree species as "preferred" or "disliked" if at least 20% of interviewees concurred in classification; remaining species were classified as "neutral." A few trees received contradictory classifications; however, this only occurred a few times so it did not create conflict during final classification. The threshold of 20% corresponds to the average plus half a standard deviation, which, based on the distribution of responses, excludes the long list of trees that were mentioned fewer than 10 times and captures the trees that are clustered with high response rates. Open-ended questions concerned farmers' tree preferences and selection criteria; responses to these questions were placed into categories based on patterns and themes and analyzed using frequencies.

We asked farmers open-and closed-ended questions to determine which sources had been most influential in shaping their knowledge and perceptions about coffee management and the role of trees in coffee farms. Answers were grouped into four common themes: learning by personal experience, from a family member, from a neighbor or colleague, and in a workshop or capacity-building event. Personal experience encompassed instances in which farmers reported personally observing the effect of the element in question. Learning from a family member included learning from a parent, son or daughter, sibling or anyone in the immediate family nucleus. Learning from a neighbor or colleague included instances of knowledge sharing among farmers during collaborative work in coffee farms, informal gatherings and conversations. Learning in a workshop or capacity-building event included formal knowledge sharing organized by non-governmental organizations, government agencies, or academics.

Floristic inventories

We selected a sample of thirty-one coffee farms among the interviewed farmers and 10 forest sites. Farms were selected to include a wide range of farm ages, sizes, and elevations. In order to control for variations in vegetation, forest sites were randomly selected in the same elevation belt as coffee farms. Soil characteristics are homogeneous in study area in terms of classification (eutric regosol), texture, and parent material (Valdivieso-Perez et al. 2012, CONANP 2013). We collected data in coffee farms in June 2011, before the weeding period, and then returned to 12 coffee farms in February 2012, after the conclusion of the weeding period, and collected data only on saplings. At the center of each plot we established three concentric circles of radii 5, 12, and 17 m. In the 17-m circle we counted, identified, and measured the diameter at breast height (DBH) of adult trees (DBH $>$ 10 cm); in the 12-m circle we counted, identified, and measured DBH of juvenile trees (5 cm $<$ DBH $<$ 10 cm); in the 5-m circle we counted and identified saplings (DBH $<$ 5 cm, height $<$ 50 cm). Coffee bushes were counted in the 17-m circle in farms. Location of sites and elevation was recorded with a global positioning system device. Farm owners assisted a taxonomist from the Herbarium at El Colegio de la Frontera Sur (ECOSUR) in Chiapas, Mexico, in matching up local names with scientific names. The taxonomist classified the successional stage of trees as pioneer, intermediate, or late-successional based on expert knowledge drawn from previous studies (González-Espinosa et al. 1991, Ramírez-Marcial et al. 1998, Galindo-Jaimes et al. 2002, Ramirez-Marcial et al. 2006). We collected voucher specimens from sampled species and deposited them at ECOSUR.

In two separate analyses, we compared the proportion of trees (DBH $>$ 5 cm) and saplings (DBH $<$ 5 cm, height $>$ 50 cm) in forests and farms composed by individuals of (1) preferred, disliked, and neutral species, and (2) pioneer, intermediate, and late-successional species. We also compared sapling composition in farms before and after weeding period. We analyzed differences by using a Welch two-sample t test. We calculated total landscape-level species richness using the non-parametric estimator Chao 1 in the statistical software R (R Development Core Team 2005).

Disentangling effects of management practices and farmers' tree selection on pioneer abundance

We conducted an analysis in order to disentangle the effects of direct and indirect processes on the proportion of pioneer trees in coffee agroforests. Direct processes refer specifically to farmers' tree preferences and selection criteria and the consequent decisions to systematically eliminate disliked adult trees and saplings and to tolerate, foster, plant, and transplant preferred tree species. Indirect processes refer to the creation of canopy gaps by trimming branches or removing trees, which alters light availability and microclimate (i.e., temperature and humidity), and weeding practices, which disturb the soil and alter sapling community. Both of these processes impact tree community composition by sustaining a systematic elimination and promotion of certain species, and by creating conditions favorable for the recruitment of a subset of species, typically pioneers.

We contrasted the mean proportion of pioneer

Table 1. Summary of characteristics of shade coffee farms and forests in the upper Tablon river basin in La Sepultura Biosphere Reserve.

Characteristic	Farm	Forest	P
Mean farm size (ha)	2.6 (1–6)	. . .	. . .
Mean farm age (yrs)	11.6 (2–40)	. . .	. . .
Mean coffee shrub density (shrubs/ha)	1380 (374–3624)	. . .	. . .
Total tree species richness	88	79	. . .
Chao estimate	139	141	. . .
Mean tree richness (per site)	7.7 (1–18)	17.9 (12–28)	***
Mean tree density (trees/ha)	220 (77–507)	628 (330–1013)	***†
Mean Shannon diversity	1.52 (0–2.81)	2.43 (1.43–2.48)	***
Elevation (m a.s.l.)	1267 (1119–1490)	1417 (1224–1524)	**

Notes: Values in parentheses correspond to minimum and maximum values.
** $P < 0.01$; *** $P < 0.001$
† P was calculated using Wilcoxon rank sum test with continuity correction; other P values were calculated using Welch two sample t test.

trees in forests and farms to determine the additional proportion of pioneers that proliferated in farms as a result of both indirect and direct processes. To disentangle direct from indirect processes, we first contrasted the proportion of pioneers among neutral species to pioneers among all species (neutral, disliked, and preferred) in farms to determine the mean proportion of pioneers that proliferated due to direct processes. Since farmers do not actively manage neutral tree species—they do not systematically eliminate or promote these trees in farms—any increase in the mean proportion of pioneer trees above that of neutral pioneer trees may be attributed to direct processes. We then determined the mean proportion of pioneer trees attributable to indirect processes by comparing the mean proportion of pioneers in forests to that of neutral pioneers in farms.

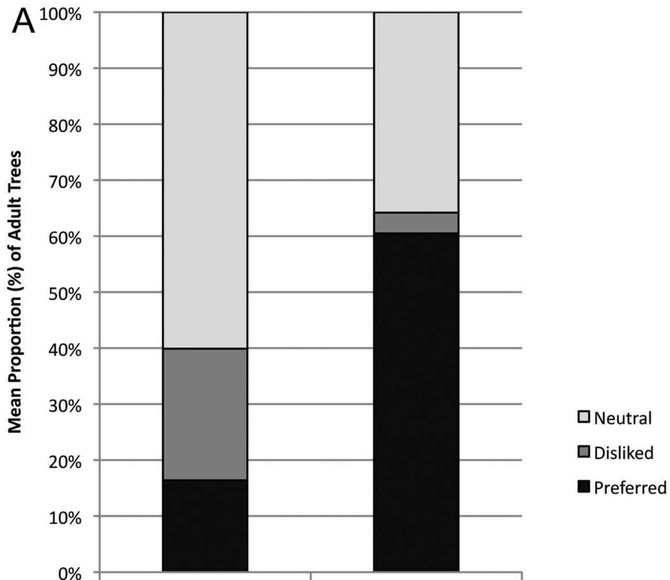
Results

Vegetation structure and community composition of shade coffee farms and forests

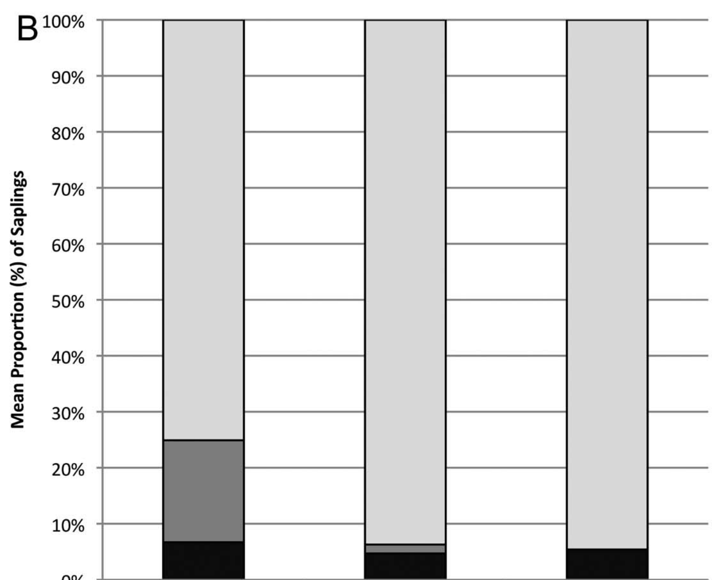
Most farms (80%) were less than 3 ha in size and were established within the past 10 years (64.5%). We sampled a total of 621 trees in coffee farms ($n = 31$), belonging to 88 different species. On average, each farm had 8 species (range: 1–18). Chao estimates, which approximate total species richness at the landscape-level (i.e., gamma diversity), indicated that the network of coffee farms might contain up to 139 native tree species (i.e., coffee was the only exotic species). The most common species was *Inga oerstediana*, which represented 37.7% of all trees in farms; the 20 most common species accounted for 70% of all trees. In contrast, we sampled 570 trees, belonging to 79 species, in forest plots ($n = 10$). On average, forest plots had 18 species (range: 12–28). Chao estimates indicated that forests might contain up to 141 species (Table 1).

Coffee agroforest and forest composition by preferred, disliked, and neutral tree species

We found that in forests the mean proportion of preferred trees accounted for 16.4% of individuals (min = 0%, max = 50%, SD = 15%) and disliked trees for 23.5% (min = 0%, max = 54%, SD = 19%). In contrast, in farms the mean proportion of preferred trees corresponded to 60.5% (min = 0%, max = 100%, SD = 26%) of individuals and for disliked trees, it decreased to 3.7% (min = 0%, max = 43%, SD = 9.5%). The genus *Inga*, the unanimously preferred tree, accounted on average for 49% (min = 0%, max = 100%, SD = 28%) of trees in farms and 10% (min = 0%, max = 31%, SD = 11%) of trees in forests. For saplings of disliked species, we observed the same trend of decline from a mean proportion of 18.2% (min = 0%, max = 63%, SD = 24%) in forests to 1.6% (min = 0%, max = 31%, SD = 6%) in farms; after the conclusion of the weeding period, saplings of disliked species were not found in sampled area. As for saplings of preferred species, we did not find a statistically significant difference in the proportions of individuals found in forests and farms, before and after the weeding period (Fig. 2).

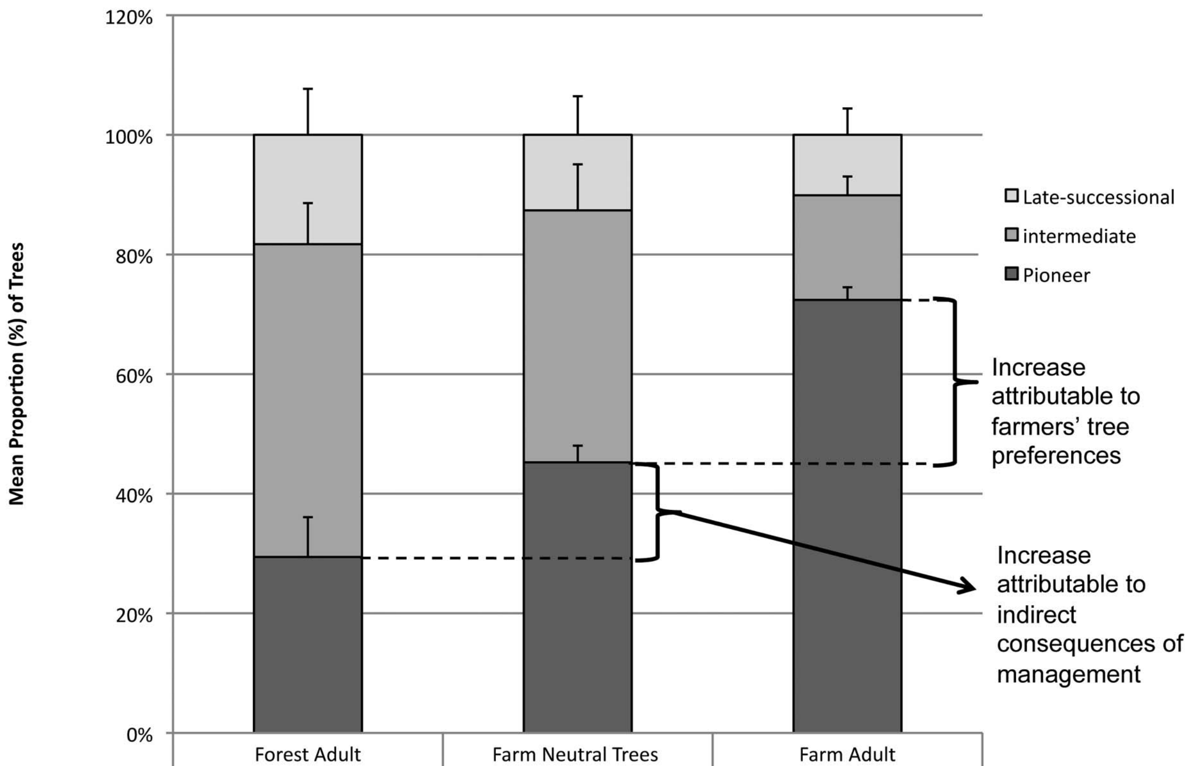


	Forest	Farm
Neutral	60.1*	35.8*
Disliked	23.5*	3.7*
Preferred	16.4*	60.5*



	Forest	Farm Pre-weeding	Farm Post-weeding
Neutral	75.1* a	93.7 b	94.6 b
Disliked	18.2* a	1.6 b	0 b
Preferred	6.7	4.7	5.4

Fig. 2. Mean proportion (%) of neutral, disliked, and preferred adult trees (A) and saplings (B), before and after weeding period, in coffee farms vs. forests. Differences in mean proportion of neutral, disliked, and preferred trees between forest and farms for adults and saplings are statistically significant ($P < 0.001$), except for preferred saplings between forests and farms, before and after weeding period. Letters show significant differences for comparisons made among saplings in forests and farms pre- and post-weeding.



	Forest Adult	Farm Neutral Trees	Farm Adult
Late-successional	18.2	12.6	10
intermediate	52.1	42.1	17.3
Pioneer	29.3	45.2	71.6

Fig. 3. Mean proportion (%) of pioneer, intermediate, and late-successional trees in farms and forests. On average, there are 42.3% more pioneer trees in farms than forests, from which a 15.9% increase may be attributed to agroecological processes and 26.4% to social processes. Bars represent standard error.

Mean proportion of pioneer trees attributable to farmers' tree selection and indirect management processes

We found that in forests on average 29.3% (min = 2%, max = 73%, SD = 24%) of trees were pioneers, whereas in farms this figure corresponded to 71.6% (min = 15.8%, max = 100%, SD = 24.3%). Among the 42.3% increase in the mean proportion of pioneers in farms, a 26.4% increment may be attributed to farmers' direct and conscious modification of tree community composition, while a 15.9% increment may be attributed to indirect and unintentional consequence of management practices (Fig. 3). In other words, 63% of the abundance of pioneers relative to forest is attributable to farmers' tree preferences and selection criteria, while 37% may be the indirect result of management practices.

Farmers' tree preferences

We asked farmers to list the trees they preferred in their coffee farms. In total, farmers mentioned 35 trees by their common names, from which we identified 23 by their scientific name. On average, farmers listed 5 preferred trees (min = 1, max = 9). The majority of trees listed (77%) were mentioned in fewer than 12% of interviews. Only 8 species were mentioned in at least 20% of interviews; this group of species was labeled as "preferred" tree species. Among the 8 preferred species, farmers unanimously agreed that the genus *Inga* was undoubtedly the most beneficial tree for coffee cultivation. The common names chalu, carnijicuil, and caspirol referred interchangeably to *Inga oerstediana*, *Inga vera*, and *Inga punctata*, the three *Inga* spp. identified during floristic inventories (Table 2).

Table 2. Preferred and disliked tree species mentioned in at least 20% of interviews.

Species	Local name	Successional stage
Preferred species		
Aiouea inconspicua Van derWerff.	Aguacatillo	late-successional
Heliocarpus donnellesmithii Rose ex donn. Sm.	Corcho	pioneer
Inga oerstedianan Benth.	Caspirol, chalum, carnijicuil	pioneer
Inga punctata Willd.	Caspirol, chalum, carnijicuil	pioneer
Inga vera Willd.	Caspirol, chalum, carnijicuil	pioneer
Ocotea spp.	Aguacatillo	late-successional
Tapirira mexicana Marchand	Duraznillo	late-successional
Ulmus mexicana (Liebm.) Planch.	Baqueta	late-successional
Disliked species		
Castanopsis lanceifolia (Oerst.) Hickel & A.Camus	Encino (oak)	intermediate succession
Quercus peduncularis Née	Encino (oak)	intermediate succession
Quercus skinerii	Encino (oak)	intermediate succession
Liquidambar styraciflua L.	Liquidambar	pioneer
Pinus maximinoi H.E. Moore	Pino (pine), ocote	pioneer
Pinus strobus var. *chiapensis* Martínez	Pino (pine), pinobeto	pioneer

We asked farmers to list the trees they disliked in their coffee farms. In total, farmers mentioned 32 trees by their common names, from which we identified 26 by their scientific name. On average, farmers listed 4 disliked trees (min = 2, max = 6) by their common name. Only 6 species were mentioned in at least 20% of interviews; this group of trees was labeled as "disliked" trees. Disliked trees included *Liquidambar styraciflua*, 3 oak species, and 2 pine species (Table 2); these oak and pine species corresponded to multiple common names, such as pinabeto, pino, ocote, roble, roble encino, encino, and roble negro.

The bulk of tree diversity (84% of identified tree species) fell under the category of neutral trees. This category comprised the remaining tree species that were not included by a significant proportion of farmers in either the preferred or disliked categories. Farmers perceived neutral trees neither as harmful nor beneficial in any significant way for coffee cultivation.

Tree selection criteria

Farmers evaluated trees in terms of the traits that they associated with the goods and services they desired or disliked. These traits included tree height, crown shape, deciduous/evergreen, organic matter production, perceived effects on soil fertility, wood quality, fruit production, tree growth rate, and harmful competitive effects. Table 3 summarizes the links between traits and goods and services as explained by farmers during interviews.

Preferred trees.—When we asked farmers to explain the reasons for preferring the trees they had listed, farmers indicated the goods and services provided by each tree. The reason most often mentioned referred to the appropriateness of the shade provided to support the growth and development of coffee bushes and to foster timely maturation of coffee beans (mentioned for 71% of listed trees and for all of trees in preferred group). Farmers considered desirable shade to be that which permitted the passage of light in a mottled pattern and contributed to a fresh microclimate, conditions perceived to support coffee bush growth and development, sustain yields, and avoid the proliferation of pathogens such as the fungus *Mycena citricolor*.

Further reasons that reinforced preferences included the provisioning of additional goods and services. For example, among the 31 trees listed, 48% produced fruits, which were particularly valuable for diminishing attacks by birds and small mammals such as coatis (*Nasua narica*) on mature coffee beans by providing an alternative source of food; 45% were perceived to benefit soil fertility; 29% were valuable for maintaining a fresh microclimate; 19% were a valuable source for timber and/or firewood; and 13% provided an additional good such as medicinal resources and non-timber construction materials. This set of secondary goods and services were considered a "bonus" in addition to the provisioning of adequate shade.

Among the 31 trees that farmers liked, 9 trees were listed (<6% of interviews) in spite of being considered inappropriate for coffee cultivation. The most important quality of these 9 trees was fruit production, followed by perceived contri-

Table 3. Links between tree traits and goods and services as perceived by farmers.

Trait	Ecosystem goods and services	Farmers' desired outcome
Maximum height	shade density and pattern	shorter trees, which are managed more easily to maintain appropriate shade
Crown shape	shade density and pattern	mottled, uniform shade
Deciduous/evergreen	shade uniformity and stability across seasons	evergreen
Organic matter production	soil fertility	trees that contribute leafs to soil
Nitrogen fixation	soil fertility	improved soil fertility
Wood properties	wood suitable for timber, firewood, and construction materials	wood that may be used for construction or cooking
Fruit production	food	food alternatives to mature coffee cherries for animal consumption
Harmful competitive effects	(disservice) stunting growth of coffee bushes, yellowing of leafs, and excessive water uptake	absence of harmful competitive effects that may damage coffee shrub or prevent its healthy growth and development

bution to soil fertility and by the provision of timber or firewood. For example, *Cedrela odorata* is considered an inappropriate shade tree for coffee cultivation, however, because it is a valuable timber tree in the mahogany family, it is conserved and its saplings protected in coffee farms.

Among the 8 species in the preferred list of trees, 100% of trees provided a desirable shade, 100% were perceived to benefit soil fertility, 75% were valuable for maintaining an appropriate microclimate, 62.5% produced fruit, 25% provided either firewood or timber, and 25% provided an additional good.

Disliked trees.—When asked for the rationale for disliking trees, the reasons most often cited referred to inappropriateness of shade and harmful competitive effects on coffee bushes. Among the 31 trees listed as disliked, 61% were considered to provide an inappropriate shade characterized primarily by insufficient light penetration, and 26% of trees were thought to cause detrimental microclimate modifications, such as reduced moisture or increased temperature. Among the trees (48%) associated with harmful competitive effects on coffee bushes, the most cited effect was stunt growth of coffee bush (35%), followed by yellowing of leaves of coffee bush (26%), excessive water uptake by shade tree (10%), and negative effects on soil (6%).

Secondary reasons for disliking a tree referred to height and deciduousness. For 29% of trees, farmers cited tallness as a disadvantage because it hindered trimming of branches to regulate shade and, in the event of fall, large trees caused greater damage on coffee shrubs. For 19% of trees, farmers mentioned deciduousness as an undesirable trait because it led to unwanted seasonal gaps in the canopy and irregularities in shade.

Among the 6 trees in the group of disliked species, all were associated with a harmful competitive effect: 100% were considered to cause stunting of coffee bushes, 75% yellowing of leafs, and 25% negative effects on soil fertility. Most of these trees were considered to provide an inappropriate shade because foliage density prevented the passage of light (87.5%) and were associated with detrimental alternations of microclimate (88%).

Farm management practices

Farm establishment.—Farmers established coffee farms on land supporting primary or secondary forest previously under no or low management (i.e., extraction of non-timber forest products, occasional removal of branches or trees for firewood or timber, occasional cattle grazing; $n = 18$), or on fallow land (i.e., forested land that was previously cleared for crop cultivation or pastureland; $n = 13$). There were no statistically significant floristic differences between farms established in fallow and forest in term of mean richness, Shannon diversity, or Simpson diversity. In a role similar to a landscape architect, farmers manipulated the forests' vegetative structure and species composition to achieve the desired canopy structure and tree community composition. Before introducing coffee in the forest understory, farmers decided which adult trees to retain in the system and which to remove following tree preferences described above. In order to create physical space for coffee shrubs to grow, farmers decided on the number and location of trees that would be removed. The result was a forest with lower tree density than before and a canopy with an increased number of gaps and a structure that permitted the diffused passage of light.

Weeding practices.—Weed management consisted of clearing of understory vegetation with a machete twice a year; first in June–August and again in September–November in preparation for coffee harvesting in February and March. Coffee farmers indicated that during weed management saplings were removed, regardless of species, to maintain the understory clear in order to facilitate coffee harvesting and to reduce competition with coffee shrubs. Farmers maintained that only under special circumstances and depending on shade requirements, saplings of preferred species were allowed to establish. Special circumstances included the undesirable creation of a canopy gap by a fallen tree or in anticipation of the fall of a dead or dying tree. Some farmers reported sparing saplings of *Inga* spp. and, to a lesser extent, other preferred tree species during weeding and "nursing" them in their farms to eventually substitute a nearby tree as part of a long-term strategy to replace canopy trees by *Inga* spp. and other preferred species.

Shade management.—The regulation of shade was closely associated with fostering high coffee yields and controlling pests. Farmers explained that yields dropped under dense shades, in which cases the removal of branches or trees was necessary to increase light availability and subsequently boost yields. Diseases, such as fungus *Mycena citricolor*, were associated with high humidity environments caused by insufficient light passage, in which case the solution was also to remove trees or trim branches.

Sources of knowledge

Coffee management practices.—When we asked farmers how they had learned to manage coffee agroforests, the most cited sources were workshops (71%), followed by learning from a colleague (35%), learning by experience (15%), and learning from a close relative (10%). Responses do not add up to 100% because some farmers listed more than one source of knowledge.

Among the farmers who had attended a workshop, 68% mentioned having attended at least one workshop organized by a local NGO, 41% reported attending workshops organized by the government agency responsible for managing the Biosphere Reserve, and a small number (15%) were unable to provide any information about the organizing body. A few farmers (14%) reported complementing what they had learned from external sources with their own personal experience.

Some farmers (29%) reported never having attended a workshop. These farmers learned primarily from their colleagues (64%) and relatives (29%). Some farmers explained that they were excluded from capacity-building events because they were not members of the cooperative of coffee growers.

Tree-specific knowledge.—We asked farmers how they had acquired specific knowledge of the trees growing in their farms. Farmers provided information on 48 trees; on average each farmer reported information on 6 trees (range: 1–11). On some occasions, farmers listed more than one source of knowledge for a tree. For all trees combined, the sources of knowledge most often cited were personal experience (48%), followed by workshops (26%), colleagues (19%), and family (7%). The source most often listed for all preferred and disliked trees was personal experience. For preferred trees the second most cited source was workshops, whereas for disliked trees it was a combination of workshops and family. In cases were more than one source of knowledge was reported, personal experience and learning in a workshop (14% of cases) and personal experience and learning from a family member (7% of cases) were cited most often jointly for the same tree. For knowledge acquired about the genus *Inga*, in 38% of cases, farmers had learned from personal experience and 32% of cases in workshops; in 17% of cases, learning from personal experience and in a workshop were reported jointly.

Discussion

Farmers' selection for utilitarian functional traits shifts tree community composition and lowers tree species diversity compared to forests

Farmers manage tree biodiversity based on the utilitarian functional traits that they associate with the ecosystem services valuable to coffee production, which include an appropriate shade, soil fertility, and habitat for pollinators and biocontrol agents. We refer to provisioning of an appropriate shade as an ecosystem services because it is one of the most important services that farmers obtain from trees, and one that is of fundamental importance for coffee production.

Farmers achieve the goal of enhancing ecosystem services of interest by increasing the abundance of the set of trees judged to contain the utilitarian traits that they associate with these ecosystem services, and by eliminating trees associated with detrimental effects on coffee plants. The result is an agroforest characterized by significantly lower tree richness, diversity, and density, and a community composition dominated by preferred and pioneer trees as compared to forests. Studies in the same coffee agroforests have also shown different floristic composition and a reduction in the proportion of endangered trees in agroforests relative to forests (Valencia et al. 2014).

Our results are congruent with other studies that have found that the main criteria for tolerating, promoting, or planting shade trees include compatibility with crop, shade production, ease of management, production of organic matter, and production of valuable goods such as food, timber, firewood, and medicinal resources (Albertin and Nair 2004, Soto-Pinto et al. 2007, Souza et al. 2010, Anglaaere et al. 2011). Farmers' knowledge of tree-crop interactions is fairly consistent with findings on the advantageous and disadvantageous ecological interactions between shade trees and crops (see Beer 1987, Beer et al. 1997). Similarly to other studies (Young 1988, Cerdán et al. 2012, Pauli et al. 2012), we found that farmers prefer multipurpose trees; that is, trees that contribute more than one significant product and/or service due to the presence of multiple utilitarian functional traits.

Farmers' preferred tree species occur at significantly higher abundance in coffee agroforests than in forests

Studies that have investigated farmers' tree preferences have suggested that although farmers may have a set of preferred trees, agroforests are not necessarily dominated by preferred trees and that tree species considered undesirable are often tolerated (Albertin and Nair 2004, Soto-Pinto et al. 2007, Pauli et al. 2012); however, field tree inventories were not conducted or were insufficient to support these claims. Our field inventories suggest that farmers' management and selection choices are resulting in an increase in the abundance of adult trees and saplings of preferred tree species and in a reduction of disliked trees relative to forests. Interviews revealed a management practice in which farmers gradually replace canopy trees of neutral and disliked species with liked species, particularly *Inga* spp. Some farmers carry out gradual tree replacement by sparing saplings of *Inga* and other preferred species during weeding, and subsequently caring for those saplings, in anticipation of or as a reaction to the death of an adult tree due to natural (e.g., wind, disease) or anthropogenic (e.g., girdling) causes. Although tree inventories demonstrated the presence of disliked and neutral adult trees in agroforests, data on sapling abundance and reported sapling management strategies fail to support that neutral and disliked tree species regenerate in agroforests.

Pioneer dominance is primarily the result of farmers' tree selection decisions

Our study is the first to our knowledge to show that pioneer proliferation is mostly attributable to farmers' direct fostering of preferred species rather than as a byproduct of management practices. This finding suggests that a greater abundance of intermediate and late successional species may be conserved in agroforests if farmers were to discontinue management aimed at promoting preferred species, in particular *Inga* spp., to the detriment of remaining tree richness. If during selection of adult trees and saplings, farmers were equally likely to favor a preferred or neutral tree, then more tree species may be conserved, including more species of conservation concern since these species are typically intermediate and late-successional. However, even in the best-case conservation scenario, we would still expect an increase in pioneer abundance relative to forests due to the indirect and unintentional consequence of management practices.

Sources of knowledge

Our findings highlight the integration of a posteriori and a priori knowledge, from internal and external sources, in the process of generating farmers' knowledge of coffee management practices and shade trees. Coffee management practices were influenced mostly by external sources (a form of a priori knowledge); while tree specific knowledge was mostly generated by personal experience (an example of empirical or a posteriori knowledge). This form of knowledge that emerges through the integration of different types of knowledge is referred to as "hybrid" knowledge (Raymond et al. 2010). The heterogeneous constitution of knowledge, made up of a blend of social, political, technical, scientific, and local elements mixed together, has been discussed in other studies (Murdoch and Clark 1994, Clark and Murdoch 1997, Evely et al. 2008, Eyssartier et al. 2011). Valuing hybrid knowledge systems calls for approaches that recognize that knowledge categories (e.g., traditional, local, scientific) are inextricably mixed.

Traditional knowledge, or knowledge that is handed down through generations by cultural transmission (either from family or other community members), did not figure as an important source of knowledge. Rather, our findings highlight the influence of outside agents (i.e., NGOs, government agencies) in shaping a community's knowledge. Research has found similar results where outside agents influence a community's knowledge and natural resource management strategies (Becker and Ghimire 2003, Ingram 2008).Other studies have also found that vertical knowledge transmission (e.g., from parent to offspring) is not necessarily the dominant form of transmission in some communities (Mathez-Stiefel and Vandebroek 2011). In the case of our study communities, a history of recent settlement by migrant, landless peasants possibly resulted in a process of knowledge generation and transmission that is constantly emerging and adapting, and that is less reliant on traditional knowledge. Research has shown that when people migrate, community knowledge and practices change (Volpato et al. 2009). Migration may change the process of knowledge transmission from "long-term", intergenerational passing to short-term learning, such as being told or taught in courses (Nesheim et al. 2006).

External sources of knowledge and the propagation of misconceptions.—The idea that *Inga* spp. trees may improve yields still lingers in coffee growing communities more than 30 years after the former Mexican Coffee Institute (INMECAFE) first promoted it (INMECAFE 1979, Nestel 1995). Since then, research has not been able to support INMECAFE's claims surrounding the benefits of the genus *Inga* on coffee production (Romero-Alvarado et al. 2002, Peeters et al. 2003). Although ECOSUR and other academic institutions in Chiapas have included discussions in their workshop agendas with farmers about the importance of a diverse shade in coffee agroforests (L. Soto-Pinto, *personal communication*), our study shows that governmental and non-governmental organizations continue to recommend *Inga* trees, thereby reintroducing or reinforcing unsupported ideas about the benefits of *Inga* trees. Our findings indicate the need to reexamine the scientific foundations of the strategies and recommendations that governmental and non-governmental organizations are promoting among farming communities.

The consequences of ecological changes in agroecosystems

Research on the relationship between biodiversity and ecosystem functioning (BEF) suggests that changes in biodiversity may bring unintended ecological and societal consequences (Chapin III et al. 2000). A possible consequence of low species diversity is a reduction in functional trait redundancy, which may render the agroecosystem less reliable in the provisioning of goods and services (Naeem 1998). Moreover, as spatial and temporal variability increase, which occurs when we consider longer time periods and larger areas, more species are needed to ensure a stable supply of ecosystem goods and services (Hooper et al. 2005). As a reduction in species richness is of concern, research has shown that species composition is at least as important in maintaining critical ecosystem processes (Hooper and Vitousek 1997). Experiments have shown that changes in plant composition can have larger effects than plant richness per se on ecosystem processes and properties (Hooper and Vitousek 1997, Tilman et al. 1997, Hooper et al. 2005). Finally, farmers' management of biodiversity to enhance a set of ecosystem services may come at a tradeoff with other services (Rodríguez et al. 2006, Raudsepp-Hearne et al. 2010). When species richness and composition is altered to support crop production, other ecosystem services may be compromised, such as carbon sequestration and habitat provisioning. Besides the immediate and evident consequences on the conservation of tree richness, of particular concern given that important coffee growing regions overlap biodiversity hotspots (Hardner and Rice 2002), the aforementioned findings raises concerns with regards to the long-term sustainability and stability of coffee agroforests. We suggest that the inclusion of BEF information in workshops and other sources of knowledge of farmers may lead to practices whose outcomes would be more favorable to what BEF theory and empirical evidence supports (Cardinale et al. 2012, Naeem et al. 2012).

Conclusion

How farmers generate and transmit knowledge about nature and incorporate it into resource management practices has important repercussions on the biodiversity and structure of forests. In this study, we showed that farmers not only rely on knowledge generated and transmitted by themselves, but that they also incorporate information from outside agents, such as NGOs and government agents, into their knowledge systems and, consequently, their resource management practices. These findings indicate that management practices are dynamic and constantly adapting, rather than being fixed in the past. Our results showed that farmers apply knowledge to management practices with tangible repercussions on the conservation of biodiversity. Farmers' preferences and dislikes for certain trees has shifted the composition and reduced the diversity of the forest towards a state that mirrors farmers' preferences and beliefs of what a productive agroecosystem should resemble. Outside sources (i.e., NGOs, government agents) are largely influencing farmers' preferences and beliefs about tree diversity by promoting unfounded ideas about the benefits of *Inga* spp. on coffee productivity. This indicates that farmers are receptive to incorporate outside knowledge into their knowledge systems and adapt their resource management practices accordingly. These findings highlight the importance of disseminating sound and clear scientific information to practitioners who work directly with farming communities to ensure that accurate and up-to-date information is being contributed to local knowledge systems.

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