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Report on data available on tree cover in coffee plantations along the MBC and its impact on productivity and biodiversity

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The Mesoamerican Biological Corridor (MBC) is one of the planet's biodiversity hotspots. It is also one of the fastest developing regions of the world with much land being converted from a forest matrix dominated by trees to an agricultural matrix dominated by cattle and cultivated plants. While the primary land conversion is to cattle ranching and range (discussed in CORRRIDOR Deliverable 2), conversion of forest to coffee agroecosystems has been equally important to deforestation and species loss because the elevation suitable for coffee locates it close to remaining forest area and is of particular importance to biodiversity conservation (see Section 3 below). Coffee is the dominant landscape element in about 1.5 million ha of Mesoamerica, including habitat that is of critical importance for wildlife species of conservation concern. This particular relationship between forest conversion and coffee production has led to an internationally recognized movement promoting the increase of tree cover in coffee agroecosystems, particularly though certification schemes, with the intention that this will improve the conservation value of coffee agroecosystems. The purpose of this report is to synthesize the existing information about tree cover in coffee-dominated landscapes (Section 1) and then to relate this where possible to coffee productivity (Section 2) and biodiversity (Section 3).

1. Tree cover on coffee farms

This synthesis is the product of several sources of data including a summary of discussion and presentations made during the coffee productivity and biodiversity workshop held at CATIE on 23-25 May 2006. In addition, we have compiled three independent databases that were the foundation for this summary of tree cover in coffee systems of Mesoamerica.

1) An extensive review of the literature resulting in 503 named tree species and 89 unknown species in coffee systems along the MBC conducted at CATIE. This database contains data on the botanical and the common name of the species, its use, status as native or exotic, and whether it is threatened or endangered. The database does not contain country specific information.
2) A database of trees found in Mexican and Central American coffee systems compiled by Dr Lorena Soto Pinto at ECOSUR naming 334 species. This database includes information on the geographic extent of where the species was found, species common name, family and life form. While the database lists multiple countries, it focuses on Mexico.
3) A database of trees found in Central American coffee systems compiled by CATIE researchers working on coffee systems, producing 255 identified species and 96 unknown species for a total of approximately 351 species. This database contains valuable farm level data on the tree species composition, tree density, coffee density, coffee yield, farm size, elevation and location. The database is limited to five Central American countries including: Costa Rica (69 farms), El Salvador (91 farms), Guatemala (35 farms), Honduras (200 farms) and Nicaragua (237 farms) for a total of 633 farms. Because the political boundaries that delineate countries are not representative of the agroecological conditions that control factors such as productivity, or the distribution of tree species, we divided the five countries into twelve agroecological zones based on expert opinion of the area and elevation of the farms (see table 4). These data focus on coffee agroforests and the rustic coffee systems that tend to have greatest species richness.

1.1 Salient points from the coffee workshop

Approximately 2.1% of Central America is in coffee production, ranging from 0.7% of Nicaragua's land area, to 7.6% of El Salvador's. These coffee systems range from highly technical where the tree species are carefully selected for particular traits, and where shade is carefully managed, to "traditional" coffee systems where wild tree biodiversity is maintained and where trees are principally derived from natural regeneration rather than systematic planting (Table 1). Large farms, classified as those that are greater than 70 ha, produce 36% of Central American coffee, whereas the 69% of farmers classified as small producers (>3.5 ha) produce 11.6% of marketed coffee. Medium-sized farmers (35-70 ha) produce 21% of Central American production.

Table 1. *Workshop members were called upon to identify the presence or absence of agroforestry systems of varying degrees of shade in Mesoamerican coffee agroforests.*

Country	Full sun	Single stratum	Two strata	Poly strata	Forest
Mexico	X	X		X	X
Guatemala	X	X	X	X	X
El Salvador	X	X		X	X
Honduras	X	X	X	X	
Costa Rica	X	X	X	X	X
Colombia	X	X	X	X	

Colombia - Representatives from Colombia reported that of the 618 farms they work on, 73% are below some degree of shade. Twenty-eight percent of these farms use a monospecific canopy cover, and 25% have a shade produced by five or more species, with 47% using between two and four species. These results conform with data from CATIE's coffee database where the mean species richness of coffee agroforests is 4.8 species.

Mexico - The amount of coffee cultivated in Mexico (761,000 ha) is approximately equivalent to the amount of land in coffee production in Central America, though the production in Mexico averages 8 quintales per ha compared to Central America's mean of 18 quintales/ha.

Costa Rica – A CATIE participatory study with eight Costa Rican cooperatives from 31 communities and 108 farms surveyed in the Guanacaste area found that 67% of the farms maintained shade with an average of 400 trees per ha. The mean shade on these farms was 44%. The trees found on farm are used for a variety of uses: 30% for market (timber, bananas and horticultural crops); 80% for on farm consumption (firewood, bananas and other fruit); and 25% for other uses (posts, and fodder for livestock). In terms of the composition of trees found on these farms, 143 tree species were tallied, of which 15% were introduced species. The remaining 85% of species were considered native, including 13 species listed as threatened or endangered. Mean farm diversity is 10 species of trees dominated by *Inga* (72% of farms), bananas (70% of farms), *Erythrina* (65% of farms), *Citrus* (62% of farms), avocado (57% of farms), laurel (40% of farms), or Spanish Cedar (*Cedrela odorata* - 30% of farms). In addition, the survey found that when shade was well managed, it had no significant negative effect on yield in the high elevation zones (1000 – 1700 m).

Nicaragua – A participatory survey of Nicaragua including 120 producers found that coffee agroforests played important roles in provisioning farms with bananas (85% of farmers), citrus crops (53% of farmers), firewood (73% of farmers), and timber (17% of farmers). These farms tended to have a relatively low density per ha or 149 individuals per ha. Most producers seemed to know which species were good for coffee agroforests, however these same producers tended to have little knowledge on how to manage shade for productivity and probably even less so for biodiversity. As found in other Mesoamerican farms, small producers tended to have a greater diversity of trees per ha than large farmers.

El Salvador – El Salvador has extensive area under coffee cultivation with one estimate of 160,945 ha under coffee. The majority of this coffee is low elevation coffee (90,500 ha) and only 25,000 ha considered as high elevation coffee. In El Salvador, 7.6% of the national territory is classified as shade coffee, it is important to note that this area (1,610 km^2) is larger than the national area officially classified as forest (1,050 km^2).

Typology of tree cover on coffee farms

Many studies have used the Moguel and Toledo (1999) classification (**Figure 1**), which was developed for studies of coffee agroforests in Mexico where species-rich rustic and traditional coffee farms are common. We were unable to track down reliable data on the extent of these different types in Mexico, the original paper refers to a thesis from Chapingo University which when consulted does not give sufficient methodological detail to determine how reliable estimates of the extent of these systems actually is. The existence of much rustic coffee, *sensu strictu*, that is, a coffee enriched lower storey with little or no other forest disturbance seems unlikely, since harvest and management of the coffee will, in most cases, require thinning of the canopy and disturbance at ground level. A typology for Mexico, is not necessarily sensible for the whole of the MBC (although there is roughly as much coffee area in Mexico as the rest of Central America combined) because systems in other countries are dominated by less species rich and more deliberate tree inclusion.

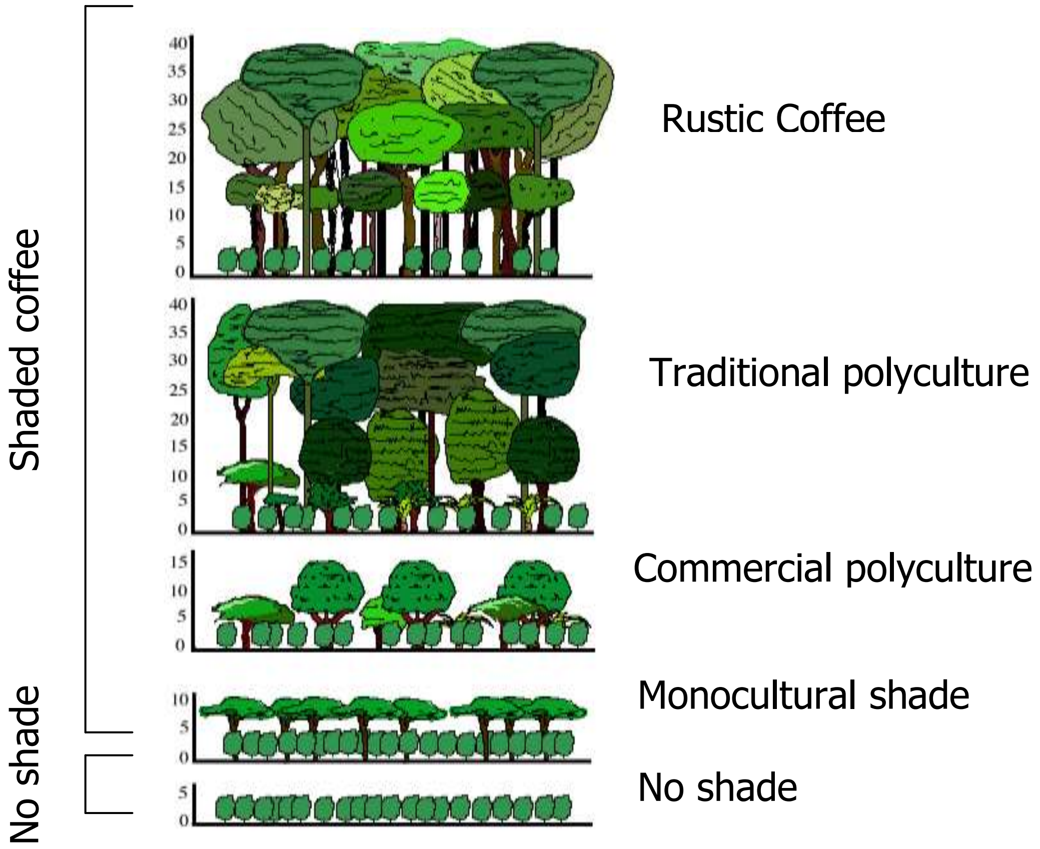


Figure 1. *Typology of coffee systems as proposed by Moguel and Toledo (1999) for Mexican coffee producing states.*

A more sophisticated typology would be appropriate to capture the variation encountered in coffee farms along the MBC (**Table 2**) that takes into account the following factors:

1) Amount of shade found on the farm: including the distribution of this shade.
2) Number of tree species per farm, or per unit area.
3) Number of tree strata found
4) Type of tree regeneration used: natural regeneration, planted, or mixed?
5) Type of tree species found: functional classification rather than taxonomic.
6) Management regime used to maintain/control shade.

Table 2. *Proposed typology of coffee shade according to tree species richness, and the number of strata. Each group would be further subdivided by three levels of intensification (low, medium and high).*

Tree Species Richness	Tree Strata (#)	Type of System	Example
0	0	Sun coffee	No tree cover
1	1	Monostrata coffee	*Erythrina, Inga* or bananas
2	2	Two strata coffee	*Inga* with bananas *Erythrina* with laurel
3-9	>2	Polystrata coffee	Diversified shade
>10	>3	Forest coffee	Diversfied strata and species

Agreeing on the universality of this classification along the MBC is challenging in two respects: 1) the diversity of environmental conditions, and management practices that coffee is subjected to between and within Mesoamerican countries, and 2) the confounding effects of increasing shade, and increasing intensification and their effects on yield. The generalization was made however, that as farm size increases, the complexity of the agroforestry systems (number of species, and number of strata) tends to decrease in favour of monospecific systems with a single tree strata and even spacing of individuals.

1.2 Tree botanic families found in coffee agroforests

A total of 98 families were found in coffee agroforests when all databases with species information were merged. The majority of these families had very few species (37% of families had only one species recorded). Trees in the Fabaceae, or legume family were by far the most prevalent (**Figure 2b**), and most dominant found in coffee agroforests. One hundred and twenty five species of legumes were documented using the merged list of species, and were found on nearly all farms of the CATIE database. The second family with the greatest species richness was Lauraceae, with only 25 species noted. Members of the Lauraceae family were found on 182 farms. In contrast, Musacaeae, the banana family, did not have many species recorded; however the family was second only to leguminous trees in the number of farms (334) on which they occurred. Though Fabaceae is one of the most diverse plant families, its species richness, and abundance on coffee farms is most likely a function of the family's ability to fix atmospheric nitrogen and so contribute to soil fertility. The abundance of Musaceae is, in contrast, a function of their fruit production.

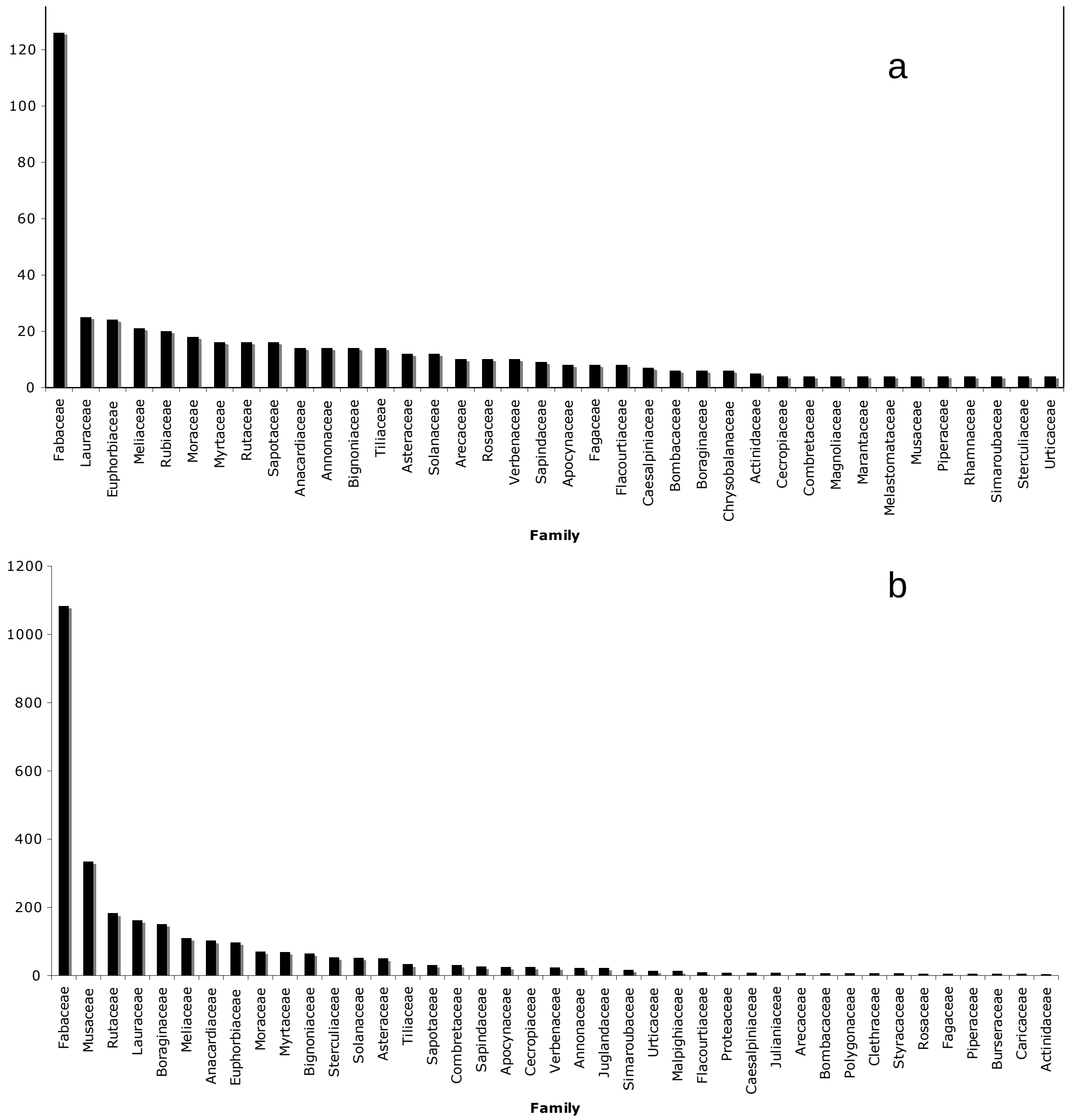
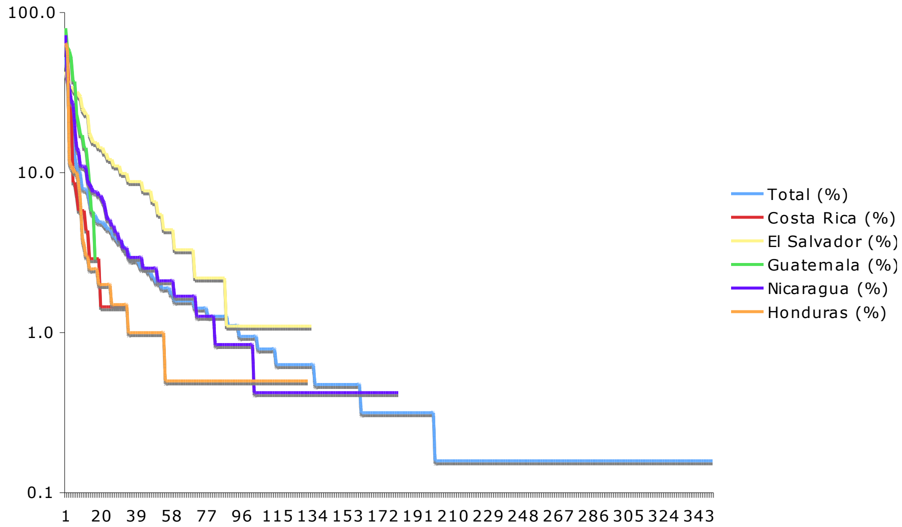


Figure 2. *(a) The number of species found in each family included in the database and (b) the abundance of individuals per family cited in the CATIE database.*

1.3 Tree species richness and abundance

We compiled the databases eliminating repeated species for a final count of approximately 630 species that have been recorded in coffee along the MBC (see **Appendix 1** for the full list). Though the list is certainly not exhaustive, it is representative of most of the species found in coffee within Mesoamerica, and contains a complete list of the most common/important species found. Most of the species were rarely observed, being found in only one or a handful of coffee farms (**Figure 3**). Rank abundance curves of absolute number of individuals, as well as the percent abundance on Mesoamerican coffee farms (**Figure 3a &3b**) show that there are a few common species, and a very large number of rare species found in these systems. Nicaragua and El Salvador are the countries that most strongly deviate from this trend with a significantly larger number of common species when compared to Costa Rica, Honduras and Guatemala. These also are two of the countries that have amongst the highest species richness (**Table 4**).

a)



b)

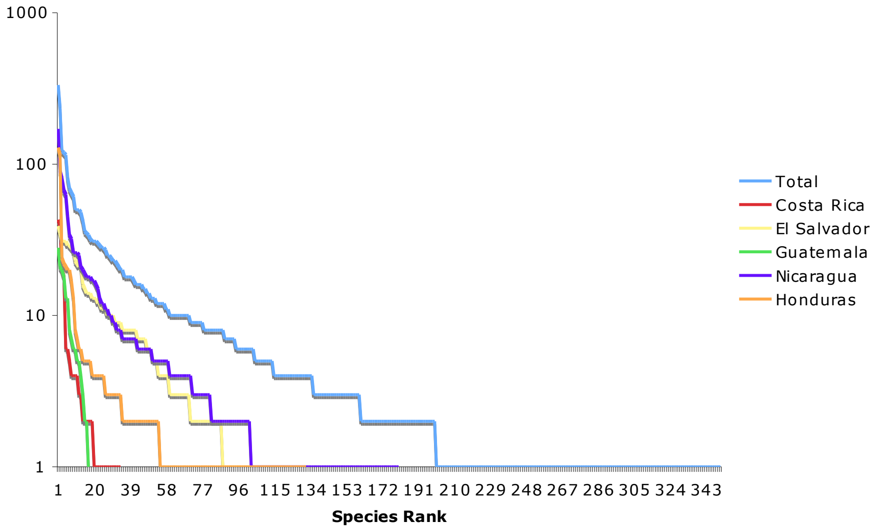


Figure 3. *Rank abundance curves for tree species found in Central America (a) using absolute numbers of occurrences, and (b) percent occurrence on Central American farms.*

In contrast, two genera, *Musa* and *Inga* are the most commonly found throughout Central America. Using the CATIE database that includes abundance values for each species by farm, we list the most abundant species found in coffee systems for each country (**Table 3**).

Table 3. *The percent presence of the ten most abundant species by country, and for all countries (total). The right hand column (countries) identifies how many countries have this species in the top 10.*

Species	Total	C.R.	E.S.	Gua.	Nic.	Hon.	Countries (#)
Cassia spp		5.8					1
Cedrela odorata	10.3	8.7		17.1	13.5		3
Citrus sinensis	12.8	5.8			19.0	12.0	3
Citrus spp		8.7					1
Cordia alliodora	18.8	30.4	30.8		28.3	8.5	4
Critonia dalcoidos			25.3				1
Croton reflexifolius			34.1				1
Erythrina poeppigiana		62.3					1
Gliricidia sepium	10.9				14.3	10.0	2
Guazuma ulmifolia					11.0		1
Inga calderonii			31.9				1
Inga calderonii			31.9				1
Inga fissialix				20.0			1
Inga guajiniquil						10.5	1
Inga laurina				37.1			1
Inga micheliana				80.0			1
Inga punctata	18.2		34.1		34.2		2
Inga spp	37.5	26.1			38.0	64.5	3
Inga spuria	7.9		29.7	60.0		11.0	3
Inga vera	19.3		42.9		26.6	10.0	3
Lonchocarpus spp			38.5				1
Macadamia integrifolia		7.2					1
Mangifera indica	9.7	5.8	34.1			4.0	3
Musa spp	52.8	56.5			72.2	57.5	3
Nectandra glabrescens				57.1	11.0	6.5	3
Persea americana				17.1			1
Roseodendron donnell				51.4			1
Terminalia oblonga				37.1			1
Zanthoxylum procerum				22.9			1
Unique Species (#)		4.0	5.0	7.0	1.0	1.0	

The mean tree species richness per farm from the CATIE dataset was 4.6 species, skewed to lower levels of species richness and with a maximum value of 17 species found in one farm in Nicaragua, and only two farms with 16 species (one in Honduras and one in Nicaragua; **Table 4**).

Table 4. *Characterization of farms from five Central American countries. Different levels indicate significant differences between agroecological zones for each category. Bold and italicized text represent the minimum and maximum values for each category. Country codes are as follows: (CR) Costa Rica, (ES) El Salvador, (Gua) Guatemala, (Hon) Honduras, (Nic) Nicaragua.*

Country	Zone	Coffee Area (ha)	Total Area (ha)	Tree Species Richness	Shade (%)	Elev. (m)	Tree Density /ha	Coffee Yield (mec.)	No. of Farms
CR	Cen. Valley	11.2c	35.9bc	2.7f	***31.0e***	866d	403abc	***35.0a***	30
CR	N. Pacific	3.5c	***4.9c***	2.9ef	50.3bc	708e	392abcd	25.1bcd	15
CR	Cen. Pacific	***2.4c***	10.3bc	2.5f	33.7e	1091bc	383abcd	29.5ab	15
ES	Occidental	29.4b	32.0bc	6.9b	52.4b	1039c	***198e***	21.5cd	40
Gua	Pacific	51.3a	89.9ab	4.7cd	no data	881d	244de	***10.6g***	35
Hon	Central	12.2c	68.9bc	2.5f	45.4cd	***1233a***	326cd	21.6bc	86
Hon	Pacific	10bc	27.2abc	8.0ab	***72.6a***	700def	516abc	15.2cdefg	***5***
Hon	Caribbean	10.8c	53.4bc	4.0de	44.2cd	888d	328cd	19.3de	60
Hon	North	10.8c	27.5c	***2.2f***	32.1e	995c	367bc	23.0bcd	48
Nic	Matagalpa	***51.7a***	***117.9a***	5.4c	49.5bc	886d	273de	16.3ef	***124***
Nic	Pacific	22.2bc	36.6bc	7b	38.9de	***522f***	472ab	19.3de	36
Nic	Esteli	5.1c	45.2bc	***8.6a***	62.2a	1222ab	***486a***	13.7fd	31

The percent shade found on farms increased with species richness (R^2 = 0.32; $p < 0.0001$; **Figure 4b**), though canopy cover ranged from 5-80% in farms with only one species of tree as well. The mean canopy cover on all farms was 45.5% with a standard deviation around the mean of 19.6. There was no relationship between species richness and elevation (**Figure 4c**). Species richness increased with tree density that averaged 333 individuals per ha (**Figure 4d**). Yield decreased with species richness and with the percent shade (R^2 = 0.03 and 0.05 respectively; (**Figures 4e & 4f**), but only a very small amount of the variation in yield was explained, indicating that shade is not the primary factor determining yield of these coffee farms. How shade interests with coffee productivity is discussed in Section 2 of this report below, however it appears that the degree of shading on a farm is not the most important variable affecting yield. Several farms with greater than 80% canopy cover have yield values that exceed the mean. The range of productivity is greatest in the single species farms, and quickly decreases as species richness increases; a result that mirrors most biodiversity/productivity studies and reflects intensity of management.

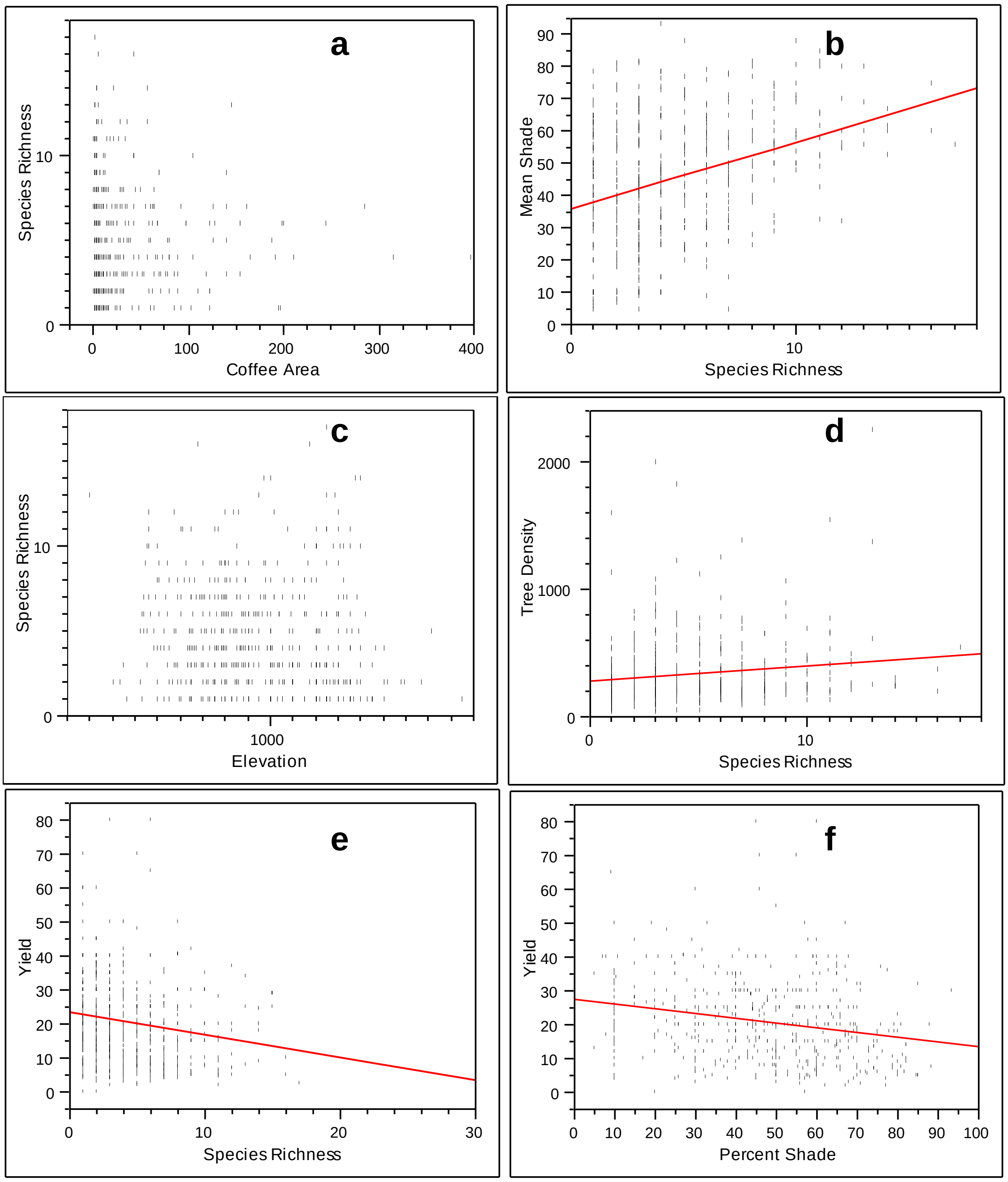


Figure 4. *The relationship between (a) species richness and farm size, (b) species richness and percent shade on each farm, (c) species richness and elevation, (d) species richness and the density of trees on coffee farms, (e) species richness and coffee yield (quintales), and (f) percent shade on yield (quintales).*

There was no direct correlation between species richness and farm size, however the variance in species richness is highest in small farms (>30 ha) and rapidly tapers down to approximately 5 species in larger farms (**Figure 2a**). Small farms are more likely to incorporate greater tree species richness in their farms than large farms.

1.4 Native versus exotic tree species

Most of the species documented in coffee were native (92.6%) and the remainder were introduced. This is an important point as coffee agroforests have remained heavily dominated by native species that may diminish the negative effects of habitat loss typically associated with land use change. As many as 19 endangered tree species were recorded in coffee (**Table 5**) but presence of individuals does not necessarily imply an effective contribution to species viability. Approximately half of the introduced species are fruit trees such as mangos (native of India), citrus (native of China) and bananas (native of Africa), though several have important timber values as well. The most important introduced species may be gaining greater importance in Central America, in particular *Eucalyptus* spp., *Macadamia integrifolia*, *Mangifera indica* (mango), *Anacardium occidentale* and *Bactris gassipaes*. In addition analysis of the CATIE database showed that mango, *Citrus sinensis* (orange), and species of *Musa* (varieties of bananas) were the most important exotic species found in Mesoamerican coffee systems, and that all of these species are included in the top ten regional species list. For example, mango was found in 9.7% of farms, particularly in El Salvador where it was found in 34% of farms surveyed by CATIE. With even greater dominance, Musa was found in 52% of Mesoamerican farms surveyed by CATIE, and in 72% of Nicaragua coffee farms.

Table 5. *List of endangered species found in coffee agroforests.*

Species	Extinction Risk
Caryocar costaricense	Endangered
Hedyosmum mexicanum	Endangered
Garcia nutans	Endangered
Sapium macrocarpum	Endangered
Sapium tuerckheimianum	Endangered
Delonix regia	Endangered
Inga donnell-smithii	Endangered
Inga micheliana	Endangered
Platymiscium dimorphandrum	Endangered
Persea schedeana	Endangered
Robinsonella mirandae	Endangered
Cedrela pacayana	Endangered
Swietenia humilis	Endangered
Simira salvadorensis	Endangered
Huertea cubensis	Endangered
Mastichodendrom capiri	Endangered
Platymiscium pinnatum	Endangered in Costa Rica
Swietenia macrophyla	Endangered en Belize
Dalbergia retusa	Endangered in El Salvador

1.5 Utility of trees

Out of the total species recorded for Mesoamerica, 351 species had at least one recorded use, 122 had two recorded uses, and 31 had more than 2 recorded uses. From our literature review we found 188 species for fuel; 233 used for timber, 129 for fruit, and 211 for fuelwood out of a total of 592 species. The other 88 represented diverse uses, such as, for food, construction, live fences, condiments, medicines, honey production, ornamental uses, beverages, crafts, green manure, resin, fodder and other more specific uses.

1.6 Loss of tree species richness with intensification

Though there has been no uniform sampling of species composition in coffee agroecosystems by country, there is evidence that species composition varies greatly. It has been suggested that countries with less technified systems, or a greater abundance of traditional systems may harbour greater species richness. For example, the state of Chiapas, Mexico is host to 310 tree species in coffee agroforests, whereas in similarly sized Costa Rica, only 71 species are reported.

2. Effects of tree cover on coffee productivity

The importance of shade for coffee cultivation is an old and controversial debate as reported by Lock (1888). In the Mesoamerican region, this debate was renewed in the late 1970s by the introduction of dwarf cultivars (Caturra, Catuai and Catimors) and the elimination of associated shade trees due to high coffee planting density and hence auto-shading. This period also corresponded to the height of the Green Revolution when intensification of agricultural systems was promoted to farmers by research and extension services in order to increase coffee yield via high inputs of chemical fertilizers and systematic control of pests and diseases by agro-chemicals. Recently, the context has changed markedly, due to an increased awareness of the negative effects of agriculture on biodiversity and natural resources. Hence, shade provided by associated trees has regained attention as its beneficial effects encompassed aspects such as beverage quality, environmental services of coffee agroforestry systems (AFS) and diversification of farmers' revenues (timber, fuel wood and other products derived from these coffee systems).

Enhanced environmental consciousness by coffee consumers in developed countries has resulted in a multiplication of eco-labels from the private sector (Nespresso, Starbucks, 4C, etc.) and NGOs (Utz Kapeh, Rainforest, etc.) during the last 15 years and several of these labels emphasize the presence of shade as one of the requirements for their eco-labelling schemes.

2.1 Importance of coffee areas in the Mesoamerican Biological Corridor

With an average of 2% of land cover, areas under coffee cultivation are considerably lower than those of silvo-pastoral systems which average over 60% across the Mesoamerican Biological Corridor (MBC). Still, there is a notable exception in the case of El Salvador where coffee areas represent 7% of the national territory (**Table 6**).

Table 6*. Coffee and protected areas in Central America and Southern states of Mexico (in square kilometres).*

	Total Area	Forest Area	Protected Area	Coffee area (%)
Costa Rica	51 100	12 480	7 006	1 060 (2.07)
El Salvador	21 040	1 050	102	1 610 (7.65)
Guatemala	108 890	38 410	18 277	2 670 (2.45)
Honduras	112 090	41 150	11 120	2 450 (2.19)
Nicaragua	130 000	55 600	9 638	1 080 (0.83)
Central America	423 120	148 690	46 143	8 870 (2.10)
Mexican states	1 972 550	902 855	146 588	7 611 (3.80)

Source: World Bank, 2003

Nonetheless, coffee areas are considered to be of strategic importance for biodiversity and environmental issues as they are located in the montane range (600-1400 m) prone to erosion and with high floral and faunal richness. These coffee areas are also located in the vicinity of wildlife parks and natural forests and hence play an important role as buffer zones relieving pressure on natural forests, as well as enhancing connectivity in these fragmented landscapes (see the coffee map in Section 3 with respect to protected areas of the MBC). In the MBC, coffee statistics are somewhat imprecise and only available at the national level. According to various sources, the percentage of coffee areas under shade is high (75%, see **Table 7**). However, it is worth mentioning that tree cover, composed of no more than 2-3 species (mainly *Erythrina poeppiginia, Inga* spp. and *Gliricidia sepium*), predominates in coffee AFS of the MBC (see Section 1 above).

Table 7. *Percentage of coffee areas under shade (traditional & technified) in MBC.*

	Traditional Shade	**Technified Shade**	**Technified Sun**
Mexico	37	52	11
Costa Rica	10	50	40
Salvador	10	80	10
Guatemala	45	35	20
Honduras	15	50	35
Nicaragua	55	15	30
Mean MBC	24	51	25

This classification is to a large extent subjective and highly dependent on the criteria selected. Discussions during the coffee agroforestry workshop in May 2006 highlighted the fact that the classification used by Moguel and Toledo (1999) for Mexico was not relevant for the whole of Central America as it did not include degree of agricultural management intensity and might be even obsolete for the Mexican coffee producing states (see Section 1.1 above).

2.2. State of knowledge on how shade affects coffee eco-physiology

Coffee has all the physiological traits of a shade-adapted plant as summarized in **Figures 5 and 6**.

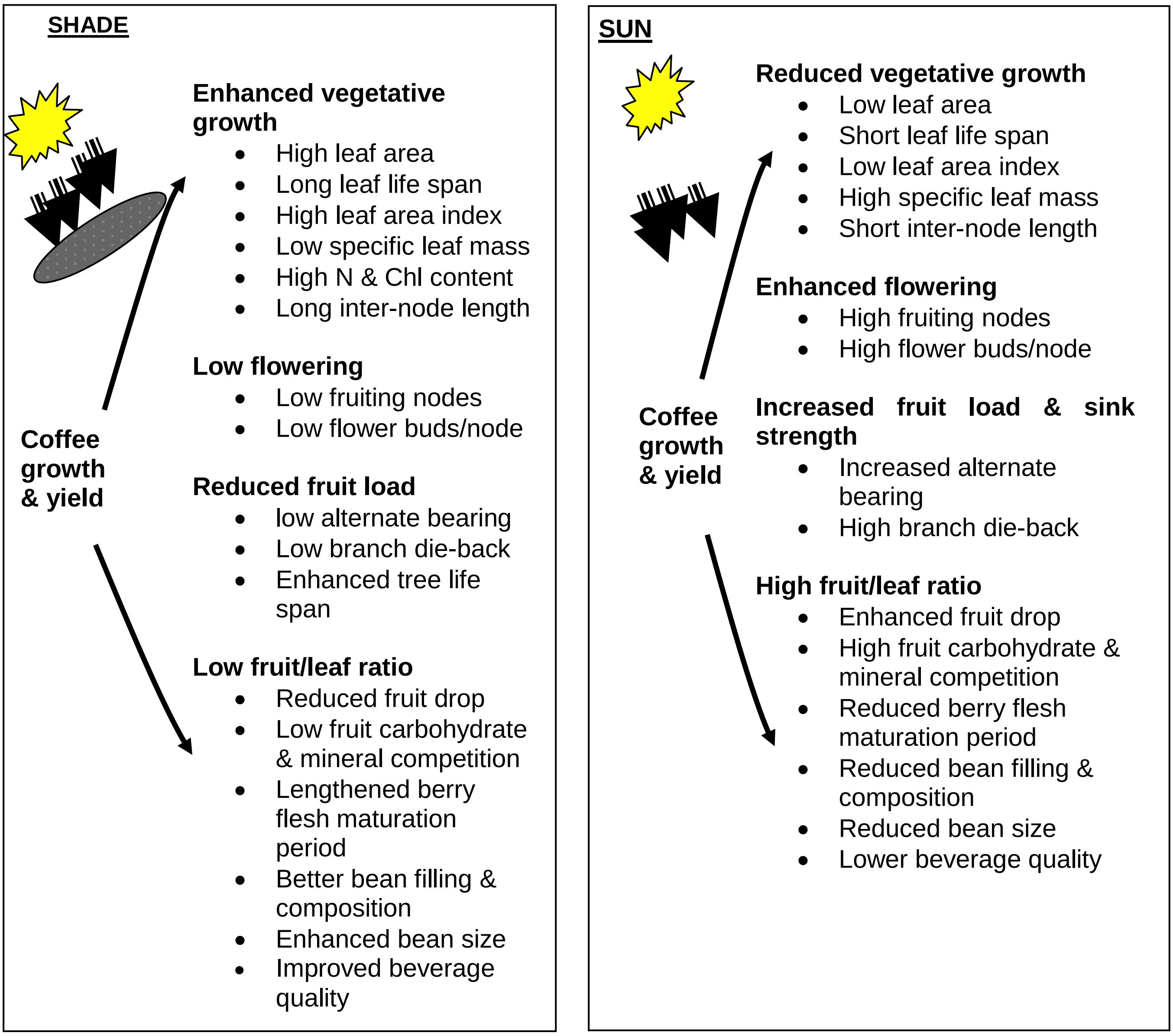


Figure 5. *Main effects of shade and full sun management on coffee vegetative and reproductive characteristics, bean characteristics and beverage quality.*

Coffee has been classified as a shade species (Cannell, 1985; Ramalho *et al.*, 1999) or shade facultative species (Fahl *et al.*, 1994). The light saturation for coffee net photosynthesis (Pn) occurs at low solar irradiance values, even for coffee cultivated in full sun (Fahl *et al.*, 1994; Frank *et al.*, 2006); the maximum Pn of sun-adapted leaves is attained at a photosynthetic photon flux density (PPFD) of around 900 µmol m^{-2} s^{-1} whereas ambient PPFD is twice that value (around 2200 µmol m^{-2} s^{-1}) on a sunny day in Central America (**Figure 7**). Leaves exposed to high solar irradiance may exhibit symptoms of chlorosis and their quantum use efficiency, light compensation point and chlorophyll content decrease with increasing PPFD (Fahl *et al.*, 1994; Franck *et al.,* 2006); e.g. shade-adapted leaves are more efficiently photosynthesising in the low PPFD range (0-500 µmol m^{-2} s^{-1}) than full-sun adapted leaves. Furthermore, leaf exposure to high PPFD leads to photo-inhibition (Ramalho *et al.*, 1999).

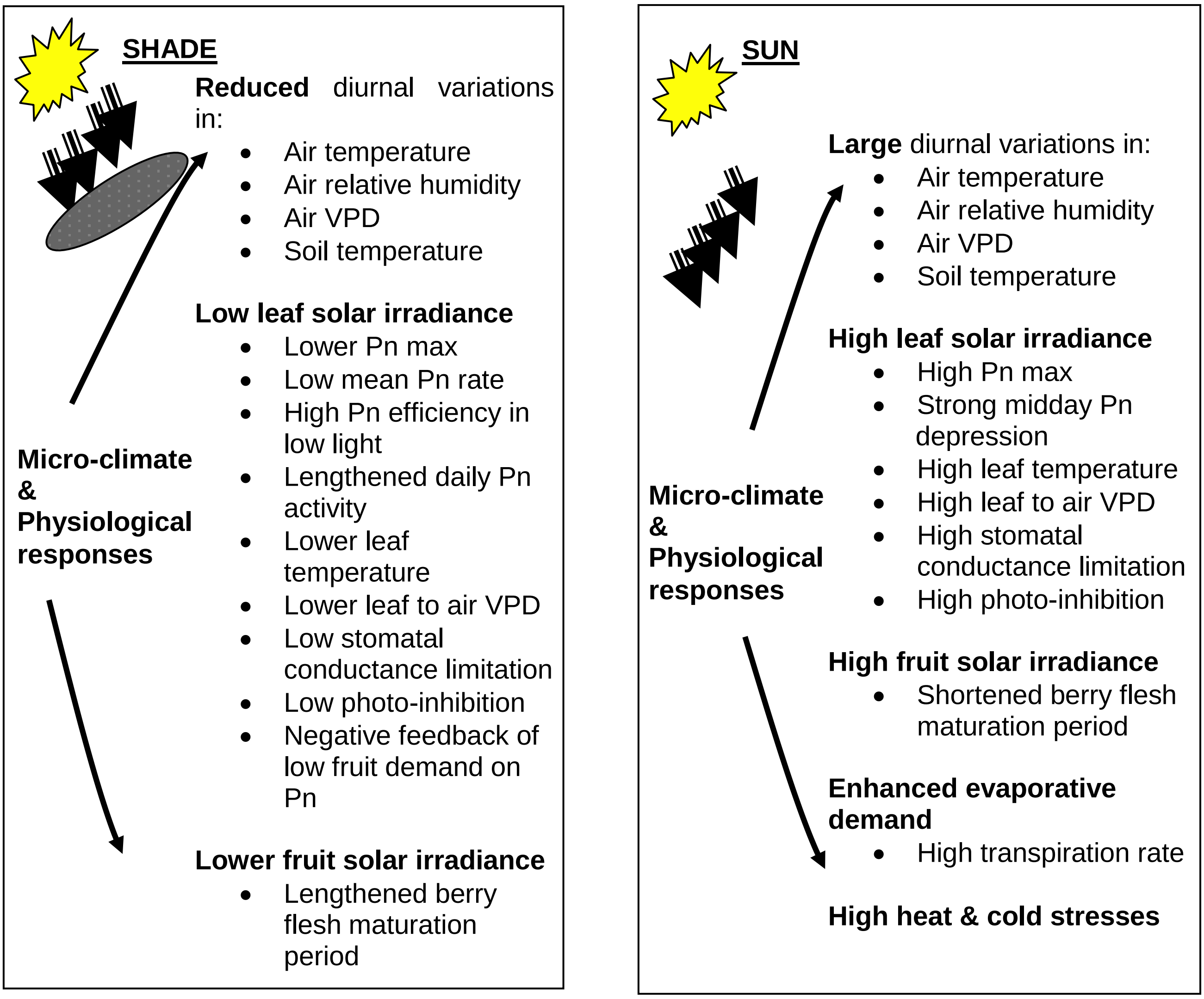


Figure 6*. Main effects of shade and full sun management on microclimatic conditions and coffee physiological responses.*

Although related to solar irradiance, other exogenous factors limit coffee leaf Pn. High air temperature and air vapour pressure deficit (VPD) induce limitation to Pn by decreasing stomatal conductance (Nunes, 1988; Da Matta, 2004; Franck *et al.,* 2006). Midday depression of Pn is generally observed in full sun coffee cultivation during a sunny day due to enhanced temperature at the leaf surface and high leaf to air VPD (**Figure 7**). On the other hand, reduction in Pn is not observed on a hot, sunny day when coffee is cultivated under shade. In this respect, shade is beneficial (i) by lowering the air temperature by up to 3-4°C and (ii) by limiting heating in coffee leaves subjected to high solar irradiances.

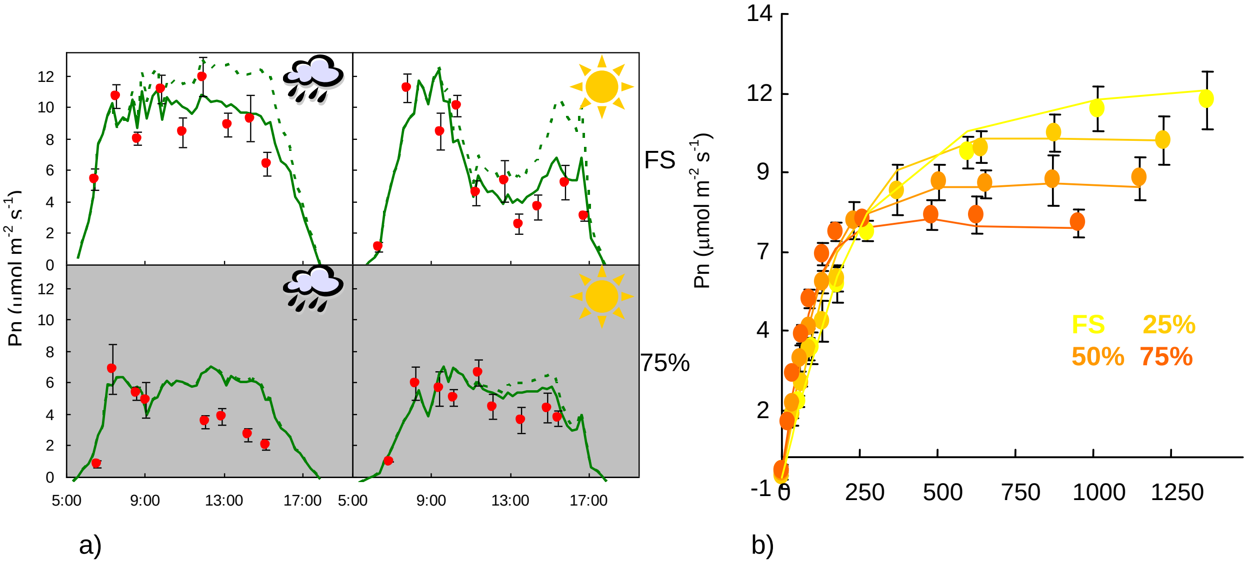


Figure 7. *a) Leaf photosynthesis (Pn) of sun-adapted (FS) and shade-adapted leaves (75%) during a sunny day (top graphs) and overcast day (bottom graphs) and b) Photosynthesis of sun-adapted (FS) and shade-adapted leaves (25%, 50% &75% of shade) as a response to PPFD levels.*

Recently, Dauzat *et al*. (2006) have developed a 3-D based coffee eco-physiological model (**Figure 8**) in order to estimate photosynthesis at the canopy level (An).

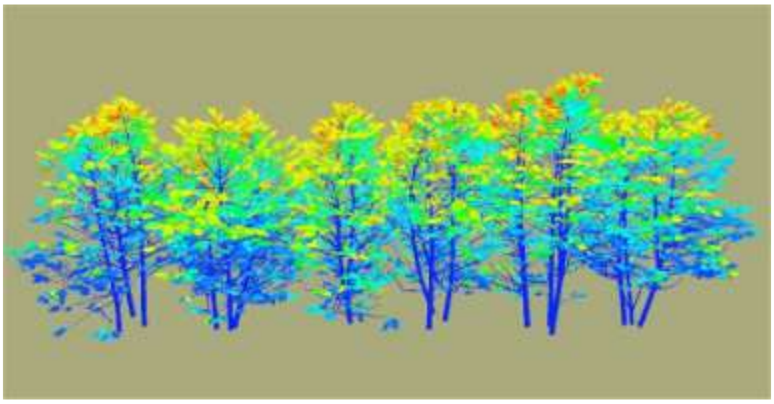


Figure 8. *Photosynthesis of individual leaves according to their position within a 3-D representation of coffee plants (red to yellow, green and blue are indicative of Pn intensity from high to low).*

Simulations show that a shaded coffee canopy is far more efficient in photosynthesizing over the whole PPFD range, and especially at low PPFD (0-900 µmol m^{-2} s^{-1}), than a coffee canopy in full sun (**Figure 9**). Despite receiving only 45% of the full solar radiation, a shaded coffee canopy fixed about the same quantity of carbon (0.45 mol C m^{-2} d^{-1}) as a coffee canopy in full sun (0.47 mol C m^{-2} d^{-1}).

Simulations suggest that shaded coffee canopy receiving on average a PPFD of 500 µmol m^{-2} s^{-1} (e.g. 25% of PPFD on a sunny day and 50% of PPFD on an overcast day) will fix the same amount of carbon per unit leaf area than a canopy in full sun. Shade has also strong effects on coffee vegetative growth and morphology as summarized in Figures 5 and 6. Compared to sun-adapted leaves, shade-adapted ones have a higher area, longer life span, lower specific mass and higher nitrogen and chlorophyll contents. This generally results in higher leaf area index with a lower carbon and nitrogen investment into the vegetative component. This adaptation to shade makes coffee an ideal crop for cultivation in agroforestry systems. Furthermore, shade has beneficial effects on microclimate (see summary of these effects in Figures 5 and 6) and soil fertility (Beer *et al.*, 1997). Nonetheless, it is commonly reported that shade levels in the range of 25-50% result in a decrease of coffee yield by around 20% compared to full sun cultivation in the high altitudinal range (1100-1500 m) considered optimal ecological conditions for coffee cultivation in the MBC. This is mostly due to the fact that shade has a strong, negative effect on coffee yield components (Cannell, 1985; Da Matta, 2004; Vaast *et al.,* 2005).

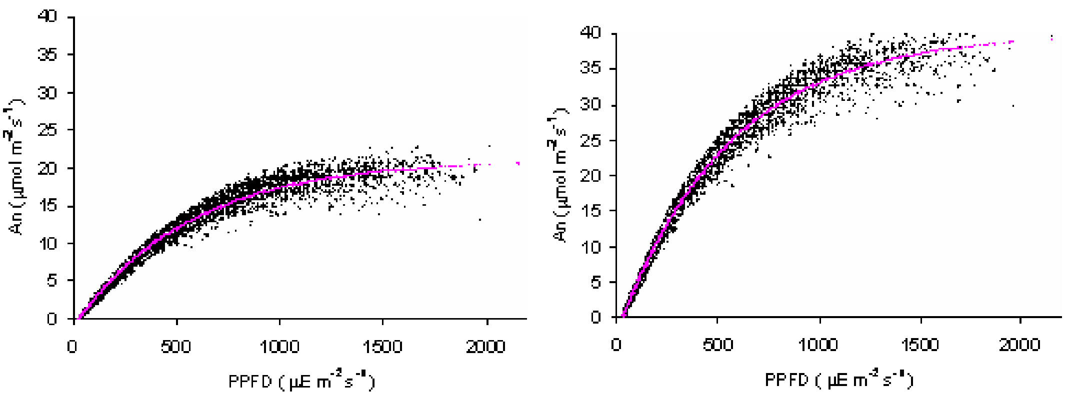


Figure 9. *Coffee canopy photosynthesis (An) of coffee plants grown in full sun (FS) or under 55% of shade over the range of PPFD commonly experienced in the field.*

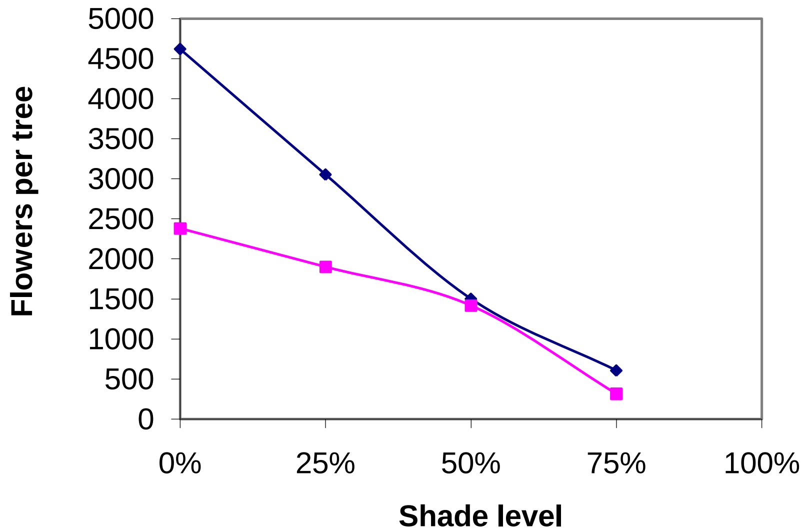


Figure 10. *Effects of shade levels on coffee flowering in two consecutive years (Year 1: blue and year 2: pink) in optimal conditions of the Orosi valley of Costa Rica.*

Indeed, lower solar irradiance decreases the number of fruiting nodes via a lengthening of the inter-node, diminishes the number of flower buds per fruiting node and hence fruit set (**Figure 10**). Under optimal conditions of Costa Rica, high shade levels of 75% and 50% result in a very strong decrease of fruit set down to 13% and 32% of that of full sun coffee. A lower shade level of 25% reduces fruit set to 66% of that of full sun coffee. This effect is more pronounced in a year of high production potential that in a year of lower production potential due to the fact that coffee exhibits a strong alternate production pattern (see explanations below). Under sub-optimal conditions (hot and low altitude), this shade effect is less drastic with a decrease of around 20% in fruit set with a shade level of 40%. This negative effect of shade on fruit set is partly compensated by a lower fruit drop during the production cycle and a higher individual bean weight due to less competition for carbohydrates among fruits and between vegetative and reproductive components (Cannel, 1985; Vaast *et al.*, 2005).

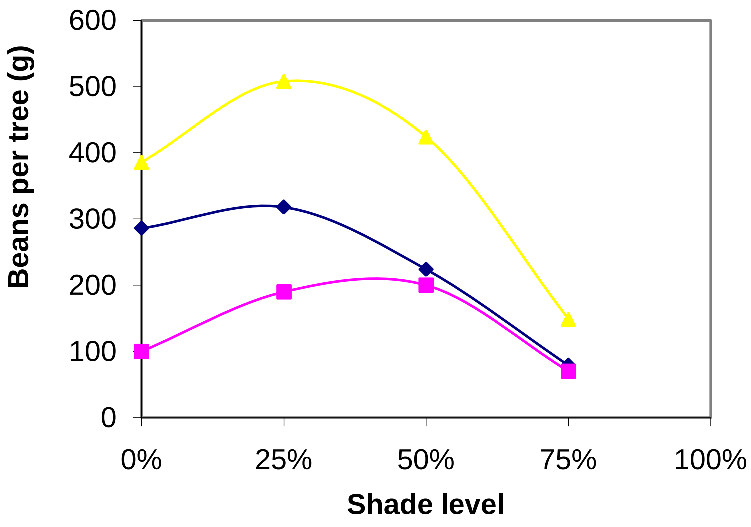


Figure 11. *Effects of shade levels on coffee productivity of two consecutive years (year 1: blue and year 2: pink) and sum of these two years (yellow) in optimal conditions and with no nutrient limitation in the Orosi valley of Costa Rica.*

Under optimal coffee cultivation conditions and intensive management (i.e. no nutrient limitation), coffee trees in full sun tend to produce heavy berry loads (**Figure 11**). This leads to a strong alternate production pattern of coffee. Studies quantifying carbohydrate allocation between fruits and vegetative part over production cycles show that coffee fruits are the most important plant sink for carbohydrates and out-compete other plant organs, especially branch apex in development (Cannell, 1985; Da Matta, 2004; Vaast et al., 2005). This leads to poor branch development and even up to the dieback of heavy bearing branches. This results in few new fruiting nodes in the next production cycle. In these conditions, shade can be a good strategy to decrease strong alternate production pattern as it decreases flowering intensity which results in lower fruit load on the coffee tree and hence more vegetative growth and production the following year. More importantly, higher leaf to berry ratios decrease competition among berries for carbohydrates and thus enhance bean size, biochemical composition and cup quality.

2.3. Issues with respect to shade quantification

Several methods are used to evaluate shade intensity and/or tree cover in coffee AFS. The most common ones are:

- Measurement of tree canopy characteristics and particularly ground crown projection,
- Assessment of tree cover via a densiometer,
- Measurement of light interception (LI) with a quantum or global radiation sensor,
- Measurement of leaf area index (LAI) with a plant canopy analyzer,
- Estimation of LI and LAI via hemispheric photographs.

Quite often, tree cover is assumed to directly translate into % of shade (i.e., % of light intercepted by shade trees and not reaching coffee plants). This is not systematically the case, due to large differences among tree species in terms of leaf characteristics, angle and distribution within the canopy. For example, Dzib (2004) showed that in Costa Rica and for coffee AFS predominantly shaded with *Cordia alliodora*, 45% tree cover translated into 30% of shade and 90% of tree cover into 85% of shade. On the other hand, in an AFS predominantly shaded with *Eucalyptus deglupta*, 50% tree cover translated into 40% of shade and 85% of tree cover into only 60% of shade for coffee. In more diverse coffee AFS of Nicaragua, Lara (2005) also showed that tree cover could not be systematically assumed to be % of shade as illustrated in **Table 8**.

In these examples, tree cover and shade (i.e., % of light intercepted by the shade tree stratum) were measured with a densiometer and a quantum sensor, respectively, during the rainy season. Moreover, tree cover and shade level vary along the year due to shade management and tree phenology. The common practice of drastic pruning of shade trees (especially *Erythrina* spp. and *Gliricidia* spp.) once or twice per year results in large variation in tree cover and shade level during the production cycle. Even without human intervention, large differences in tree cover and shade level are also observed due to leaf shedding of shade tree species. Siles and Vaast (2002) registered a strong decrease in shade level from 60% down to 30% in a coffee AFS predominantly shaded with *Terminalia ivorensis* from the rainy season to the dry season due to heavy leaf shedding. It is likely that differences are less pronounced in more diversified coffee AFS. Still, Lara (2005) registered a decrease in shade level from 61% down to 47% in coffee AFS shaded with enriched forest remnants. Finally, tree cover is less evenly distributed in diversified AFS or AFS with natural regeneration than in coffee systems inter-planted with a mono-specific shade stratum (especially *Erythrina* spp., *Gliricidia* spp. and to a lesser extent *Inga* spp.). For example, Soto-Pinto et al (2003) and Romero-Alvarado et al (2002) report that shade in traditional coffee systems of Mexico varied greatly with patches between 25 and 70% while shade dominated by *Inga* species was more homogeneous at about 35%.

Table 8. *Percentages of tree cover and shade in various coffee AFS of Nicaragua (Rustic, REF = Remnant of enriched forest, Inga = Inga sp, Musa = Musaceas, I+M = Inga sp + Musaceas, PM = Polyculture multi-strata, I+C+M = Inga sp + Cordia alliodora + Musaceas, M+ = Musaceas + other species (adapted from Lara, 2005)).*

AFS	n	Shade[1] (%)	Tree Cover[2] (%)	Richness[3] (Nb. sp)	Altitude (m)
Rustic	3	64±12	59±18	7±1	1065±66
REF	5	61±15	45±15	8±2	883±180
I+M	28	58±16	43±16	3±1	991±137
I+C+M	5	58±21	44±22	7±2	871±118
Inga	11	54±26	52±23	2±1	1003±197
PM	3	46±30	26±19	7±2	898±111
M+	3	31±29	28±28	3±1	1063±107
Musa	8	25±10	14±10	2±1	1193±134

[1]Shade = measured via PPFD sensor during rainy season, [2]Tree cover measured with densiometer
[3]Richness = Number of shade tree species ha^{-1}.

Therefore, a standardized method of assessing shade level in coffee AFS needs to be proposed. The densiometer is a cheap instrument (less than 50$) and thus measuring tree cover with such an apparatus should therefore become the standard methodology. Nonetheless, a relationship between tree cover and light intercepted by shade trees must be performed over the range of tree cover encountered in the field to be useful for assessing light availability for coffee underneath. When shade management and/or tree phenology result in large variation in tree cover, measurements need to be repeated during key periods of the production cycle.

2.4. Coffee productivity in the MBC

Yield

Mean coffee productivity in Mexico is lower (9 bags/ha) than Central American productivity (18 bags/ha) as illustrated by historic data in **Table 9**.

Table 9. *Historic data on national coffee yield in Central American countries and Mexican states (qq/ha).*

	1990	1995	2000	2004
Costa Rica	28.8	30.3	32.0	30.8
El Salvador	19.1	18.7	17.4	13.0
Guatemala	15.8	17.9	20.2	20.1
Honduras	13.1	13.0	17.4	14.5
Nicaragua	13.4	10.7	20.8	16.6
Mexico	16.3	9.7	10.5	9.1

Sources: CEPAL & FAO

Large variations exist between regions within a country. For example, average coffee yield of the region of Antigua in Guatemala is twice that of the Pacific region due to more favorable ecological conditions (mostly higher altitude and more humid) and management intensity. The same observation is true in Costa Rica between high-altitude regions of the Central Valley and Tarrazu and low altitude, less favorable of regions of Turrialba and San Isidro. It is also the case in Nicaragua between medium to high altitude zones (Matagalpa-Jinotega) and the low-altitude, hot and drier Pacific region. As a general trend in Central America, favorable, high altitude zones for coffee cultivation are usually characterized by a more intensive management (high fertilization, chemical control of pests and diseases, chemical weeding etc.) and a lower tree cover and tree diversity. In Mexico, large variations between zones are also observed; regions such as Veracruz and Soconusco are potentially the most productive if farmers have access to technology and financial support. In Mexico, high altitude zones are not generally associated with higher productivity because (1) Mexican coffee states are located farther north and characterized by cold climate and (2) high altitude zones coincide with highly forested areas where coffee is mostly cultivated by indigenous people in rather rustic systems with low inputs.

Clearly, yield is only one component of the economic viability of coffee cultivation. Coffee quality is another important aspect to consider because coffee premiums paid for high quality can be as high as 20-40$ per bag. Economic contribution of products derived from associated trees in coffee AFS is also important to consider. Although mostly in the form of pilot projects at local level, payment for environmental services (water, biodiversity conversation, carbon sequestration) could become a subsequent, additional sources of revenue for coffee farmers in the medium to long term.

Coffee quality

In Central America, coffee cultivated at higher altitude (>1000 m) has higher beverage quality than at lower altitude due to cooler growing conditions and hence a longer production cycle (Bertrand *et al.,* 2006). In Mexico, Santoyo *et al.* (1996) also reported that cooler cultivation conditions resulted in better coffee quality but at lower altitude (800 m) due to the more northern latitude of Mexican coffee producing regions. At low altitude in Central America, coffee berry flesh ripens faster in full sun than in shade due to exposure to higher temperatures. Under these sub-optimal conditions, the presence of shade (around 40-50%) decreases temperatures experienced by coffee plants by up to 3-4°C and delays the harvest peak by about six weeks. Under optimal conditions, the harvest peak is delayed by about a month due to 45% shade (Vaast *et al.*, 2005). These delays in the coffee pulp maturation translates into enhanced bean filling, larger bean size, better biochemical composition and higher quality of coffee under shade compared to full sun (Guyot *et al.,* 1996; Muschler, 2001; Vaast *et al.*, 2002; Decazy *et al.*, 2003; Avelino *et al.*, 2005).

Bean size is particularly important as it is often the main criterion with bean colour and percentage of physical defects on which quality assessment is based in MBC producing countries and hence the price paid to coffee producers. Under optimal coffee cultivation conditions, coffee trees tend to produce heavy berry loads which can be detrimental to coffee quality. In these conditions, shade can be a good strategy to decrease flowering intensity resulting in lower fruit load, less competition among berries for carbohydrates and higher bean size, biochemical composition and cup quality. This translates into more uniform coffee revenues for farmers over the years. Furthermore, the decrease in coffee productivity can be economically compensated by a premium paid for higher coffee quality (Vaast *et al.*, 2006).

Income diversification

Recent studies undertaken in low altitude regions of Central America demonstrate the importance for farmers' revenues of the sales of timber and fuel wood derived from trees in coffee agroforestry systems. In Costa Rica, sales of timber can account for 15 to 34% of the value of coffee revenues accumulated over a rotation period of 25 years while timber and fuel wood represent up to 52% and 25%, respectively, of the annual coffee revenues of low altitude farms in Guatemala. The commodity chains are generally poorly organized with an absence of agreements and little cooperation among stakeholders so that farmers would benefit more by eliminating intermediaries and selling directly to wholesalers. In Mexico, timber production and total tree biomass are significantly higher in traditional plantations and amounted to ten times the timber production of Inga-shaded plantations (Peeters *et al.,* 2003)

2.5 Shade and management intensity

As mentioned previously, shade, management intensity and coffee yield are closely intertwined. To buffer unfavorable effects of ecological conditions of low to medium altitudes on coffee (mostly heat and water stresses), farmers tend to prefer a high tree density in their coffee plantations (**Figure 12** and **Table 10**). Generally, diversity of tree cover is also high with co-habitation of legume trees for nitrogen fixation and nutrient cycling with timber and fuel wood trees, fruit trees and plantain. On the other hand, farmers tend to manage mono-specific shade (*Erythrina poeppigiana*, *Inga* spp., *Gliricidia sepium* or *Grevillea robusta*) intensively, through pruning one to three times a year in more favorable conditions of high altitudes, characterized by cooler temperature and lower solar radiation levels caused by frequent occurrence of fog. Finally, socio-economic status of farmers also influences management intensity. Small holders tend to shade their coffee plantations more heavily with more diverse tree species and rely less on agro-chemicals (fertilizers, chemical control of pests & diseases and herbicide) than medium to large landholders.

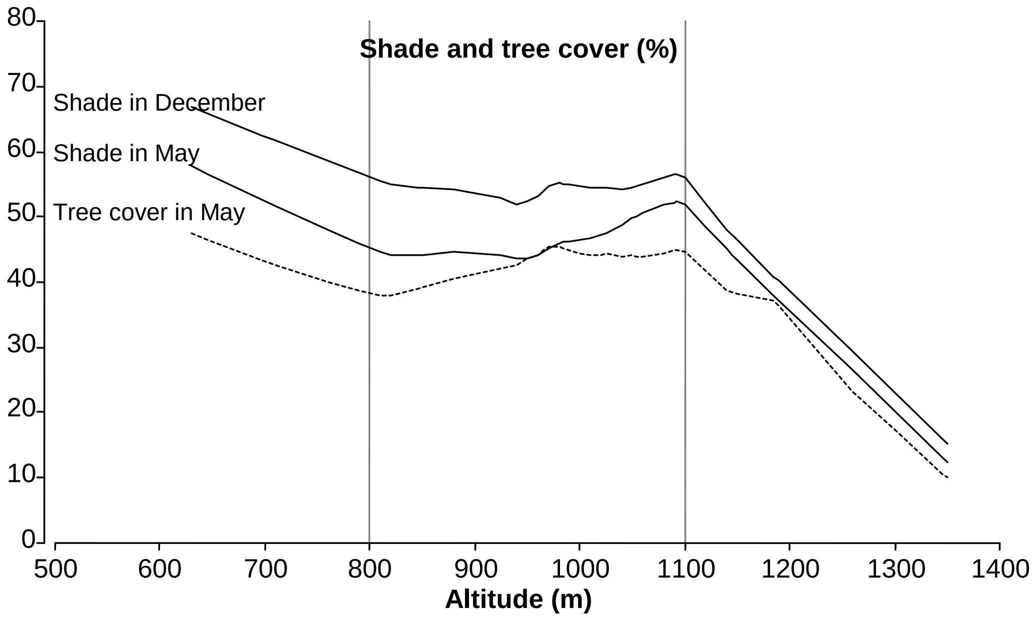


Figure 12. *Shade level with respect to altitude in the region of Matagalpa-Jinotega in Nicaragua (adapted from Lara 2005).*

Table 10. *Relationships between altitude, shade, fertilization and yield in Nicaragua (adapted from Lara, 2005).*

Factor	Altitudinal Range (m)	N	Altitude (m)	Shade (%)	Fertilization (Number/year)	Coffee yield (kg ha^{-1})
Altitude (m)	630 – 850	15		59	1.67 B	860
	880 – 1050	23	-	52	2.39 A	1310
	1055 – 1350	29		47	2.14 A	1157
Shade (%)	0 – 25	13	1157 A		2.69 A	1520
	30 – 55	22	980 B	-	1.91 B	996
	60 – 85	32	964 B		2.03 B	1090
Fertilization (Number per year)	0 – 1	15	923 B*	59		780
	2 – 3	29	1029 A	54	-	1030
	>3	23	1032 A	44		1522

* p ≤0.05 and **p ≤ 0.1 (Duncan test)

2.6 Effects of shade on pest and disease incidence

In a recent keynote presentation at the 21st International conference on coffee research (ASIC, Montpellier, France, September 2006), Avelino highlighted the fact that the incidence of pests such as coffee borer was not affected by the shade level in the Central American region. On the other hand, Soto-Pinto et al (2002) found that a high level of diversified shade did reduce the incidence of berry borer in Mexican coffee plantations. These contradictory results may be due to the fact that incidence of coffee borer in Mexico was far lower (<10% coffee berries infested) than those encountered in the more productive coffee systems of Central America (>30% of infested coffee berries). No information is available in the literature on whether the effects of biological control agents against coffee borer (such as the fungus *Beauveria bassiana* or the natural enemy, *Cephalonomia stephanoderis*) are reinforced when applied in a shaded plantation compared to a full sun plantation. Avelino also reported that the incidence of fungal diseases such as leaf rust and leaf spot diseases tend to increase with increasing levels of shade and productivity in Central America. In a study in the Chiapas highlands of Mexico, Soto-Pinto and colleagues (2002) found that the incidence of coffee leaf rust was lower in coffee farms with higher vertical stratification of the tree cover. In another study in the Soconusco region of Chiapas, Mexico, Philpott and others (unpublished data) also found that the prevalence of coffee leaf rust and coffee leaf spot negatively correlated with tree cover – areas with less tree cover had significantly higher numbers of fungal lesions per plant. These differences between Central America and

Mexico can be attributed to the fact that (1) these fungal diseases, especially leaf rust, are more damaging when trees bear high fruit load - coffee productivity is higher in Central America than in Mexico, and (2) the more diverse shaded systems in Mexican plantations certainly harbor more natural enemies than the Central American coffee systems with a lower level of shade and tree diversity. In Costa Rica, R. Rice (unpublished data) found that fungal spores spread significantly further in sun coffee plantations where wind speed was higher, compared to farms with shade tree cover. With the usually recommended shade level of 30-40% kept constant, a high fungal disease pressure (especially leaf rust, most damaging at low altitude) can result in a less beneficial effect of shade on yield at low altitude (600-900m) in Central America. The same is true at higher altitude (>1100 m) due to the fact that leaf spot is more damaging in a more confined, cooler and humid microclimate provided by tree cover.

2.7. Pollination and other ecosystem services influencing coffee production

In addition to the direct influences over ecophysiological processes in coffee plants, tree cover (in the coffee plantations or in nearby forests) may indirectly affect coffee yields due to changes in pollinator communities and associated fruit set. In both Arabica and Robusta coffee, shade trees over coffee plants are associated with increased pollination and fruit set (Klein et al. 2003a, 2003b). Arabica coffee is a self-compatible species that does not require outcross pollination, but may nevertheless benefit from pollinator presence. A study in coffee agroforests in Indonesia demonstrated an increase in fruit set of *Coffea arabica* with the number of flower visiting bee species (Klein et al. 2003b). Furthermore, this and other studies have shown the importance of a diverse suite of pollinators, including both social and solitary bees, for pollination (Klein et al. 2003a) and pollen deposition (Ricketts 2004). Two recent studies in Brazil (DeMarco and Monteiro Coelho 2004) and Costa Rica (Ricketts et al. 2004) calculated that for coffee plants located near forest fragments, native bees increased yields by more than 14% and 20% respectively. Ricketts estimated that this represents a total dollar value of $62,000 for the farm studied in Costa Rica (Ricketts et al. 2004). This represents substantial benefits to farmers and highlights the importance of maintaining forest fragments within coffee landscapes, even if small. Finally, another study has documented that under high shade management, where activity of pollinators (including ants) is greater, the presence of ants, or some interaction between ants and flying pollinators, affords higher fruit weights than under low shade conditions (Philpott et al. 2006b). Although some researchers have found no effects of pollinators on coffee pollination (Nogueira-Neto et al. 1959), more recent evidence clearly indicates that in fact both diversity and abundance of bees, and potentially other pollinators, do increase yields, weights, and quality of coffee.

Protection against frost and wind damage

Shade buffers environmental conditions and this is particularly important for coffee heat stress in low-altitude, hot coffee zones of the MBC. Beneficial effects against wind damage to coffee leaves provided by tree cover and windbreaks around the coffee plantation have also been reported. Shade cover is also associated with much less loss from frosts in Brazil, leading to overall higher coffee yields in farms with shade in frost years (Da Matta, 2004).

Carbon sequestration

The potential of coffee ASF to act as a sink for carbon (C) is of high interest within the framework of the Mechanisms of Clean Development following the Kyoto accords as it could lead to financial reward to farmers for carbon sequestration in their coffee AFS. From 2001 to 2005, the CASCA project (Coffee Agroforestry Systems in Central America: www.casca-project.com) gathered data from selected coffee systems (7 trials and over 100 farms) in Costa Rica, Guatemala and Nicaragua (with and without shade trees) in order to quantify plant biomass (above and belowground) and soil organic C and to evaluate change in C stocks of different systems. Data were gathered from 8 regions of Costa Rica, Guatemala and Nicaragua in 8 systems (full sun and shade by *E. poepiggiana*, *T. amazonia, E. deglupta*, *C. alliodora*, *T. amazonia, G. sepiu*m and *I. densiflora)* conventionally or organically managed. CASCA also developed a database on C stored in soil and plant biomass of coffee AFS in Central America, initially with already published information (~20 studies representing 90 different coffee systems) and thereafter complemented by data collected from above-mentioned studies. These studies show that carbon accumulation in the coffee biomass varies from 5-16 t C ha^{-1} whereas that of associate shade trees ranges from 5-100 t C ha^{-1} depending of species and age. More importantly, carbon sequestration in soil can account up to 220 t C ha^{-1}. Coffee AFS can greatly increase top soil organic matter content and contribute to an additional 5-15 t C ha^{-1} in the soil with an extra carbon accumulation in the litter layer of 3-5 t C ha^{-1}. Consequently, a coffee AFS can sequester an extra 100-150 t C ha^{-1} in comparison to a full sun system (**Table 11**). A recent study in Chiapas, Mexico (Aguirre-Dávila, 2006), shows carbon storage of the same order of magnitude (**Table 12**).

***Table 11.** Means, minima and maxima of carbon stocks in the different components of shaded and unshaded coffee plantations registered in the CASCA database.*

	Carbon stocks (t C ha^{-1})								
	Coffee trees[a]	Shade trees[b]	Coffee + Shade trees	Litter	Weeds	Total aboveground	Roots	Soil[c]	Total
Mean	4.8	7.1	21.7	1.9	1.9	25.6	1.4	102.1	129.1
Min.	0.2	0.5	2.2	0.8	0.1	3	1	12.7	18
Max.	16.4	31.8	97.2	11.3	10.9	119.4	8	224	351.4

[a]Coffee planting densities between 1250 and 6340 trees ha^{-1}
[b]Shade trees planting densities between 50 and 833 trees ha^{-1}
[c]Soil sampled between 0 and 45 cm depth

***Table 12.** Accumulated carbon in living biomass, dead organic matter, soil organic matter, total carbon (Mg C ha^{-1}) in coffee systems: natural coffee (CN), Monoculture shade (MS) and polyculture shade (PT) in Chiapas, Mexico.*

		CN			MS			PT	
			%			%			%
Living biomass	a	***35.14 ± 6.93***	***27.1***	ab	***46.84 ± 13.72***	***27.5***	b	***57.47 ± 14.41***	***26.7***
Trees>10 cm DBH		17.02 ± 6.45	***13.1***		27.30 ± 9.49	***16.0***		37.89 ± 10.45	***17.6***
Trees < 10 cm DBH		0.14 ± 0.09	***0.1***		0.36 ± 0.27	***0.2***		0.85 ± 0.52	***0.4***
Coffee plants		11.37 ± 3.02	***8.8***		11.03 ± 4.36	***6.5***		8.83 ± 2.62	***4.1***
Weeds		0.44 ± 0.18	***0.3***		0.12 ± 0.06	***0.1***		0.24 ± 0.14	***0.1***
Roots (fine & large)		6.16 ± 1.13	***4.7***		8.03 ± 2.15	***4.7***		9.67 ± 2.18	***4.5***
Dead organic matter	a	***6.72 ± 2.50***	***5.2***	a	***6.28 ± 2.11***	***3.7***	a	***6.04 ± 1.71***	***2.8***
Dead branches		1.48 ± 1.53	***1.1***		0.68 ± 0.20	***0.4***		0.33 ± 0.14	***0.2***
Leaf litter		5.24 ± 1.72	***4.0***		5.60 ± 1.99	***3.3***		5.72 ± 1.84	***2.7***
Soil organic matter	a	**87.97 ± 24.35**	***67.8***	ab	**117.35 ± 23.77**	***68.8***	b	**152.12 ± 20.72**	***70.5***
Soil organic matter		87.97 ± 24.35	***67.8***		117.35 ± 23.77	***68.8***		152.12 ± 20.72	***70.5***
Total C of system	a	***129.82 ± 30.45***	***100***	ab	***170.46 ± 26.78***	***100***	b	***215.64 ± 24.56***	***100***

Treatments with same letters do not differ significantly at 10%.

Water quality and quantity

In a study in the central valley of Costa Rica, Babbar *et al.* (1995) demonstrated that coffee AFS was resulting in lower losses in terms of nitrogen (denitrification and leaching) than full sun coffee. More recently, Harmand et al. (2006) found that NO_3^- leaching and contamination of ground water was reduced by 3 times in an organically managed system fertilized with coffee pulp (≈150 kg N ha^{-1} yr^{-1}) than in an intensive coffee system shaded by the legume tree *Erythrina poeppigiana* and highly fertilized (250 kg N ha^{-1} y^{-1}). Few studies have monitored the effect of tree cover on run-off in coffee AFS. The CASCA project found that run-off can be reduced by up to 15% in the presence of a mono-specific tree cover of *Inga.* spp. or *Eucalyptus deglupta*. This is mostly due to rain interception by tree foliage (up to 30% of rainfall with low-medium rain intensity – 5 to 30mm day^{-1}), soil litter and improved filtration brought about by an increase soil organic matter content and hence soil structure in coffee AFS compared to sun full systems. This certainly results in lower soil erosion and hence better water quality but data are lacking in that respect. Several studies in Mexico and Costa Rica (Jimenez and Goldberg, 1992; van Kanten and Vaast, 2006) have demonstrated that combined water consumption of coffee and associated shade trees is greater than coffee cultivated in full sun with transpiration of the shade tree stratum accounting to 15-35%. In comparison to full sun coffee systems, enhanced transpiration of the coffee AFS is offset partially or fully by a reduction in water run-off, depending on rainfall regime and slope, and hence soil water recharge is likely to be enhanced when yearly rainfall is above 2000 mm.

2.8. Existence and variation in tree cover thresholds for coffee productivity

There are strong and complex interrelationships between shade, ecological conditions (especially altitude), disease pressure and management intensity in coffee AFS along the MBC so that it is unlikely that a single series of thresholds of tree cover (or shade) can be derived with respect to coffee yield. This was exemplified by the weak tendency of decreasing yield with increasing level of shade in coffee plantations in 12 regions of 4 countries of Central America presented earlier in Figure 4f. There are many reasons that explain this weak relationship between shade and yield:

(1) Year of production: due to the strong alternate bearing pattern of coffee, yield differences between full sun coffee and shade coffee is either large during a year of high production potential or small during a year of low production potential,
(2) Farm size and farmer status affect yield, as small holders tend to manage their coffee plantations less intensively for a given level of shade than medium to large holders.
(3) Coffee price also plays an important role, as farmers tend to increase the level of shade in times of low prices to reduce their production costs whereas they tend to intensify the management (high inputs of fertilizers and other agro-chemicals) and reduce tree cover to maximize yield when prices are high (**Figure 13**).
(4) Soil fertility also influences the relationship between yield, shade level and climatic conditions (especially altitude) as shown below (**Figure 14**).
(5) Pests and diseases pressure can vary greatly from one coffee zone to the next which affects the relationships between shade and yield (as explained and theorized in **Figure 15**).

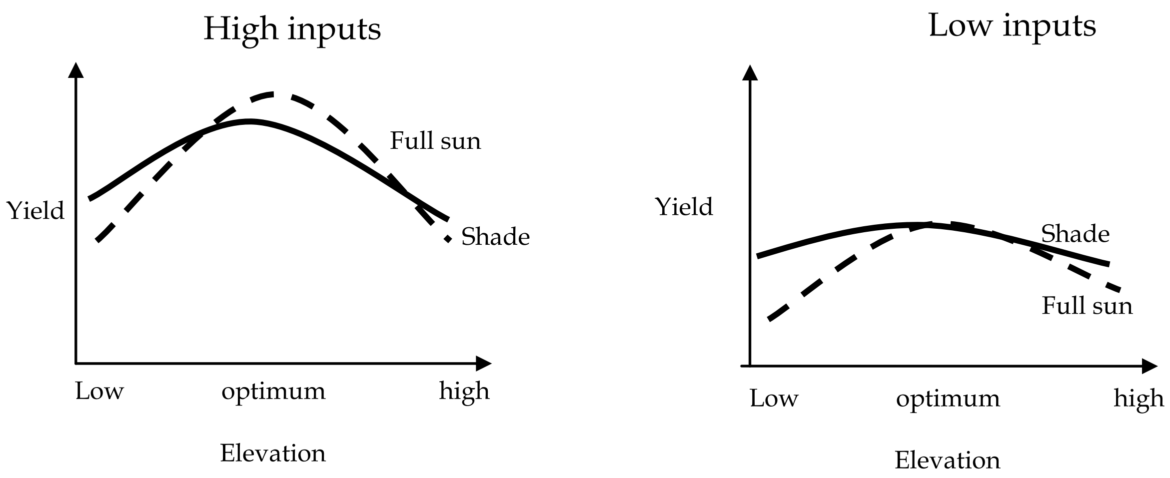


Figure 13. *Theoretical relationships between yield, elevation and shade according to management intensity.*

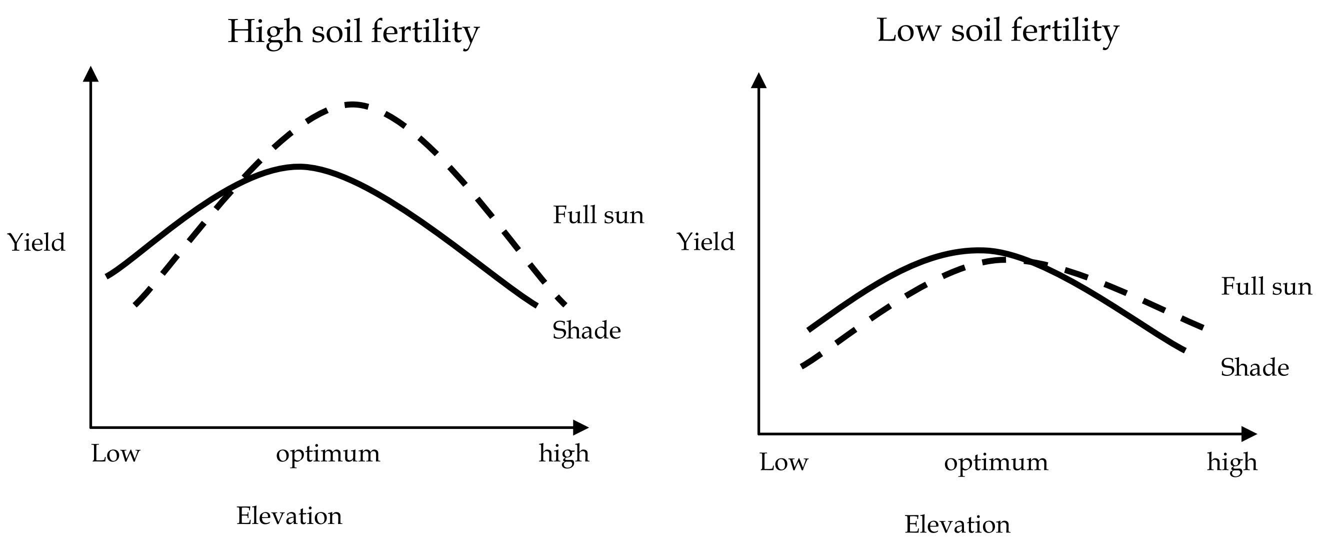


Figure 14. *Theoretical relationships between yield, elevation and shade according to soil fertility.*

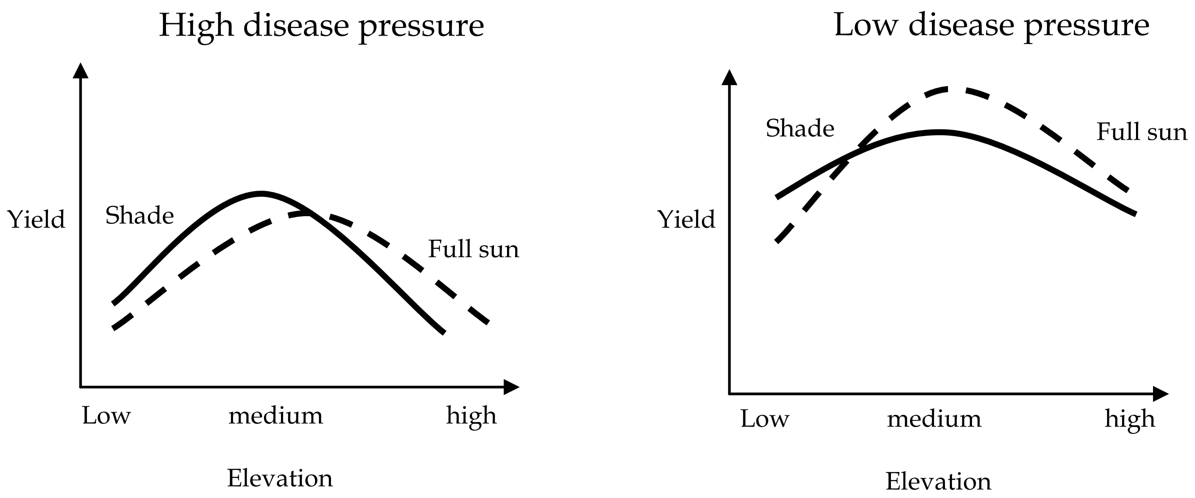


Figure 15. *Tentative shade - fungal disease pressure (leaf rust and leaf spot) – production functions for Central America.*

3. Impacts of tree cover on biodiversity

Tree cover, including tree diversity, has already been discussed in Section 1 above, and so we focus more on other flora and fauna in this section and what information is available on how their diversity within coffee farms is a function of tree cover.

3.1 Location of coffee growing areas in relation to forest habitat connectivity

As mentioned previously, a key reason for interest in tree cover within coffee farms relates to their position within landscapes and regions. Because of the elevations at which it is grown, coffee landscapes often border remaining areas of forest, many of which along the MBC are protected. Tree cover in coffee has been heralded as important for providing habitat and improving connectivity of remaining forest for some wildlife species, particularly migratory birds that move between the MBC and North America. This has been used in retailing bird friendly coffee, amongst other more holistic eco-labeling schemes that rest on the premise that trees within coffee farms promote biodiversity conservation.

Mapping where coffee is grown along the MBC is difficult because available statistics comprise administrative units within which coffee is grown rather than delineating the precise area that coffee is being grown on. Peter Laderach at CIAT compiled such data supplied by national contacts for the CORRIDOR project (**Figure 16**). The ratio of mapped area (from GIS) to reported area of coffee grown (national production statistics) varies from 0.04 in Mexico to 0.37 in El Salvador (typically, the reported area is 10-20% of the mapped area). In Mexico the administrative units that are mapped as coffee are large, resulting in mapping coffee where it certainly is not being grown (e.g. down to the coast in places). These data could be adjusted by applying elevation thresholds, that vary with latitude as discussed in Section 2 above, but the strategic position of coffee growing areas in relation to protected forest areas is discernible from the present maps.

The restriction of coffee to key elevation ranges is more evident if we focus in on the middle section of the MBC Guatemala, Honduras and El Salvador with a finer altitudinal scale (**Figure 17**). This shows the coffee areas clothing the mid-slopes of the mountainous terrain, thereby occupying a key position with respect to connecting rain and cloud forest reserves along the MBC, as well as sitting along migration paths for birds that move up and down the isthmus as well as those that move from central highland areas to the coast.

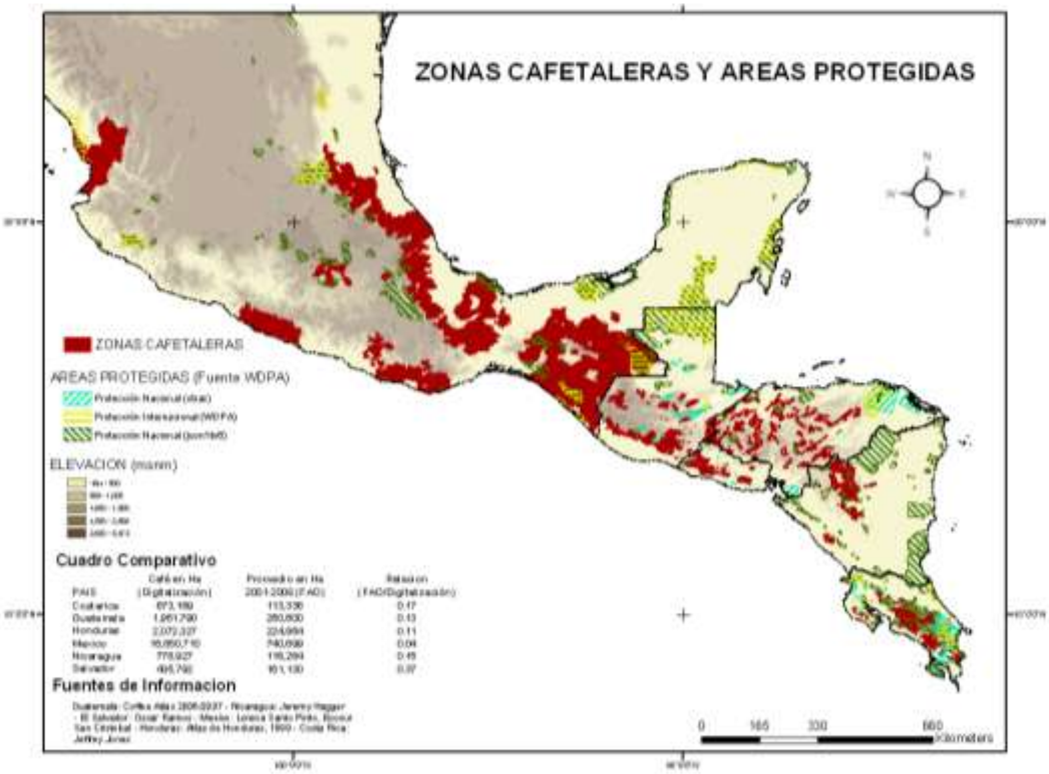


Figure 16. *Location of major coffee growing areas from Mexico to Panama in relation to protected areas.*

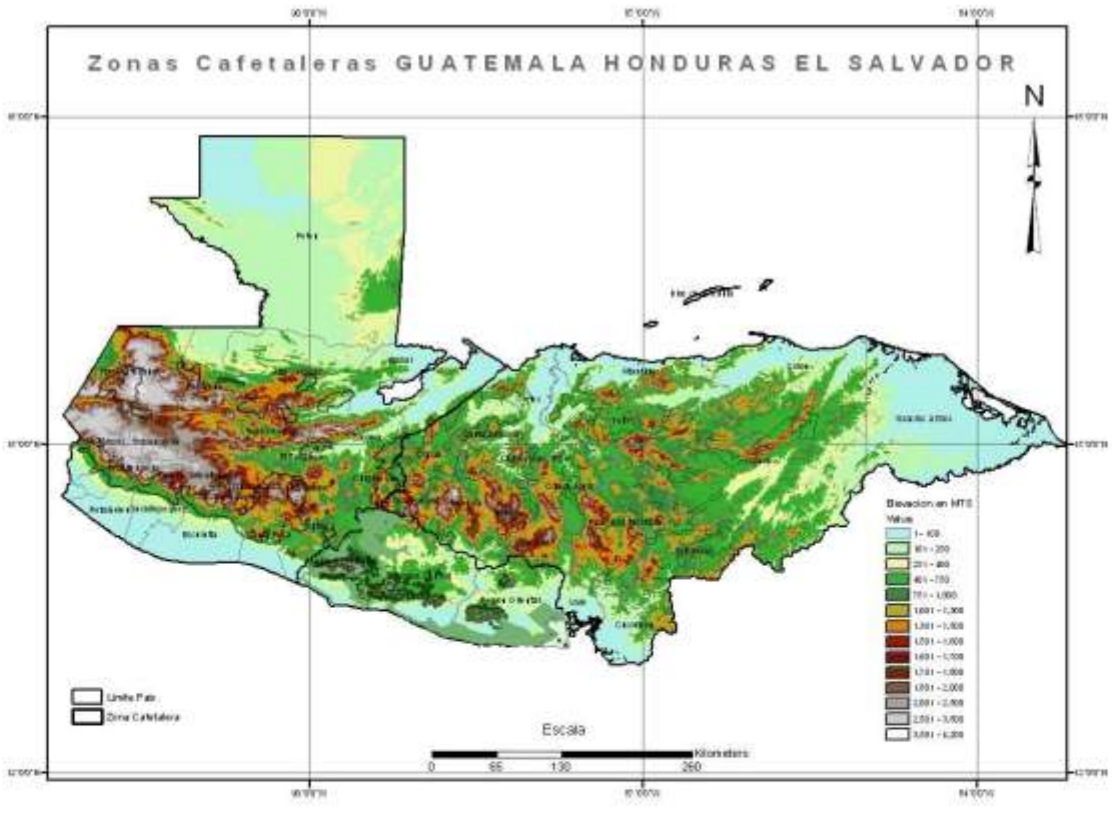


Figure 17. *Coffee growing areas in relation to elevation for Guatemala, Honduras and El Salvador.*

3.2 Information about tree cover and biodiversity on coffee farms

We compiled a database of literature on biodiversity in coffee along the MBC from Mexico to Panama combining electronic literature searches with contributions from participants at the CORRIDOR workshops and consulting libraries at participating institutions that have been active in this area, particularly CATIE and Ecosur. This comprised 161 articles (Appendix 2) that were entered into an Endnote database. We were able to obtain 140 of these and, where possible, data on farm size, elevation, management intensity, yield, canopy cover (%), shade (%), tree species recorded, density of each tree species, animal species recorded and plant species recorded were abstracted.

In summarizing what information was available for various taxa by country we examined each article and selected those that met at least one of the following three criteria.

1. the article contained a comparison of biodiversity in coffee farms with two or more forms of tree cover
2. the article, although only having biodiversity for one coffee site, included detailed information on tree cover
3. the article contained a comparison of biodiversity in one or more coffee contexts and nearby forest

These articles were then used to populate a matrix showing how many articles contained information on different taxa in different countries (**Table 13**), a single article may have entries in multiple cells. This revealed that studies of biodiversity in coffee were geographically and taxonomically skewed, with by far the most effort on birds and ants in Mexico. There were also four studies of each of these taxa in Costa Rica as well as six on insects. There were no data meeting our criteria on biodiversity associated with coffee in Honduras. Considerable research on weeds and insects from a pest perspective, contributed to the knowledge available on biodiversity in coffee but with the same geographical bias towards Mexico as for other taxa.

Table 13. *Numbers of articles with information about tree cover and biodiversity in coffee systems along the MBC by country and taxon that met at least of one of the three criteria for inclusion (see text). Compiled by Stacey Philpott (reviewed 79 articles, focus on birds and ants) and Maybeline Escalente (reviewed 61 articles, all other taxa).*

	Mexico	Guatemala	El Salvador	Honduras	Nicaragua	Costa Rica	Panama	Total
Trees	7	1	1	0	2	3	2	**16**
Epiphytes	3	0	0	0	0	0	0	**3**
Orchids	2	0	0	0	0	0	0	**2**
Weeds + herbs	10	0	0	0	0	0	0	**10**
Birds	17	4	1	0	1	4	3	**30**
Amphibians	2	0	0	0	0	0	0	**2**
Reptiles	1	0	0	0	0	0	0	**1**
Bats	2	1	0	0	0		0	**3**
Non-flying mammals	4	0	0	0	0	1	0	**5**
Ants	12	0	0	0	0	4	0	**16**
Beetles	3	1	0	0	0		0	**4**
Spiders	4	0	0	0	0	0	0	**4**
Butterflies	1	0	0	0	0	1	0	**2**
Other insects	2	0	0	0	0	6	0	**8**
General	4	0	1	0	0	1	0	**6**
Total	**74**	**7**	**3**	**0**	**3**	**20**	**5**	**112**

The geographical skew is particularly marked with most information for Mexico (74 entries) at the northern end of the corridor and Costa Rica (20 entries) near the southern end and very little information available for the central part of the corridor. In terms of taxa, only for birds was information available along the whole corridor (all countries except Honduras), ants were only studied in Mexico and Costa Rica.

Clearly, as result of this patchy distribution of information in relation to taxa and position along the corridor, it is not possible to comprehensively understand the impact of tree cover in coffee on biodiversity in terms of the corridor as a whole. Very few studies have both detailed description of tree cover and other taxa. The individual studies that do, show variable results on how tree cover affects biodiversity. This is not entirely surprising since taxa may vary in sensitivity to tree cover and intensity of coffee management and there may be regional differences. For example, shade and sun coffee were found to be not very different in the biodiversity they supported in Costa Rica (Rickets et al 2001) but in Mexico shaded coffee has been associated with higher biodiversity of birds and ants than full sun coffee (Philpott and Armbrecht, 2006; Komar, 2006). This may reflect that shaded coffee in Costa Rica is generally of one or two tree species with intensive management whereas in Mexico, rustic and traditional polyculture coffee farms (see Section 1.1) have many tree species and low management intensity. While there are studies that have made comparisons of bird, tree or arthropod biodiversity in coffee under different management intensity or compared coffee with forest and/or other agricultural land uses, few have examined multiple taxonomic groups at the same time, or related biodiversity to detailed data on tree cover. There are review articles on both ant (Philpott and Armbrecht, 2006) and bird (Komar, 2006) diversity in coffee systems, but these are qualitative and limited by problems in comparing data across sites and studies due to differences in sampling intensity and measurement methods.

A major attempt at meta-analyses of tree, bird and ant data across studies is in progress under the auspices of the working group on Biodiversity and Conservation Value of Agricultural Landscapes of Mesoamerica at the National Center for Ecological Analysis and Synthesis in California led by Stacey Philpott who has been a key participant in the CORRIDOR review of biodiversity in coffee. They have obtained comparable data on these taxa from four coffee growing regions in Mexico and one each in Guatemala and Nicaragua in the MBC as well as data from Colombia and Peru beyond the southern end of the corridor.

In summary, studies document a general reduction in biodiversity associated with reduction in tree canopy richness and complexity in coffee. But sensitivity of different taxa, forest dependent species and functional groups within taxa and amongst regions remain unclear. We expect relationships between tree cover and biodiversity to vary with taxon, and that while trees in coffee can provide habitat connectivity for canopy species (especially some threatened bird and butterfly species), they do not necessarily do so for understorey species (other bird, butterfly, insect and mammal species).

Priorities for future research are firstly to include detailed description of tree cover and proximity to forest where other taxa are inventoried in coffee systems, secondly to encourage collection of data on multiple taxa at the same time so that differences in responses amongst taxa can be understood and thirdly to encourage separation of taxa by functional groupings and forest dependence and fourthly to encourage equitable sampling effort along the MBC rather than concentration of studies at the two ends (Mexico and Costa Rica) so that patterns along the MBC can be better understood. There is also a key requirement for use of standard measurement methods and transparent reporting so that data from studies are comparable (this is addressed in CORRIDOR Deliverable 5).

3.3 Tree cover thresholds for productivity and biodiversity

We found no studies where biodiversity and productivity were studied simultaneously. Despite the large number of biodiversity studies in Mexico, Perfecto et al. found no instances where coffee productivity and biodiversity were measured at the same site and had to resort to taking data on tree cover and ant diversity from one site and modelled coffee productivity in relation to tree cover, based on data from a different site, to explore this trade-off. Their results (**Figure 18**) suggested that there was a direct trade-off between biodiversity and productivity more acute for butterflies (diversity steeply rises after a shade level allowing only 25% of maximum coffee yield) than ants (75% of ant species occur at a shade level permitting 75% of coffee production).

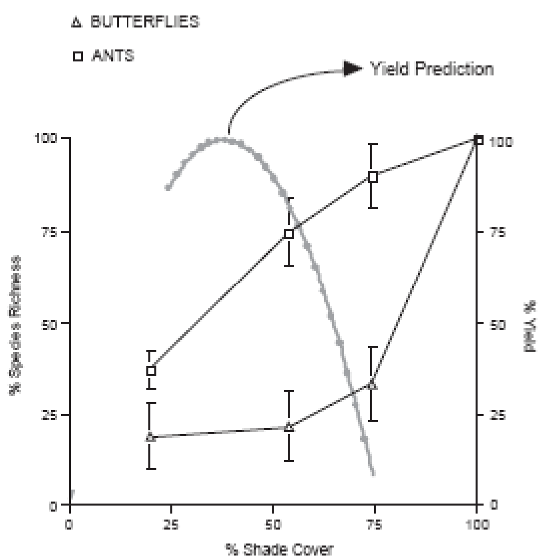


Figure 18. *Relationship between ant and butterfly diversity (measured at one site in Chiapas, Mexico), and coffee yield (modelled with data from elsewhere in Chiapas) and shade in coffee systems. Source: Perfecto et al. 2005.*

It is clear from Section 2 that productivity functions in relation to shade will vary with region, elevation and management and will be further affected by pest and disease incidence that itself varies in relation to these same variables (see Figures 13-15). Progress in modelling coffee productivity should allow context specific prediction of productivity functions. Similar response data for taxa of conservation interest along the MBC would be required to explore a suite of context specific trade-offs between tree cover, productivity and biodiversity. The most important gap in data is for species diversity responses for taxa other than birds and ants in the central section of the Mesoamerican Biological Corridor.

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Appendix 1. Species list of coffee agroecosystems. Total abundance values given only to those species from the CATIE coffee database, "X" indicates presence confirmed.

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Actinidaceae	*Saurauia belizensis*							x	N	
	Saurauia kegeliana	4		4						
	Saurauia scabrida							x	N	
	Saurauia villosa							x		
	Saurauia yasiace							x		
Agavaceae	*Yucca elephantipes*	3	1	1			1	X	N	
	Yucca guatemalensis			x						
Anacardiaceae	*Anacardium excelsum*		x						N	
	Anacardium occidentale	3		2		1			N	
	Astronium graveolens	9		7		2		x	N	
	Magnifera indica	9	4	1		4				
	Mangifera indica	61	1	31		21	8	x	E	
	Mauria heterophylla								N	
	Mosquitoxylum jamaicense	5				5		X	N	
	Rhus striata							x	N	
	Spondias dulcis								E	
	Spondias purpurea								N	
	Spondias spp	3		3						
	Sponidas mombim	11		1		8	2	x	N	
	Sponidas purpurea	1				1				
	Tapirira mexicana								N	
Annonaceae	*Annona cherimola*	6				3	3		N	
	Annona diversifolia							x		
	Annona diversifolia								N	
	Annona muricata	13	1	9		3		X	N	
	Annona purpurea							x	N	
	Annona reticulata							x	N	
	Annona scleroderma							x	N	
	Annona spp	2	2							
	Annona squamosa								N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Annonaceae	*Cymbopetalum mayarum*							x		
	Guatteria galeottiana							x		
	Oxandra venezuelana								N	
	Rollinia rensoniana							x	N	
	Unonopsis pittier	1				1				
Apocynaceae	*Alstonia buxifolia*	14		14						
	Aspidosperma dugandii								N	
	Aspidosperma megalocarpon								N	
	Aspidosperma spruceanum								N	
	Plumeria rubra	1		1						
	Stemmadenia donnell-Smithii	8		8						
	Stemmadenia littoralis								N	
	Stemmadenia obovata	2		2					N	
Aracaceae	*Elaeis guineensis*								E	
	Thrinax argentea								N	
Araliaceae	*Dendropanax arboreus*	4				4		X	N	
	Oreopanax xalapensis								N	
	Schefflera morototonii							x		
Arecaceae	*Asterogyne martiana*	1				1				
	Astrocharium mexicanum							x	N	
	Bactris gasipaes	4	2			2			N	
	Chamaedorea cataractarum							x	N	
	Chamaedorea pinnatifrons							x		
	Chamaedorea tepejilote							x	N	
	Cocos nucifera	1				1			E	
	Desmoncus schippii							x	N	
	Orbignya cohume								N	
	Roystonea sp.								N	
Asclepiadaceae	*Calotropis procera*								E	
Asteraceae	*Clibadium arboreum*							x	N	
	Critonia dalcoidos	23		23						
	Critonia morifolia								N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Asteraceae	*Eupatorium araliaefolium*							x		
	Eupatorium chiapensis							x	N	
	Eupatorium pittieri	1				1			N	
	Neurolaena lobata							x	N	
	Perymenium grande	15		5		5	5		N	
	Senecio espaciosa									
	Tithonia rotundifolia							x		
	Vernonia deppeana							x	N	
	Lasianthaea fruticosa							x	N	
	Vernonia sp.							x		
	Vernonia patens	11		11				x	N	
Betulaceae	*Alnus acuminata*		x						N	
Bignoniaceae	*Amphitecna macrophylla*							x		
	Amphitecna tuxtlensis								N	
	Crescentia alata								N	
	Cybistax donell								N	
	Jacaranda copaia								N	
	Jacaranda sp.								N	
	Roseodendron donnell	18			18					
	Spathodea campanulata	1				1			E	
	Tabebuia chrysantha			x					N	
	Tabebuia donnell-smithii								N	
	Tabebuia guayacan	1	X				1		N	
	Tabebuia ochracea								N	
	Tabebuia rosea	34		13		19	2	x	N	
	Tecoma stans	10		10					N	
Bixaceae	*Bixa orellana*	1				1			N	
Bombacaceae	*Bernoullia flammea*								N	
	Bombacopsis quinata		x						N	
	Ceiba pentandra	6		1		4	1		N	
	Ochroma pyramidale								N	
	Pseudobombax ellipticum							X	N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Bombacaceae	*Quararibea funebris*							x	N	
Boraginaceae	*Cordia alliodora*	119	21	14		67	17		N	
	Cordia bicolor	4				4				
	Cordia cana			x					N	
	Cordia colococca								N	
	Cordia spp	28		28						
	Lepidocordia williamsii								N	
Burseraceae	*Bursera simarouba*	5	x			3	2	X	N	
	Protium copal							x	N	
Caesalpiniaceae	*Cassia grandis*								N	
	Cassia laevigata								N	
	Cassia reticulata								N	
	Cassia simea	3				3				
	Cassia spp	4	4							
	Hymenaea courbaril								N	
Capparidaceae	*Capparis odoratissima*	1				1			N	
	Capparis sp							x		
Caprifoliaceae	*Sambucus canadensis*							x	E	
	Sambucus mexicana							x	N	
	Viburnum harwegii	1				1			N	
Caricaceae	*Carica papaya*	5	1	3		1		X	N	
	Carica pennata							x	N	
Caryocaraceae	*Caryocar costaricense*								N	E
Casuarinaceae	*Casuarina equisitifolia*	1	x			1			E	
Cecropiaceae	*Cecropia insignis*	2				2				
	Cecropia obtusifolia	8		8					N	
	Cecropia peltada	14		4		5	5	X	N	
	Cecropia spp	1	1							
Celastraceae	*Crossopetalum* sp.							x		
Chloranthaceae	*Hedyosmum mexicanum*	2				1	1		N	E
Chrysobalanaceae	*Chrysobalanus icaco*								N	
	Licania spp.			x					N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Chrysobalanaceae	*Licarna arborea*			x					N	
	Licarna lipoteuca	1				1				
	Licarna platypus		x					x	N	
	Lycania platypus	1				1				
Clethraceae	*Clethra mexicana*	6		6					N	
Clusiaceae	*Calophyllum brasiliense*								N	
	Garcinia intermedia							x	N	
	Mammea americana	4				4			N	
Cochlospermaceae	*Cochlospermum vitifolium*							x	N	
Combretaceae	*Terminalia amazonica*							x	N	
	Terminalia cattapa								E	
	Terminalia ivorensis								E	
	Terminalia oblonga	31		13	13	5			N	
Cucurbitaceae	*Sechium edule*								N	
Cupressaceae	*Cupressus lusitanica*								N	
Cyatheaceae	*Cyathea* sp.								N	
Dilleniaceae	*Curatella americana*								N	
Euphorbiaceae	*Alchornea costaricenses*									
	Alchornea latifolia							x	N	
	Bernardia interrupta							x	N	
	Caryodendron orinocense	4		2			2			
	Cnidoscolus multilobus							x		
	Croton billbergianus							x	N	
	Croton draco	18				17	1		N	
	Croton glabellus							x		
	Croton monteverdensis								N	
	Croton niveus	1				1			N	
	Croton reflexifolius	32		31		1			N	
	Garcia nutans							x	N	E
	Hyeronima alchorneoides								N	
	Jatropha curcas	1		1					N	
	Jatropha sp.								N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Euphorbiaceae	*Manihot dulcis*								N	
	Manihot esculenta							x	N	
	Omphalea oleifera								N	
	Ricinus communis	23		10		10	3		E	
	Sapium glandulosum	18				18			N	
	Sapium lateriflorum							x	N	
	Sapium macrocarpum								N	E
	Sapium sp.							x		
	Sapium tuerckheimianum							x	N	E
Fabaceae	*Abarema obovalis*								N	
	Acacia cornigera							x	N	
	Acacia farnesiana								N	
	Acacia hindsii	1		1						
	Acacia mangium								E	
	Acacia millenaria									
	Acacia pennatula	2				1	1			
	Acacia usumacintensis							x		
	Acrocarpus fraxinifolius	3			3					
	Albizia adinocephala	12	x	12					N	
	Albizia carbonaria								N	
	Albizia caribaea	2		x		2			N	
	Albizia guachapele	7				7			N	
	Albizia purpusii							x		
	Andira inermis	6		1		4	1		N	
	Bauhinia divaricata								N	
	Caesalpinia velutina								N	
	Caesalpinia violacea	1				1			N	
	Cajanus cajan	2		2					E	
	Calliandra sp.							x	E	
	Cojoba arborea							x	N	
	Dalbergia retusa								N	El Salvador
	Dalgerbia glomerata								N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Fabaceae	*Delonix regia*							x	E	E
	Dialium guianense							x	N	
	Diphysa floribunda								N	
	Diphysa robinioides	5	X	2		2	1	X	N	
	Diphysa spp	9		9				x		
	Enterolobium cyclocarpum	10	1	2		6	1		N	
	Enterolobium saman	2				2			N	
	Erythrina berteorana	12	x	3	x	7	2		N	
	Erythrina chiapasana							x		
	Erythrina folkersii							x		
	Erythrina fusca	16				11	5		N	
	Erythrina mexicana								N	
	Erythrina poeppigiana	48	43			5			N	
	Erythrina spp	2		1		1		x		
	Erythrina standleyana				x				N	
	Erytrhina chiapasana								N	
	Eysenhardtia adenostylis							x		
	Feuillea spuria				x					
	Gliricidia sepium	69	2	13		34	20		N	
	Haematoxylon brassiletto	1				1				
	Inga berteroana				x					
	Inga calderonii	29		29					N	
	Inga donnell-smithii				x				N	E
	Inga edulis		x						E	
	Inga espuria	27		27						
	Inga fagifolia	16		16						
	Inga fissialix	7			7					
	Inga guajiniquil	22				1	21			
	Inga jinicuil		x					x	N	
	Inga latibracteata							x		
	Inga latibracteata								N	
	Inga laurina	14		1	13					

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Fabaceae	*Inga leptoloba*				x				N	
	Inga micheliana	28			28				N	E
	Inga minutula			x						
	Inga mociniana				x					
	Inga muinutula									
	Inga negra	1				1				
	Inga oerstediana							x	N	
	Inga paterno	8		7			1	x	N	
	Inga paterno			x				x		
	Inga pavoniana									
	Inga pavoniana								N	
	Inga popoyanensis				x				N	
	Inga preussi	8		8						
	Inga puctata	31		31						
	Inga punctata	146	X	60	5	81		X		
	Inga rodrigueziana								N	
	Inga ruiziana			x					N	
	Inga spp	237	18			90	129			
	Inga spuria	50			21	7	22			
	Inga tetraphylla				x					
	Inga thibandiana									
	Inga vera	122		39		63	20			
	Leucaena diversiflora							x	N	
	Leucaena glauca							x	E	
	Leucaena leucocephala	2				2				
	Leucaena sp.							x		
	Lonchocarpus guatemalensis							x	N	
	L. latifolious	6				6			N	
	L. lineatus							x		
	L. minimiflorus	31		21		9	1		N	
	L. parviflora	12				12			N	
	L. rugosus	2		2					N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Fabaceae	*L. salvadorensis*	1		1						
	Lonchocarpus spp	35	x	35				x		
	Lysiloma acapulcense								N	
	Lysiloma auritum								N	
	Lysiloma divaricatum	2		2				x	N	
	Lysiloma kellermanii							x		
	Lysiloma microphyllum	2				1	1		E	
	Mimosa fagifolia				x				N	
	Mimosa laurina				x					
	Mimosa sericea				x					
	Mimosa spuria				x					
	Mimosa tetraphylla				x					
	Myroxylon balsamum								N	
	Ormosia coccinea	1				1				
	Ormosia sp							x		
	Parkia spaciosa	2				2			E	
	Piscidia piscipula								N	
	Piscidia spp							x		
	Pisidia grandifolia	5				4	1		N	
	Pithecellobium arboreum								N	
	Pithecellobium saman	2				2			N	
	Pithecellobium sp.							x		
	Platymiscium dimorphandrum								N	E
	Platymiscium pinnatum	1				1		x	N	Costa Rica
	Platymiscium pleiostachium	7				7				
	Pterocarpus officinalis	1				1				
	Pterocarpus rohrii								N	
	Samanea saman								N	
	Schizolobium atomara	1				1				
	Schizolobium parahyba								N	
	Senna atomaria	1				1				
	Senna fruticosa							x	N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Fabaceae	*Senna multijuga*							x	N	
	Senna nicaraguensis								N	
	Senna papillosa	8				8		x	N	
	Senna siamea	3				3			E	
	Senna spectabilis								N	
	Sickingia salvadorensis								N	
	Styphnolobium monteviridis								N	
	Tamarindus indica	2				2			E	
	Vatairea lundellii							x	N	
Fagaceae	*Quercus candicans*							x	N	
	Quercus corrugata								N	
	Quercus oleoides	1				1			N	
	Quercus sapotifolia								N	
	Quercus segoviensis								N	
	Quercus skinneri	3		3					N	
	Quercus skinneri								N	
	Quercus spp	1	x				1	x		
Flacourtiaceae	*Casearia argula*	4		4						
	Casearia corymbosa							x	N	
	Casearia sylvestris	1		X		1			N	
	Macrohasseltia macroterantha	1				1				
	Pleuranthodendron mexicana								N	
	Xylosma exelmum									
	Xylosma horrida	1				1			N	
	Zuelenia guidonia	2				2			N	
Guttiferae	*Vismia baccifera*	1				1			N	
	Vismia ferruginea								N	
Hamamelidaceae	*Liquidambar styraciflua*	4	X			1	3	X	N	
Hippocastanaceae	*Billia colombiana*								N	
Hydrophyllaceae	*Wigandia urens*								N	
Icacinaceae	*Calatola costaricensis*	1				1			N	
	Oecopetalum greenmanignum							x		

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Icacinaceae	*Oecopetalum mexicanum*							x	N	
Juglandaceae	*Juglans olanchana*	18	x			18			N	
	Juglans pyriformis								N	
	Junglans olanchanum	4				4				
Julianiaceae	*Amphipterygium adstringens*	7				7				
Lamiaceae	*Hyptis verticilla*									
Lauraceae	*Beilschmedia riparia*	5				5		X	N	
	Cinnamomum costaricanum	12				12			N	
	Cinnamomum zeylanicum								E	
	Licaria capitata							x	N	
	Licaria sp							x		
	Nectandra ambigens								N	
	Nectandra glabrescens	20			20				N	
	Nectandra globosa							x	N	
	Nectandra heydeana							x	N	
	Nectandra longicaudata									
	Nectandra martinicensis	50		11		26	13		N	
	Nectandra nervosa								N	
	Nectandra nitida								N	
	Nectandra reticulata								N	
	Nectandra sanguinea							x	N	
	Nectandra sinuata								N	
	Ocotea austinii								N	
	Ocotea cernua							x	N	
	Ocotea helicterifolia	6				6			N	
	Ocotea tonduzii								N	
	Ocotea veraguensis	3		2			1		N	
	Ocotea whitei								N	
	Persea americana	50	3	14	6	26	1	x	N	
	Persea caerulea	15				15			N	
	Persea schedeana	1				1		X	N	E
Laxmanniaceae	*Cordyline terminalis*								E	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Lythraceae	*Lafoensia punicifolia*								N	
Magnoliaceae	*Magnolia portorricenses*			x					N	
	Magnolia yoroconte								N	
	Michelia falcata									
	Talauma mexicana							x		
Malpighiaceae	*Bunchosia lanceolata*							x		
	Byrsonima crassifolia	10	1	1		3	5	X	N	
	Malpighia glabra	3		3						
Malvaceae	*Malvaviscus arboreus*								N	
	Robinsonella lindeniana								N	
	Robinsonella mirandae								N	E
Marantaceae	*Calathea lutea*							x		
	Calathea macrochlamys							x		
	Calathea sp.							x		
	Thalia sp.							x	N	
Melastomataceae	*Bellucia grossularioides*								N	
	Conostegia xalapensis							x	N	
	Miconia argentea							x	N	
	Miconia ibaguensis								N	
	Miconia minutiflora							x	N	
Meliaceae	*Azadirachta indica*								E	
	Carapa guianensis								N	
	Cedrela mexicana							x		
	Cedrela odorata	65	6	15	6	32	6	x	N	
	Cedrela pacayana								N	E
	Cedrela spp	1				1				
	Guarea bijuga							x	N	
	Guarea glabra	1				1		x	N	
	Guarea guidonia								N	
	Guarea palmeri	1		1						
	Guarea trompillo								N	
	Melia azedarach							x	E	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Meliaceae	*Swietenia humilis*	10		6		1	3		N	E
	Swietenia macrophyla	1		X		1		X	N	Belize
	Trichilia glabra								N	
	Trichilia havanensis							x	N	
	Trichilia hirta	13				13			N	
	Trichilia moschata							x	N	
	Trichilia trifolia								N	
	Trichillia havanensis	8		8						
	Trichillia martiana	10		10						
Monimiaceae	*Mollinedia oaxacana*							x	N	
Moraceae	*Artocarpus altilis*							X	E	
	Brosimum alicastrum	7			2	5		X	N	
	Castilla elastica							x	N	
	Chlorophora tintoria	2					2		N	
	Ficus brazilencis	1				1				
	Ficus cetinifolia								N	
	Ficus costaricana		x						N	
	Ficus glabrata			x				x	N	
	Ficus isophlebia	8				8			N	
	Ficus obtusifolia								N	
	Ficus ovalis	25				25			N	
	Ficus pertusa	8		8					N	
	Ficus spp	18		12		4	2	x		
	Ficus tecolutensis								N	
	Maclura tinctorIa								N	
	Morus celtidifolia							x	N	
	Pseudolmedia oxyphyllaria								N	
	Trophis mexicana	1				1			N	
Moringaceae	*Moringa olifera*								E	
Musaceae	*Musa paradisiaca*							x	E	
	Musa regia								E	
	Musa sapientum		x	x				x	E	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Musaceae	*Musa* spp	334	39	9		171	115		E	
Myricaceae	*Myrica cerifera*							x	N	
Myristicaceae	*Virola guatemalensis*								N	
Myrsinaceae	*Ardisia compresa*	1				1			N	
	Rapanea myricoides	1		1				x	N	
Myrtaceae	*Eucalyptus deglupta*	3	1	2					E	
	Eucalyptus saligna		x						E	
	Eucalyptus spp	1		1						
	Eucalyptus torelliana	2			2					
	Eugenia acapulcensis							x	N	
	Eugenia guatemalensis	10				10			N	
	Eugenia malaccensis	1		1					E	
	Eugenia salamensis								N	
	Eugenia stipitata								N	
	Pimenta dioica							x	N	
	Psidium friedrichsthalianum	1	x	1					N	
	Psidium guajava	30	1	7		18	4	x	N	
	Psidium molle							x	N	
	Syzygium caryophyllus								E	
	Syzygium jambos	21	X	21				X	E	
	Syzygium malaccense		x							
Nyctaginaceae	*Pisonia macranthocarpa*	1				1			N	
	Neea laetevirens	1				1			N	
	Neea psychotriodes	3		3					N	
Ochnaceae	*Cespedezia macrophylla*									
	Ouratea sp.							x	N	
Olacaceae	*Minquartia guianensis*								N	
Oleaceae	*Fraxinus* sp.									
	Ligustrum lucidum								E	
Onagraceae	*Hauya heydeana*							x		
Oxalidaceae	*Averrhoa carambola*	1				1			E	
Papaveraceae	*Boconia arborea*			x					N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Pinaceae	*Pinus caribaea*	1	x			1			N	
	Pinus oocarpa								N	
	Pinus spp	2					2			
Piperaceae	*Piper amalago*	5		5						
	Piper auritum							x		
	Piper marginatum							x		
	Piper patulum							x		
Platanaceae	*Platanus lindeniana*								N	
Poaceae	*Bambusa sapientum*								E	
	Bambusa vulgaris								E	
Polygonaceae	*Coccoloba barbadensis*							x	N	
	Coccoloba hirtella								N	
	Triplaris melanodendron	6	2	5		2			N	
Proteaceae	*Grevillea robusta*	2	x	1	x		1		E	
	Macadamia integrifolia	6	5	1					E	
	Roupala complicata								N	
Rhamnaceae	*Colubrina arborescens*	4				4			N	
	Colubrina ferruginosa			x						
	Colubrina sp.							x		
	Rhamnus capraefolia							x	N	
Rosaceae	*Crataegus pubescens*							x	N	
	Eriobotria japonica	4					4		E	
	Prunus annularis								X	
	Prunus armeniaca								E	
	Prunus brachybotrya								N	
	Prunus cerasus								E	
	Prunus lundelliana							x	N	
	Prunus persica								E	
	Prunus spp	1	1						N	
	Rosa sempervirens			x						
Rubiaceae	*Alibertia edulis*							x	N	
	Blepharidium mexicanum							x	N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Rubiaceae	*Calycophyllum candidissimum*	2				2			N	
	Chomelia spinosa								N	
	Cinchona officinalis								N	
	Famarea schultesii							x		
	Faramea occidentalis								N	
	Genipa americana	1		1					N	
	Hamelia calycosa							x	N	
	Hamelia patens		x						N	
	Hoffmania carlsoniae							x		
	Hoffmania excelsa							x		
	Hoffmania nicotanaefolia							x		
	Posoqueria latifolia							x	N	
	Psychotria chiapensis							x	N	
	Psychotria costivenia							x		
	Psychotria panamensis							x	N	
	Simira salvadorensis							x	N	E
	Simira sp.							x	N	
	Sommera grandis							x		
Rutaceae	*Casimiroa edulis*	13		4		6	3	x	N	
	Citrus aurantifolia	24	1	9		7	7	X	E	
	Citrus grandis		x						E	
	Citrus limettoides	1	1							
	Citrus limon	4				4				
	Citrus medica								E	
	Citrus nobilis								E	
	Citrus paradisi	5	1			4			E	
	Citrus reticulata	8	X	3		5		X	E	
	Citrus sinensis	81	4	8		45	24	X	E	
	Citrus spp	36	6	22	5	3				
	Esenbeckia belizensis							x	N	
	Zanthoxylum kellermanii								N	
	Zanthoxylum limoncello								N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Rutaceae	*Zanthoxylum microcarpum*								N	
	Zanthoxylum procerum	10			8	2			N	
Salicaceae	*Salix* spp	1				1				
Sapindaceae	*Allophylus sp.*							x		
	Cupania cinerea	2				2			N	
	Cupania cubensis	1				1				
	Cupania dentata	10				6	4	X	N	
	Cupania glabra								N	
	Cupania sp.							x		
	Exothea paniculata								N	
	Melicoccus bijugatus	5		2		3			N	
	Sapindus saponaria	8				8		x	N	
Sapotaceae	*Calocarpum mammosum*	1		X		1			N	
	Calocarpum sapota			x				x		
	Chrysophyllum cainito	10		8		2		X		
	Chrysophyllum mexicanum							x	N	
	Dipholis minutiflora								N	
	Lucuma campechiana								N	
	Lucuma laurentifolia								N	
	Manilkara chicle	3		2		1			N	
	Manilkara spp	1		1						
	Manilkara zapota								N	
	Micropholis mexicana								N	
	Pouteria campechiana							x	N	
	Pouteria durlandii							x	N	
	Pouteria sapota	9		1		6	2		N	
	Sideroxylon spp	6		6						
	Sideroxylum capiri	1				1				
Simaroubaceae	*Alvaradoa amorphoides*								N	
	Picramnia sp.							x		
	Quassia amara								N	
	Simarouba glauca	16		5		11			N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Solanaceae	*Acnistus arborescens*	9				9			N	
	Cestrum dumetorum							x		
	Cestrum sp.							x	N	
	Datura stramonium	1		1					N	
	Nicotiana glauca								N	
	Solanum aphyodendron							x		
	Solanum bansii	25	2	2		17	4			
	Solanum erianthum	17		8		6	3		N	
	Solanum lanceolatum			x					N	
	Solanum rovirosanum							x		
	Solanum rugosum							x		
	Solanum sp.							x		
Staphyleaceae	*Huertea cubensis*								N	E
	Turpinia occidentalis	1				1			N	
Sterculiaceae	*Guazuma ulmifolia*	42	3	7		26	6		N	
	Sterculia apetala	2		1			1		N	
	Sterculia mexicana							x	N	
	Theobroma cacao	9	1	1	1	5	1	X	N	
Styracaceae	*Styrax argenteus*	6		4		1	1		N	
Symplocaceae	*Symplocos pycnantha*							x	N	
Theaceae	*Laplacea grandis*								N	
Thunbergiaceae	*Psidia grandiflora*								N	
Tiliaceae	*Apeiba tiboubou*	1		1					N	
	Belotia campbellii								N	
	Belotia mexicana							x	N	
	Carpodiptera ameliae								N	
	Heliocarpus appendiculatus	20				20		x	N	
	Heliocarpus donnell-smithii							x	N	
	Heliocarpus mexicanus	2		2				X	N	
	Heliocarpus reticulatus							x		
	Heliocarpus sp.							x		
	Luehea candida								N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Tiliaceae	*Luehea speciosa*	7				7			N	
	Mortoniodendron vestitum							x		
	Muntingia calabura							x	N	
	Mutingia calabura	3				2	1			
Turneraceae	*Erblichia odorata*							x		
Ulmaceae	*Trema micrantha*							x	N	
	Ulmus mexicana							x	N	
Unknown	*Amirys pinnata*	1				1			N	
Unknown	*Amonis gricea*			x						
Unknown	*Chiococca nocturna*								N	
Unknown	*Cojoyo colorado*	1				1				
Unknown	*Conurtia pyramidata*									
Unknown	*Elytharia imbricata*								N	
Unknown	*Iverine calea*	2		2						
Unknown	*Jaracatia mexicana*	1				1				
Unknown	*Koanophyllom pittieri*									
Unknown	*Laetia thania*	1				1				
Unknown	*Languncularia racemosa*	1				1				
Unknown	*Mastichodendrom capiri*	8		1		5	2		N	E
Unknown	*Mediosma* spp									
Unknown	*Mirandaceltis monoica*								N	
Unknown	*Montanoa dumicela*									
Unknown	*Ojoche colorado*	1				1				
Unknown	*Parmetierra edulis*	1					1		N	
Unknown	*Penthaclera macroloba*	1				1				
Unknown	*Pseudosamanea guachape*								N	
Unknown	*Trichosppermun mexicanum*	10		10						
Unknown	*Vanguena madagascarinsis*	1		1						
Urticaceae	*Myriocarpa longipes*	11		11				X	N	
	Urera caracassana	1				1				
	Urera corallina								N	
	Urera eggersii	2				2			N	

Family	Species	Total Abundance	C. Rica	El Sal.	Guat.	Nic.	Hon.	Mex.	Native	Extinction Risk
Verbenaceae	*Callicarpa* sp.							x		
	Citharexylum caudatum								N	
	Cornutia grandiflora							x		
	Cornutia pyramidata	4	1			3			N	
	Cornutia sp.							x		
	Gmelina arborea								E	
	Lippia chiapasensis							x	N	
	Lippia myriocephala	16		x		16		X	N	
	Lippia umbellata								N	
	Tectona grandis	4	2			2			E	
Violaceae	*Orthion subssesile*							x	N	
Vochysiaceae	*Vochysia guatemalensis*								N	
Winteraceae	*Drimys granadensis*	1				1				

Appendix 2. Biodiversity Coffee References (161 Total).

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