Agroforest Syst (2010) 78:269–286
DOI 10.1007/s10457-009-9241-y

Effects of *Inga densiflora* on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica

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Received: 9 February 2009 / Accepted: 10 June 2009 / Published online: 28 June 2009

Abstract The advantages of associating shade trees in coffee agroforestry systems (AFS) are generally thought to be restricted mostly to poor soil and sub-optimal ecological conditions for coffee cultivation whereas their role in optimal conditions remains controversial. Thus, the objective of this study was to investigate, under the optimal coffee cultivation conditions of the Central Valley of Costa Rica, the impact of *Inga densiflora*, a very common shade tree in Central America, on the microclimate, yield and vegetative development of shaded coffee in comparison to coffee monoculture (MC). Maximum temperature of shaded coffee leaves was reduced by up to 5°C relative to coffee leaf temperature in MC. The minimum air temperature at night was 0.5°C higher in AFS than air temperature in MC demonstrating the buffering effects of shade trees. As judged by the lower relative extractable water (REW) in the deep soil layers during the dry season, water use in AFS was higher than in MC. Nevertheless, competition for water between coffee and associated trees was assumed to be limited as REW in the 0–150 cm soil layer was always higher than 0.3 in shaded coffee compared to 0.4 in monoculture. Coffee production was quite similar in both systems during the establishment of shade trees, however a yield decrease of 30% was observed in AFS compared to MC with a decrease in radiation transmittance to less than 40% during the latter years in the absence of an adequate shade tree pruning. As a result of the high contribution (60%) of shade trees to overall biomass, permanent aerial biomass accumulation in AFS amounted to two times the biomass accumulated in MC after 7 years. Thus provided an adequate pruning, *Inga*-shaded plantations appeared more advantageous than MC in optimal conditions, especially considering the fact that coffee AFS provides high quality coffee, farmers' revenue diversification and environmental benefits.

Keywords Agroforestry · Biomass · Coffee yield · Fuelwood · Leaf temperature · Light interception · Shade

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Introduction

Coffee (*Coffea arabica* L.) presents features of a shade plant, with a low light compensation point and photo-inhibition at high solar radiation (Kumar Tieszen 1980; Da Matta 2004; Franck 2005). Nonetheless, coffee is cultivated under various management schemes from heavy shade to full sun, distinct climate conditions from optimal to sub-optimal ones, and varying intensification regimes according to farmers' constraints and needs in a highly fluctuating market context. Coffee cultivation under agroforestry systems (AFS) may be advantageous with respect to coffee grown in full sun monoculture for the following reasons: (1) by modifying the micro-environment, shade trees reduce coffee stress and flowering intensity, and hence overbearing and dieback of coffee plants while improving coffee quality; and (2) trees also enhance soil fertility by nitrogen fixation, soil organic matter accumulation and improved nutrient cycling (Beer 1987; Willson 1985; Barradas and Fanjul 1986; Vaast et al. 2005a). On the other hand, shade trees may compete with coffee for resources such as light, water and soil nutrients (Beer 1987; Willey 1975). For these reasons, trees can reduce coffee yield in optimal cultivation conditions, especially when tree density is high (Muschler 1999; Tavares et al. 1999; Viera et al. 1999; Harmand et al. 2007a).

The influence of shade trees on coffee depends on soil and climatic conditions, but also on the tree species themselves, fertilization regime, and pest and disease control (Beer et al. 1998). It is demonstrated that advantages of associated shade trees are very important for coffee production in poor soils and under sub-optimal ecological conditions (Muschler and Bonnemann 1997; Muschler 1999) while their effects under optimal conditions remain controversial. On top of reducing coffee flowering intensity and hence yield, shade can result in a very humid micro-environment conducive to higher incidence of fungal diseases such as leaf rust (*Hemileia vastatrix*) and American leaf spot (*Mycena citricolor*), especially at high altitude and cloudy conditions (Avelino et al. 2006, 2007).

In addition to their effects at plot scale, coffee AFS are also relevant in terms of carbon sequestration, conservation of biodiversity, reduced pressure on forest remnants via fuel wood provision by associated trees, and enhanced tree cover and connectivity at the landscape level (Vaast et al. 2005b). Albrecht and Kandji (2003) considered AFS as a major potential sink for C, with trees managed together with crops and/or animals. AFS may be eligible as C sinks in LULUCF (Land Use, Land-Use Change and Forestry) projects in the framework of the CMD (Clean Mechanism Development) of the Kyoto Protocol, depending on the definition of forest given by the host country (Pearson et al. 2005). AFS offer great potential as biomass energy providers and thus present interesting opportunities in CO_2 mitigation through the substitution of fossil fuel by wood energy and the protection of existing forests (Verchot et al. 2005).

Thus, the objective of this study was to investigate, in the optimal coffee cultivation conditions of the Central Valley of Costa Rica, the impact of *Inga densiflora*, a shade tree predominant in coffee areas of Central America, on the microclimate, growth and yield of coffee as well as the aerial biomass of the shade tree itself.

Materials and methods

Site description and experimental design

The study was conducted on the experimental farm of the research station of the Coffee Institute of Costa Rica (ICAFE), located in San Pedro de Barva in the Central Valley of Costa Rica (10°02′16″N, 84°08′17″O) at an altitude of 1,200 m. The climate is relatively cool with a mean annual temperature of 21°C, a mean annual precipitation of 2,300 mm and a definite dry season from January to April.

The experimental design included two adjacent coffee plots following the same coffee monoculture for over 15 years: a shaded one or agroforestry system (AFS) with an area of 1,500 m^2 and a second one without shade trees or monoculture (MC) with an area of 1,200 m^2. In both plots, coffee was planted in 1997 with a spacing of 2 m between rows and 1 m within a row, which resulted in densities of 5,000 and 4,722 coffee plants ha^{-1} for MC and AFS, respectively, and with an average of three coffee stems per planting hole. In AFS, *Inga densiflora* (Benth) was planted within the coffee rows at a spacing of 6 m × 6 m (278 trees ha^{-1}). The plots were equally intensively managed with a fertilization regime composed of 250 N; 30 P; 100 K; 80 Mg; 5 B_2O_3; 50 S and 60 CaO kg ha^{-1} year^{-1}, following the recommendations of ICAFE (1998).

The slope of the site was about 5%. The soil, derived from the weathering of volcanic ashes, belongs to the Andosols, and is classified as a Dystric Haplustands with loamy clay texture, well-structured, deep and permeable, with low bulk density and high organic matter content (Mata and Ramirez 1999). Soil analyses were undertaken in 2004; pH was measured in a water suspension, and total soil C and N contents by total combustion using a Thermo Finnigan analyzer. The cation exchange capacity (CEC) was analyzed as described by Sumner and Miller (1996). The exchangeable Ca, Mg were extracted with KCl, and K and P extracted in sodium bicarbonate. Texture was determined by the method of Bouyocos. The water field pore space (WFPS) at field capacity and wilting point (pressure plate) were determined as described by Henríquez and Cabalceta (1999).

Species involved

Coffea arabica L. "Caturra" is a highly productive dwarf variety, but depends on intensive fertilization to maintain a high productivity. Coffee forms its flower buds mainly on branches that developed during the previous year. In the present experiment, flowering initiated after the first rains at the beginning of April–May and the peak of harvest occurred in December and January. Pruning of coffee plants was undertaken once a year at the beginning of the rainy season and consisted in the elimination of orthotropic suckers on the main stems according to the recommendations of ICAFE (1998). No coffee coppicing (i.e., rejuvenation of the aerial part of the coffee plants) was performed during the 6 years of production.

Inga densiflora Benth. (*I. langlassei*, *I. microdonta*, *I. mollifoliola*, *I. montealegrei*, *I. monticola*, *I. sordida*, and *I. titiribiana*) is a fast-growing legume tree species distributed from Mexico to Brazil. It is used as a shade tree for coffee and cocoa from Mesoamerica to Brazil and is well adapted to a wide altitudinal range (100–1,400 m), but is more common above 600 m (Zamora and Pennington 2001). This is a low tree (on average 6–18 m in height) with an irregular canopy and leaves slightly hairy. It produces flat and banana-shaped fruits, up to 30 cm long, sometimes sold in markets of Latin America. Its wood is of low timber value and is mainly used as fuel wood. Consequently, this tree species is mostly used as a service tree in agroforestry systems as it provides shade for coffee and mulch through pruning during the production cycle. In the present experiment, trees were managed to maintain 2–3 stems, with an annual pruning of the lower branches in the month of September to reduce the excessive shade for coffee during the late period of the rainy season, according to the recommendations of ICAFE (1998).

Meteorology

An automatic weather station was installed in an open area next to the experimental plots and meteorological variables were monitored during the 2 years (2004–2005) of experimental data collection. Relative humidity (RH in %) and air temperature (T in °C) were measured by sensors (HMP45C, Campbell Scientific Corp., Logan, UT) at a height of 2 m. The photon flux density (PFD) was measured with quantum sensors (SOLEMS PAR-CBE 80, Palaiseau, France) and wind speed with an anemometer (Model 05103-5 Wind-monitor) also installed at a height of 2 m. Rainfall was measured with a tipping bucket gauge (Model ARG 100). Values were measured every 30 s and averages over 15 min were recorded with a datalogger (CR10X Campbell Scientific Instruments). Quarter-hourly reference evapo-transpiration (ETo in mm) was estimated by the FAO Penman–Monteith equation (Allen et al. 1998) with the following inputs from the meteorological station in the open: wind speed, T, RH and solar radiation estimated from PFD values with the conversion factor of 2.07 μmol m^{-2} s^{-1} per J m^{-2} as recommended by Ting and Giacomelli (1987).

Radiation transmission and interception

Level of shade was measured as the proportion of PFD intercepted by shade tree canopy relative to PFD in the open during 10 days (day 7–day 16) per month during the 2 years of study. PAR-CBE 80 sensors were fixed on the top of the orthotropic stem of four coffee plants positioned at 1 and 3 m from shade trees to measure coffee PFD availability under shade trees. Sensors were cross-calibrated with each other prior to installation in the field. They were fixed horizontally on an iron rod at an approximate height of 2.5 m to ensure that these sensors remained above the coffee canopy during the whole experimental measurement period. Values were measured every 30 s and averages over 15 min were recorded with a datalogger (CR10X Campbell Scientific Instruments). In order to provide an estimate of spatially averaged light transmittance and shade level at the plot scale, hemispherical photographs were undertaken twice a year (detailed methodology provided below).

Leaf temperature

Leaf temperature was measured with a copper-constantan micro-thermocouple attached to the underside of seven leaves per system. These leaves were selected on branches located in three strata (upper, medium and lower) of the coffee plant canopy. For each stratum, selected leaves were located at the periphery or in the middle part of the branch. Values were measured every 30 s and averages over 15 min were recorded with a datalogger (CR10X Campbell Scientific Instruments). During the measurements, all sensors and cables were placed in the shade to avoid heating effects due to direct sun exposure.

Soil water content

The soil volumetric water content was monitored in the following layers: 0–30, 30–60, 60–90, 90–120 and 120–150 cm with time domain reflectrometry (TDR) probes installed at 50 cm away from coffee plants (6 and 9 TDR probes for MC and AFS, respectively). Every 10 days, measurements of TDR reading time were undertaken with a portable apparatus (MP-917, ESI, Environmental Sensors Inc.) for each probe and at every layer. During 1 year, soil was also sampled monthly with an auger at the same depths at approximately 1 m away from each TDR probe and at 50 cm away from coffee plants in order to calibrate the time reflectrometry of each probe and every layer with the soil water content measured gravimetrically and converted to volumetric water content using bulk density for each soil layer. With these data, the relative extractible water (REW) was calculated as follow:

$$\mathrm{REW} = \left[\frac{\theta - \theta_{\mathrm{wp}}}{\theta_{\mathrm{fc}} - \theta_{\mathrm{wp}}}\right]$$

where θ is the actual soil volumetric water content, θ_{wp} is soil volumetric water content at wilting point and θ_{fc} is soil volumetric water content at field capacity.

Tree growth leaf area index and biomass monitoring

The architecture of the tree species consisted in a short trunk ramifying into two to three vertical stems at a mean height of 75 cm. Therefore, diameter at breast height (DBH at 130 cm) of all stems, generally two to three per tree, for all individual shade trees (41 trees) was measured in October 2002, January 2004, July 2004, January 2005 and August 2005 to estimate the total tree stem basal area of the plantation. The volume of the non-ramified, lower part of the trunk was measured in January 2005 and converted into dry matter (DM) using a specific weight of 447 kg DM m^{-3} established from oven-dried wood samples. Furthermore, total biomasses of ten and seven stems of *I. densiflora* were measured in 2004 and 2005, respectively. Allometric relationships between stem diameter at 130 cm height (D_{130}) and biomasses of all components were developed to provide reliable estimates of leaves, branches, stems and total above-ground tree biomass. These relationships enabled to estimate tree biomass non-destructively throughout the experimental period. Additionally, seasonal estimation of tree leaf area index (LAI) was carried out with hemispherical photographs. Based on the general phenology of the shade trees observed on the ICAFE research station, two series of hemispherical photographs were undertaken; one series during the dry season (February) when trees shed their foliage and a second one during the rainy season (August–September) when the foliage density is high. The hemispherical photographs were taken above the coffee canopy at 100 grid points in a 400 m^2 plot. The hemispherical photographs were analyzed with the gap light analyzer (GLA) software and were also used to estimate seasonal fluctuations in radiation transmittance and shade level through the canopy of *I. densiflora*.

Coffee growth, leaf area index and biomass monitoring

In both systems, coffee stem basal diameter was measured at 10 cm above soil surface in a sub-plot area of 312 m^2 (156 coffee plants) in January 2004, August 2004, January 2005 and August 2005. These measurements were used to estimate the total coffee stem basal area in each coffee system on a per-hectare basis. The leaf area of eight coffee plants was measured per system to estimate coffee LAI in February 2004, September 2004, February 2005, April 2005, June 2005 and October 2005. In February 2004, it consisted in the scanning of all the individual leaves of each plant with an image-scanning program (Whinrhizo, V.3.9, Regent Instruments) to determine precisely their respective leaf area as well as the measurements of their length and the width; an estimation for the individual leaf area (leaf area = 0.69 LW) was determined as the product of leaf length (L) and width (W) by correlation with the precise leaf area derived from the scanning process ($R^2 = 0.96$). As these measurements were labor intensive and time-consuming, a simplification was developed to estimate LAI for the subsequent dates. It consisted in counting all the leaves of a coffee plant and multiplying this total leaf number by the average leaf area derived from measurements undertaken in February 2004. Biomass measurements were carried out on eight coffee plants in May 2004, January 2005 and July 2005. For each coffee plant, the total length and basal diameter of all the stems (at 10 cm above soil surface) were recorded. Fresh weight of stems, branches, leaves, tap roots and coarse roots was measured. For each plant, sub-samples of these components were taken and oven dried at 60°C during 72 h to estimate their dry biomasses and thereafter to extrapolate the total biomass of each component.

The specific leaf area (SLA) of coffee was measured for both systems on six plants and at four strata within the coffee canopy, located on the node positions 8th, 22nd, 37th and 51st from the stem top. Precise leaf area of individual leaves was determined via the scanning process exposed previously. Individual leaves were oven dried at 60°C during 72 h and weighted thereafter with a high precision balance to derive their individual SLA.

Yield monitoring

Coffee production was measured during six consecutive harvests from 1999 to 2005. In both MC and AFS, harvest was monitored on 10 rows (sub-plots) constituted of 15 coffee plants. The annual production was obtained by summing the weight of fresh coffee fruits harvested during the 4–5 harvest events of the harvest season. Data were extrapolated to yield per ha and the green bean coffee yield was obtained from sub-samples after wet processing of berries, drying of coffee parchments down to a 12% moisture content and de-husking.

Fine roots studies

Measurements of fine root (diameter < 2 mm) biomass of coffee in MC and of coffee together with shade tree in AFS were undertaken during the rainy season of 2005. Roots were sampled with a cylindrical auger of 80 mm internal diameter. In AFS, fine root biomass was studied with respect to the following factors: (1) distance from the nearest shade tree; (2) position relative to the coffee row and inter-row; and (3) soil depth. To assess the effect of distance to the nearest shade tree on the root system, samples were collected on a diagonal across each plot at 1.5 and 3.6 m from the trees. At the two distances from the tree, root samples on the coffee row were collected at 50 cm from the coffee stem while root samples on the coffee inter-row were collected 1 m from the coffee stem. To study the vertical distribution of fine roots, samples were collected at each position and distance, down to a depth of 100 cm in 10 cm increments. After sampling, soil cores were stored at 10°C and processed within 2 week. Roots were separated from soil and organic debris to evaluate root biomass after oven drying at 60°C during 72 h. For AFS, roots were not separated according to plant species due to the difficulty in distinguishing roots of *I. densiflora* from that of *C. arabica*. Total fine root biomass per hectare was evaluated as the mean of the two sampling positions.

Statistical analyses

For coffee yield, aerial biomass, root biomass, SLA and the microclimate variables (PFD and leaf temperature), mean and confidence intervals were computed. Regression analyses were performed with SAS release 8 (SAS Institute Inc. Cary, NA, USA, 1999) to develop allometric relationships for the biomass of *I. densiflora*.

Results

Soil properties

There were small differences in soil properties from one sub-plot to another (Table 1). CEC was high in both sub-plots due to the high clay content and relative high values of organic carbon. Both soils had low pH and moderate values of exchangeable Ca, Mg and K. These results are in agreement with that of Mata and Ramirez (1999) indicating that soil nutrient concentrations of this volcanic region are generally adequate for coffee cultivation due to the naturally high soil fertility and frequent fertilizations.

Rainfall and evaporation patterns

The annual rainfall was particularly high in 2004 with 3,245 mm compared to 2,685 mm in 2005. Rainfall was concentrated from May to November with 3,057 mm (94%) and 2,495 mm (93%) for 2004 and 2005, respectively. Monthly rainfall ranged from 0 to 650 mm for the driest month and the wettest one, respectively. Monthly Penman-Monteith reference evaporation (ETo) varied between 70 and 170 mm and amounted to 1,310 and 1,178 mm year^{-1} for 2004 and 2005, respectively. Monthly ETo was higher than monthly rainfall from December to April with the cumulative rainfall of 188 mm (27% of ETo) and 190 mm (30% of ETo) in 2004 and 2005, respectively.

Table 1 Soil characteristics of the top 10 cm under a coffee agroforestry system (AFS) with *Inga densiflora* and in a coffee monoculture (MC) in San Pedro de Barva, Costa Rica. Mean ± standard error

Soil properties	Coffee system	
	MC	AFS
pH	4.92 ± 0.24	4.67 ± 0.06
Total C (%)	3.60 ± 0.14	3.70 ± 0.16
Total N (%)	0.32 ± 0.01	0.36 ± 0.01
CEC[a] (cmol kg^{-1})	42.47	44.12
Ca (cmol kg^{-1})	6.25	5.22
Mg (cmol kg^{-1})	2.08	2.48
K (cmol kg^{-1})	1.50	2.34
Sand (%)	36.9 ± 0.9	40.6 ± 0.7
Silt (%)	35.3 ± 1.0	37.1 ± 0.4
Clay (%)	27.9 ± 1.0	22.3 ± 0.7
Bulk density	1.00 ± 0.05	0.90 ± 0.05
WFPS[b]		
At field capacity	0.65	0.69
At wilting point	0.39	0.40

[a] Cation exchange capacity (CEC)

[b] Water field pore space (WFPS)

Effects of trees on microclimate

The mean diurnal time course of radiation transmitted through shade tree canopy in AFS depended on the season (Fig. 1). During the dry season (2005), the mean percentage of transmittance was 40% whereas it was only 25% during the wet season. In AFS, daily transmitted radiation was also affected by the loss of foliage during the dry season and canopy pruning reducing shade level during the month of September in the middle of the wet season (Fig. 1). During both years (2004 and 2005), shade level was lower in the dry season with values ranging from 40 to 50% whereas values were in the range of 70–75% in the wet season. During the dry months (January–April), solar radiation was high due to low cloudiness so that the total daily radiation available for coffee was almost 30–50% higher in the dry season (22–23 MJ m^3 day^{-1}) than in the wet season (12–15 MJ m^3 day^{-1}) in both systems.

The discontinuous nature of the tree canopy caused substantial local variation in shade level depending on the proximity of coffee plants to shade trees. The percentages of the radiation transmitted at one and 3 m from shade trees were quite different (Fig. 2). In the dry season, transmitted radiation measured at 1 m represented only 23% of the radiation measured in the open, while it represented 60% at 3 m. Furthermore, the solar angle affected the transmittance pattern; at 3 m from the shade tree, the highest values of transmittance were recorded around midday with values of 95%, while values were in the range of 30–35% in the morning and the afternoon. At a distance of 1 m, the highest values were registered between 9:00 and 11:00, after which they decreased down to 15–19%. During the wet season, the differences in transmittance between the two

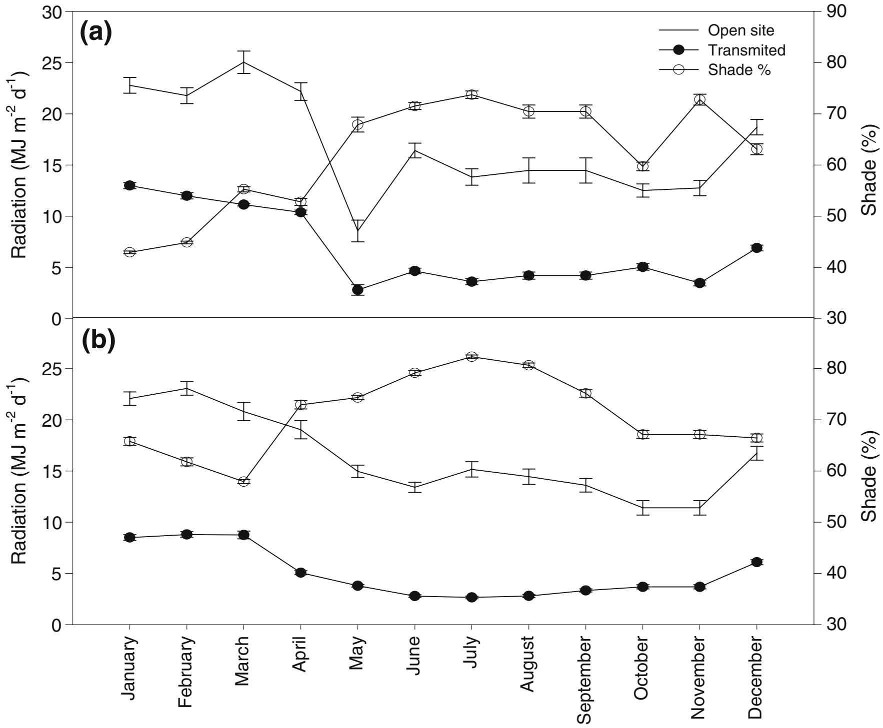


Fig. 1 Annual dynamics of daily transmitted radiation and shade level in a coffee agroforestry system with *Inga densiflora* in San Pedro de Barva, Costa Rica, in **a** 2004 and **b** 2005. *Vertical bars* denote ± standard errors

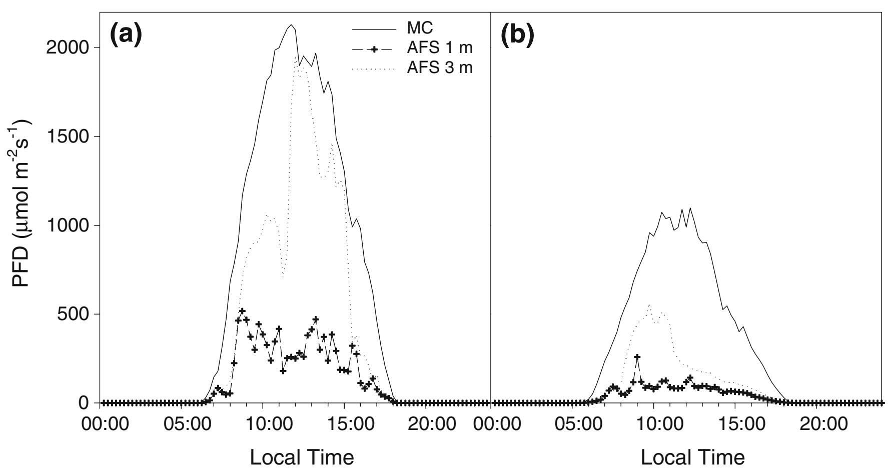


Fig. 2 Mean diurnal time courses for transmitted radiation in coffee monoculture (MC) and at 1 and 3 m from the base of *Inga densiflora* trees ($n = 8$) in a coffee agroforestry system (AFS) in San Pedro de Barva, Costa Rica, from consecutive measurements during 15 days in **a** April 2005 (dry season) and **b** October 2005 (rainy season)

distances were also important, but with lower values of transmittance at 3 m reaching their maximum (50–65%) in the morning hours (9:00–11:00) whereas the highest values at 1 m ranged from 24 to 35% between 8:00 and 13:00.

Seasonal differences between mean LAI of *I. densiflora* at plot scale were relatively small. The overall decrease in LAI from the wet season 2004 to the dry season 2005 was about 35% (or 0.47 m^2 m^{-2}), which translated into a seasonal change in the light transmittance (estimated by hemispherical photographs) to the coffee canopy (Table 2).

Measurements of leaf temperature in un-shaded coffee canopy and in coffee canopy grown under shade of *I. densiflora* showed a substantial buffering effect of shade on the thermal microenvironment (Fig. 3). During the dry and wet seasons, coffee leaves without shade experienced temperatures higher than air temperature (Fig. 3c, d), except for leaves located in the lower part of the canopy during

Table 2 Seasonal changes in canopy openness, leaf area index (LAI) and radiation transmittance through the canopy of *Inga densiflora*, estimated from hemispherical photographs, in a coffee agroforestry system in San Pedro de Barva, Costa Rica

	2004		2005	
	Dry season	Wet season	Dry season	Wet season
Canopy openness (%)	33.4 ± 0.7	30.25 ± 0.6	43.97 ± 0.7	33.8 ± 0.7
LAI ($m^2\ m^{-2}$)	1.14 ± 0.04	1.32 ± 0.03	0.85 ± 0.03	1.22 ± 0.04
Radiation transmittance (%)	43.2 ± 1.2	40.4 ± 1.1	54.72 ± 1.3	41.7 ± 1.4

Mean ± standard error

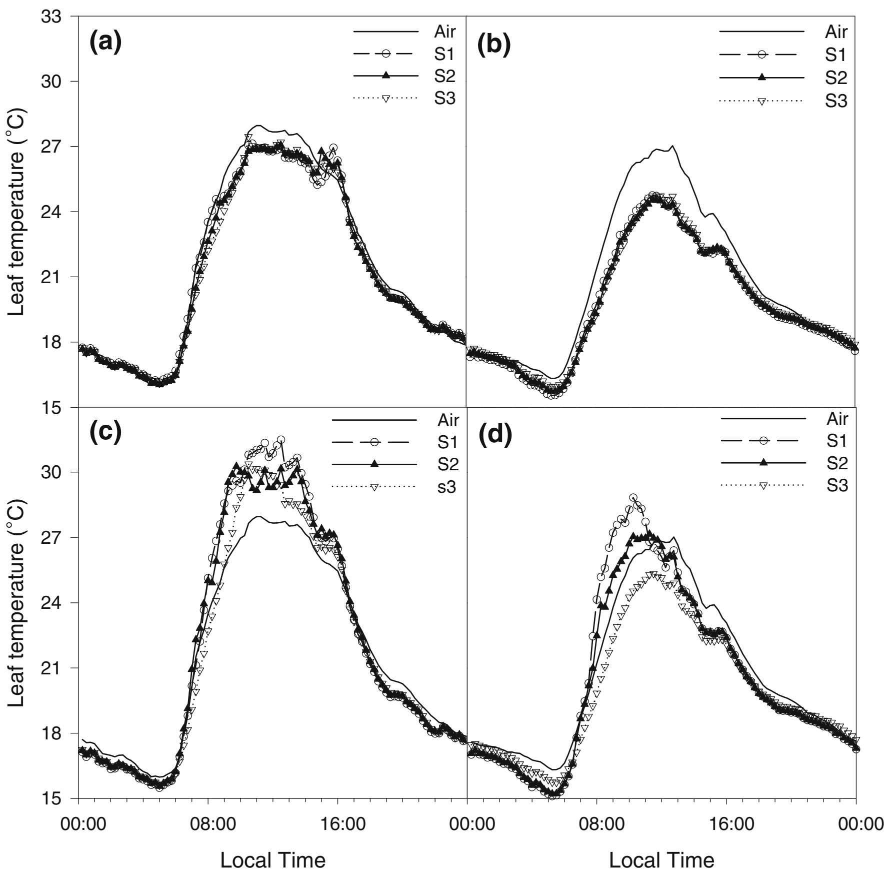


Fig. 3 Mean diurnal courses of coffee leaf temperature in three coffee canopy strata shaded by *Inga densiflora*[**a** dry season in April 2005, **b** rainy season in July 2005] and in monoculture [**c** dry season in April 2005, **d** rainy season in July 2005] in San Pedro de Barva, Costa Rica. (S1: *upper* coffee canopy stratum; S2: *middle* coffee canopy stratum; S3: *low* coffee canopy stratum. Values are monthly averages)

the rainy season. On the other hand, leaf temperature of shaded coffee was always lower than air temperature (Fig. 3a, b). Still, the differences between unshaded leaf temperature and air temperature were less important during the wet season, the main period of vegetative and reproductive growths. Mean maximum shaded coffee leaf temperature was reduced by up to 5°C relative to coffee leaf temperature in MC. The minimum leaf temperature at night was 0.5°C higher in AFS than air temperature demonstrating a two-way buffering effect of shade trees.

Effect of trees on soil water content

The lowest values of soil volumetric water content were registered from February to April 2004 corresponding to the last part of the dry season with the relative extractable water (REW) decreasing down to 0.23 in the 0–60 cm layer. MC and AFS profiles showed similar REW values at the 0–60 cm (Fig. 4). On the other end, soil moisture at deeper layers (60–120 and 120–150 cm) was lower in AFS than in MC. This difference was more pronounced during the dry season 2004 due to low rainfall in December 2003 and a marked dry season that ended late at the beginning of May 2004, compared to the shorter dry season 2005 with rainfall registered during March and April. Consequently, REW was always higher than 0.4 in both systems during the dry season 2005.

Effect of trees on coffee growth and production

For the six production cycles (1999/2000–2004/2005), annual coffee green bean yield were found to be higher at the experimental site for both systems (MC and AFS) than the average national yield (1.7 Mg ha^{-1}), except for 2003/2004 (Fig. 5). The cumulative yield over these six consecutive years was 10% lower in AFS than in MC. However, tree shade pruning in AFS was heavier in the period from 1997 to 2002 compared to the period from 2003 to 2005. Clearly, this strongly influenced coffee yield. Mean annual productions from 1999 to 2003 were similar in AFS and MC. During this period, shade level was low due to the small size of shade trees combined with

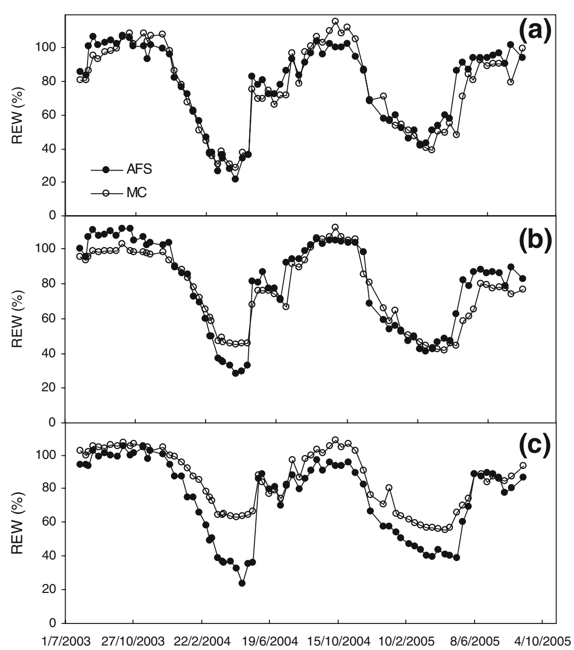


Fig. 4 Time course of the relative soil extractable water (REW) at depths of **a** 0–60 cm, **b** 60–120 cm and **c** 120–150 cm in a coffee monoculture (MC) and a coffee agroforestry system (AFS) in San Pedro de Barva, Costa Rica, measured from July 2003 to October 2005

heavy pruning twice a year. On the contrary, coffee yield in AFS was reduced by 29% compared to MC during the period from 2003 to 2005 due to a denser tree shade from already well developed trees and low pruning (Fig. 5). The highest yield reduction (38%) was registered during the last year of the study when the actual light transmittance varied between 40 and 50%.

Coffee stem basal area was higher in MC than in AFS (data not shown) due to a slightly higher stem diameter of individual coffee plant, together with a slightly higher coffee density in MC. Above-ground biomasses of coffee vegetative components were similar between AFS and MC during the 2 year period of monitoring, except for lower leaf and higher stem biomasses in AFS than in MC at the last measurement (Table 3). Estimated total above-ground coffee biomass was at its highest during the wet season 2004.

During the wet season 2004 when both aerial and below-ground biomasses were measured, the biomass of tap root and lateral coarse roots accounted for about 20% of the total coffee biomass (Table 3).

Although shade provided by *I. densiflora* had no major effect on coffee biomass, it strongly influenced leaf characteristics. SLA of shaded coffee plants was 18–21% higher than that of sun-grown coffee plants in all leaf positions within the coffee canopy. Width, length and area of individual leaves were also higher under the shade of *I. densiflora* compared to MC (data not shown). Despite this higher mean individual leaf area of shaded coffee, coffee LAI was similar in both systems from August 2003 to April 2005 with values ranging from 4.7 m^{-2} m^{-2} during the two wet seasons to as low as 2.2 m^{-2} m^{-2} during the two dry seasons.

Fine root characteristics

Fine root biomass was not affected by the proximity of shade trees in AFS as no biomass difference was observed at 1–3.5 m from the tree stem (data not shown).

In both systems, fine root biomass was concentrated within coffee rows and showed a marked decline in the inter-row. Additionally, fine root biomass was lower in MC than in AFS in the top 40 cm in the inter-row (Fig. 6) and consequently total fine root biomass recovered in augers was lower in

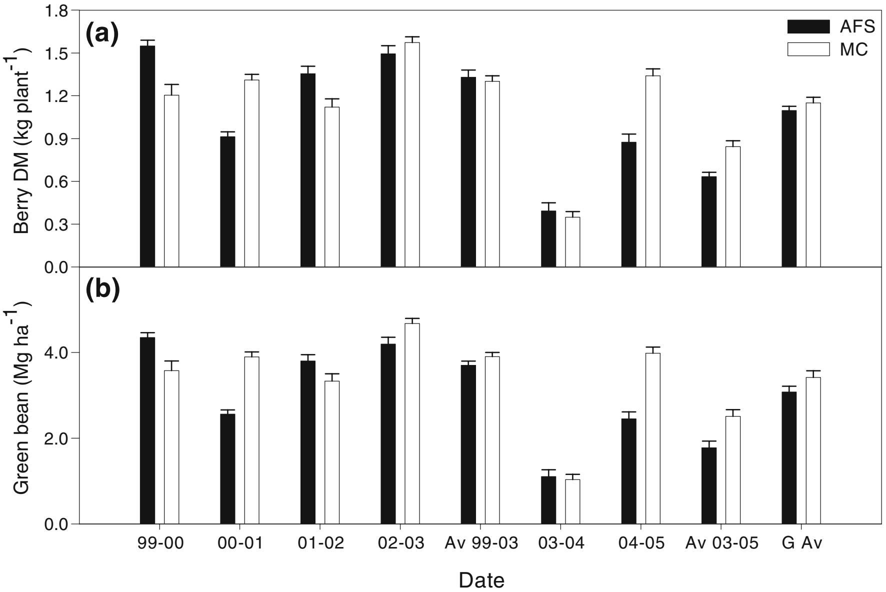


Fig. 5 Coffee berry dry matter per plant **a** and coffee green bean yield **b** in monoculture (MC) and in an agroforestry system (AFS) shaded by *Inga densiflora* in San Pedro de Barva, Costa Rica during six consecutive production cycles (Av: average over the considered period, G Av: grand average for the six production cycles). *Vertical bars* denote ± standard errors

Table 3 Dry biomass (Mg ha^{-1}) of the different coffee components (except berries) and tree components in an agroforestry system (AFS) and a monoculture (MC) in San Pedro de Barva, Costa Rica

	May 2004		January 2005		July 2005	
	AFS (Mg ha^{-1})	MC (Mg ha^{-1})	AFS (Mg ha^{-1})	MC (Mg ha^{-1})	AFS (Mg ha^{-1})	MC (Mg ha^{-1})
Coffee leaves	3.7 ± 0.5	3.8 ± 0.4	2.2 ± 0.2	2.7 ± 0.4	2.6 ± 0.2	3.7 ± 0.4
Coffee branches	5.3 ± 0.6	5.0 ± 0.3	4.5 ± 0.5	5.0 ± 0.5	3.4 ± 0.2	3.3 ± 0.5
Coffee stems	10.2 ± 0.9	9.2 ± 0.6	9.8 ± 0.9	8.8 ± 0.4	10.6 ± 0.7	8.9 ± 0.6
Total aerial coffee	19.2 ± 1.2	18.0 ± 0.8	16.5 ± 1.2	16.6 ± 1.0	16.5 ± 0.8	15.9 ± 1.3
Coffee tap root	3.3 ± 0.1	3.4 ± 0.3	–	–	–	–
Coffee lateral roots	1.8 ± 0.1	1.8 ± 0.2	–	–	–	–
Total coarse roots	5.1 ± 0.1	5.2 ± 0.4	–	–	–	–
Total coffee biomass	24.3 ± 1.2	23.2 ± 0.9	–	–	–	–
Tree leaves	3.74				2.23	
Tree branches	6.23				4.81	
Tree stems	15.10				15.42	
Tree trunk	3.93				4.49	
Total aerial tree	29.0				26.95	
Total fine roots					4.7 ± 1.3	4.1 ± 1.7

Mean ± standard error

MC (4.1 Mg DM ha^{-1}) than in AFS (4.7 Mg DM ha^{-1}; Table 3). Nevertheless, no differences in fine root biomass were found within rows between the two systems. In both systems, the root distribution within rows was relatively homogenous in the first 60 cm of soil where 75% of the total fine root biomass of the top 100 cm was concentrated. On the other hand, only 50% of the fine root biomass was present in the top 60 cm in the inter-row in MC in comparison to 70% in AFS, which demonstrated not only a difference in biomass but also in term of distribution. Trenches down to a depth of 1.5 m revealed the presence of fine roots of both species at this depth in both systems.

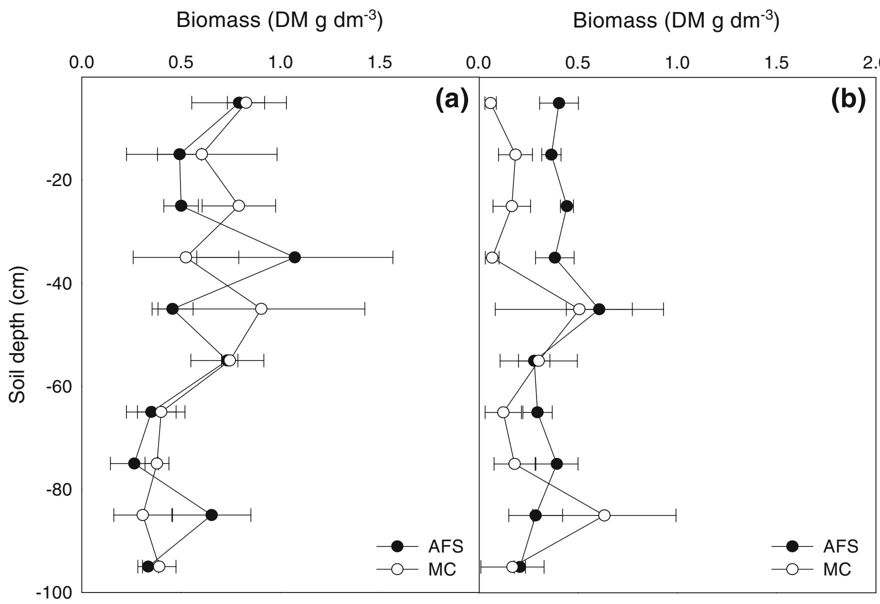


Fig. 6 Mean fine root biomass at various soil depths for *Coffea arabica* in monoculture (MC) and for *Inga densiflora* + *Coffea arabica* in an agroforestry system (AFS) in San Pedro de Barva, Costa Rica, **a** in coffee row and **b** in coffee inter-row. *Vertical bars* denote ± standard errors

Tree growth

Inga densiflora was severely pruned at approximately 1.3 m above ground after 2 years of growth in order to force trees to branch and grow on 2–3 stems. Thereafter, regular pruning of the basal branches ensured that trees continued to grow on these stems and precluded excessive shading of the under-storey coffee plants. Based on destructive measurements, the allometric relationships between DBH and biomasses (total, stem, branches and leaves) could be described as power functions (Table 4). The stems represented the main biomass component of the aerial tree biomass followed by secondary branches, trunk and leaves (Table 3).

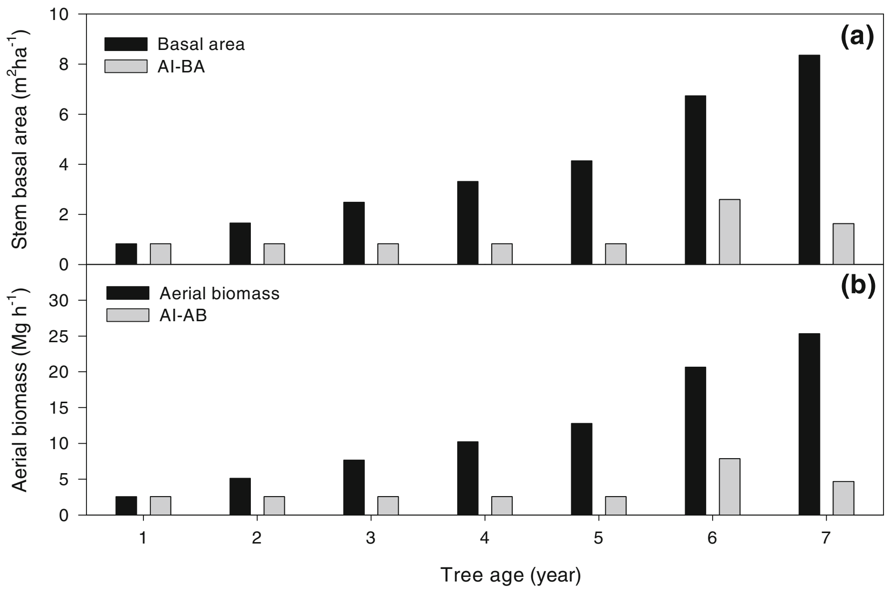
After 5 years, trees were well established with a mean stem DBH of 8.5 cm (minimum of 5.1 cm and maximum of 12.4 cm) and a stem basal area of 4.14 m^2 ha^{-1}. At 7 years, the stem basal area was 8.36 m^2 ha^{-1} with a mean annual increment of 1.2 m^2 ha^{-1} $year^{-1}$ for the whole period of 7 years, but with the highest annual increment observed during the last 2 years with 2.11 m^2 ha^{-1} $year^{-1}$ compared to the mean increment of 0.83 m^2 ha^{-1} $year^{-1}$ for the first 5 years (Fig. 7). After 5 years, the estimated tree aerial biomass was 14.9 Mg ha^{-1} (with an annual increment of 2.98 Mg ha^{-1} $year^{-1}$) whereas it was 29 Mg ha^{-1} after 7 years (with an annual increment of 7.04 Mg ha^{-1} $year^{-1}$ during the last 2 years). The mean annual increment in tree aerial biomass for the monitoring period of 7 years was 4.14 Mg ha^{-1} $year^{-1}$. The density of *Inga* trees (278 trees ha^{-1}) did not influence the total aerial biomass of coffee plants either at 7 years (2004) or 8 years (2005). At plot scale, the estimated coffee biomass was similar between systems, even though coffee density was slightly lower in AFS than in MC (Table 3). Due to the large contribution of shade tree (60%) to the total biomass, the total aerial biomass per plot in 2004 was 2.7 times higher in AFS (48.2 Mg ha^{-1}) than in MC (18 Mg ha^{-1}; Table 3).

Table 4 Allometric relationships between stem diameter at 130 cm (D_{130} in cm) and dry matter (DM in kg) of stem, branches, leaves and total aerial stem biomass for *Inga densiflora* in a coffee agroforestry system at San Pedro de Barva, Costa Rica

Biomass component	*a*	*b*	R^2	*P*
Stem	0.128	2.04	0.93	0.0001
Branches	0.06	1.99	0.93	0.0001
Leaves	0.014	2.36	0.92	0.0001
Total aerial stem biomass	0.34	1.8	0.92	0.0001

The relationships DM (kg) $= a \times (D_{130})^b$ were established with 17 tree stems whose values of D_{130} range from 8.5 to 18.5 cm

Fig. 7 Stem basal area (**a**) and total aerial biomass (**b**) of *Inga densiflora* in an agroforestry system in San Pedro de Barva, Costa Rica. [AI denotes annual increment for basal area (BA) or aerial biomass (AB)]



Discussion

Effects of shade trees on microclimate

In the present study, the canopy of *I. densiflora* trees had a strong influence on the microclimate experienced by coffee plants growing underneath, primarily through a reduction in light availability. Furthermore, the transmitted light was probably partially depleted in red wavelengths affecting the SLA and architecture of the under-story plants as documented by Staver et al. (2001). In AFS, coffee canopy light availability varied between 50 and 25% of the open radiation in the dry season and the wet season, respectively. These reductions are in the commonly observed range for coffee (40–70%) according to many studies (Beer et al. 1998; Muschler and Bonnemann 1997; Vaast et al. 2005a). The low radiation values during the wet season are explained by the high canopy development of associated shade trees. In the central region of Costa Rica, farmers commonly pruned shade trees to reduce shade level for coffee. These low radiation levels are common and acceptable because coffee photosynthetic rates are at their maximum at intermediate radiation levels (PFD of 600–900 μmol m^{-2} s^{-1}) in many coffee growing conditions (Vaast et al. 2005c; Franck et al. 2006). Indeed, coffee presents the characteristics of a shade adapted plant with a low light compensation point (15–20 μmol m^{-2} s^{-1}), low values of light saturation (500 and 900 μmol m^{-2} s^{-1} for shade and sun leaves, respectively) and photo-inhibition at high radiation values, especially under water or nitrogen limiting conditions (Kumar and Tieszen 1980; Cannel 1985; da Matta and Maestri 1997; Franck 2005).

In the present study, radiation distribution below the canopy of *I. densiflora* varied notably with distance to the shade tree and time of day as reported by many authors for various agroforestry systems (Feldhake 2001; Ong et al. 2000; Vaast et al. 2005a). Trees casted a shadow in their close surroundings resulting in a low transmittance of around 25% of open radiation, but with a quite stable daily pattern. On the other hand, the transmittance was much higher further away from shade trees, but coupled with a higher variability along the day. Large changes in transmittance at small scale clearly indicated that a characterization at large scale (whole shade tree canopy and even more so at plot scale) might not be sufficient to adequately describe the light availability for coffee plants growing underneath and the micro-environment effects on coffee physiological responses such as transpiration (van Kanten and Vaast 2006) and photosynthesis (Dauzat et al. 2001; Franck et al. 2006). Shade trees influence other microclimate variables such as temperature, humidity and wind as highlighted for coffee by several studies (Barradas and Fanjul 1986; Fernández and Muschler 1999; Muschler 1999; Dauzat et al. 2001; Vaast et al. 2005a). In the present study, temperature differences between coffee leaves in the open and under shade were found to vary between 1 and 7°C depending on time of the day, season and leaf position within the coffee canopy. These leaf temperature differences were similar to those reported in the literature for various coffee systems. In Mexico, Barradas and Fanjul (1986) reported that the presence of *Inga* trees (205 trees ha^{-1}) reduced the daily maximum temperature by 4–5°C and increased the minimum temperatures by 1–2°C. Similarly, 40–70% of shade provided by *Erythrina poeppigiana* or *Terminalia ivorensis* or *Eucalyptus deglupta* lowered leaf and soil temperatures in low elevation coffee zones to levels that are closer to optimum for coffee (Muschler and Bonnemann 1997; Vaast et al. 2007b). This reduction is of particular importance since the temperature range is between 18 and 24°C for an optimal photosynthesis of Arabica coffee (Cannel 1985; Vaast et al. 2005c; Franck et al. 2006) and with a detrimental effect of temperature above 25°C related to stomatal closure (Kumar and Tieszen 1980; Fanjul et al. 1985; Gutiérrez et al. 1994; Dauzat et al. 2001; van Kanten and Vaast 2006). Furthermore, additional positive temperature buffering effects of trees in AFS are also reported such as improved crop establishment, reduced soil evaporation, and enhanced activity of soil organisms (Ong et al. 2000; Rao et al. 1998; Martius et al. 2004).

Effect of shade trees on soil moisture

In many agroforestry studies, water competition between the main crops and associated trees appeared to be the most important factor causing a crop yield reduction (Rao et al. 1998; McIntyre et al. 1997; Govindarajan et al. 1996). However, most of these water studies in AFS have been undertaken in the semiarid tropics with a maximum of 600–700 mm during the cropping season. In the present study, the annual rainfall greatly exceeded ETo with rainfall/ETo ratios of 2.47 and 2.27 in 2004 and 2005, respectively. Soil water recharges were frequent even during the relatively long dry season of 4 months (January–April) as rainfalls represented 27% (188 mm) and 30% (190 mm) of ETo in the dry season of 2004 and 2005, respectively. The water use in AFS was 28 and 33% higher than in MC during 2004 and 2005, respectively (Siles 2007). With lower radiation and leaf temperature, water demand by coffee plants in AFS was lower than in MC (Siles 2007). On the other end, the water use of shade trees, fully sun-exposed, was certainly higher than that of coffee at all soil layers. Nonetheless, soil moisture did not appear to be more reduced in AFS than in MC over the profile down to a depth of 60 cm during the 2 years of monitoring; clearly REW was lower at deeper soil depths (60–120 and especially 120–150 cm). Volumetric water content data expressed as REW, suggest that soil water was not limiting in either systems. Although the first dry season 2004 was very pronounced, REW values of at least 0.3 and 0.4 were still observed in the top 150 cm in AFS and MC, respectively. During the milder dry season of 2005, REW (0–150 cm) was higher than 42% in both systems. These observations strongly suggest the presence of a low competition of limited duration between species for water use in this AFS due to the deep rooting pattern of *I. densiflora* (Zamora and Pennington 2001). With Grevillea trees (*Grevillea robusta* A. Cunn.; Proteaceae), a very common shade tree species in coffee systems of Guatemala and India, low water competition has also been reported in association to various crops due to its deep rooting pattern (Howard et al. 1996).

Effects of shade trees on coffee biomass and yield

In the present study, shade of *I. densiflora* resulted in a low decrease (10%) in coffee yield over 6 years in comparison with that in MC which are among the highest yields recorded worldwide, with production averaging 3.5–4.0 Mg of green bean per ha compared to less 500 kg in a large majority of producing countries (ICO 2008). However, during the latter years, the reduction in coffee yield accounted for 38% due to the fact that well developed shade trees provided a too dense shade in the absence of sufficient pruning. These values are in accordance with reports of many authors demonstrating that coffee yield generally decreased by 10–30% under shade conditions, depending on local ecological conditions and altitude in Central America (Beer et al. 1998; Staver et al. 2001; Vaast et al. 2005a, Harmand et al. 2007a, b). In Chiapas, Mexico, Soto-Pinto et al. (2000) reported that more than 50% of the coffee plantations gave poor yield (between 0.05 and 0.5 Mg/ha) because they were maintained under too high shade tree densities ranging from 100 to 998 trees ha^{-1} that considerably reduced light availability for coffee. Similar observations were also reported in Costa Rica for coffee associated with timber tree species (*Cordia alliodora*, *Terminalia amazonia* and *Eucalyptus deglupta*) in three low-altitude regions of Costa Rica where tree densities were too high and tree management virtually non-existent (Dzib et al. 2006). At low altitude in Southern Costa Rica, Vaast et al. (2007a) reported that a reduction (50–60%) in light availability for coffee shaded by *E. deglupta* and *Terminalia ivorensis* decreased noticeably the number of fruiting nodes, flowers and fruits in coffee AFS with respect to MC. In absence of other limiting conditions, Franck (2005) also observed a strong reduction in flowering intensity and hence fruit load down to 10% of the one registered in full sun for coffee exposed to an artificial shade of 75%. These observations confirmed the suggestions made by Cannell (1975, 1985) that the most important components of coffee yield, i.e., fruiting nodes and fruits per node, are both affected by low light level even when other ecological factors are favorable. Consequently, poor management of the shade strata such as the absence of shade tree thinning and inadequate canopy pruning is generally responsible for low coffee yield and has led to recommendations of shade elimination, especially at medium to high altitude (>1,100 m) in Central America. In these optimal conditions, the intensive practices promoted in the region are generally based on a shade reduction, up to a complete elimination, accompanied by an enhanced reliance on high-yielding cultivars planted at high densities, intensive use of chemical inputs and frequent pruning (Perfecto et al. 1996). With a proper shade management, a yield reduction in the range of 10–20% will still be resulting in yield 2–3 times higher than the world average one. Furthermore, this reduction can be financially compensated by the premium paid for improved quality (i.e., larger bean size and higher cup quality) as demonstrated in sub-optimal and optimal conditions of Central America (Guyot et al. 1996; Vaast et al. 2005a, 2006). An increased awareness of the negative impacts of intensive coffee monoculture on the environment is also contributing to the emergence of new markets for environmentally-friendly coffee in consuming countries. Especially in Central America, many certified sustainable coffee seals (Organic, Fair Trade, Rainforest Alliance, Bird friendly, Starbucks Coffee Practices, 4C, Nexpresso AAA) that promote the inclusion of shade trees in coffee systems, have penetrated the coffee sector and provided access to nice markets with a premium ranging from 20 to 100%, under the condition that coffee is of high quality (Vaast et al. 2005b). Central American countries, particularly Costa Rica, have also started implementing pilot schemes rewarding farmers for maintaining tree in their coffee plantations via payment for environmental services.

No differences in coffee dry matter components (except coffee berries) were observed between AFS and MC with the exception of lower values of coffee leaf dry matter and LAI during the wet season 2005 in AFS. Therefore, the similar permanent coffee biomass of both systems suggested an absence of competition for resources between the shade species and coffee in AFS under the optimal conditions and intensive fertilization regime of the present study. Although the shade of *I. densiflora* did not affect coffee biomass (except coffee berries), it had a strong effect on coffee leaf traits such as enhancing SLA and mean individual leaf area in AFS compared to MC. Vaast et al. (2005c) and Franck (2005) also found a highly significant effect with uniform shade provided by artificial shade on leaf traits such as SLA, individual leaf area, and leaf nitrogen content. Despite the higher individual leaf area of coffee in AFS, similar LAI values in AFS and MC during the first five monitoring dates and over a period of 18 months, can be explained by a higher quantity of leaves per coffee plant in MC that compensated the lower mean individual leaf area. It is worth mentioning that for both systems the seasonal variation in LAI followed that of the soil moisture as reported by Matoso Campanha et al. (2004).

Small but important differences were observed in terms of biomass and distribution of roots between MC and AFS. In AFS, the higher root biomass, observed in the inter-row than on the coffee row, might be due to the soil colonization by tree roots, but the attempt to differentiate coffee and tree roots was unsuccessful. On the coffee row, no differences in root biomass were observed between MC and AFS. In another study on roots of *E. deglupta* associated with coffee, Schaller et al. (2003) showed that there was complementarity in root distribution of coffee and shade trees that promoted a more homogeneous distribution in AFS than in MC, hence suggesting an enhanced efficiency in terms of soil exploration and exploitation. This complementarity in root distribution between the shaded crops (with more superficial root systems concentrated on the row) and associated trees (with deeper root systems) is generally cited as the main reason for the low competition for nutrients and water in AFS (Beer et al. 1998). In the present study, the low competition for soil resources could be explained by the deep and easily colonized volcanic soil, which allowed root colonization down to more than 200 cm (visual estimate). Furthermore, coffee vegetative and reproductive growth were concentrated in the wet season during which there was no water limitation due to the fact that rainfall exceeded ETo and soil was almost constantly at field capacity. Competition for nutrients is often cited as a major concern in coffee AFS (Beer et al. 1998), but was unlikely in the present study due to the large annual applications of fertilizers (250 kg N; 30 kg P; 100 kg K, 80 kg Mg and 60 kg Ca) in excess of plant uptake (Harmand et al. 2007a, b) in a fairly fertile soil and thus can be excluded as an explanation of the observed coffee yield reduction in AFS compared to MC. Therefore, it appears that in the present study light reduction is the most probable cause for the reduction in coffee yield in AFS, since the shade affected directly the production of productive nodes and flowers buds, and that no other limiting effect was apparent when comparing the two systems.

The basal area and aerial biomass of *I. densiflora* trees were 8.36 m^2 ha^{-1} and 29 Mg ha^{-1} at 7 years, with a mean annual increment of 1.2 m^{-2} ha^{-1} $year^{-1}$ and 4.14 Mg ha^{-1} $year^{-1}$, respectively. This mean annual biomass accumulation in the shade trees is much larger than the reduction in coffee biomass production under shade evaluated at 1.5 Mg DM berries ha^{-1} $year^{-1}$ for the period 2003–2005. Other coffee AFS studies reported similar values for stem basal area and aerial biomass accumulation with respect to the present study (Suarez et al. 2004; De Miguel et al. 2004). Nevertheless, these values appeared to be low when compared with the annual increments of 9.9 Mg ha^{-1} $year^{-1}$ for *I. densiflora* after 3 years in plantation in Jatun Sacha, Ecuador (Pennington 1998) with tree density four times higher than on the present site as well as a forest-like management without pruning.

With the permanent coffee biomass in AFS not being affected by the shade of *I. densiflora*, the combined aerial biomass of coffee and shade trees was three times higher than in MC. This demonstrates the advantage of a mixed system in terms of biomass productivity and accumulation. This aerial biomass accumulation represents an important carbon (C) sequestration by the system. In Central America where *Inga* species predominate in coffee plantations, fuel wood originating from coffee AFS is an important resource for rural families as household energy and/or revenues (Beer et al. 1998; Vaast et al. 2007b). Murphy and Yau (1998) recorded high calorific values of different *Inga* species and concluded that these calorific values combined with high biomass productivity represent a great potential in terms of energy for the coffee regions.

Conclusion

The major effects of shade trees on the microclimate experienced by coffee plants can be summarized as: (1) a reduction in transmitted light and (2) an improvement in microclimatic conditions through a reduction of air and coffee leaf temperature extremes. As indicated by REW values above 0.3 at the end of the dry seasons, we suspect that the water conditions were apparently non-limiting and low competition for water use between coffee and shade trees might have occurred only for a very short period of time. Over the first four consecutive production cycles, the low yield reduction due to shade can be attributed to frequent tree pruning combined with an intensive fertilization and highly favorable ecological conditions for coffee cultivation. During the last 2 years in the absence of an adequate pruning, light reduction was the most obvious reason for coffee yield reduction with a decrease of 38% in AFS compared to MC when radiation transmittance decreased to less than 40%. Aerial biomass accumulation in AFS amounted to three times that accumulated in MC as shade trees accounted for 60%. This is certainly a major source of household energy and revenue diversification for coffee communities. Thus provided an adequate pruning, *Inga*-shaded plantations appeared more advantageous than MC in these optimal conditions, especially considering the fact that coffee AFS provides high quality coffee, access to premium from eco-certification schemes, revenues diversification and environmental benefits such as

C sequestration, conservation of soil fertility, reduced pressure of forest remnants via fuel wood provision by associated trees, and enhanced tree cover and connectivity at the landscape level.

Acknowledgments The authors would like to thank the Coffee Institute of Costa Rica for facilitating the use and maintenance of the experimental plot on the research station of San Pedro de Barva and the European Commission (ICA-4-CT-2001-10071) for their financial support of the scientific equipment and field measurements performed within the framework of the CASCA project (Coffee Agroforestry in Central America).

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