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Leaf Area Index and Measurements of Light Transmission as Management Tools in Banana Production in Central American Coffee Agroforestry Systems

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Abstract

Sixty smallholders intercropping coffee, banana (*Musa spp.*) and trees in Costa Rica and Nicaragua were described, of which twenty farms were intensively investigated. The aim was to identify promising management tools which may help to improve banana production; this was based on the assumption that bananas have to face deep-shaded conditions, and that coffee, banana, and trees may influence each other.

As a result to this assumption, interrelationships between Leaf Area Index (LAI), above ground dry matter, percent-intercepted incident radiation, and banana production were evaluated. Transmitted radiation was estimated with hemispherical photography. Leaf area and dry matter of banana were partly estimated with non-destructive methods. Linear regression analysis between destructive leaf area and non-destructive leaf area estimation was conducted, with an equation promoted by Turner (2003), is promising in the field (R^2 = 0.96). A linear regression between above ground dry matter and circumference may allow dry matter estimation (R^2 = 0.84).

Thirteen different banana cultivars were identified; most common are AAA 'Gros Michel' and AAA 'Cavendish' cultivars. Mean LAI is 0.5 at plant density of 349 banana ha^{-1}. Mean percent transmitted light was 45% at 300 - 340 cm height and decreased to 28% in 90 cm height. LAI and dry matter seem to increase with percent intercepted light which may indicate that light is a limiting factor in the system. Tree canopy area and tree crown surface are significantly negative linear, correlated to percent intercepted light of banana. There is a linear interrelationship between LAI and above ground dry matter of banana on farm level (R^2=0.95; linear regression). Dry matter is weakly correlated to number of hands per banana bunch which could be the link between LAI, intercepted light and banana production. Further research should focus on optimum LAI of banana in coffee agroforestry systems, and light response of promising banana cultivars.

List of Abbreviations

γ	radiation use efficiency; total dry matter / intercepted radiation (g MJ^{-1})
b	grade of Sigatoka Infection Index (here: from 0 to 5)
d_m	percent dry matter in the fruit tissue
DBH	Diameter at breast height (here: 130 cm)
D	total above ground dry weight, excluding the fruit tissue
f_{stem}	ratio of dry weight sample stem (g) and fresh weight sample stem (g)
f_{leaf}	ratio of dry weight sample leaf (g) and fresh weight sample leaf (g)
f	ratio of dry weight sample (g) and fresh weight sample (g)
Hi	Harvest Index; ratio of fruit dry matter and total dry matter (%)
I	incident radiation below canopy (MJ m^{-2} d^{-1})
I_0	radiation above the canopy (MJ m^{-2} d^{-1})
k	attenuation coefficient; measure of leaf angle; 0 = steep leaf, 1 = plain leaf
LAI	Leaf Area Index; the (one-sided) unit area of leaf per unit area of land
n	sample size
n_{grade}	number of leaves in each grade of Sigatoka Infection Index
n_{leaf}	Leaf number of parent crop when the ratoon crop begins to grow
$\overline{n}$	mean number of sample size
N	number of grades in the scale of Sigatoka Infection Index (here: 6 grades)
P	plant crop; the first production cycle of banana
PAR	photosynthetic active radiation
R	ratoon crop; banana sucker which follows the last production cycle
R1	first ratoon crop; follows the first production cycle called plant crop
R2, R3	second ratoon crop, third ratoon crop
R_1	Number of leaves produced in a period of time
s	standard deviation
T	total number of leaves scored to be infected by Black Sigatoka
T_c	temperature coefficient; 0 = bad temp. conditions, 1 = optimum temp.
w	bunch weight
$\overline{x}$	sample mean

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1. Introduction

Banana and plantain (*Musa spp.*) are produced in different farming systems throughout the world; in monocropping, but also in intercropping and agroforestry systems (Stover and Simmonds 1987). In Central America banana production in agroforestry systems is in association with cacao and coffee, or as a single crop under tree shade (Guiracocha *et al.* 2001, López *et al.* 2003, Schibli 2001). Coffee in Central America is produced on an area of ~1.6 million ha, and a significant part is managed by small-holders (www. fao.faostat.org; De Clerck *et al.* 2007). *Musa spp.* is the most abundant fruit crop in coffee agroforestry systems in Central America (De Clerck *et al.* 2007). Growers associate coffee with banana because it is a second, whole year income source, gives shade to coffee and is fast growing. In addition, banana is a valuable stable crop, or fodder (Schibli 2001). Yields are even acceptable at low input levels and therefore widely used from resource poor farmers (Robinson 2000).

The three components, coffee, banana and trees, are intercropped in several different planting systems. Factors like density, basal area, canopy area, and canopy openness may change between regions (Espinoza 1985). Also species composition may differ, and crop management may be more or less intense (De Clerck *et al.* 2007, López *et al.* 2003). Banana is thereby a component of the lower canopy storey (Espinoza 1985, De Clerck *et al.* 2007). Light transmission to banana is reduced (Dold *et al.* 2007, unpublished data).

Reduction of transmitted light prolongs crop cycle and decreases yield of banana (Israeli *et al.* 1995). However, when other factors such as water, disease pressure, nutrients or below ground competition are more limiting, some amount of shade may be beneficial for the crop (Israeli *et al.* 2002, Galán Sauco *et al.* 1992, Vicente-Chandler 1966, Murray 1961, Akyeampong *et al.* 1999). Light response curves indicate that certain banana cultivars may adapt better to shade (Turner 1998b, Turner *et al.* 2007). There may be a compensation effect of leaf area and leaf angle which could improve light interception (Turner 1998b).

According to Beer's law, light transmission depends exponentially from leaf area index (LAI) and attenuation coefficient (k). Stover (1984) used measurements of LAI, and PAR transmission to evaluate optimum density of banana in monoculture in Central America. Morse and Robinson (1996a) found optimum LAI and k in relation to banana yield. However, there are problems to compare optimum indices (Robinson and Nel 1988), and application may only be useful on local level (Turner 1998a).

Small-scale farmers produce banana in mixed systems, but management level and production might be low. Thus, there is a need of easy applicable management tools for banana production in agroforestry systems.

Also, there is still a lack of data on shade response of banana (Turner 2007 *et al.*). Above ground interactions between coffee, banana, and trees could influence light transmission and production. Banana in coffee agroforestry systems might grow under great light reduction. Under this scenario, shade could be one limiting factor.

The aim of this work is to analyze leaf area index and light transmission as possible management tools for banana production in agroforestry systems. This study might also contribute to a better understanding of agroforestry systems with coffee, banana and trees.

2. Hypothesis and Objectives

2.1. Objectives

- To describe the differences between coffee agroforestry systems associated with bananas and trees
- To analyze relationships between parameters of coffee, banana and trees
- To describe parameters influencing Leaf Area Index of banana
- To analyze parameters of banana production, intercepted light, and Leaf Area Index

2.2. Hypothesis

1. There is a relationship between Leaf Area Index of banana and production parameters
2. Leaf Area Index of banana changes under distinct radiation levels in coffee agroforestry systems
3. Leaf Area Index of banana and light transmission is related directly or indirectly to density, basal area, or canopy area of coffee, banana and trees

3. State of the Art

3.1. Terminology and Botany of Banana

The genus *Musa* belongs to the family Musaceae. There are five sections of the genus *Musa*, of which the section Eumusa includes edible cultivars and is of global importance. This section includes two wild species; *Musa accuminata* (Genome A) and *Musa balbisiana* (Genome B). All edible cultivars belonging to Eumusa originate from these two species. Cultivars can be diploid, triploid or tetraploid, and belong to Genome A, Genome B or both (Stover and Simmonds 1987). The terms ‘banana’ and ‘plantain’ refer to the consumption of the fruit. Bananas can be eaten fresh, while plantain is eaten cooked. *Musa accuminata* cultivars are mostly sweeter and suitable for fresh consumption, while *M. balbisiana* cultivars are typically used for cooking and have greater disease and drought resistance.

There is certain formulation to differentiate between bananas and plantains within the section Eumusa. It is common agreement to formulate the genus followed by the genome group followed by the subgroup followed by the popular name of the cultivar; for example *Musa* (genera) AAA (genome group) Cavendish (subgroup) ´Grand Nain` (cultivar) (Robinson, 1996). In this study cultivars are described with the genome group, subgroup and cultivar name.

Banana and plantain is an herbaceous, evergreen perennial. The rhizome (some authors refer to it as the ‘corm’) contains of the central cylinder which is the true stem of the banana, and the cortex, a tissue of starchy parenchyma. The rhizome has very short internodes. At vegetative growth buds grow at the outer surface of the cortex. Three to five buds will develop to new rhizomes and later to plants attached to the mother plant. The rhizome remains fully or partly below ground, at least in the beginning of plant development. The upper parts consist of leaves, the pseudostem, and the fruit or flowering stalk. The pseudostem or ‘trunk’ is formed of leaf sheaths. All above ground parts develop from the central cylinder. A certain number of leaves evolve from the central cylinder and eventually the plant flowers. At flower emergence the plant produces no more leaves (Robinson 1996, Stover and Simmonds 1987).

The term 'bunch' describes the inflorescence of the plant. The single fruit is called 'finger' and two rows of fingers attached together at the axis of the bunch is called 'hand'. At the basal end of the inflorescence is the male flower or male bud. New plants attached to the mother plant are called 'suckers'. The sucker which remains for the next production cycle is called 'ratoon' (R). The pseudostem of the first crop cycle is called 'plant crop' (P). The whole plant including plant crop and suckers is called 'mat' (Stover and Simmonds, 1987; Robinson 1996).

'Desuckering' describes the method of erasing unwanted suckers. The term 'debudding' refers to the removal of the male bud. 'Deleafing' is the removal of leaves that disturb production, for example leaves infected with diseases (Stover and Simmonds 1987).

3.2. Leaf Area Index as a Management Tool in Banana Production

"Leaves are primary harvesters of light and a net manufacturer of chemical energy…Since a proportion of the carbohydrates generated by leaves is allocated to fruit, leaves are important for productivity...Leaf Area Index (LAI), the area of leaf per unit area of land, is a useful concept to apply at the plantation level of organization." (Turner 1998a).

The leaf sheaths form the pseudostem of banana. Thus, leaves make up the majority of above ground biomass. Biomass production is high, but can differ from variety. For example, above ground fresh weight and bunch of cv. 'Grand Nain' makes up 153 kg, while rhizomes and roots are 20 kg. AAA 'Gros Michel' giant cultivars can reach total fresh weight of 500 kg. In general, total dry matter content is only about 10% (Stover and Simmonds 1987).

Hence, leaf area has a strong relationship to height ($R^2 = 0.79$; simple linear correlation) and circumference ($R^2 = 0.76$, simple linear correlation). Height and circumference are related to production parameters (No. Hands, both $R^2 = 0.71$, both simple linear correlation) (Stover and Simmonds 1987).

Table 1. Data summary of Leaf Area Index from monoculture plantations in the tropics and subtropics; some authors mentioned also optimum and maximum levels of LAI. Percentages of transmitted light refer to radiation measured below the banana canopy; attenuation coefficient k (which is the angle of the leaf; the steeper the leaf angle, the nearer to 0) was calculated from data of LAI and light (here: PAR; photosynthetic active radiation) by the authors

LAI	% Trans. Light	k	Cultivar	Author
optimum: 4 - 5	optimum: 14 -18% PAR	0.45 - 0.75	Valery, Grand Nain	Stover (1984), Turner (1998a).
optimum: 5.5 - 6.5	---	---	Williams Grand Nain	Morse and Robinson (1996a).
3.4	34±8% PAR	0.33	Plantain	Jimenez and Lhomme (1994).
optimum: 4.5	10% at LAI = 4	---	---	Turner (1982) found in Robinson and Nel (1988).
4 – 7.4 (max.)	14%	---	Williams, Cavendish AAA	Robinson and Nel (1988).
optimum: 5 – 6	---	---	---	Robinson and Nel (1989) found in Morse and Robinson (1996a).
---	---	0.7	AAA-EAHB cv. Kisansa	Nyombi *et al.* 2009.
2-5	10% at LAI=4.5	---	Banana	Turner *et al.* 2007.

Circumference measurements can also predict above ground biomass in the vegetative stage (regression analysis; $R^2 = 0.99$, $y = 0.0001x^{2.35}$), at flowering stage (regression analysis; $R^2 = 0.79$; $y= 0.325*e^{0.036x}$), and at harvest (regression analysis; $R^2 = 0.96$; $y = 0.069*e^{0.068x}$) (Nyombi *et al.* 2009).

As leaf area has strong interrelationships to biomass and yield parameters, Leaf Area Index may be useful to identify optimum production (Turner 1998a). Morse and Robinson (1996a) estimated the interrelationship between LAI at flowering and yield. The authors analyzed optimum LAI at highest yield. Stover (1984) suggests an optimum LAI = 4 - 5 on plantation level. "Readings considerably above or below these levels would indicate overpopulation and underpopulation." (Stover 1984). Turner *et al.* (2007) recommend an optimum LAI = 4.5. Higher LAI values would not increase yield, because most incoming light is intercepted at LAI 4.5 (see also Table 1).
However, optimum LAI depends on several factors, and has to be adjusted to the given circumstances.

3.3. Factors Influencing Optimum Leaf Area Index

LAI depends on plant development stage and changes within one crop cycle. Eckstein *et al.* (1995) found that maximum LAI of the plant crop (P) was 2.27 in the vegetative stage. However, LAI decreased to 1.56 until harvest.
With every new leaf, leaf area and leaf width increases. Shortly before flowering, leaves have a similar leaf area. Leaf area of the last leaf usually decreases again (Stover and Simmonds 1987) (see also Figure 1).
There is a change of dry matter distribution which influences LAI; in the vegetative stage mainly to leaves, and at harvest to the bunch and the sucker (Eckstein *et al.* 1995, Turner 1972, Morse and Robinson 1996b).

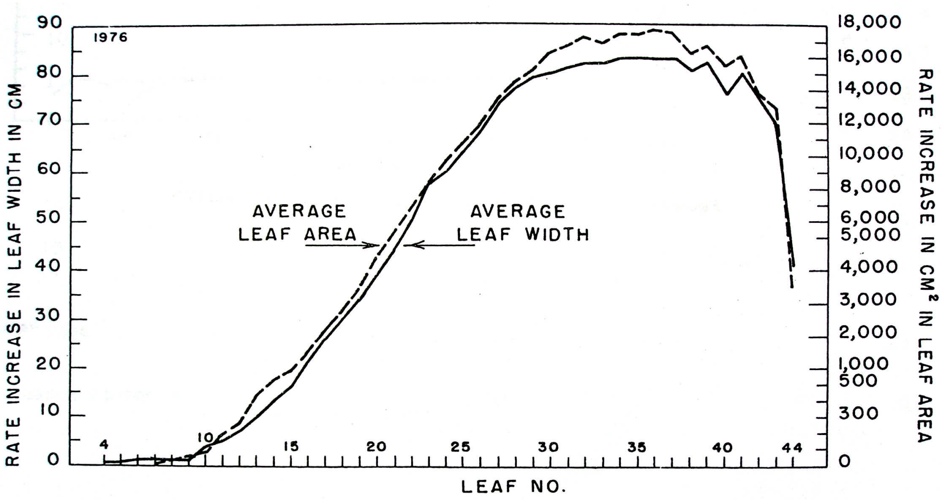

Figure 1. Increase of leaf area and leaf width of 15 *Musa* AAA Cavendish cv. 'Grand Nain' in Honduras (Stover 1979)

Leaf Area Index also alters by plant age. Robinson and Nel (1988) found that LAI increased from the first crop cycle (P, plant crop) to the third crop cycle (R2, second ratoon crop) from 2 (P) to 4.53 (R1) up to 5.5 (R2). At R3, leaf area index decreased again to 4.55.

Additionally, plant vigour has influence on Leaf Area Index of banana. Robinson (2000) states that low plantation vigour will be reflected in a low value of LAI. Furthermore, LAI is not an adequate management tool, when plant vigour (vigorous root growth and the factors influencing it) of the plantation is low. At low plant vigour LAI is decreasing. It is not possible to compensate low LAI by higher plant densities to gain the same yields in low vigorous plantations. A high vigour plantation with 2222 plants ha^{-1} had LAI of 6.3 with bunches of 44.9 kg, while a low vigour plantation with the same density had LAI of 3.5 and bunches of 26.7 kg. An increased density of 3333 plants ha^{-1} of a low vigorous plantation did not achieve the same results; LAI was increased until 5, and bunch weight was 19.7 kg (Robinson 2000).

Leaf area differs within variety. Stover (1982) found that leaf area of AAA Cavendish subgroup cv. ‘Grand Nain’ is 20% lower than leaf area from AAA Cavendish subgroup cv. ‘Valery’. Stover (1982) proposed that ‘Grand Nain’ should be cultivated at higher plant densities to reach the same LAI than ‘Valery’ plantations.

Leaf Area Index of banana can be altered with desuckering (Turner 1998a). Desuckering is a necessary method to maintain high yields. If all suckers are left to grow and bear fruits, as it is common in resource limited plantations, every stem will only bear small bunches (Robinson 2000). In big plantations in the tropics, two to three pseudostems are left at each plant (Stover and Simmonds 1987).

Leaf area differs also by soil types (Stover 1984). Fertile soils result in larger plants and foliage (Stover and Simmonds 1987). However, Stover (1984) found only a slight difference of LAI (5.33 and 5.36, respectively) of the same banana variety grown on two soil types; on loam and on light clay.

Season and temperature influence LAI, especially in the subtropics. Turner (1972) reports that leaf area decrease from 6 m^2 to 3 m^2 during winter. It increases again until 12.5 m^2 until May. Eckstein *et al.* (1995) report LAI = 1.56 at harvest on single plant level. Morse and Robinson (1996b) measured LAI of the same variety of 3.1 at harvest, arguing that the difference is due to a favorable temperature at their study site.

Black Sigatoka disease (*Mycosphaerella fijiensis*) influences leaf area, and thus LAI. It destroys functional leaf area and fruits can not ripen (Robinson 2000). Vicente-Chandler (1966) describes a typical situation of banana production without control of Black Sigatoka: “Leaf spot damage increased so rapidly as the plants matured, that many of the sun-grown plants had no healthy leaves at all and were incapable of developing the lower hands”.

Turner (1998b) suggests by an analytical approach that leaf area of banana may increase in shaded conditions. However, Israeli *et al.* (1995) found no difference of leaf area until 60% light, and decreased leaf area at 30% light, observing two crop cycles (P and R1).

Optimum LAI is depending on several preconditions. Therefore it is difficult to compare LAI from different plantations and locations. As previously described, leaf area is depending on development stage of the plant. Robinson and Nel (1988) had argued that comparing data on LAI from previous studies was not possible because the development stage of the plantations at data taking were not mentioned by the authors.
Younger plantations are fruiting faster than older plantations (Stover 1984). At harvest the pseudostem is cut or dies back (Turner 1994). Harvest diminishes LAI at once, and before harvest LAI is high (Stover 1984).

3.4. Light Transmission as a Management Tool in Banana Production, and Theoretical Background

Estimation of transmitted light is a management tool to determine plant density in monoculture banana production (Stover 1984, Turner 1998a, Robinson and Nel 1988, Robinson 2000). Transmitted light is measured below plant crop canopy, at ground level, or at ratoon crop height (Stover 1984; Robinson and Nel 1988). Measuring light above and below banana canopy allows the estimation of intercepted light (Jimenez and Lhomme, 1994). Optimum light transmission rates for tropical Central America are 14% to 18% at ground level in monoculture banana plantations (Stover 1984) (see Table 1). At transmission rates below 10% PAR (1900 plants ha^{-1}), plants do not produce marketable fruits because plant density is too high (Stover and Simmonds 1987).

Light transmission depends on leaf area, since incoming light decreases exponentially by LAI and the attenuation coefficient k (see also Figure 2). The relationship between light transmission, LAI and k is described in Beer's Law:

$$I = I_0 * e^{[-kLAI]} \qquad (1)$$

Where

I = incident radiation below the canopy (MJ m^{-2} d^{-1})
I_0 = radiation above the canopy (MJ m^{-2} d^{-1})
LAI = leaf area index
k = attenuation coefficient.

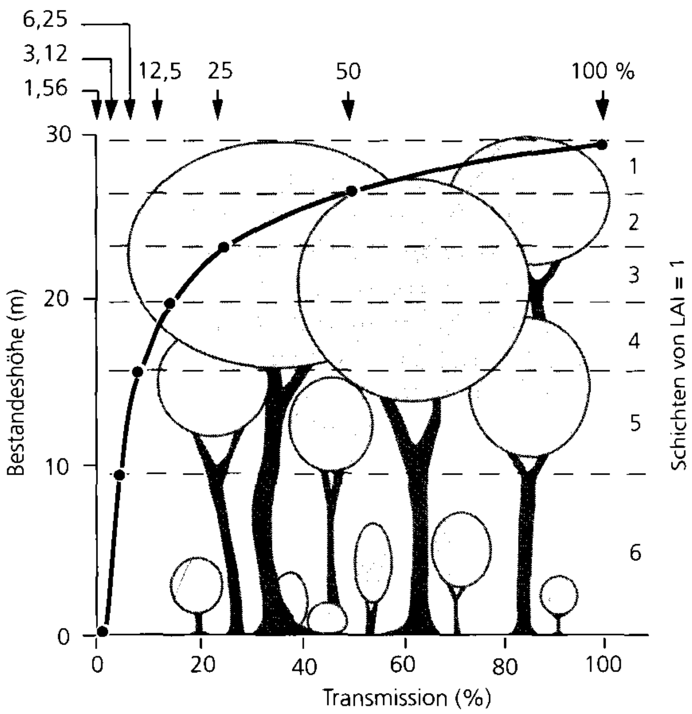

Figure 2. Light transmission is decreasing exponentially in plant stands. According to Beer's Law the reduction of light depends on Leaf Area Index and attenuation coefficient, found in Körner (2002)

Equation 1 is also used to estimate k of banana (Jimenez and Lhomme, 1994; Nyombi *et al.* 2009) (see Table 1). Turner (1972, 1994) discussed the change of leaf attenuation (k) of banana canopies. Younger leaves are steeper than older leaves. This changes k inside the canopy. Leaf blades of banana fold (heliotropism) which changes k within the day (Turner 1998b, Thomas and Turner 2001).

Turner (1994, 1998a, 1998b) also tried to model influences on bunch weight with respect on radiation among others:

$$w = \{I_0 * [1-e^{-kLAI}] * \gamma * T_c * Hi\} / \{[R_1/n_{leaf}] * p * d_m\} \qquad (2)$$

Where

w = bunch weight (g)

$I_0[1-e^{-kLAI}]$ = Beer's Law as described in equation 1

γ = radiation use efficiency (total dry matter / intercepted radiation) (g MJ^{-1})

T_c = temperature coefficient (0 = bad temp. conditions, 1 = optimum temp. cond.)

Hi = harvest index (fruit dry matter / total dry matter)

d_m = % dry matter in the fruit tissue (one possible unit of expressing yield)

n_{leaf} = Leaf number of parent crop when the ratoon crop begins to grow

R_1 = Number of leaves produced in a period of time

p = plant density

Reasonable values for the parameters of equation 2 are available. Bunch weight depends on various factors. Stover and Simmonds (1987) present values from ~14kg up to ~70kg which makes up 10 – 40% of total fresh weight. LAI = 4 – 7; k = 0.33 – 0.75 (see Table 1); Radiation use efficiency γ = 1.5 g MJ^{-1} (Turner 1994, but data needs further verification). d_m = 0.2 (for AAA cultivars) to 0.35 (cultivars with B Genome) (Turner, 1994). The Harvest Index Hi = 0.16 to 0.57 depending on cultivar (Stover and Simmond 1987). The R1/n ratio should reflect how vigorous a plantation is; the faster the ratoon crop begins to grow, the more vigorous the plant. R1/n = 0.8 (subtropics, high plant vigour) to 1.5 (tropics, high plant vigour) (Turner 1998a). The temperature coefficient represents the influence of temperature on plant development. Dry matter accumulation in vegetative plants is optimal at ~20°C, but leaf growth is best at temperatures ~30°C. For fruit ripening, optimum temperature is in the range of 13°C to 32°C (Turner 1994). Plant density differs by location. For the tropics, Stover (1984) found optimum LAI and k at densities of ~1500 to less than 1900 plants ha^{-1} for Central America. For the subtropics, Robinson and Nel (1988) recommend densities of ~2200 plants ha^{-1}. Morse and Robinson (1996a) were testing six cultivars and recommended planting densities of ~2000 – 2600 plants ha^{-1}. Until now no approach combined all parameters to verify this model (Turner 1998a, 1998b), and data are still missing (Turner *et al.* 2007).

Most research concentrate on banana monocropping. Banana production in intercropping or agroforestry systems is different compared to plantation production. In the following, I will mainly focus on banana production in coffee agroforestry systems.

3.5. Banana in Coffee Agroforestry Systems

World's production of bananas and plantains in 2007 was about 89,100 kt and 980 kt, respectively. However, only 19% of banana, and 2% of plantain production are exported. Banana is important for national markets, on regional and local level. Second, it is an important crop in subsistence farming (www. fao.faostat.org, Stover and Simmonds 1987, Robinson 2000, Schibli 2001). In Central America export rate is higher. 64% of banana production and 18% of plantain production are for export, with strong differences between countries (see Table 2) (www. fao.faostat.org).

Table 2. Production and export of banana and plantain in Central America; data from 2007; www.faostat.fao.org

	Banana		Plantain	
Country	Production (kt)	Export (kt)	Production (kt)	Export (kt)
Costa Rica	2350	2272	86	30
Guatemala	1569	1408	345	116
Honduras	910	566	290	0.78
Nicaragua	44	38	55	23

Banana and plantain is an important additional crop for small-scale growers. As a second income source banana makes up 15% of gross income of coffee for Nicaraguan coffee growers. It is also a crop of subsistence farming, and fodder. It is fast growing, and gives yield the whole year round. Additionally, it gives shade in coffee plantations (Schibli 2001, Lopez et al 2003). It does not need much management, and will give acceptable yields even at low resource inputs (Robinson 2000).

Banana and plantain is produced in monocropping, intercropping and agroforestry systems (Stover and Simmonds 1987). In Central America banana production in agroforestry systems is common in association with cacao and coffee, or as a single crop under tree shade (Guiracocha *et al.* 2001, López *et al.* 2003, Schibli 2001).

Table 3. Coffee agroforestry systems with banana in three different regions of Costa Rica (Espinoza1985)

Parameters	Puriscal	Tabarcia	Acosta
Size of Farm (ha)	14.3	4.2	5.3
Coffee Field Size (ha)	1	0.9	0.9
Coffee Production (kg ha^{-1})	8313	6401	5457
Coffee Plants (plants ha^{-1})	5088	5199	5433
Trees ha^{-1}	98	246	211
Banana ha^{-1}	228	275	343
Trees Basal Area (m^2 ha^{-1})	4.33	8.57	8.24
Banana Basal Area (m^2 ha^{-1})	4.13	4.00	5.37
Tree Canopy Area (m^2 ha^{-1})	3517	5266	4403
Banana Canopy Area (m^2 ha^{-1})	1587	1701	2328
Height Trees (m)	8.3	8.5	8.4
Height Banana (m)	5.8	5.6	5.5
Canopy Coverage (%)			
Below 7m	52	50	62
7 – 11m	23	26	21
Above 11m	25	24	17

Banana production in monoculture and in coffee agroforestry systems differ mainly in plant density, cultivars, and management level. In monocropping, densities of ~2000 plants ha^{-1} and higher are possible (Stover and Simmonds 1987). Espinoza (1985) found in Costa Rica density of 228 – 343 bananas ha^{-1} in agroforestry systems (see Table 3). Lopez et al. (2003) report density in Nicaragua from 52 – 212 plants ha^{-1}, depending on farm size. Schibli (2001) counted density 4100 to 4800 ha^{-1} bananas. However, it seems that the author refers to number of stems, rather than to single individuals, since densities would be enormous.

In monoculture mainly cultivars AAA subgroup Cavendish are cultivated. In mixed cropping systems, small-scale farms prefer to cultivate various banana cultivars (Stover and Simmonds 1987). In comparison to monoculture production, intensity of management in mixed cropping systems on small farms is low (Stover and Simmonds 1987, Lopez *et al.* 2003).

Table 4. Coffee agroforestry systems in Central America; categorized by tree strata; adapted from De Clerck *et al.* 2007

Tree Strata	Type of System	Tree species	Example
0	Sun Coffee	0	No tree cover
1	Monostrata Coffee	1	*Erythrina, Inga* or *Musa*
2	Two Strata Coffee	2	*Inga* with *Musa*
>2	Polystrata Coffee	3 to 9	*Erythrina, Cordia*
>3	Forest Coffee	10	Diversified Shade

Table 5. Most abundant perennial species in coffee agroforestry systems in Costa Rica and Nicaragua; adapted from De Clerck *et al.* (2007)

Costa Rica	Nicaragua
Erythrina poeppigiana	*Musa spp*
Musa spp	*Inga spp.*
Cordia alliodora	*Cordia alliodora*
Inga spp	*Citrus sinensis*
Citrus spp	*Gliricidia sepium*
Cedrela odorata	*Cedrela odorata*

Coffee agroforestry systems in Central America are very distinct. They can differ in number of strata (see Table 4), in the species composition (see Table 5), and within countries and regions (see Table 6). Especially in Nicaragua and Costa Rica, banana is an important species intercropped with coffee (Table 5).

Surveys of 630 coffee agroforestry farms indicate that *Musa spp.* (52%) and *Inga sp.* are the most frequent genera intercropped with coffee (De Clerck *et al.* 2007). Especially resource poor farmers tend to increase the number of banana in their coffee fields (Espinoza, 1985) (see Table 3). 69% of Central American coffee growers have farm sizes below 3.5 ha, but produce 11.6% of marketed coffee (De Clerck *et al.* 2007).

Table 6. Characterization of coffee farms in Costa Rica and Nicaragua; adapted from De Clerck *et al.* 2007

Country	Zone	Coffee Area (ha)	Shade (%)	Elevation (m)	Trees ha^{-1}
Costa Rica	Cen. Valley	11.2	31.0	866	403
	N. Pacific	3.5	50.3	708	392
	Cen.Pacific	2.4	33.7	1091	383
Nicaragua	Matagalpa	51.7	49.5	886	273
	Pacific	22.2	38.9	522	472
	Estelí	5.1	62.2	1222	486

Banana with coffee and trees grows in high shaded conditions; since it is part of the lower strata (see Table 3). Dold *et al.* (2007, unpublished data) found that new planted banana in coffee agroforestry systems received 37% of total light at low tree density, and relatively low coffee density , but decreased until 13% with increasing number of overstorey trees and coffee plants. Such strong light reduction has impact on growth and yield; the plant responds differently in shade than in full sun (Turner 1998b).

3.6. Banana in Shade

Banana has the C3 pathway (Stover and Simmonds 1987). Light saturation point is between 700 to 2000 µmol quanta $m^{-2}s^{-1}$. Net photosynthesis is 5 to 25 µmol CO_2 $m^{-2}s^{-1}$. Data vary by cultivars, experiments, environmental factors, and plant development (Turner *et al*. 2007). For comparison, photon flux density exceeds 2200 µmol m^{-2} s^{-1} above a tropical forest canopy on a clear day in the dry season (Chazdon *et al.* 1996).

Data on shade response of banana show that reduced light can be beneficial in certain circumstances. When other factors are more limiting than light, shade had positive effects on production. Turner *et al.* (2007) concluded that in little shade other factors are more limiting. In high shade, light is most limiting and production is linear to intercepted radiation.

Vicente-Chandler *et al.* (1966) found doubled yield in banana and plantain intercropped with *Inga sp*. (light reduction of ~50%) because Yellow Sigatoka infestation was lower in shade than in full sun. However, maturation time was prolonged; hence, harvest per time would give different results.

Israeli *et al.* (2002) concluded that light reduction of 17% to 28% is beneficial to production in the dry areas of Israel, since water is the most limiting factor, and wind is reduced. Galán Sauco *et al.* (1992) found that light reduction of 22% to 27% in greenhouse cultivation resulted in higher yields (~20% higher) due to better temperature and humidity conditions than in field.

Murray (1961) found higher yields in shaded banana. The author also recognized higher nutrient contents in the leaves under shade. Since only two plants were measured statistical analysis was not possible. However, the author discussed the possibility that shade might be beneficial under nutrient limited soil conditions.

Akyeampong *et al.* (1999) assessed a field trial of local cultivar *Musa* AAA 'Igitsiri' intercropped in the shade of *Grevillea robusta* at different tree densities in Burundi, and compared it to sole banana trial. Yields were higher in intercropping system at tree density of 320 plants ha^{-1}. The author concluded that root competition was more limiting than light competition. However, a similar trial with shade nets showed that light reduction of 75% led to a prolongation of yield up to 5 months (Torquebiau and Akyeampong 1994).

Israeli *et al.* (1995) tested banana (P and R1) keeping every limiting factor constant but light. In the plant crop (P) light reduction of 80%, 60% and 30% (+ strong mutual shading due to high densities), reduced bunch weight by 0%, 7% and 32%. In the ratoon cycle (R1) bunch weight reduction was even stronger (8%, 21% and 55% less bunch weight, respectively). The reason was the reduced carbon assimilation and allocation to sucker and bunch.

Additionally, in shade diurnal leaf folding is less which might change the attenuation coefficient k (Thomas and Turner 2001, Turner 1998b). Leaf Area Index may increase in shade compared to full light. Intercepted light would be increased in these conditions, a possible adaptation from the plant to shade (Turner 1998b).

4. Methods

This study was a collaborative work, and part of a project from Bioversity and Gesellschaft für Technische Zusammenarbeit (GTZ). Data was taken by Dr. Pablo Siles, Dr. Oscar Bustamante, Paulo Lichtemberg, and Christian Dold.

We decided randomly from a list of 80 to 100 farmers on 30 farms in Central Costa Rica and from a list of ~100 farmers on 30 farms in Northern Nicaragua. All growers produced coffee together with banana, and trees on at least one field of the farm. The growers were mainly small-scale farmers (here: 1 – 10 ha).
In Costa Rica we conducted the study in farms nearby CATIE (Centro Agronomico de Investigacíon y Enseñanza), Turrialba. 16 farms were in the communities of San Juan Sur, San Juan Norte, and Chitaria, and 14 farms were in the region of Bajo Pacuare, and Alto Quetzal. 15 growers produced organic or traditional, and 15 were conventional growers. In Nicaragua, we conducted the study on 15 farms in the region of Monterrey nearby Jinotega, and 15 farms in Yassica Sur, nearby Matagalpa.

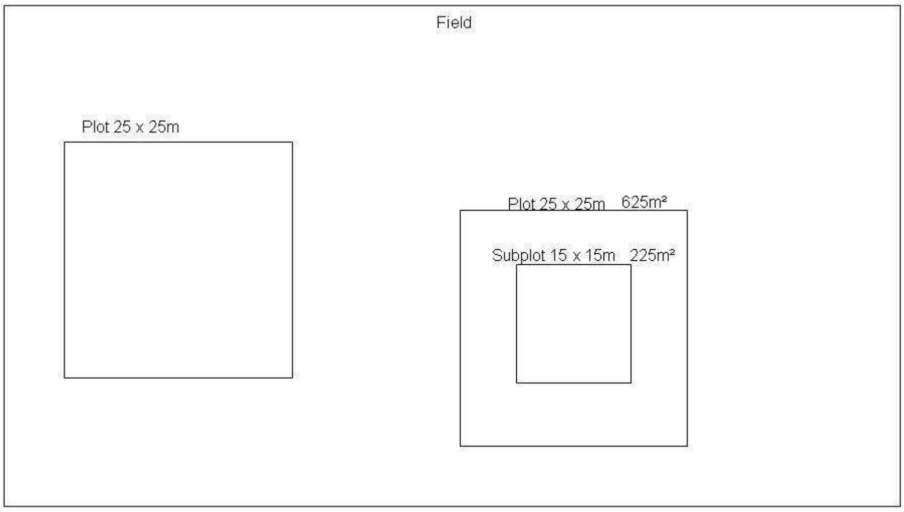

Figure 3. Two plots 25 m x 25 m were established on 30 farms in Costa Rica and 30 farms in Nicaragua; additionally one subplot 15 m x 15 m was established on 10 farms in Costa Rica and 10 farms in Nicaragua

We established jointly a questionnaire. The questionnaire included open questions and closed questions. We tested the questionnaire with coffee growers and expertise. The interview was in Spanish, and 4 interviewers asked the growers. 2 interviewers were native speakers, and 2 interviewers had sufficient Spanish language skills. The interview lasted from 30 minutes to 60 minutes. The interview was semi-narrative; the order of the questions changed according to the topics mentioned by the grower. 1 grower was not available for the interview. See Appendix I for the relevant parts of the questionnaire.

On each farm we chose randomly on two plots with 25 m x 25 m (2 x 625 m^2). In Costa Rica, three farms were such small that we decided on only one plot per farm. From the 60 farms we chose 20 farms for detailed measurements; 10 farms in Costa Rica and 10 farms in Nicaragua. We chose one plot (25 m x 25 m), and within this plot we established a subplot (15 m x 15 m) (see also Figure 3). Data was taken from several parameters of coffee, banana and trees (see Table 7).

4.1. Coffee

We established a questionnaire, asked 59 growers about *coffee production*, and calculated total processed green coffee (Oro) in kg ha^{-1} a^{-1} (1 fanega = 2 quintales Pergamino = 1 quintal Oro = 46 kg Oro = 256 kg cherries; 1 quintal pergamino = 92 kg Oro; roughly the relation Oro : Pergamino : Cherry is 1:2:5) (Cerdan, 2009; pers. communication).

On 60 farms, we walked in each 2nd line and stopped at every 3rd step taking notes on the coffee plant to our right side. We estimated visually and categorized *coffee height* (Intervals of <1 m, 1-2 m and >2 m), and *productive stage* (missing plant, needs pruning, needs deep pruning, needs replacement, deep pruned or replaced, productive). Additionally, we categorized canopy openness by using a *visual index* (intervals of 10% canopy openness above the coffee plant). We assumed a radius of 6 m above the coffee plant and then categorized visually percentage of gaps within the canopy. We took notes whether banana shaded coffee, or not. Several observers worked with the visual index in coffee. At last, we counted each plant inside the plot and calculated *density* ha^{-1}.

Table 7. We took data of several parameters concerning coffee, banana and trees; different plots sizes were chosen for data taking; 30 farms in Costa Rica and 30 farms in Nicaragua; from these 60 farms we chose 20 farms for detailed measurements

Coffee	Banana	Tree	Farm
	60 Farms 2 Plots 25 m x 25 m		
# Plants	# Plants	# Plants	Soil Texture
Height	# Stems 1-2m	Height	Altitude
Visual Index	# Stems >2m	Stem diameter	Gap Fraction
Presence of banana	# Bunches	Canopy diameter	Farm Size
Yield	Yield	Species	Field Size
Plant Stage	Varieties	Pruning	
	Visual Index		
	Management		
	20 Farms 1 Plot 25 m x 25 m		
		Circumference	
		Stem Height	
		Total Height	
		Canopy diameter	
	20 Farms 1 Subplot 15 m x 15 m		
Circumference	Circumference		Light transmittance
	Stem height		
	Black Sigatoka		
	# Leaves		
	Leaf area		
	Dry weight		
	# Hands, # Fingers		
	Bunch weight		
	Plant age		
	Canopy diameter		

In the subplot of 15 m x 15 m (20 farms) we estimated *stem basal area* of coffee. We measured circumference in 15 cm above ground and calculated stem basal area ha^{-1}. Therefore, we calibrated our sample size n. We measured circumference of all plants in the subplot of two farms. We analyzed the data of the two farms, and therefore calculated for each sample size the 95% - Confidence Interval from circumference data. We plotted the sample size (x) against the 95% - Confidence Interval (y) and decided visually on the sample size needed for measurements of stem basal area.

4.2. Banana

We asked 59 farmers about *banana management* in the questionnaire, especially desuckering, deleafing, debudding, frequency of banana management, pest management, and fertilizer application. Furthermore, we asked about the importance of banana in coffee agroforestry systems. Additionally, we asked 59 farmers about *banana production*. Since growers knew yield production in different units, we assumed an “average bunch” with number of hands, number of fingers and bunch weight. We converted banana production in one single unit; bunches ha^{-1} a^{-1}.

We measured bunches on farm, or received data from interviews. We counted number of hands and number of fingers of the 2nd hand from available bunches on farm, or plot. We calculated mean number on hands and mean number of fingers of the 2nd hand. We calculated total number of fingers by multiplying mean number of hands with mean number of fingers. In Nicaragua we weight 11 mature bunches on one farm and computed mean bunch weight. In Costa Rica, we asked two retailers about typical bunch weight of banana from small-scale farms, and calculated mean bunch weight. In Costa Rica, 16 farmers know yield data in kilogram, 13 farmers in number of bunches, and 1 farmer in number of fingers. In Nicaragua, 15 farmers know yield data in number of bunches, 1 farmer in number of hands, 9 farmers in number of fingers and from 5 farmers data was not available. This is important because conversion of data in bunches relied on the calculated “average bunch”.

In the plot 25 m x 25 m (60 farms), we estimated *density* of banana and *pseudostem height*. We counted number of plants for each variety and calculated plants ha^{-1}.

We counted number of pseudostems in a height of 1 m to 2 m, and in a height above 2 m. We then calculated number of stems ha^{-1}. We ignored pseudostems and plants less than 1 m height. Additionally, we counted *bunches* of the pseudostems. We categorized canopy openness above banana as described previously for coffee. Only one observer was working with the *visual index* in banana. Banana height differs stronger due to the development stage of the plant; hence, we took visual index in different heights.

In the subplot 15 m x 15 m (20 farms), we measured *circumference* in 1 m height and calculated *stem basal area* ha^{-1}. We measured canopy radius in four directions from the centre of the mat to the edge of the leaf. We then calculated *canopy basal area* ha^{-1}.
We assumed age of the plant by *number of harvests*. We categorized number of harvests in less than 2 harvest, 2 to 3 harvests, and more than 3 harvests. We therefore counted harvested pseudostems. Since in field several stems can have fruit at the same time we considered also size of the whole mat and predicted number of harvests.
For each stem we measured *pseudostem height* from the ground to the last petiole pair of fully evolved leaves, and counted number of functional leaves (here defined as: leaf width >10 cm; less than 50% damaged). We mainly ignored bananas with stems smaller than 2 m.

We estimated *leaf area* on 20 farms (subplot 15 m x 15 m). Here, we included also data on some stems smaller than 2 m. On 5 farms in Costa Rica and 5 farms in Nicaragua we measured every leaf of all banana plants. We calculated leaf area of each leaf by

$$\text{Leaf Area (cm}^2\text{)} = \text{Length (cm)} * \text{Width (cm)} * 0.8 \qquad (3)$$

On 5 farms in Costa Rica and 5 farms in Nicaragua we estimated leaf area using the equation proposed by Turner (2003). This equation requires only leaf area from the youngest and the oldest leaf and total number of leaves.
We tested the equation of Turner (2003). We used our measured leaf area data and estimated leaf area with the same data using the equation of Turner (2003). We tested each pseudostem separately. We plotted the estimated results (x) and the real data (y). We

analyzed the data with linear regression. Additionally, the 95% - Confidence Interval for real leaf area and the estimated leaf area was computed.

We calculated total leaf area per stem, plant, variety and farm. We calculated Leaf Area Index (LAI) on farm level by summing up total plant leaf area and dividing it by plot size (225 m^2). We estimated LAI for each plant by summing up leaf area of all leaves and dividing it by canopy basal area.

We estimated total *dry weight* on 20 farms (subplot 15 m x 15 m). Here, we included also data on some stems smaller than 2 m. We weighed all banana plants in 8 farms (3 farms in Costa Rica, 5 farms in Nicaragua), and estimated total plant weight in 12 farms. We weighed the above ground plant material (pseudostem, leaves, and bunch) separately for each stem, plant, variety and farm.

We calculated total dry weight for each pseudostem (D) by:

$$D\ (kg) = (\text{fresh weight stem (kg)} * f_{stem}) + (\text{fresh weight leaf (kg)} * f_{leaf}) \qquad (4)$$

Where

$$f = \text{dry weight sample (g)} / \text{fresh weight sample (g)}$$

We did not include bunch weight in the calculation of dry weight.

We estimated dry weight for 12 farms. Therefore, we analyzed the interrelationship between circumference and dry weight. We plotted circumference (x) and total dry weight (y). We analyzed the data with linear regression. We used the derived equation to calculate dry weight for the other farms. Additionally, the 95% - Confidence Interval of the calculated dry weight, and real dry weight was computed.

We calculated dry weight in Nicaragua and Costa Rica differently. In Nicaragua, we took one leaf sample and one stem sample of fresh weight, randomly chosen on each farm (mixing varieties). In Costa Rica, we took one leaf sample and one stem sample of one pseudostem per variety in three farms. Hence, for Nicaragua we calculated dry weight for each farm, for Costa Rica we calculated dry weight for each variety. In Nicaragua, the samples were dried at UNAN León (Universidad Nacional Autonoma Nicaragua, León). In Costa Rica, we dried the samples at CATIE for 3.5 days at 70 degrees, and measured dry weight.

We analyzed the relationships between leaf area and total dry weight. We plotted LAI (x) on farm level against total dry weight (y) on farm level (n = 20). We analyzed the interrelationship with linear regression. We neglected all pseudostems bearing fruits. The reason for our decision was that once the plant is flowering, no more leaves are produced. However, the remaining leaves normally are destroyed by Black Sigatoka leaf disease (*Mycosphaerella fijiensis*). Therefore, the relationship between leaf area and dry weight is disturbed; the biomass is remaining, while leaves responsible for building up biomass are missing.

Additionally, we evaluated the *infection index* of Black Sigatoka (*Mycosphaerella fijiensis*) on 3 farms in Costa Rica and 5 farms in Nicaragua on different varieties. We used the approach proposed by Gauhl (1989) and Carlier *et al.* (2002) using following infection index:

$$\text{Infecion Index} = \Sigma\, n_{grade} b \,/\, \{(N - 1)^*T\} \times 100 \qquad (5)$$

Where

n_{grade} = number of leaves in each grade

b = grade

N = number of grades used in the scale (here: 6 grades)

T = total number of leaves scored

Carlier *et al.* (2002) suggest a 7-grade system (from 0 to 6). We used only 6 of 7 grades, ignoring the last grade No. 6 (damages above 50%, Figure 4), since our aim was only to evaluate damages on functional leaves. We only included plants in the vegetative phase, since at flowering no new leaves evolve and the remaining leaves are destroyed by Black

Sigatoka (Robinson 2000, Vicente-Chandler *et al.* 1966). Thus, we assumed that infection index may be higher in the generative phase. We calculated infection index per plant, summing up all leaves of all stems for one plant.

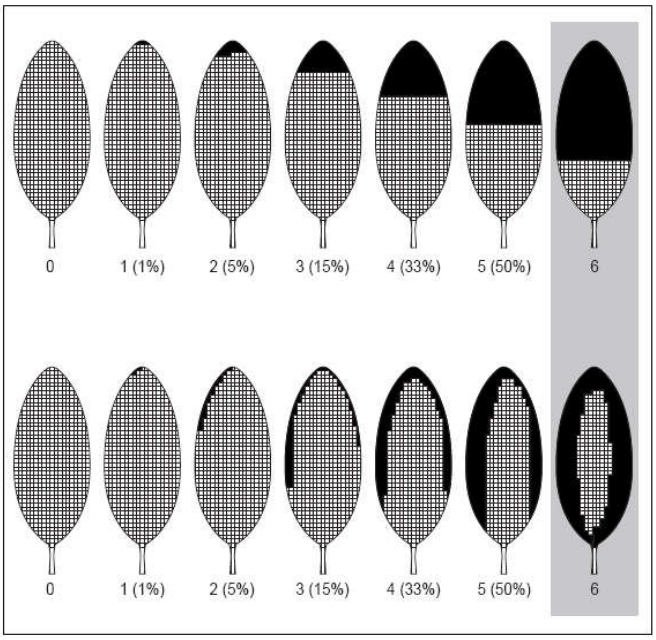

Figure 4. Gauhl's severity scoring system from 0 to 6; leaves with Sigatoka infestation over 50% (only necrosis) are defined as non-functional, found in Carlier *et al.*, (2002)

4.3. Trees

In 60 farms we established two plots of 25 m x 25 m, and estimated tree *density*. We counted all trees and calculated plants ha^{-1}. Trees with a diameter in breast height (DBH; here at 130 cm height) less than 5 cm were ignored. We defined the different *tree species*. We estimated visually and categorized *DBH, total height* and *canopy diameter*. We categorized DBH in intervals of 5 cm to 20 cm, 20 cm to 40 cm and above 40 cm. Total height was categorized in intervals of 2 m to 10 m, 10 m to 25 m, and above 25m. We separated canopy diameter in intervals of less than 2 m, 2 m to 6 m, 6 m to 10 m, and above 10 m. At last, we evaluated the *pruning management* of each tree, and categorized therefore trees in strictly pruned (the canopy is massively pruned), little pruned (some branches are cut), or not pruned tree (the tree has its typical canopy; no cuts).

In 20 farms (25 m x 25 m, one plot), we measured *circumference* in 130 cm and calculated *stem basal area* ha^{-1}. We measured radius of the canopy in four directions, or diameter of the canopy in two directions. We then calculated *canopy basal area* ha^{-1}. For each farm we measured *total tree height*. We measured *stem height* which is the height from the ground to the first major tree branch. Then we calculated canopy depth (total height – stem height), and with the canopy radius we estimated *tree crown surface* ha^{-1} (assuming tree shape of a cone).

4.4. Farm and Plots

We asked in the questionnaire 59 growers about total *farm size* and cultivated land of coffee, banana and trees. We converted the data in ha (1 manzana = 0.7 ha).
In 60 farms (two plots of 25 m x 25 m), we categorized *soil texture* in four categories; clay soils, loamy soils, sandy soils, and silt soils. We used a key for defining soils (http://forest.mtu.edu/classes/fw4220/wetlands/SoilFeelMethod.pdf) provided by the Michigan Technology University. We took a sample randomly chosen from the upper soil inside the plot. We measured plot *inclination* and *azimuth* of inclination. We took *altitude*, *latitude* and *longitude* with GPS in the centre of the plot.
In 60 farms (two plots of 25 m x 25 m), we measured percent *gap fraction* with densiometer. We took data in circa 1.5 m height at five points inside the plot; in the centre of the plot, and 3 m to 5 m away from the four corners of the plot. We avoided locations nearby trees, bananas, or high coffee plants of at least 1 m distance from the stem. We averaged the data for each farm.
In 20 farms in the subplot of 15 m x 15 m, we estimated incoming light as percent *transmitted light* and transmitted light in MJ m^{-2} day^{-1}. We estimated percent *canopy openness*. We averaged the data for each farm.
We used hemispherical photography (Nikon Coolpix 8700, Fisheye DC-E9, equidistant projection). We mounted the camera on a tripod and leveled the camera. We assumed that

four photographs will represent the incoming radiation for the whole subplot of 15 m x 15 m. Becker and Smith (1990) tested spatial distances in semi-evergreen tropical moist forests in Panama. The authors recommend a distance of 5 m or less between measurements with hemispherical photography. We took pictures at four points in a grid of 5 m x 5 m, and in three heights, 90 cm, and 130 cm to 200 cm, and 300 cm to 340 cm (see also Figure 6).

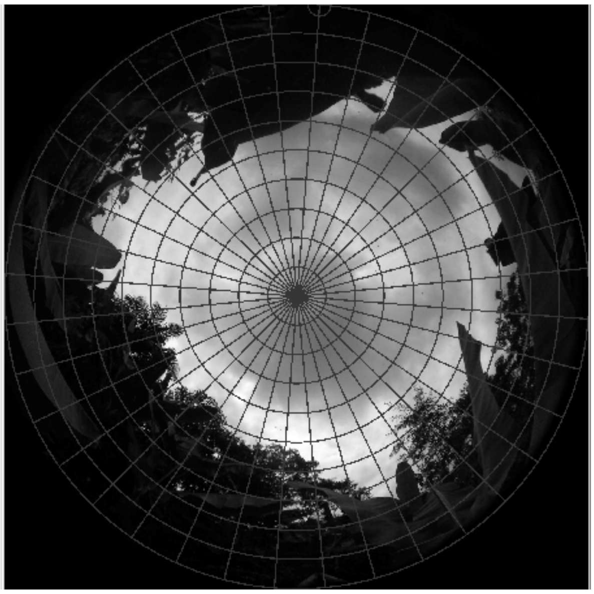

Figure 5. Hemispherical photography in a height of 300 cm – 340 cm with an overlaying grid of azimuth and zenith regions; in the centre of the picture is zenith angle = 90°, and at the edge of the picture zenith angle = 0°

At 300 cm – 340 cm we were always above coffee canopy. 90 cm height is below coffee canopy. Hence, we assumed that *light interception of coffee* is the difference of mean light transmittance at 300 – 340 cm and mean light transmittance at 90 cm height.

After taking the photos we cut all banana plants in 15 m x 15 m, and took again photographs at the same four points in 130 cm to 200 cm height. We assumed that *light interception of banana* is the difference between light transmittance at 130 cm to 200 cm height before cutting banana and light transmittance at 130 cm – 200 cm height after cutting banana.

We assumed that chopping all bananas in 15 m x 15 m would erase all bananas in the hemispherical pictures. However, there were still banana inside some pictures until zenith angle 60° - 65° (see also Figure 5). Hence, I also calculated percent transmitted light per zenith angle in steps of 10° at all heights, and with and without banana. We averaged the data for each zenith angle, and for each height.

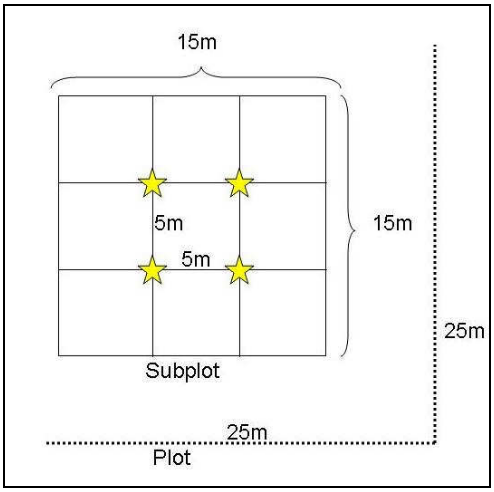

Figure 6. Structure and position of hemispherical photos; we decided on a grid of 5 m x 5 m. We took photos at four points (indicated with stars) assuming that this represent mean light transmission inside the subplot of 15 m x 15 m; at every position we took photos in a height of 90 cm, 130 cm – 200 cm (before and after cutting all banana), and 300 cm – 340 cm

I analyzed the hemispherical photographs with the software Gap Light Analyzer (GLA). I configured the software according to the manual (Frazer *et al.* 1999). For each farm, I chose Longitude, Latitude, Altitude, and correction to magnetic north, separately. I chose zenith angle intervals of 10 degrees and azimuth intervals of 10 degrees. For general configuration data see also Appendix II. Further configuration requires data of Cloudiness Index, Spectral Fraction and Beam Fraction which can be calculated with solar radiation data. For Costa Rica, I configured the program with average daily solar radiation data available at CATIE, Turrialba, Costa Rica (602 m, N 9º 53'; W 83º 38'). For Nicaragua, I used monthly data from 1970 to 1986 from the weather station at Muy Muy nearby Jinotega and Matagalpa (320 m, 12° 45' 48'' N, 85° 37' 36'' W).

Fraser *et al* (1999) suggested equations to estimate Cloudiness Index, Spectral Fraction, and Beam Fraction using daily solar radiation data. Only monthly radiation data was available for Nicaragua. Thus, I used the recommended equations with monthly data.

4.5. Statistical Analysis

For quantitative and qualitative data analysis we chose SPSS 16.0 and SigmaPlot 11.0. Data bases were established with Excel 2003.

We calculated means, standard deviation, standard error of the mean, and frequencies.

For calibration of methods we analyzed data with linear regression and estimation of 95%-Confidence Interval.

For testing significant differences in means between the countries we used Independent Student T-Test.

For testing significant differences in means between cultivars of banana we used one factorial ANOVA and Tukey Test. For testing significant differences between frequencies we chose Pearson chi-square test.

For analyzing interrelationships between parameters of coffee, banana and trees, we chose linear regression analysis and Pearson linear correlation.

The significant differences between means of transmitted light with and without banana were analyzed with Paired Student T-Test.

5. Results

5.1. General Farm Data

Mean *farm size* was 4.6 ha in Costa Rica, and 4.2 ha in Nicaragua. In two cases growers mentioned farm size of 60 ha and 80 ha. Those are excluded in farm size estimation and analysis. Growers cultivate coffee in banana tree systems on a *field size* of 2 – 3.3 ha. There is a high standard deviation of field size and farm size. There is no significant difference in farm size between the countries. There is a statistical difference in field size between Costa Rica and Nicaragua, but significance is not strong with 0.036 (see Table 8).

Table 8. Farm and field size, altitude, inclination, and soil texture from coffee banana agroforestry systems; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is α = 0.05; analysis of frequency differences between countries and categories with 2-sided Pearson chi-square test; significance level α = 0.05

Parameter		Costa Rica	Nicaragua	Sign. 2-tailed
Farm Size (ha)	Mean	4.6	4.2	0.705
	Std Dev	3.6	3.5	
Field Size (ha)	Mean	2.0	3.3	0.036
	Std Dev	1.9	2.6	
Altitude (m)	Mean	899	922	0.456
	Std Dev	197	138	
Inclination (degr.)	Mean	21	14	0.000
	Std Dev	10	7	
Soils	Sand	0%	0%	0.026
	Silt	10%	2%	
	Clay	77%	63%	
	Loam	13%	34%	

Mean *altitude* is 899 m in Costa Rica, and 922 m in Nicaragua. Minimum altitude is 614 m in Bajo Pacuare, Costa Rica, and maximum altitude is 1378 m in Alto Quetzal, Costa Rica. There is no significant difference in the mean of altitude between both countries. There is a significant difference in coffee field *inclination* between both countries. There is a high standard deviation of field inclination
In Costa Rica, 77% of the *soils* are clay soils, 13% are loamy soils, and 10% are silt soils. In Nicaragua around 63% of the soils are clay soils, 34% are loamy soils and a minority are silt soils. In both countries there are no sandy soils in coffee fields. There is a weak significant difference between frequency distribution of soil type categories (see Table 8).

5.2. Coffee Results

There is a significant difference in the means of *coffee production*, and coffee cherries per plant in Nicaragua and Costa Rica. Coffee production and coffee cherries per plant have high standard deviations. The means of coffee plant *density* in both countries are significantly different at $\alpha = 0.05$, but significance is not strong (see Table 9).
Productive stage of the plant was also described. In Costa Rica, 20.1% of the observed coffee was missing, and in Nicaragua 21.4% was missing. In Costa Rica 36.2% of the plants need a better management practice (pruning, deep pruning, or replacement of the plant). In Nicaragua, 27.9% need a better management practice. In Costa Rica, 31.7% of the plants are productive, and in Nicaragua 50.4% are productive. In Costa Rica, 12.1% of the plants are replaced or deep pruned, while in Nicaragua nearly 0.2% are replaced or deep pruned. There is a significant difference between the frequency distribution of productive stages (see Table 9).
In Costa Rica, 11% of the observed coffee plants have a *height* of less than 1 m, and in Nicaragua there are 9% with a height less than 1 m. In Costa Rica, 69% of the plants are between 1 m and 2 m high, and in Nicaragua 48% of the plants are between 1 m and 2 m high. In Costa Rica 20% of the plants are higher than 2 m, and in Nicaragua 43% of the plants are higher than 2 m. There is a significant difference between the frequency distribution of coffee height (see Table 9).

There is no significant linear correlation between coffee production and plant density or basal area of banana, coffee, and trees. There is no linear correlation between coffee production and light interception of coffee, gap fraction, or visual indices. There is also no linear correlation between coffee production and tree crown surface, LAI of banana, canopy area of banana or trees. There is no linear correlation between coffee production and tree pruning or productive stages of coffee. Banana production, and total canopy area have significant weak positive correlations to coffee production (see Table 10).

Table 9. Differences in means of production and density; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is $\alpha = 0.05$; frequency of productive stages and height of coffee in Costa Rica and Nicaragua; analysis of frequency differences between countries and categories with 2-sided Pearson chi-square test; significance level $\alpha = 0.05$

Parameter		Costa Rica	Nicaragua	Sign. 2-tailed
Production (kg green bean ha^{-1} a^{-1})	Mean	472	1184	0.000
	Std. Dev.	409	855	
	n	30	28	
Cherries Harvest (kg $Plant^{-1}$)	Mean	0.67	1.45	0.005
	Std. Dev.	0.62	1.31	
	n	30	28	
Plants ha^{-1}	Mean	4244	4852	0.045
(n= 30)	Std. Dev.	1326	940	
Productive Stage	Missing	20.1%	21.4%	0.000
	Replaced/Deep Pruned	12.1%	0.2%	
	Needs Replacement	7.4%	9.3%	
	Needs Deep Pruning	7.4%	11.5%	
	Needs Pruning	21.4%	7.1%	
	Productive	31.7%	50.4%	
Coffee Height	less than 1 m	11%	9%	0.000
	1 m to 2m	69%	48%	
	>2 m	20%	43%	

Table 10. Pearson linear correlation between coffee production and banana production, plant density, basal area, canopy area of coffee banana and trees; also light interception of coffee, and canopy openness, tree pruning, and productive stage of coffee; the second column shows Pearson correlation coefficient r from coffee production and different parameters of the agroforestry system; * indicate differences at significance level α = 0.05; ** indicate differences at significance level α = 0.01

Pearson Correlation	Coffee Production	Sign. 2-tailed	n
Bunches ha^{-1} a^{-1} and year	.399**	0.003	55
Banana ha^{-1}	-0.06	0.652	58
Stems ha^{-1}	0.20	0.123	58
Trees ha^{-1}	-0.20	0.123	58
Coffee ha^{-1}	0.10	0.433	58
Basal Area Coffee m^2 ha^{-1}	-0.25	0.296	20
Basal Area Banana m^2 ha^{-1}	0.22	0.355	20
Basal Area Tree m^2 ha^{-1}	0.10	0.685	20
Canopy Area Banana m^2 ha^{-1}	0.32	0.170	20
Canopy Area Tree m^2 ha^{-1}	0.35	0.127	20
Total Area m^2 ha^{-1}	.506*	0.023	20
Tree Crown Surface m^2 ha^{-1}	0.23	0.324	20
Leaf Area Index Banana	0.19	0.414	20
Gap Fraction	0.14	0.312	58
% Intercepted Light Coffee	-0.11	0.635	20
Visual Index Coffee	0.00	0.971	58
Visual Index Banana	0.21	0.119	58
Tree, no pruning	-0.12	0.376	58
Tree, little pruning	-0.13	0.344	58
Tree, strict pruning	-0.13	0.340	58
Missing	0.15	0.265	58
Replaced/Deep Pruned	-0.23	0.084	58
Needs Replacement	0.06	0.665	58
Needs Deep Pruning	-0.04	0.746	58
Needs Pruning	-0.14	0.298	58
Productive	0.24	0.066	58

5.3. Banana – Relation of Dry Matter and Circumference, and Leaf Area Estimation

An evaluation of the equation of Turner (2003) for *leaf area estimation* was tested in its usability in field. This would facilitate the field work. We compared the real leaf area data from pseudostems with leaf area estimated with Turner's equation. There is a strong linear regression within the two methods (see also Figure 7). The data includes pseudostems from several cultivars in different development stages. Those cultivars are AAA Gros Michel cv. 'Guineo Blanco' (n = 75), AAA Gros Michel cv. 'Coco' (n = 16), AAA Cavendish cv. 'Congo' (n = 43), AAA Red Subgroup cv. 'Guineo morado' (n = 16), AAA Red Subgroup cv. 'Caribe Verde' (n = 9), cv. 'Platano' (n = 3), and ABB Bluggoe cv. 'Guineo cuadrado' (n = 2). Pseudostems were in different vegetative development stages, and in the generative stage.

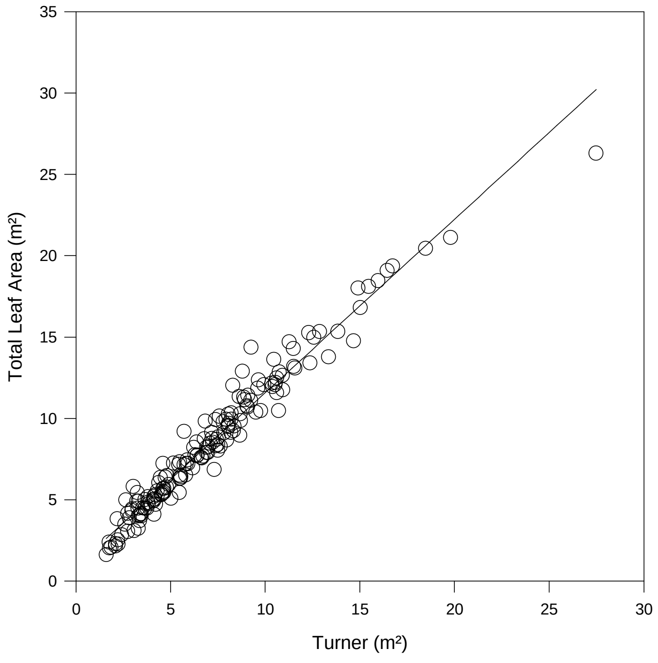

Figure 7. Linear regression analysis of leaf area calculated with Turner´s equation (2003) and real measured data. We set our real data of pseudostem leaf area in relation to our calculate data, n = 164 pseudostems; coefficient of determination $R^2 = 0.96$

The coefficient of determination is $R^2 = 0.96$. Mean leaf area from real measurements has a 95% - Confidence Interval = [7.85 m²; 9.18 m²]. Mean leaf area estimated with Turner (2003) has a 95% - Confidence Interval = [6.51 m²; 7.74 m²].

It would facilitate field work when *dry matter* could be predicted by circumference measurements. Therefore, the relationship of dry matter and circumference from pseudostems is evaluated with regression analysis. An estimation of total dry matter of above ground parts is possible with a polynomial equation of 2nd order. The coefficient of determination $R^2 = 0.84$ (see also Figure 8). Real mean dry weight data has a 95% - Confidence Interval = [3.37 kg; 4.19 kg]. Estimated mean dry weight data has a 95% - Confidence Interval = [3.40 kg; 3.95 kg].

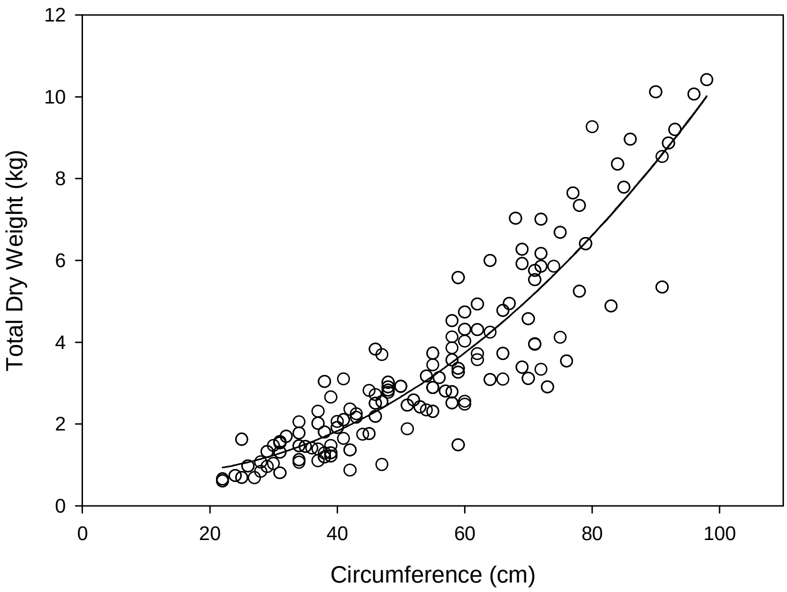

Figure 8. The relationship between circumference and dry weight; n = 226 pseudostems of different varieties; regression analysis; coefficient of determination $R^2 = 0.84$; equation for estimation of total dry weight (kg) (D):

$$D\ (kg) = 0.897 - (0.0247 * Circ.\ (cm)) + (0.00120 * Circ.\ (cm)^2) \qquad (6)$$

5.4. Banana – Cultivars, Density, Leaf Area Index and Dry Matter

Plant *density* of banana was significant different in both countries. There is no significant difference in number of stems higher than 2 m. There is a significant difference of number of stems of 1 m to 2 m height in both countries. In average every banana has 2 – 3 stems per plant. Plant and stem density have high standard deviations.
Number of harvests was the measure of plant age. In Costa Rica 33.3% of the observed plants have less than 2 harvests, 53.3% have 2 – 3 harvests, and 13.3% have more than 3 harvests. In Nicaragua, 46% of the observed plants have less than 2 harvests, 37% have 2 – 3 harvests, and 17% have more than three harvests. There is no significant difference between the frequency distribution of number of harvests (see Table 11).

Altogether we identified 13 different *banana cultivars,* of which most belong to the triploid AAA genome group. In Nicaragua there are mainly banana from AAA subgroup Gros Michel, and some of AAA Red Subgroup. The two groups make up 97.6% of all banana found in Nicaragua. In Costa Rica, there are mainly two cultivars of AAA subgroup Gros Michel and one cultivar of AAA subgroup Cavendish. Together the three cultivars make up 91.1% of all bananas found in Costa Rica. There is a significant difference between the frequency distribution of banana cultivars (see also Table 12).

There are significant differences between banana cultivars and genome groups in the mean of *total leaf area* per plant and in the mean of *single leaf area*. Cultivars of the AAA Red Subgroup have higher plant leaf area than AAA Gros Michel 'Coco', and AAA Cavendish 'Congo'. AAA Cavendish cv. 'Congo' has lower total leaf area and single leaf area than AAA Gros Michel 'Guineo Blanco'.
AAA Gros Michel cv. 'Coco' has similar total leaf area and single leaf area than AAA Gros Michel 'Guineo Blanco', and AAA Cavendish 'Congo'.
There is no significant difference between cultivars or genome groups in the mean of *total leaf number* (see also Figure 9). We had varying sample sizes between cultivars.

Table 11. Density of banana plants and stems, and plant age (described as frequency of number of harvests) in Costa Rica and Nicaragua; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is α = 0.05; analysis of frequency differences between countries and categories with 2-sided Pearson chi-square test; significance level α = 0.05

Parameter		Costa Rica	Nicaragua	Sign. 2-tailed
Banana ha^{-1}	Mean	579	358	0.000
n = 30	Std. Dev.	287	123	
Stems >2m ha^{-1}	Mean	667	645	0.831
n = 30	Std. Dev.	520	221	
Stems 1-2m ha^{-1}	Mean	634	415	0.002
n = 30	Std. Dev.	321	172	
# Harvest	< 2 Harvests	33.3%	46%	0.092
(Plant Age)	2-3 Harvests	53.3%	37%	
	> 3 Harvests	13.3%	17%	

Table 12. Frequency of banana cultivars in coffee agroforestry systems on 30 farms in Nicaragua and 30 farms in Costa Rica; analysis of frequency differences between countries and categories with 2-sided Pearson chi-square test; significance level α = 0.05

Cultivar	Costa Rica	Nicaragua
Guineo Blanco (AAA Gros Michel)	31.4%	84.9%
Congo (AAA Cavendish)	46.7%	0%
Coco (AAA Gros Michel)	13.0%	0.2%
Guineo morado (AAA Red Subgroup)	0.4%	8.8%
Caribe Verde (AAA Red Subgroup)	0.2%	3.7%
Datil (AA Sucrier)	2.1%	0.2%
Platano	3.7%	0.4%
FHIA-25	1.7%	0.1%
Guineo cuadrado (ABB Bluggoe)	0.6%	1.3%
Guineo negro	0.1%	0%
FHIA-23 (AAAB)	0%	0.2%
Filipino (ABB Bluggoe)	0%	0.1%
Manzano (AAB Silk)	0%	0.2%
Sign. 2-sided: 0.000		

There is a significant difference between banana cultivars in the mean of *pseudostem height* and *circumference*. There is no statistical difference in the mean of pseudostem height from AAA Gros Michel ‘Guineo Blanco’, AAA Red Subgroup ‘Caribe Verde’ and AAA Red Subgroup ‘Guineo Morado’. The three cultivars have higher pseudostems than AAA Gros Michel ‘Coco’ and AAA Cavendish ‘Congo’. The two cultivars of AAA Red Subgroup have higher circumference than AAA Cavendish ‘Congo’. There is no statistical difference in the mean of circumference between the cultivars AAA Red Subgroup ‘Guineo Morado’, AAA Red Subgroup ‘Caribe Verde’, AAA Gros Michel ‘Guineo Blanco’ and AAA Gros Michel ‘Coco’ (see also Figure 10). We had varying sample sizes between cultivars.

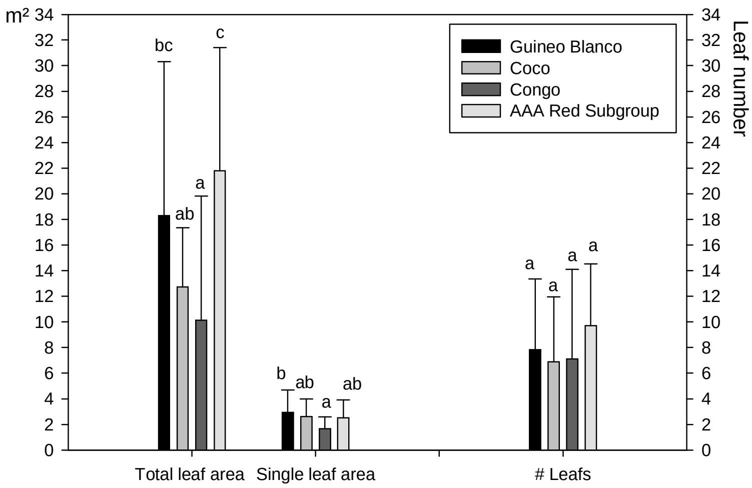

Figure 9. Total leaf area per plant (m²), mean leaf area of a single leaf and number of leaves per plant, Test of four banana cultivars and genetic subgroup; AAA Red Subgroup includes data from cv. ‘Guineo Morado’ and cv. ‘Caribe Verde’; different letters show significant differences between cultivars ($\alpha = 0.05$); error bars show standard deviation; analysis with One Way ANOVA and Tukey Test

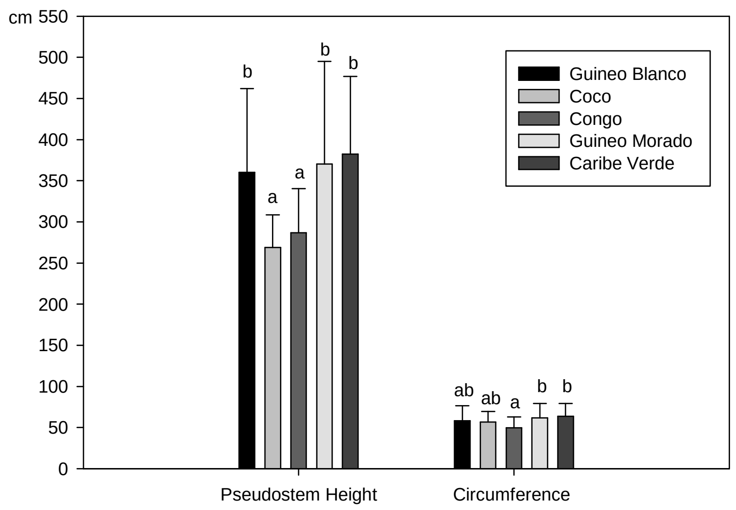

Figure 10. Pseudostem height, and circumference of five different cultivars; different letters show significant differences between cultivars (α = 0.05); error bars show standard deviation; analysis with One Way ANOVA and Tukey Test

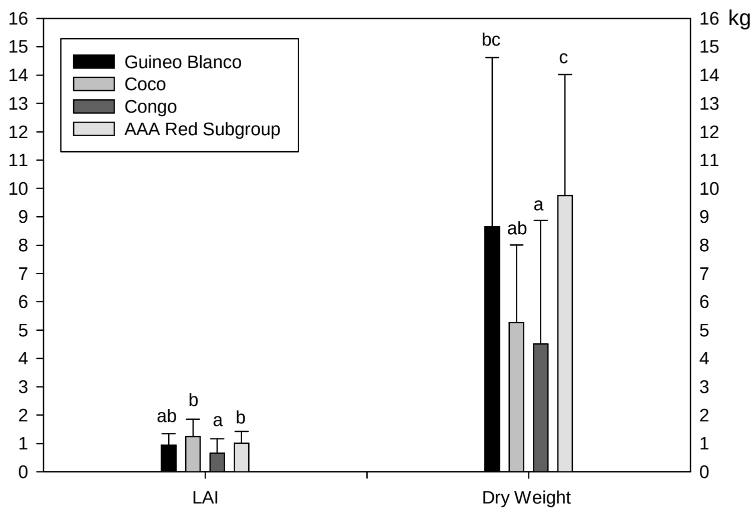

Figure 11. Leaf Area Index and above ground dry weight per plant from four different cultivars and genetic subgroup; Data of AAA Red Subgroup includes the cultivars ‘Guineo Morado’ and ‘Caribe Verde’; different letters show significant differences between cultivars (α = 0.05); error bars show standard deviation; analysis with One Way ANOVA and Tukey Test

There is a significant difference between banana cultivars and genome subgroups in the mean of *LAI* and *dry weight* per plant. LAI of 'Coco' and cultivars of AAA Red Subgroup are higher than LAI of 'Congo'. There is no statistical difference in the mean of LAI from 'Coco' and cultivars of AAA Red Subgroup (see Figure 11). Dry weight per plant is significantly higher in cultivars of AAA Red Subgroup than 'Coco' or 'Congo'. 'Guineo Blanco' has higher dry weight than 'Congo' (see Figure 11). We had varying sample sizes between cultivars.

There is a strong coefficient of determination $R^2 = 0.95$ from linear regression of total above ground dry matter and Leaf Area Index (LAI) on farm level. This data includes all cultivars found in one farm in 225 m^2. Pseudostems with bunches (generative phase) are excluded in this estimation. However, it was not possible to compute optimum LAI on farm level (Figure 12). Average LAI = 0.5 ± 0.3 ($\bar{x} \pm s$) at plant density of 349 ± 148 banana ha^{-1} ($\bar{x} \pm s$). This data refers to density measured in 20 farms, counted in 225 m^2.

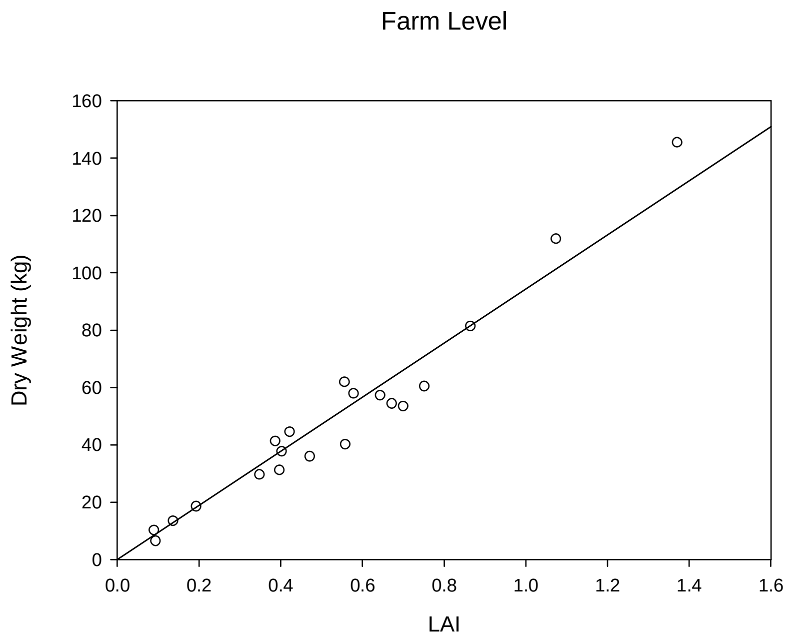

Figure 12. Leaf Area Index and total dry weight of banana of 20 farms in Nicaragua and Costa Rica; data include all plants from all cultivars found on farm, but exclude stems in the generative phase; coefficient of determination $R^2=0.95$; from linear regression; Dry Weight D (kg) = -4.998 + (101.302 * LAI)

Table 23 shows Pearson linear correlation of LAI and dry matter to different parameters of the coffee agroforestry system among others.
There is a strong positive linear correlation between LAI and dry matter. There is also a strong positive linear correlation of LAI and stem basal area and canopy area of banana. There is a positive linear correlation of LAI and Intercepted light of banana. There is no significant linear correlation between LAI and banana plant and stem density. There is no linear correlation of LAI and Gap Fraction, or basal area, canopy area, and density of coffee, and trees.
Banana dry weight is significantly positive linear correlated with banana basal area, banana canopy area, and intercepted light of banana. There is a weak negative linear correlation of dry weight and tree basal area. It is not significantly linear correlated to banana plant and stem density, and gap fraction. There is no significant linear correlation to coffee density and basal area, tree density, canopy area and crown surface.

5.5. Banana Production

Means of *number of hands* and *number of fingers* of the 2nd hands are significantly different between both countries. We could not analyze *bunch weight* because there was not sufficient data on bunch weight of mature fruits available (see also Table 13). There is a significant difference between the mean numbers of hands from different banana genome groups. Mean number of hands from AAA Red Subgroup is significantly lower than mean number of hands from AAA Gros Michel and AAA Cavendish. Mean number of fingers from the 2nd hand is significantly lower in AAA Red Subgroup than AAA Cavendish (see Figure 13). We had varying sample sizes between cultivars.

There is no significant linear correlation between numbers of hands and stem basal area, number of stems, pseudostem height, and leaf area per stem. There is a significant weak positive correlation between number of hands and pseudostem dry weight as well as circumference (see Table 14).

Table 13. Bunch weight, number of hands and number of fingers in coffee agroforestry systems in Nicaragua and Costa Rica; data from different cultivars, in Costa Rica from AAA Gros Michel, and AAA Cavendish; in Nicaragua from AAA Gros Michel and AAA Red Subgroup; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is α = 0.05

Parameters		Costa Rica	Nicaragua	Sign.2-tailed
# Hands	Average	8	6	0.015
	Std. Dev.	2	2	
	n	25	39	
# Fingers 2nd Hand	Average	15	13	0.005
	Std. Dev.	4	3	
	n	21	39	
Total # Fingers		121	80	
Bunch Weight (kg)	Average	17.5	9	---
	Std. Dev.	---	3	
	n	---	11	

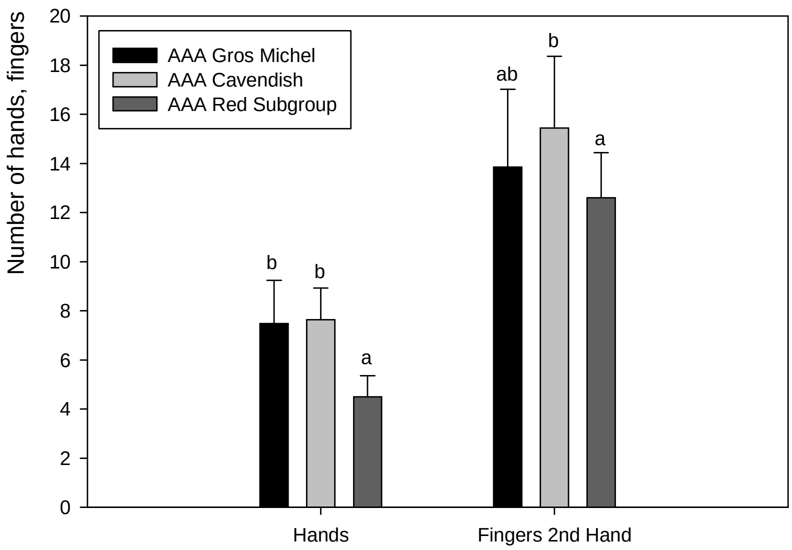

Figure 13. Mean number of hands and fingers of the second hand from three genetic subgroups from both countries; different letters show significant differences between cultivars (α = 0.05); error bars show standard deviation; analysis with One Way ANOVA and Tukey Test

We asked growers in the interview about *banana yield* and converted the data in bunches per ha and year. There is a high standard deviation of mean banana yield. Mean number of bunches per plant varies between 0.49 – 0.76, and mean number of bunches per stem varies between 0.21 – 0.26. There is no statistical difference in the mean of banana production between both countries (see Table 15).

Table 14. Pearson linear correlation between number of hands and growth parameters of banana; second column shows Pearson correlation coefficient r from number of hands and different parameters of banana * indicate differences at significance level $\alpha = 0.05$

Pearson Correlation	# Hands	Sign. 2-tailed	n
Circumference (cm)	0.369*	0.010	47
Stem Basal Area Stem^{-1}	0.184	0.210	48
# Stems Plant^{-1}	0.155	0.292	48
Pseudostem Height (cm)	-0.001	0.991	48
Dry Weight per Stem(kg)	0.285*	0.049	48
Leaf Area (m² Stem $^{-1}$)	-0.01	0.907	48

Table 15. Yield data from the questionnaire is converted in Bunch ha^{-1} a^{-1}; then bunch per plant and stem is estimated; bunches counted on farm show number of fruiting plants at data taking; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is $\alpha = 0.05$;

Parameters		Costa Rica	Nicaragua	Sign. 2-tailed
Bunch ha^{-1} a^{-1}	Mean	233	270	0.587
(from Questionnaire)	Std. Dev.	231	264	
Bunch ha^{-1}	Mean	574	354	0.748
(counted on Farm)	Std Dev	289	121	
Bunch Plant^{-1}	Mean	0.49	0.76	0.090
(from Questionnaire)	Std. Dev.	0.44	0.73	
Bunch Stem^{-1}	Mean	0.21	0.26	0.444
(from Questionnaire)	Std. Dev.	0.17	0.26	

There is no significant linear correlation between banana production and dry weight of banana, LAI of banana, canopy area of banana and trees, tree crown surface, basal area and density of banana stems, coffee plants or trees. There is a significant weak positive correlation between coffee berries per plant and banana production. There is no significant linear correlation between banana production and intercepted light, gap fraction, visual indices, or tree pruning (see Table 16).

Table 16. Pearson linear correlation between banana production and parameters of coffee, banana and trees, tree pruning as well as light interception and canopy openness; second column shows Pearson correlation coefficient r from bunches per ha and year and different parameters of the agroforestry system; ** indicate differences at significance level α = 0.01

Pearson Correlation	Bunches ha^{-1} a^{-1}	Sign. 2-tailed	n
Coffee berries $plant^{-1}$ (kg)	.536**	0.000	55
Dry Weight Banana (kg)	0.05	0.700	55
All Stems ha^{-1}	0.11	0.409	55
Trees ha^{-1}	-0.14	0.315	55
Coffee ha^{-1}	-0.13	0.346	55
Basal Area Coffee (m^2 ha^{-1})	-0.12	0.616	19
Basal Area Banana (m^2 ha^{-1})	0.11	0.663	19
Basal Area Tree (m^2 ha^{-1})	0.02	0.951	19
Canopy Area Banana (m^2 ha^{-1})	0.17	0.494	19
Canopy Area Tree (m^2 ha^{-1})	0.22	0.370	19
Tree Crown Surface (m^2 ha^{-1})	0.37	0.116	19
Leaf Area Index Banana	0.19	0.426	19
Gap Fraction	-0.06	0.648	55
% Intercepted Light Banana	0.09	0.721	19
Visual Index Coffee	-0.03	0.831	55
Visual Index Banana	0.16	0.246	55
Tree, no pruning	-0.03	0.848	55
Tree, little pruning	-0.19	0.173	55
Tree, strict pruning	-0.04	0.790	55

5.6. Black Sigatoka Infestation of Banana

Mean *Infection Index* of Black Sigatoka was 19.5% for all plants and cultivars. There is a significant difference between cultivars in the mean of Black Sigatoka Infection Index. ‘Guineo morado’ had lowest mean infection index of 9.7%, and ‘Coco’ had highest mean infection index of 30.6% (see Figure 14). We had varying sample sizes between cultivars.

There is no significant linear correlation between gap fraction and Sigatoka infection index (Pearson correlation coefficient r = 0.447, 2-tailed Sign.: 0.267, n = 8). There is no significant linear correlation between intercepted light and Sigatoka infection index (Pearson correlation coefficient r = 0.349, 2-tailed Sign.: 0.396, n = 8).

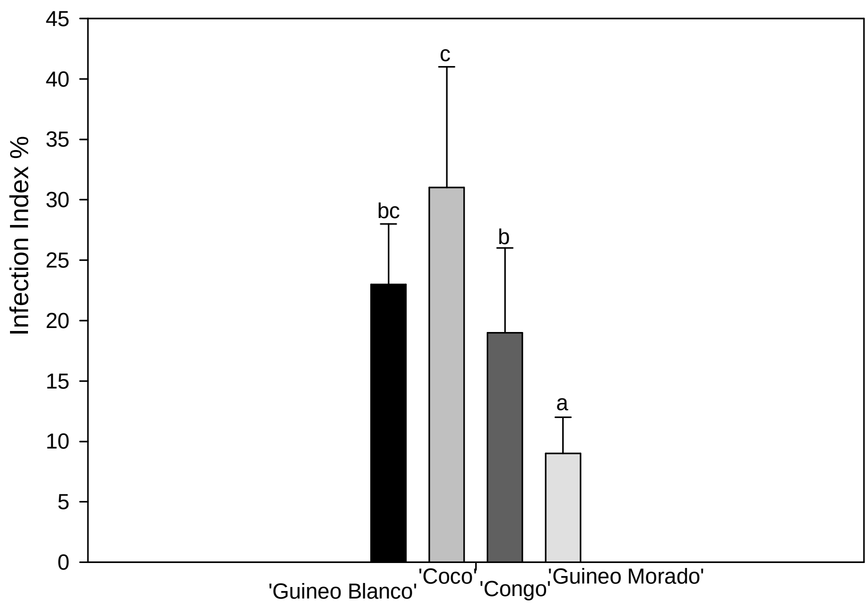

Figure 14. Mean infection index of Black Sigatoka in banana intercropping; only plants in the vegetative development phase are included; Test of four cultivars; different letters show significant differences between cultivars (α = 0.05); error bars show standard deviation; analysis with One Way ANOVA and Tukey Test

5.7. Importance of Banana, and Management

We asked the growers which *importance* has banana to include it in coffee fields. We grouped the frequency of the answers in four categories (see Table 17). In Nicaragua, 12 growers argued that subsistence farming of banana is important, while no farmer in Costa Rica mentioned this topic. 5 growers in Nicaragua and 12 growers in Costa Rica argued that banana is a whole year income source. In both countries 19 growers mentioned several other economic reasons. And in both countries 4 growers mentioned reasons concerning the management of the growing system.

Mean frequency of *banana management* is 3.5 times per year in Costa Rica, and 2.1 times per year in Nicaragua. There is a high standard deviation in frequency of banana management. In Costa Rica, two growers manage banana 26 times per year, and one grower 28 times per year. In Nicaragua, one grower manage banana 12 times per year and one grower 24 times per year. I excluded the data, since most growers manage banana less frequently. There is no significant difference of frequency of banana management in both countries (see Table 18).

We asked the growers, if they perform management practices on banana; *deleafing, desuckering,* and *debudding*. In Costa Rica, 14 of 19 growers do debudding, 25 of 28 growers do deleafing, and 23 of 25 growers do desuckering. In Nicaragua, 2 of 14 growers do debudding, 14 of 19 growers do deleafing, and 14 of 29 growers do desuckering. There is no significant difference in frequency distribution of desuckering, and deleafing. There is a significant difference in frequency distribution of debudding management (see Table 18).

We also asked, if the growers apply *fertilizer* and *pest management* on banana. In Costa Rica, 12 of 30 growers apply fertilizer to banana, and in Nicaragua none of 28 growers apply fertilizer to banana. There is a significant difference of frequency distribution of fertilizer application. In Costa Rica, 12 growers do no pest control on banana, 1 grower uses pesticides and 11 growers use other forms of pest and disease management. In Nicaragua, 21 growers do no pest control, 1 grower uses pesticides and 3 growers use other forms of pest and disease management (see Table 18).

Table 17. Importance of banana for coffee growers; reasons argued by the growers summarized in four categories; frequency of upcoming answers and total number of interviewed growers in both countries

Importance of Banana?	Costa Rica	Nicaragua	Total n CR/NIC
Subsistence	0	12	26/26
Whole Year Income Source	12	5	26/26
Other Economic Reasons	19	19	26/26
Management of the System	4	4	26/24

Table 18. Frequency of annual banana management; number of growers who undertake debudding, deleafing, desuckering, fertilizer and pesticide application of banana; analysis of frequency differences between countries and categories with 2-sided Pearson chi-square test; significance level α = 0.05

Parameters		Costa Rica	Nicaragua	Sign. 2-sided
Frequency	Mean	3.5	2.1	0.117
Management (times a^{-1})	Std Dev	2.1	1.6	
Debudding	Yes	14	2	0.001
	No	5	12	
Deleafing	Yes	25	14	0.163
	No	3	5	
Desuckering	Yes	23	14	0.118
	No	2	15	
Pest Management	No Pest Control	12	21	---
on Banana	Use of Pesticides	1	1	
	Other Forms of Disease Management	11	3	
Fertlizer Application	Yes	12	0	0.000
on Banana	No	18	28	

5.8. Tree Results

Tree species of all trees within the plot were determined. In Costa Rica, 59.6% of all observed trees are *Erythrina poeppigiana*. In Nicaragua, 47.4% of all observed trees are from the genus *Inga*. The six most common tree species and genera on farms make up 80.8% and 71% of all trees found in Costa Rica and Nicaragua, respectively (Table 20). Mean tree density is significantly different in Costa Rica and Nicaragua. There is a high standard deviation in tree *density*. In Costa Rica 58.9%, and in Nicaragua 63% of the trees have a *DBH* of 5 cm – 20 cm. In Costa Rica 31.4%, and in Nicaragua 28.8% have a DBH of 20 cm – 40 cm. The rest of the trees have a DBH higher than 40 cm. There is no significant difference between frequency distribution of DBH categories (Table 19).
In Costa Rica 87.6%, and in Nicaragua 76.4% of the trees have a *height* of 2 m – 10 m. In Costa Rica, 9.8% of the observed trees have a height of 10 m – 25 m. In Nicaragua, 21.9% of the trees have a height of 10 m – 25 m. The rest of the trees are higher than 25m. There is a significant difference between frequency distribution of tree height categories (Table 19). In Costa Rica, 51.3% of the trees have a *canopy diameter* less than 2 m, and 40.4% of the trees have a canopy diameter of 2 m – 6 m. The rest of the trees have a canopy diameter of 6 m – 10 m or above 10 m. In Nicaragua, 13.3% of the trees have a canopy diameter less than 2 m, and 61.4% have a canopy diameter of 2 m – 6 m. In Costa Rica 7.4%, and in Nicaragua 19.9% of the trees have a canopy diameter of 6 m – 10 m, and the rest of the trees have a canopy diameter of 6 m – 10 m or above 10 m. There is a significant difference between frequency distribution of canopy diameter categories (Table 19). The analysis of *stem height* and *total height* measurements was done for each farm separately. Data is the mean of farm means, and standard error. There is no significant difference of stem height and total height on farm level in both counties. Mean tree height of the observed farms is 9 m – 9.8 m, and mean stem height is 3.4 m – 4.3 m (Table 19). There is a significant difference between frequency distribution of *tree pruning* categories. In Costa Rica 31.1% of the trees are not pruned, and in Nicaragua 54.1% of the trees are not pruned. In Costa Rica 22.7% of the trees are little pruned, and in Nicaragua 37.9% are little pruned. In Costa Rica 46.1% of the trees are strict pruned, and in Nicaragua 8% of the trees are strict pruned (Table 19).

Table 19. Density, DBH, total height, stem height, canopy diameter and management of trees associated with coffee and banana from 60 farms in Costa Rica and Nicaragua; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is α = 0.05; analysis of frequency differences between countries and categories with 2-sided Pearson chi-square test; significance level α = 0.05

Parameter		Costa Rica	Nicaragua	Sig. 2-tailed
Density (Plants ha^{-1})	Mean	341	185	0.01
	Std Dev	253	101	
DBH	5-20cm	58.9%	63.0%	0.178
	20-40cm	31.4%	28.8%	
	>40cm	9.7%	8.2%	
Total Height (in intervals)	2-10m	87.6%	76.4%	0.000
	10-25m	9.8%	21.9%	
	>25m	2.6%	1.7%	
Stem Height per farm (m)	Mean	4.3	3.4	0.367
	Std Error	0.7	0.6	
Total Height per farm (m)	Mean	9.0	9.8	0.649
	Std Error	1.6	1.0	
Canopy Diameter	<2m	51.3%	13.3%	0.000
	2-6m	40.4%	61.4%	
	6-10m	7.4%	19.9%	
	>10m	0.9%	5.4%	
Management	not pruned	31.1%	54.1%	0.000
	little pruned	22.7%	37.9%	
	strict pruned	46.1%	8.0%	

Table 20. Most common genera and species on farm in Nicaragua and Costa Rica; the second and fifth column show the number of farms where at least on individual of the species was found; the third and sixth column show the share of total trees counted in 30 farms in each country

Costa Rica			Nicaragua		
Species	# Farms (n=30)	Percent Individuals	Species	# Farms (n=30)	Percent Individuals
Erythrina poeppigiana	24	59.6%	*Inga sp.*	30	47.4%
Cordia sp.	21	14.4%	*Persea americana*	14	5.1%
Psidium sp.	8	0.8%	*Cordia sp.*	12	9.4%
Citrus sp.	7	1.4%	*Pouteria sp.*	8	3.5%
Bactris gasipaes	7	0.7%	*Cupania glabra*	6	3.9%
Inga sp.	6	3.9%	*Citrus sp.*	6	1.7%

5.9. Canopy Area, Basal Area, and Density Relationships

We estimated sample size of *coffee basal area* by computing 95% - Confidence Interval of different sample sizes from coffee circumference data of two farms. We plotted sample size n (x) against 95% - Confidence Interval (y) and decided visually according to the graph (see Figure 15). Measuring half of the plot 15 m x 15 m seems reasonable because 95% - Confidence Interval does not change strongly when reducing sample size by the half.

In the first farm we measured 62 plants. Mean circumference of coffee for n = 62 has a 95% - Confidence Interval = [34 cm; 43 cm], and for n = 32 it has a 95% - Confidence Interval = [31 cm; 43 cm]. On the second farm we measured 80 plants. Mean circumference of coffee for n = 80 has a 95% - Confidence Interval = [43 cm; 51 cm], and for n = 40 it has a 95% - Confidence Interval = [41 cm; 51 cm]. On the other eighteen farms mean sample size was $\bar{n} = 50$.

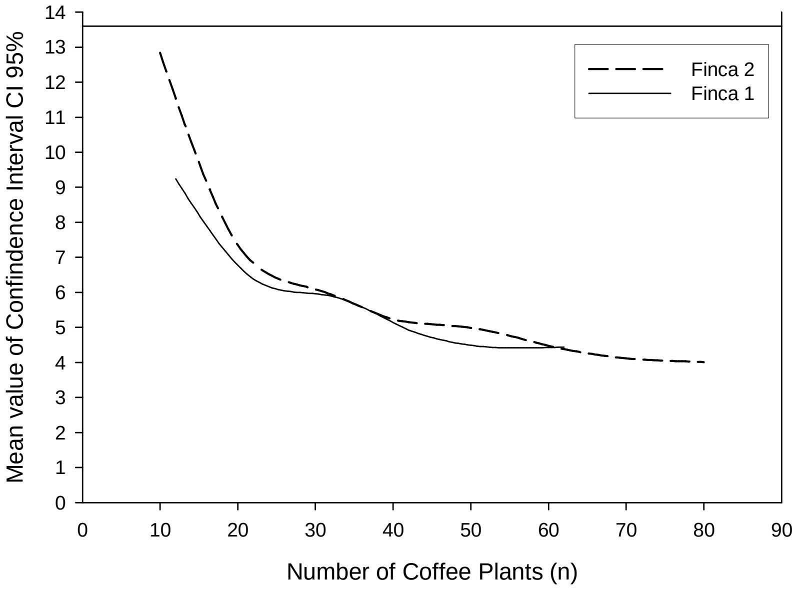

Figure 15. To decide on sample size n for circumference and basal area in coffee, 95% - Confidence Interval of circumference was plotted against sample size n; data from two farms in Costa Rica; visual decision to measure half of the plants found within the subplot (15m x 15m); in 20 farms mean sample size was $\bar{n} = 50$

There is a significant difference of *basal area* of banana between the two countries, but significance is weak. Basal area of coffee and trees show no significant difference between the countries. There is no statistical difference in total basal area between the countries. There is a high standard deviation at all basal area data. Relation of basal area shows the composition of the system; coffee > banana and trees (Table 21).

There is no statistical difference in the mean of *canopy area* of trees or bananas between the countries. There is a weak statistical difference of total canopy area between the countries. Mean relation between canopy area of bananas and trees in Costa Rica is 0.46 and 0.54, and in Nicaragua the relation is 0.52 and 0.48. Standard deviation of all canopy area data is high. There is no statistical difference of *tree crown surface* between the countries. Mean tree crown surface is 14,100 to 16,300 m^2 ha^{-1} (see Table 22).

Table 21. Basal Area of the three agroforestry system components; coffee, banana and tree, and its relation to total basal area; analysis of differences of means between countries with 2-tailed Independent T-Test; n = 20; significant level is α = 0.05

		Basal Area(m^2 ha^{-1})			
		Coffee	Banana	Tree	Total
Costa Rica	Mean	46.7	14.6	16.2	77.5
	Std Dev	23.6	9.4	7.8	31.5
	Relation	60%	19%	21%	100%
Nicaragua	Mean	31.8	27.8	12.3	71.9
	Std Dev	24.9	15.6	6.6	31.8
	Relation	44%	39%	17%	100%
Difference	Sign.				
Countries	2-tailed	0.189	0.034	0.236	0.700

Table 22. Canopy area of bananas and trees, and tree crown surface in coffee agroforestry systems in Costa Rica and Nicaragua; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is α = 0.05; n = 20

		Canopy Area (m^2 ha^{-1})			Crown Surface (m^2 ha^{-1})
		Banana	Tree	Total Area	
Costa Rica	Mean	5029	5924	10953	14172
	Std Dev	4161	3966	5233	10824
	Relation	0.46	0.54	1.00	
Nicaragua	Mean	8176	7590	15766	16319
	Std Dev	3720	3738	4400	9208
	Relation	0.52	0.48	1.00	
Difference	Sign.				
Countries	2-tailed	0.091	0.347	0.039	0.639

Table 23 shows Pearson linear correlation of canopy area and basal area of coffee, banana, and trees. There is no significant linear correlation between coffee basal area and density, basal area or canopy area of coffee, banana, and trees. There is no significant linear correlation between coffee basal area and gap fraction, or intercepted light, dry weight and LAI of banana.

There is a significant linear correlation of tree basal area and tree canopy area and tree crown surface. There is a significant linear correlation between tree basal area and intercepted light and dry weight of banana. There is no significant linear correlation of tree basal area and canopy area, tree density, basal area and density of coffee, and banana.

There is a weak negative linear correlation of tree canopy area and banana plant and stem density. There is a positive linear correlation of tree canopy area and tree crown surface: There is a negative linear correlation to intercepted light of banana. There is no significant linear correlation of tree canopy area and canopy area or basal area of banana. There is no significant linear correlation of tree canopy area and density of coffee or trees. There is a significant negative linear correlation of tree crown surface and banana stem density, and intercepted light of banana. There is no significant linear correlation of tree crown surface and density of banana, coffee, and tree. There is no significant correlation of tree crown surface and basal area, and canopy area of banana.

There is a linear correlation of banana basal area, banana canopy area and intercepted light of banana. There is no significant linear correlation of banana basal area and density of coffee, banana plants, stems, trees. There is a significant linear correlation of banana canopy area and banana plant and stem density. There is a significant linear correlation of banana canopy area and intercepted light of banana. There is no linear correlation of banana canopy area and density of coffee and trees.

There is no significant linear correlation between density of coffee, banana and trees. Stem density of banana is significantly linear correlated to banana plant density. There is no significant linear correlation of tree density and intercepted light of banana. There is no significant difference of coffee density and intercepted light of banana. There is a significant linear correlation of banana plant and stem density and intercepted light of banana (see Table 23).

Table 23. Pearson linear correlation between parameters of coffee, banana and trees, gap fraction as well as light interception, LAI and dry weight of banana; numbers are Pearson correlation coefficient r; ** indicate differences at significance level α = 0.01; * indicate differences at significance level α = 0.05

Units	$m^2\ ha^{-1}$	$m^2\ ha^{-1}$	$m^2\ ha^{-1}$	$m^2\ ha^{-1}$	$m^2\ ha^{-1}$	$m^2\ ha^{-1}$	ha^{-1}	ha^{-1}	ha^{-1}	ha^{-1}	%	%	kg
	Coffee Basal Area	Basal Area Banana	Basal Area Tree	Canopy Area Banana	Canopy Area Tree	Tree Crown Surface	Banana Density	Tree Density	Coffee Density	Banana Stems	Gap Fraction	Intercepted Light	Dry Weight
Basal Area Banana	.154	---	---	---	---	---	---	---	---	---	---	---	---
Basal Area Tree	.150	-.372	---	---	---	---	---	---	---	---	---	---	---
Canopy Area Banana	.098	.769**	-.336	---	---	---	---	---	---	---	---	---	---
Canopy Area Tree	-.043	-.261	.567**	-.122	---	---	---	---	---	---	---	---	---
Tree Crown Surface	-.084	-.259	.596**	-.133	.950**	---	---	---	---	---	---	---	---
Banana Density	.211	.150	-.100	.452*	-.464*	-.440	---	---	---	---	---	---	---
Tree Density	.378	-.144	.235	-.393	-.076	-.091	.124	---	---	---	---	---	---
Coffee Density	.207	.247	.137	.015	.244	.161	-.231	.438	---	---	---	---	---
Banana Stems	.161	.409	-.280	.633**	-.473*	-.529*	.826**	-.176	-.125	---	---	---	---
Gap Fraction	-.130	.133	-.414	-.053	-.580**	-.600**	.216	.084	-.008	.285	---	---	---
Intercepted Light	.132	.677**	-.627**	.690**	-.561*	-.539*	.524*	-.030	-.002	.610**	.495*	---	---
Dry Weight	.127	.948**	-.445*	.770**	-.233	-.236	.084	-.213	.109	.360	.046	.633**	---
LAI	.157	.957**	-.383	.756**	-.189	-.187	.088	-.117	.221	.340	.099	.634**	.975**

5.10. Gap Fraction and Transmitted Light

There is no significant difference in the mean of Gap Fraction with densiometer between both countries. Mean Gap Fraction is 45% in both countries. The analysis of Gap Fraction was done for each farm separately. Table 24 shows the mean of farm means, and standard error. There is no significant difference of *Visual Index* at banana height. Mean Visual Index is about 68% in Costa Rica, and 66% in Nicaragua. There is only a weak significant difference of Visual Index at Coffee Height between the countries. Mean Visual Index at coffee height is 54% in Costa Rica and 48% in Nicaragua. In 62% of the evaluated visual index at coffee height in Costa Rica, and 61% in Nicaragua coffee is shadedü by banana (presence of banana). There is no significant difference between frequency distribution of banana shading coffee (see Table 24).

Table 24. Gap Fraction and Visual Indices above coffee and banana of 30 farms in Nicaragua and Costa Rica, respectively; Method: Densiometer, and visual measurements; Five measurements of gap fraction per farm; here: mean of mean gap fraction on farm; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is α = 0.05; n = 20

Parameter		Costa Rica	Nicaragua	Sig. 2-tailed
Percent Gap Fraction	Mean	45	45	0.911
	Std. Err.	3	3	
	n	30	30	
Visual Index Coffee(%)	Mean	54	48	0.047
	Std. Dev.	9	13	
	n	30	30	
Presence of Banana (%)		62%	61%	0.529
Visual Index Banana (%)	Mean	68	66	0.524
	Std. Dev.	13	17	
	n	30	30	

There is no significant linear correlation between Gap Fraction and plant density of banana, coffee, and trees, or banana stem density. There is no significant linear correlation between Gap Fraction and basal area of coffee, banana and trees. There is no significant linear correlation between Gap Fraction and canopy area of banana, dry weight or LAI of banana. There is a significant linear correlation between Gap Fraction and tree canopy area, tree crown surface and percent intercepted light (see Table 23).

There is no significant difference of *canopy openness* and *total transmitted light* in Costa Rica and Nicaragua in heights of 90 cm, 130 cm – 200 cm, and 300 cm to 340 cm. Mean total transmitted light is 45% - 46% in 300 cm to 340 cm height and decreases until 28% in 90 cm height. Canopy openness is 30% - 35% at 300 cm – 340 cm and decreases to 17% - 20% at 90 cm height. There is a high standard deviation of canopy openness and transmitted light at all heights (see Table 25).

Table 25. Canopy Openness and Transmitted radiation in three different heights on 20 farms in Costa Rica and Nicaragua; Method: hemispherical camera; value= $\bar{x}$±s.; n = 80; analysis of differences of means between countries with 2-tailed Independent T-Test; significant level is α = 0.05

Parameter	Height (cm)	Costa Rica	Nicaragua	Sign. 2-tailed
Canopy Openness	90	20±7%	17±8%	0.084
(%)	130-200	26±11%	22±9%	0.06
	300-340	35±15%	30±11%	0.167
Percent Total	90	28±11%	28±12%	0.981
Transmitted Light	130-200	35±16%	34±13%	0.757
	300-340	45±21%	46±18%	0.821

Figure 16 shows the variation of transmitted light. In 300 cm – 340 cm height single measurements of transmitted light varied from 8% to 91%. In 130 cm – 200 cm height before cutting the bananas single measurements of light transmittance varied between 11% - 74%, and at 90 cm height it varied between 11% - 77%. After cutting the banana single measurements of light transmittance varied between 10% - 89%.

Available light above canopy was estimated to 5.68 MJ m^{-2} d^{-1}. Transmitted light is reduced to 2.58 MJ m^{-2} d^{-1} at 300 – 340 cm height. In 130 – 200 cm height light is reduced to 1.99 MJ m^{-2} d^{-1}. At 90 cm height light is reduced to 1.59 MJ m^{-2} d^{-1}. About half of the light transmitted is direct sunlight, and half is diffuse sunlight. There is a significant difference of light transmittance at heights of 340 cm – 300 cm, 130 cm – 200cm and 90 cm height (see Figure 17).

We assumed that the difference of mean transmitted light at 300 cm – 340 cm height and mean transmitted light at 90 cm height is mean *intercepted light of coffee*. Mean intercepted light is of coffee is 25% - 29% of above canopy light for both countries.

Figure 18 shows the decay of light transmittance per zenith angle. At zenith angle of 90° light transmittance is 45% at height of 90 cm, and 59% at height 300 cm at 340 cm. At zenith angle of 0° light transmittance is 0.5% at 90 cm, and 2.9% at 300 cm – 340 cm.

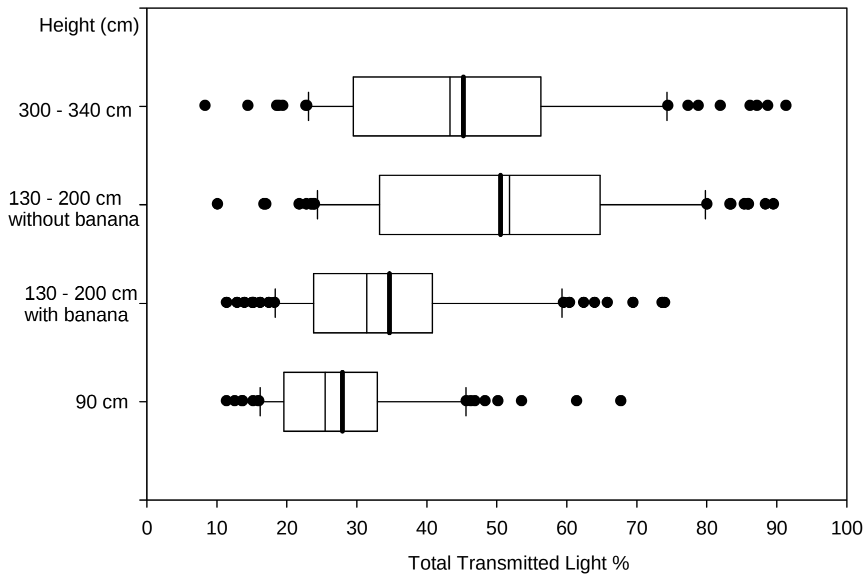

Figure 16. Variation of radiation in three heights (90cm, 130-200cm, 300-340cm), In 130 – 200 cm light was measured with banana, then all banana was cut and light was measured again without banana; on 20 farms in Costa Rica and Nicaragua; bold dash represents the mean value; thin dash is the median

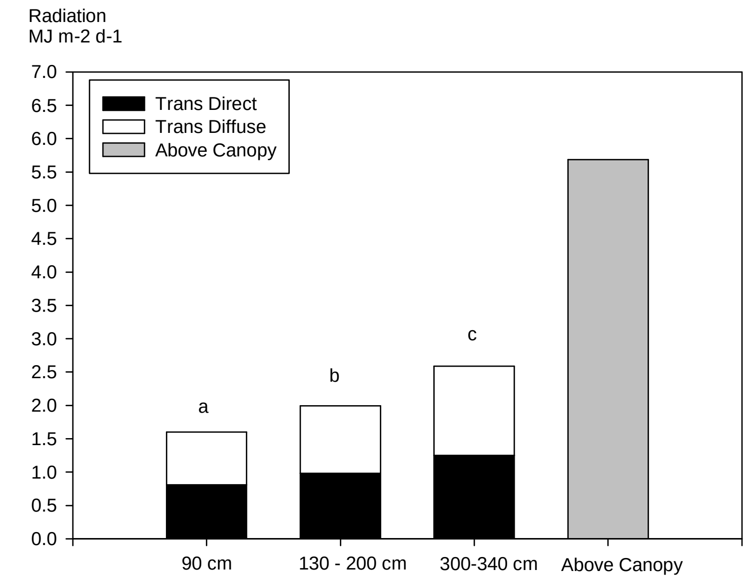

Figure 17. Differences in means of transmitted direct and diffuse radiation in three different heights (90cm, 130-200cm, 300-340cm) of 20 farms in Costa Rica and Nicaragua; for comparison also the total radiation above canopy; significant differences refer to total transmitted light; ; different letters show significant differences between light transmittance at different heights (α = 0.05); analysis with One Way ANOVA and Tukey Test

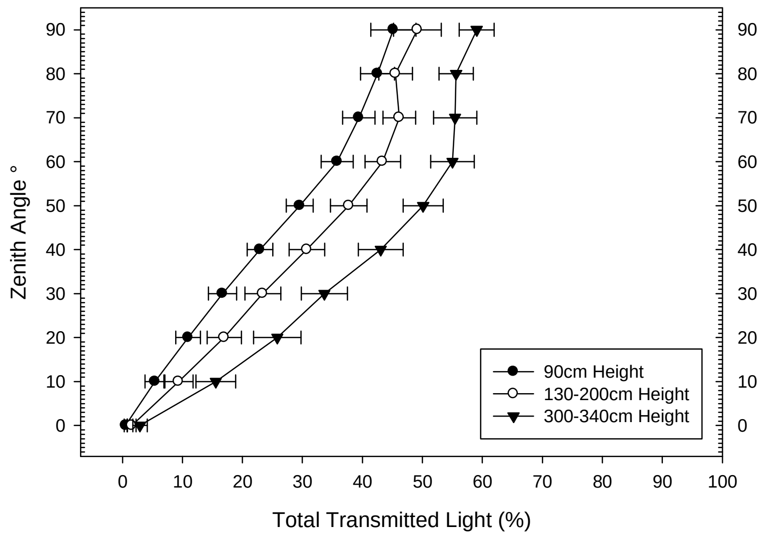

Figure 18. Transmitted radiation per zenith angle in three heights on 20 farms in Costa Rica and Nicaragua; the error bars show Standard Error Mean;

We also assumed that *light interception of banana* would be the difference of mean transmitted light in 130 cm – 200 cm height with banana and without banana, in the same plot. We therefore measured light with banana, cut all bananas, and measured again light. The difference of both estimations makes up around 16% ± 14% ($\bar{x} \pm s$) of total transmitted light or 0.9 MJ m^{-2} day^{-1} at all zenith angles. There is a significant difference in the mean of light transmission with banana, and light transmission when all banana is cut (2-tailed Paired T-Test; Sign.: 0.000; $\alpha = 0.05$) (see Figure 19). However, there was still some banana in the hemispherical pictures, especially at lower zenith angles. From zenith angle 60°/65° to 90° there was no banana. A 2-tailed paired T-Test ($\alpha = 0.05$) shows that there is no significant difference in the mean of light transmittance at zenith angle 0°. There are significant differences in the mean of light transmittance at zenith angle 10° - 90° (2-tailed paired T-Test; $\alpha = 0.05$) (see Figure 20).

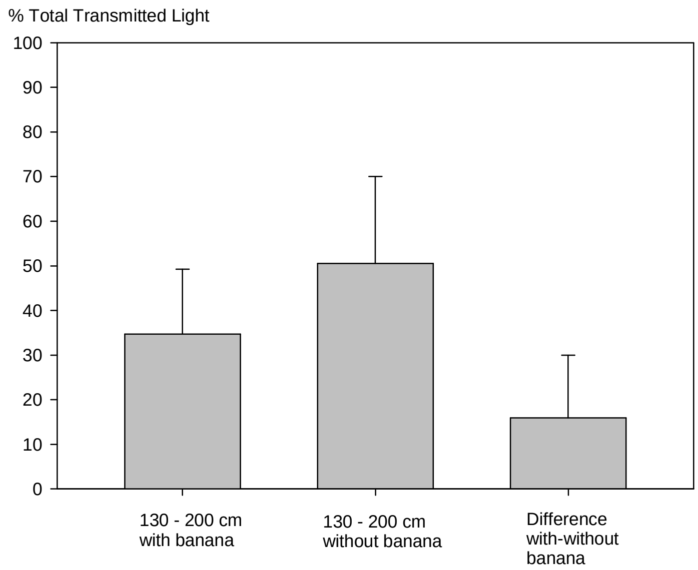

Figure 19. Difference in mean radiation in the same height (130-200cm); light was measured with banana, then banana was cut, and light was measured without banana; error bars represent the standard deviation; 2-tailed paired T-Test shows a significant difference in 130 cm – 200 cm height with banana, and without banana (Sign.: 0.000)

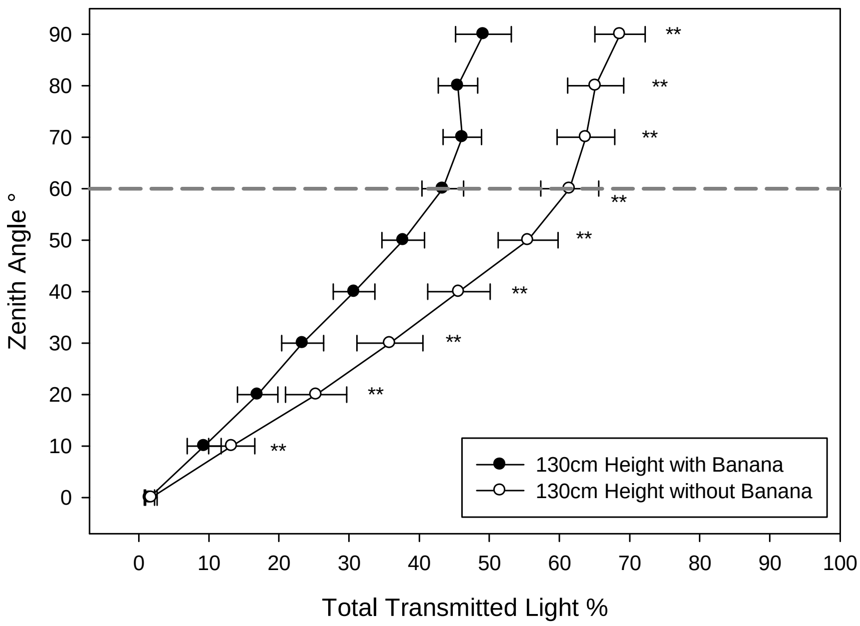

Figure 20. Transmitted Radiation per zenith angle in 130 – 200 cm, light was measured with banana, and then banana was cut and measured again without banana; on 20 farms in Costa Rica and Nicaragua; the error bars show standard error mean; from zenith angle 60°/65° to 90° there were no banana in the hemispherical pictures; ** indicate significant differences between light transmittance with banana and light transmittance without banana at zenith angles 0° to 90°, 2-tailed paired T-Test; α = 0.05

6. Discussion

Smallholders produce banana in coffee agroforestry systems in several structural compositions. This is indicated by high standard deviations of several parameters of coffee banana and trees, and by significant differences between farms of Costa Rica and Nicaragua. There is high variation in farm size and field size in both countries. Also inclination of the plots has high variations. Density, basal area and canopy area show high standard deviations.
This study included several communities and regions in Costa Rica, and two regions in Nicaragua. The high standard deviation may indicate that agroforestry systems can vary between different regions within the country.
Coffee fields in both countries are between 2 ha to 3 ha. Altitude is about 900 m. Inclination is higher in Costa Rica than in Nicaragua. The weak significant difference in soil texture may indicate that we found more silt soils in Costa Rica, and more loamy soils in Nicaragua. However, further research is necessary to prove this suggestion.

Coffee density is significantly higher in Nicaragua, but significance is weak and there may be no difference between both countries. There is a significant difference of coffee height. It may be that coffee plants in Nicaragua have more often heights above 2 m, or that there are more plants above 1 m in both countries. Further analysis is needed.

Banana plant density is significantly higher in Costa Rica, but stem density of stems higher than 2 m is the same in both countries. Thus, banana density is lower with a higher number of stems > 2m per plant in Nicaragua. In Costa Rica there are 2 pseudostems per plant, and in Nicaragua there are 3 pseudostems per plant.
Typical cultivars are AAA Gros Michel ‘Guineo Blanco’, AAA Cavendish ‘Congo’, AAA Gros Michel ‘Coco’, and AAA Red Subgroup ‘Guineo morado’. There is a significant difference between cultivars. Data indicates that ‘Guineo Blanco’ is most common in Nicaragua. Cultivars of AAA Red Subgroup are typical in coffee agroforestry systems in Nicaragua. In Costa Rica ‘Guineo Blanco’, ‘Coco’ and ‘Congo’ may be the most common cultivars. In this study there were two growers with mainly ‘Coco’, and

one grower with mainly ‘Datil’. It seemed that many growers preferred some plantains for self-consumption (‘Guineo cuadrado’, ‘Filipino’, Platano). FHIA-25 and FHIA-23 are introduced from grower associations or other projects.

Tree density is significantly higher in Costa Rica. Trees have no difference of DBH in both countries. There is a significant different in frequency of height intervals, but no significant difference in measured total tree height. This would indicate that there is no difference in the categories in the both countries, but within the categories. Thus, it may be that there are significant more trees in a height of 2 m to 10 m than in other categories. Mean tree height is 9 m – 9.8 m. Further analysis is needed for a better understanding.

There is a significant difference of canopy diameter between the countries. This may indicate that canopy diameter in Costa Rica is more often lower than 2 m. There is also a significant difference in tree pruning. This may indicate that trees are more often strict pruned in Costa Rica. *Erythrina poeppigiana* is the most common species in coffee farms in Costa Rica. The tree is frequently pruned by coffee growers (Schütt und Lang, 1994). However, further data analysis is needed to confirm the suggestions.

Plant densities are 4244 – 4852 coffee plants ha^{-1}, 185 and 341 trees ha^{-1}, 358 and 579 bananas ha^{-1}. Mean total plant density is 5164 plants ha^{-1} in Costa Rica, and 5395 plants ha^{-1} in Nicaragua. Espinoza (1985) reports for Costa Rica a coffee density of 5088 – 5433 plants ha^{-1}, tree density of 98 – 246 plants ha^{-1}, and banana density of 228 – 343 plants ha^{-1}. Total plant density is 5414 – 5987 plants ha^{-1}

Mean basal area of coffee and trees is not statistically different in both countries, and basal area of banana has a weak statistical difference. This may confirm that plant density of coffee and trees is not statistically different. Also DBH of trees has no significant difference in frequencies. The weak statistical difference of banana may confirm that number of stems > 2m is not different in both countries. However, stems between 1 m and 2 m are significantly different in both countries.

Mean canopy area of banana is not significantly different between the two countries. Total canopy area has a weak significant difference. Tree canopy area and tree crown surface are not significantly different. Intervals of tree canopy diameter and tree pruning are significantly different. Data on canopy area is very high; total area is 1 – 1.5 ha ha^{-1}. There may be distortions due to the method of data taking. Further research may focus on this topic.

Density or basal area of coffee, banana and tree is not significantly correlated to each other. There are weak negative correlations between tree canopy area and banana plant density, banana stem density, intercepted light of banana and gap fraction.

This may indicate that not tree and coffee density, but composition of the canopy and light availability determines banana density. The more “open” the upper canopy, the more bananas can be included. Or the more bananas a grower desires the more open has to be managed the canopy. Coffee growers in Costa Rica may prune their plants stricter than in Nicaragua and have higher densities of banana. This suggestion may be interesting for further research.

There are more significant correlations of canopy area and basal area than from plant density. Basal area and canopy area of banana is correlated to dry weight, LAI, and intercepted light of banana. Tree crown surface is an easy way to evaluate foliage of the upper canopy. It is correlated to banana stem density and intercepted light of banana. This may indicate that canopy area, crown surface and basal area are more useful parameters to describe the coffee banana agroforestry system.

Coffee basal area and coffee density are not correlated to other parameters of the system. Further research may analyze why coffee response is low although it is the most frequent crop in the system.

It has been indicated that subsistence, and economic reasons are important for producers, because these were the most frequent answers. Some coffee growers in Costa Rica see banana as an additional income source or even as their first income source. There are several other economical reasons. Growers mentioned that banana is a fast crop with

good prices and easy to sell. It also needs low labor input, and is especially important when prices of coffee are low, or when coffee yield is bad. In general, it serves as additional source of income. Furthermore, growers see banana as a chance to enter an additional or new market. In Costa Rica, growers also speak positively about the infrastructure of the market, since retailer and companies come directly to the fields to buy the banana. This makes it easier for growers to sell their fruits.
Growers mentioned also other important reasons. Banana gives organic matter to the soil, and shade to the coffee plants. Shade functions also as weed control.
Espinoza (1985) stated that coffee growers increase their fruit production in coffee fields, when resources are low. We focused on small scale farmers. This may be the reason that we found higher tree and banana density and lower coffee density than Espinoza (1985). The answers were categorized according to our interpretation of the data. This may have led to result distortions. Further verification of the data is needed.

Desuckering and deleafing are not significantly different in both countries. Desuckering is a necessary practice to receive big bunches (Robinson 2000). Data indicates that growers in Nicaragua prefer 3 stems >2 m, and growers in Costa Rica prefer 2 stems > 2 m. Additionally there are stems from 1 m – 2 m. Compared to tropical monoculture number of stems in agroforestry systems is still too high (Stover and Simmonds 1987). A better desuckering management may be necessary, but further research is needed.

There is a significant difference in frequency of debudding. This may indicate that more farmers do debudding in Costa Rica. Debudding is necessary to gain high yields. Further research is needed to verify the data.

There is a significant difference in frequencies of fertilizer application. Data indicates strongly that growers in Nicaragua do not apply fertilizer to banana. If there is a significant difference in Costa Rica cannot be analyzed here. Further research is therefore needed focusing on nutrients in banana production in coffee agroforestry systems. In this estimation we excluded cases where growers apply fertilizer when planting banana.

Data on pest management cannot be analyzed and is only descriptive. Most growers do not have a pest management of banana. Pesticides are mainly not used in banana. Other forms of pest management include cutting leaves against Black Sigatoka or treat the young sucker before planting. This data depended on my own interpretation because growers did not always mention other forms of pest management directly, but explained it during the interview speaking about other topics. In Costa Rica, growers are producing organic or traditional and do not use pesticides. Banana is mostly a second income source, and use of pesticides may be too expensive or is not affordable. Further research is needed to verify the data.

Coffee production is significantly higher in Nicaragua. We found a significant difference of the productive stage of the plants. This may indicate that coffee plants in Nicaragua are more productive and require no pruning. Then this may explain why coffee production is higher in Nicaragua. However, there is no significant linear correlation between coffee production and productive stage of the coffee plants.
We found 0.7 kg and 1.5 kg coffee cherries per plant in Costa Rica and Nicaragua, respectively. Espinoza (1985) reports production of 1 – 1.6 kg per plant in Costa Rica.

We could not find a strong correlation, or no correlation between coffee production and other parameters of banana and trees, incoming light or management practices. Espinoza (1985) recommended a density of 120 bananas ha^{-1} and 120 fruit trees ha^{-1} since the lower storey gives most shade to coffee. Above this limits exceed shade would reduce coffee yield. In this study no similar relationship is indicated.
Data from the questionnaire may be too vague, data may not be sufficient, or other parameters are influencing coffee production. Espinoza (1985) stated that there might be data distortions in interviews concerning coffee production. In this study coffee growers seemed to be aware about their coffee production. Highest production of coffee is about 2 kg cherries per plant (Cerdan, 2009; pers. Communication). But in six cases in Nicaragua and in one case in Costa Rica growers overestimated their production; the production of berries per plant exceeded the possible 2 kg per plant. It may also come to distortions by converting production data in one unit.

Banana production is not significantly different in both countries. Comparing banana production from the questionnaire with plant or stem density, banana production is low. Every fifth stem has a bunch. We counted also bunches in field and this data would indicate that every plant has a bunch.
It may be that production losses are high; this could be due to diseases. It could be that growers do desuckering in another period of time, and stem density is usually lower. Growers do banana management 2 to 4 times per year. The high standard deviations show the strong variation of management frequency between farms. But further verification is needed.

Data from the questionnaire of banana production is not correlated to other parameters, except coffee production.
Data may be too vague. Growers might not be aware of banana production. Two growers in Nicaragua even left bunches in field due to economic reasons. Additionally, we received data in different units and time; bunch, fingers, hands, and kilos, per month, two-week, or other time periods. This depends on how the grower is selling or harvesting the crop. Hence, we were forced to convert the data in one unit – bunch per ha and year. This may have influenced the results.
Banana production is low, and influences between changing parameters of the system show no response. This may indicate that other parameters are more limiting, or that all systems have the same response on banana production.

There is no significant linear correlation between number of hands and basal area of banana, and number of stems. Desuckering has influence on yield. These parameters are related to number of pseudostems. This would indicate that desuckering of banana is not influencing number of hands. Robinson (2000) states that bunch are small when one plant has too many pseudostems. All unwanted suckers should be removed before they exceed 300 mm height. Total bunch weight may be reduced, but number of hands may be similar.

There is a weak positive linear correlation between number of hands and circumference, and there is no significant correlation between number of hands and pseudostem height. Stover and Simmonds (1987) report a significant linear correlation between number of hands and height, and circumference for AAA Dwarf Cavendish and AAA Gros Michel. This was not the case in this study. It may be that data was not sufficient (n~50), and from different cultivars.

AAA Red Subgroup has high pseudostems and high circumference but low number of hands and number of fingers of the 2^{nd} hand. 'Coco' (AAA Gros Michel) has small pseudostems but more hands per bunch than AAA Red Subgroup cultivars. AAA Cavendish cv. 'Congo' is smaller and has smaller circumference than AAA Red Subgroup cultivars. 'Congo' has more number of hands and more number of fingers of the 2^{nd} hand than AAA Red Subgroup cultivars. 'Guineo Blanco' and 'Coco' are both AAA Gros Michel, but have significantly different pseudostem height. This may explain that correlation was not strong. There is a need to investigate interrelationships of each genome subgroup, or cultivar.

There is no significant correlation between number of hands and leaf area per stem. But there is a strong linear regression between LAI and total above ground dry matter. And there is a significant positive linear correlation between number of hands and dry matter. Although the correlation is weak this may be the missing link between LAI and banana production. The correlation is weak and this may be due to mixing data from several cultivars. 'Congo' has lowest dry weight, but higher number of hands than AAA Red Subgroup. Morse and Robinson (1996) report regression analysis between LAI and banana yield. It is possible to determine optimum LAI for highest yields. It is not possible in this study. Data is not being sufficient. Especially data from farms with higher LAI of banana is missing (see Figure 12). Maximum LAI found on farm is 1.4 at a density of 578 banana ha^{-1}. Morse and Robinson (1996a) related LAI to yield for six cultivars, and found optimum LAI between 5 and 6 for two cultivars at densities of ~2000 to ~2300 bananas ha^{-1}. The other four cultivars did not reach peak values up to 6.5.

Data from Literature and the presented results suggest that measurements of LAI, dry matter and number of hands are a good approach to analyze banana production in coffee agroforestry systems. I strongly recommend further research in this field of work.

In Literature there are several factors mentioned which influence LAI. One objective of this study was to describe and analyze these factors.
In this study, LAI was not correlated to plant density, and stem density. However, there is a strong linear positive correlation between LAI and stem basal area. Hence, LAI is increasing with increasing stem basal area Thus, desuckering may alter LAI. Data from literature indicate that desuckering is influencing yield (Robinson 2000). We found different number of stems between the countries. This indicates that growers prefer different number of stems, or do not erase suckers intensively. Hence, desuckering might be an important aspect in coffee agroforestry systems. Further research is needed how desuckering is influencing yield and LAI in coffee agroforestry systems.

Soils may have influence on LAI (Stover 1984). There is a significant difference between soils, but significance is weak. It may be that there are more silt soils in Costa Rica, and more loamy soils in Nicaragua. If this has influence on LAI cannot be answered here. I suggest that other factors may have influenced LAI. Stover (1984) does not find differences in LAI of the same cultivar on loam and light clay. But further verification on this topic is needed.

Low plant vigour is reducing LAI, and younger plantations are earlier harvested (Robinson 2000, Stover 1984). The assumption in this study is that number of harvests may indicate plant age, and vigour. There is no significant difference between the categories of harvest frequency. This may indicate that plant vigour and plant age is similar in all farms. There may be no distortions in LAI data. However, the method is subjective. From own observations, it is not easy to categorize banana in number of harvests. More effort is needed to improve the method. It may be useful to ask the growers about plant age in the questionnaire. But it seems that growers replant banana permanently and there are banana of different ages in field. A long-term study may analyze this aspect better.

Vicente-Chandler *et al.* (1966) reports doubled yield because Yellow Sigatoka infection was higher in full sun. In this study Black Sigatoka infection index is ~20%. This means that 20% of measured leaf area is damaged by the fungus; thus leaf area and LAI may be altered by Black Sigatoka.

There is a significant difference between cultivars. 'Coco' has highest infection index of ~30%, and 'Guineo morado' has ~10%. There is no correlation between intercepted light and Infection Index, but sample size is low (n = 8). Literature indicates that light is altering infection of Sigatoka disease. Coffee growers with mainly 'Coco' had also high light interception rates. Further verification is needed how light and cultivars are influencing Infection Index.

Stover (1984) found different LAI in two cultivars. In this study there is a significant difference of LAI between cultivars and genetic subgroups. 'Congo' has significantly lower LAI than cultivars of the AAA Red Subgroup. Hence, LAI altered by cultivars.

In this study the interrelationships between LAI, dry matter and intercepted light was analyzed. One assumption of this study is that banana in coffee agroforestry systems grow in shade and that light reduction influences plant response.

Turner *et al.* (2007) state that yield is proportional to intercepted light in deep shade, since it is the most limiting factor. There is a significant positive linear correlation between dry matter and intercepted light, and there is a significant weak positive linear correlation between dry matter and number of hands. This might be the link between banana yield and intercepted light. Dry matter increases with intercepted light. This may indicate that light is the most limiting factor for banana in coffee agroforestry systems, and other factors would not influence yield. Intercepted light of banana is 16% of total radiation. Percent transmitted light was ~45% in 300 cm – 340 cm height and decreases of 28% at 90 cm height. Further research is needed to confirm that light is a limiting factor and to analyze optimum light transmission in coffee agroforestry systems.

Turner (1998b) suggested that LAI is increasing in high shade. Israeli *et al.* (1995) could not find increased LAI in high shade. There is a significant positive linear correlation between LAI and intercepted light. In this study correlation would indicate that LAI is increasing with increasing light transmittance.

The assumption that light intercepted by banana is the difference between light transmission before and after cutting banana appears too vague. In one case the difference between light transmission before and after cutting banana had even a negative result. In this case banana density is low, but demonstrates the problem of the method. There were also some difficulties in field; branches of low tree canopies and coffee may move while cutting banana plants. Hence, it is never the “same” hemispherical photograph. The dependence of the weather made also the use of hemispherical camera difficult. Sunflecks led to overestimation; also processing the pictures led to overestimation. From Nicaragua only monthly data of solar radiation was available. Radiation data was from two weather stations. This may have influenced calculation of transmitted light. This may also explain the weak correlation between light interception and leaf area index. But intercepted light seems to be an important parameter, since it is correlated with several parameters of the coffee agroforestry system.

Measurements in a vertical and horizontal (5 m x 5 m) structure describe light reduction in general. However, the assumption that a grid of 5 m x 5 m may be sufficient should be tested in field, since coffee banana agroforestry systems vary in density and structure. There is a high variation in transmitted light and canopy openness. Light is changing significantly from ~300 cm to ~100 cm height. Light decreases per zenith angle. Further research should consider testing the distance between hemispherical pictures in order to face the circumstances in field.

Hemispherical photography seems still most promising to take light measurements in situations where farms cannot be observed over a long time. The equation of Turner (2003) for semi-destructive leaf area measurements in banana may allow getting reliable data on farm for leaf area, and hence, leaf area index. The 95% - Confidence Interval

indicates that Turner's (2003) equation underestimates leaf area. But linear regression has a strong coefficient of determination.
Dry matter may be estimated with circumference measurements in different development stages and from different cultivars. This is indicated by data from literature and from the results of this study. Here, the coefficient of determination from linear regression is $R^2 = 0.84$. The 95% - Confidence Interval from real dry weight measurements and estimated dry weight is overlapping. This indicates that mean values may be similar.

In this study, sample size of coffee basal area was tested visually by plotting the 95% - Confidence Interval and sample size from circumference measurements from two coffee farms. We decided visually on sample size. Mean sample size was $\bar{n} = 50$. There might be better methods of sample size determination. It would have been the better method to decide on half of the plants in the plot and not half of the plot area.

A long-term research plot is required now. This may include both, bananas as a sole crop, under controlled conditions – light, water, nutrients, and management of banana, and banana production in a "typical" coffee banana agroforestry system on farm.

This study lacks a strong link between LAI and yield of banana in coffee agroforestry systems. There is only the weak positive linear correlation between dry matter and number of hands, which link LAI, and intercepted light to yield. Morse and Robinson (1996a) showed already the relation between LAI at flowering and yield. We could not find this relationship because this would have required a long term research plot. Research should focus on light on single banana individuals in field. This would allow taking data of LAI, dry matter, and intercepted light, and correlate the data to each other. It would allow estimating attenuation coefficient (k), and radiation use efficiency (γ) among others, considering the approach of Turner (1998a) (see equation 2).
This study misses sufficient data on bunch weight which is possible in a long-term study. It allows analyzing several production cycles in coffee agroforestry systems. Some cultivars have low dry matter but high number of hands. We may estimate the Harvest

index (Hi) from different cultivars. We may correlate light interception to banana production or harvest index.
Additionally, upcoming research has to distinguish between cultivars. Several banana cultivars in coffee agroforestry systems are identified in this study. Research should focus on the most promising or common cultivars. Those are AAA Gros Michel cv. ‘Guineo Blanco’ and cv. ‘Coco’, AAA Cavendish ‘Congo’, and AAA Red Subgroup ‘Guineo Morado’ and cv. ‘Caribe Verde’. At last, light response curves of several cultivars may be established. This would indicate which cultivar may be best for shaded conditions.
Further research is also needed to understand possible relationships in agroforestry systems. Especially canopy area and basal area seem to be valuable parameters. Tree crown surface is an easy way to determine leaf area of the trees. Tree management and pruning may have strong impact on banana cultivation, and light availability.
Desuckering practices has influence on yield. Here we could not find this relationship. We may check the parameters on desuckering and yield, and investigate possible relationships, or at least keep management practices constant in further research.

Research is ongoing on banana in coffee agroforestry systems at CATIE, Costa Rica. The high variations between the farms are grouped in categories. A long-term research plot with different banana cultivars in shaded conditions will be established. Promising approaches are planned.
Coffee growers in Costa Rica and Nicaragua are willing to participate in studies. This would allow us to observe banana in a “real” situation to understand response on light, nutrients, and management of banana in the long run. We could see how coffee is responding, too, and how trees have to be treated to benefit both, coffee and banana.
At last, we may receive reliable data and relationships between coffee production and banana or trees, and other influencing factors. Coffee is for most farmers still the major crop. Only if we can improve banana production without reducing coffee production, we can match the necessities for most coffee growers intercropping banana.

7. Conclusion

Coffee banana agroforestry systems in Nicaragua and Costa Rica are distinct, and may differ also within communities. There is a high variation of field size, inclination, transmitted light, density, basal area, and canopy area. 13 different banana cultivars were identified on farm, of which 90% are from 3 – 4 cultivars. The six most frequent tree species in all farms make up 70% - 80% of all trees. Banana production is low, and also level of banana management seems to be low.
The interrelationships between coffee, banana and tree need further verification. There were no promising significant correlations between coffee production and parameters of coffee, banana, and trees. Also banana bunch yield had no relevant significant correlations. Tree canopy area was significantly correlated to banana density and intercepted light of banana. Tree crown surface was significantly correlated to banana stem density and intercepted light of banana. This might indicate that the upper storey is influencing the banana crop.

Leaf Area Index, Intercepted light, and dry matter of banana are important parameters for analyzing banana in shade. Leaf Area Index of banana was mainly influenced by cultivar, basal area, and probably Black Sigatoka infestation. Leaf Area Index may increase with intercepted light. Furthermore, there is a high interrelationship between Leaf Area Index and Total above ground dry matter of banana. There is no interrelationship between Leaf Area Index and number of hands in this study. However, there is an interrelationship between total above ground dry matter and number of hands. Furthermore, there is an interrelationship between intercepted light and total above ground dry matter. This may indicate that light is the most limiting factor in coffee agroforestry systems. Dry matter might be the link between Leaf Area Index, Intercepted light, and banana production.

Further research should focus on light interception, leaf area index, dry matter, and production parameters of relevant banana cultivars. For further analysis of coffee banana agroforestry systems, basal area, canopy area and tree crown surface might be valuable parameters.

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Appendix I

Relevant questions of the questionnaire in Spanish and English:

1- ¿Podría usted hacer una descripción general de su finca? (Explicar cuántos lotes tiene, tamaño de cada lote, qué cultivos tiene sembrados y de éstos, cuáles comercializa)? / Could you make a general description of your farm? (To tell number of fields, size of each field, which plants are cultivated, and which of them are commercialized)?

Número de lotes/Number of fields: ________

Cultivos/Crops:

Café, Banano, Arbol/Coffee, Banana, Tree: ________

Cafe (sin banano)/ Coffee (without banana)______

Banano (solo, con arbol)/ Banana (sole crop, intercropped with trees) : ________

Otros/Others: ________

4- Que importancia tiene el banano para usted?/ What importance has banana to you?

5- ¿Cuál es la producción de café en su finca?/ What is the coffee production of your farm?

[ ] Quintales (año/year mes/month, [ ] Fanegas (año/year mes/month) Finca/Ha/mz

6- ¿De qué forma vende el café?/ How do you sell the coffee?

□ Fruta/Cherries, □ Pergamino/Washed Seeds, □ Oro/Green Beans.

14- ¿Cuál es la producción de banano en su finca?/ How much is the banana production of your farm?

Finca/Farm: ( )kilos ( )días/mes days/month ( )manos/hands ( )dedos/fingers ( ) racimos/bunch ( )tamano mz/ha – size manzana/hectare

Asocio/Coffee, Banana, Trees: ( )kilos ( )días/mes ( )manos ( )dedos ( ) racimos ( ) mz/ha

15- ¿Cómo vende el banano?/ How do you sell the banana?

□ Racimo/Bunch, □ Manos/Hands, □ Caja/Box

28 - ¿Cómo controla otras enfermedades y plagas en banano? ¿Qué productos aplica?/ How do you control diseases and pests in banana? Which products do you apply?

Si/Yes No

Enfermedad/Pest	Producto/Product
Nematodos/Nematodes	
Picudo/Banana weevil	
Sigatoka	

29 - ¿Realiza algún tipo de fertilización al banano? Do you apply some type of fertilizer to the banana? □ Si/Yes □ No

36 - ¿Qué actividades realiza en el cultivo del banano?/ Which activities do you practice in your banana cultivation?

Actividad/Activity	Vezes annual / Times per year	de □Finca/Farm □ha □mz/manzana
Manejo/Management		
Abono/Fertilizer		
Veneno/Pesticides		

¿Cuál manejo hace en el banano? / Which manangement do you do in banana?

□ deshojar/deleafing □ deshijar/desuckering □ deschirar/debudding

Appendix II

General configuration data for processing hemispherical pictures with software GLA according to the software manual (Frazer et al. 1999)

General Configuration Data	
Initial Cursor Point	359,93 degrees
Solar Time Steps	every 2 mins
Growing Season	1.1 - 31.12
Azimuth Regions (from 0° to 360°)	36
Zenith Regions (from 0° to 90°)	10
Solar Constant	1367
Output Units	MJ m^{-2} d^{-1}
Input Data Specified by Month.	
Sky Brightness Dist.:	UOC Model
Clear-Sky Trans.:	0.75
Picture Registration	
X	1729
	195
Y	1573
	2163

Curriculum Vitae

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Education

Since 4/2008	Master of Science at University of Bonn - Agricultural Sciences and Resource Management in the Tropics and Subtropics
02/2008 – 10/2004	Bachelor of Science at University of Applied Science Wiesbaden – Horticultural Management; focus on International Horticulture and Economics
7/2004 – 9/2003	Matriculation standard; Economics; Fachoberschule Aschaffenburg
1995 – 1992	Secondary school; Economics, leading to O-levels, Realschule Aschaffenburg

Employment

9/2003 – 3/2008	Temporary employments as gardener, specializing in landscaping within my studies of matriculation and Bachelor of Science
8/2003 – 9/2001	Apprenticeship as gardener, specializing in hardy nursery stock production at Baumschule Helmstetter, Großwallstadt
7/2001 – 3/2000	Employment as gardener, specializing in landscaping
9/1999 – 2/2000	Temporary employment as cook
2/1999 – 8/1999	Employment as gardener, specializing in landscaping
8/1998 – 9/1995	Apprenticeship as bank clerk at HypoVereinsbank Aschaffenburg

Work Experience and Studies Abroad

3/2007 – 9/2007	Research for Bioversity International, c/o CATIE, Turrialba, Costa Rica concerning the improvement of Coffee-Banana-Agroforestry Systems
1/2007 – 8/2006	One semester term at the Swedish Department of Agricultural Science, SLU, Department of Crop Science, Alnarp, Sweden
10/2005 – 7/2005	Voluntary internship at Productos Ecológicos del Vergel, Oxkutzcab, Mexico concerning the establishment of a nursery
1/1999 – 10/1998	Temporary voluntary work connected to agriculture and horticulture in Spain and France