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Water dynamics and use in coffee shaded with *Tabebuia rosea* Bertol. and *Simarouba glauca* D.C. compared to full sun coffee in sub optimal environmental condition for coffee cultivation

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Water dynamics and use in coffee shaded with *Tabebuia rosea* Bertol. and *Simarouba glauca* D.C. compared to full sun coffee in sub optimal environmental condition for coffee cultivation

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Dedication

To Cloves, Pedro and Daniel

To the coffee producer Olindo Padovan *in memorian*

my inspiration

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SUMMARY

Water availability is predicted to be reduced and temperature to rise in the global climate change context. Future climate conditions may thus represent a serious risk for coffee cultivation especially in less favorable environment. Agroforestry has been postulated as a promising strategy to adapting to climate changes. Shade tree may minimize radiation and temperature near the soil surface and reduce soil evaporation. Shade tree may enhance infiltration, reduce runoff and increase rainfall water use efficiency by taking up water from deep soil layers. However, shade tree may reduce the water that reaches the soil by rainfall interception. Trees may consume additional water and can establish a competitive relationship depending on tree species characteristics, soil water availability, site conditions and management.

In this experiment water dynamics and use was monitored in a mature agroforestry experiment where coffee shaded by a mixture of *Tabebuia rosea* and *Simarouba glauca* is compared to full sun coffee over 2012 and 2013. The water balance was obtained by two independent approaches: 1) measuring directly all components of water balance (trees and coffee transpiration; soil evaporation; rainfall interception); and 2) measuring changes in the soil water stock through Time Domain Reflectometers (TDR) probes.

Agroforestry (AFS) showed greater transpiration and lower soil surface evaporation compared to full sun (FS). Shade tree did not represent a serious constraint for coffee water use during most of the period of the experiment. Coffee water consumption represented 75% of the total transpiration in agroforestry while *Tabebuia rosea* transpired 17% and *Simarouba glauca* 8%. Complementarity was demonstrated by root niche differentiation between coffee and *Simarouba glauca* that seemed to be more suitable as coffee shade tree compared to *Tabebuia rosea*. We also demonstrated high competition between coffee and shade tree when an atypical very dry season occurred. Transpiration was stabilized although the high evaporative demand and coffee leaf water potential reached its lowest value in AFS which suggested high level of coffee water stress. Adaptation strategies for coping with climate change using shade trees need to be devised taking into account this quantified information into account.

RESUMEN

En el contexto del cambio climático global disminución de la disponibilidad de agua y el aumento de la temperatura han sido esperados en el futuro próximo. Variaciones en las condiciones climáticas futuras pueden por lo tanto representar un grave riesgo para el cultivo del café, especialmente en condiciones menos favorables. Los sistemas agroforestales han sido postulados como una estrategia promisora para la adaptación a los cambios climáticos. Árboles de sombra pueden minimizar la radiación y la temperatura cerca de la superficie del suelo y reducir la evaporación. Además pueden mejorar la infiltración, reducir la escorrentía y aumentar la eficiencia del uso del agua de lluvia, tomando el agua de las capas profundas del suelo. Sin embargo, árboles de sombra puede reducir el agua que llega al suelo mediante la interceptación de la lluvia. Los árboles pueden consumir mucha agua y pueden establecer una relación de competencia en función de las características de las especies de árboles y la disponibilidad de agua del suelo. En este experimento, la dinámica y el uso del agua fueron monitoreados en café bajo la sombra de *Tabebuia rosea* y *Simarouba glauca* comparados con el café a pleno sol durante 2012 y 2013. El balance hídrico se obtuvo mediante dos métodos independientes: 1) se midió directamente los componentes del balance hídrico (transpiración de café y árboles, la evaporación del suelo y la intercepción de lluvia); y 2) se midió el cambio en el contenido de agua del suelo por medio de sensores TDR – Time Domain Reflectometers. Es sistema agroforestal presentó mayor transpiración y menor evaporación de la superficie del suelo en comparación con café pleno sol. Árboles de sombra no representaron una limitación para el uso del agua de café durante la mayor parte del período del experimento. El consumo de agua del café representó el 75% del total de la transpiración en AFS mientras que *Tabebuia rosea* transpiró 17% y *Simarouba glauca* 8%. La complementariedad fue demonstrada por la diferenciación de nicho de raíces de café y *Simarouba glauca* la cual pareció ser más adecuada como árbol de sombra para el café en comparación con *Tabebuia rosea*. Se demostró además una competencia potencial entre café y árbol de sombra cuando se produjo una estación atípica muy seca. La transpiración se estabilizó aunque la gran demanda evaporativa y el potencial de agua en la hoja del café alcanzó su valor más bajo en AFS lo que sugirió alto nivel de estrés hídrico en el café. Las estrategias de adaptación para hacer frente al cambio climático utilizando árboles de sombra deben ser concebidas teniendo en cuenta esta información.

CONTENTS

LIST OF TABLES

Chapter IV

Chapter V

LIST OF FIGURES

Chapter I

Chapter III

Chapter IV

Chapter V

Chapter VI

CHAPTER I

GENERAL INTRODUCTION

1.1. INTRODUCTION

World population is forecast to exceed nine billion people by 2050 (FAO 2009). The global agricultural production will have to increase by about 70% from its 2005 level and nearly 100% in developing countries to guarantee global food security (FAO 2009). Thirty percent of the earth's land surface is used for agriculture. The expansion of food production is the biggest factor responsible for increasing deforestation worldwide that in turn is considered to be one of the contributing factors to global climate change (FAO 2013). Fewer forests mean larger amount of greenhouse gases entering the atmosphere. Also, trees play an important part in the water cycle, absorbing the water via their roots and releasing it into the atmosphere. Without forests, the climate may become dryer in some regions.

Furthermore, 70% of the extracted freshwater is used for irrigation for food production. But irrigation systems dependent on groundwater are at risk once aquifers have been depleted by over pumping. The world's irrigated agriculture tripled from 1950 to 2000, has stabilized since then and begun to decline in some countries. Falling water tables are forcing a number of countries, that were once self-sufficient in grain, to become heavily dependent on imports (FAO 2013). In most countries where rain fed agriculture is a common practice, the effects of change in the patterns of temperature and precipitation increase the vulnerability of available water to match the agricultural requirements (Lin *et al.* 2008).

In such a context, there is a need to maximize food production with efficient land use and water consumption. The combined production of crops with tree species and animals on the same site is a traditional land-use practice which provides heterogeneous agricultural landscapes with great potential for ecosystem services maintenance such as natural pest management, carbon sequestration, biodiversity, water and soil conservation (Harvey *et al.* 2008). Greater complexity leads to greater stability of ecosystems in the context of the global climate change. Studies on the effects of the hurricane Mitch in Nicaragua and Honduras in 1998 demonstrated that intercropping and integrated farming systems may improve resistance of extreme climate events. Traditional, mixed farms retained more topsoil, higher soil moisture, more vegetation within the system and therefore lower economic losses when compared to intensively managed systems (Holt-Giménez 2002). Also, the lower vulnerability of agroforestry systems is closely related to lower external inputs such as water and nutrients that are cycled within the system (Tilman *et al.* 2002).

Water loss may be minimized in agroforestry by reducing runoff, soil evaporation, and the transpiration demand and by increasing efficiency in soil water use (Beer 1987). Researches have demonstrated improvements in soil physical properties and enhancing infiltration in agroforestry (Sklenicka *et al.* 2002; Udawatta *et al.* 2006; Kumar *et al.* 2008). Litter cover combined with dense root systems slowed runoff, reducing susceptibility to erosion and diminish nutrient and water loss (Udawatta *et al.* 2002). Shade trees minimized solar radiation and temperature near the soil surface and, consequently reduced soil evaporation (Ritchie 1971; Jackson and Wallace 1999). Coffee shade trees also reduced radiation incidence, enhancing air humidity and, thereby reduced the vapor pressure deficit and potential crop transpiration rates (Gutiérrez and Meinzer 1994). Studies in coffee agroforestry in Costa Rica showed that shade trees contributed to diminishing of solar radiation incidence on the coffee leaf surface. This reduced leaf temperature by up to 7^0C under shade when compared to the open system, depending on time of the day and leaf position (Siles *et al.* 2009). That is very important since leaf high temperature favors excessive water loss in the gas exchange process. Moreover, trees may contribute to greater efficiency in soil water use by taking up water and nutrients that would otherwise be lost by leaching. This benefit from agroforestry, however, depends on root niche differentiation in which shallow rooting crops and deep tree root systems have a complementarity relationship in resource use, extracting water and nutrients from different layers of the soil profile (Sanchez 1995; Cannell *et al.* 1996; Schaller *et al.* 2003).

Traditional shaded coffee cultivation that imitated its understory native condition (Sylvain 1955) has been progressively changing to more intensive systems. The belief that more light would prevent fungal diseases led to a massive conversion of coffee cultivation towards full sun production in Brazil in the 1950s (Da Matta 2004). In Mexico, Colombia, the Caribbean and Central America, unshaded coffee was extended in the early 1990s motivated by increasing prices on the international market (Rice and Ward 1996). As pressure to grow coffee increased, it inevitably spread into less suitable environments for coffee production such as unfavorable temperatures and water shortages. However, the current and potential impacts of global warming, especially in unsuitable environmental conditions for coffee cultivation, associated with external market forces that lower coffee prices due to increased production, and the increasing trend toward green consumerism, resulted in calls to reduce agrochemicals use and renewed the interest in shaded coffee production (Muschler and Bonnemann 1997; Haggar *et al.* 2001).

Moreover, despite coffee not being a food crop, by value it is the most important agricultural commodity in the international market and involves more than 60 million people in 80 countries on four continents. Family and smallholder farming dominate the vast majority of coffee growing worldwide. In El Salvador, 74% of coffee farms are smaller than 7 ha (Méndez 2008). In Guatemala and Costa Rica more than 50 and 92% respectively are smaller than 5 ha (Samper 1999; Fisher and Victor 2014) and in Mexico 99% of coffee farmers manage less than 10 ha (Lin 2007). Secondary incomes from coffee production such as firewood, fruit and timber, are very important for small-scale producers. It has been recognized that family farming comes closer to diversified agriculture and sustainable food production than intensive, industrialized agriculture. Nevertheless, investigations on coffee crop and shade timber tree interactions are remain few.

Competition for water between coffee and shade trees depend on tree species characteristics, soil water availability, site characteristics and management (Ong 1995). In optimal environmental conditions the risk to coffee cultivation was found to be minor and no competition for water between coffee and shade trees was reported (Siles *et al.* 2009). In sub optimal environmental conditions for coffee cultivation little information is available. It is known that all components of ecosystem water balance are affected by shade trees (Rutter 1963; Jaramillo and Chaves 1999). For example, water balance comparisons between coffee monoculture (FS) and coffee shaded with *Inga densiflora* (AFS) in optimal environmental conditions for coffee cultivation in Costa Rica were carried out by using rainfall interception, transpiration, runoff and soil water content measurements. It was found that total water use varied from 30 - 35% in full sun (FS) to 40 - 45% in agroforestry system (AFS) of the annual gross rainfall. Lower interception and more rainfall reaching the soil increased the runoff to 7.5% - 9.5% in FS compared to 3.5% - 5.5% in AFS. Soil water uptake was enhanced at soil water between 100 and 200 cm depth in AFS, which suggested complementarity in water use by coffee and shade trees (Cannavo *et al.* 2011).

Competition or a complementarity relationship between coffee and shade trees is influenced by water balance calculations based on changes in soil water content due to inputs (rainfall) versus outputs (evaporation, transpiration and runoff) over a particular period of time. However, studies that independently measure all components of the agroforestry water balance are limited. Studies on coffee water relations in different environmental conditions focused on shade timber tree effects will allow the development of multi-functional agriculture able to cope with the forecast lack of water for production, maintenance of current forest lands and increased incomes for farmers.

1.2. CONTEXT OF THE RESEARCH

The investigation was conducted in sub-optimal conditions for *Coffea arabica* cultivation which can be summarized as:

- Mean annual temperature of 27^{0}C. This is higher than normally recommended for *Coffea arabica*;

- 455 m altitude. This is considered to be rather low for *Coffea arabica* cultivation at this latitude (11^0 53′ 54″ N);

- Mean annual rainfall of 1470 mm with a six-month long dry season (which on average receives only 9% of the annual rainfall);

- Rooting depth was limited to 2 m depth, below which a pan constituted by coarse volcanic ejecta impeded root penetration;

- Additionally, a hardened layer (*talpetate*) crossed this accessible 2 m layer and further impeded root growth.

Originally in the Ethiopian tropical forests, *Coffea arabica* is adapted to altitudes of 1600 to 2800 m, air temperature about 20^{0}C and rainfall ranging from 1600 to more than 2000 mm per year. Differences in the rainfall pattern over the period of study, being 968 mm in 2012 and 1312 mm in 2013, provided the opportunity to compare water dynamics in relatively normal and abnormally dry conditions in FS and AFS (Fig 1.1).

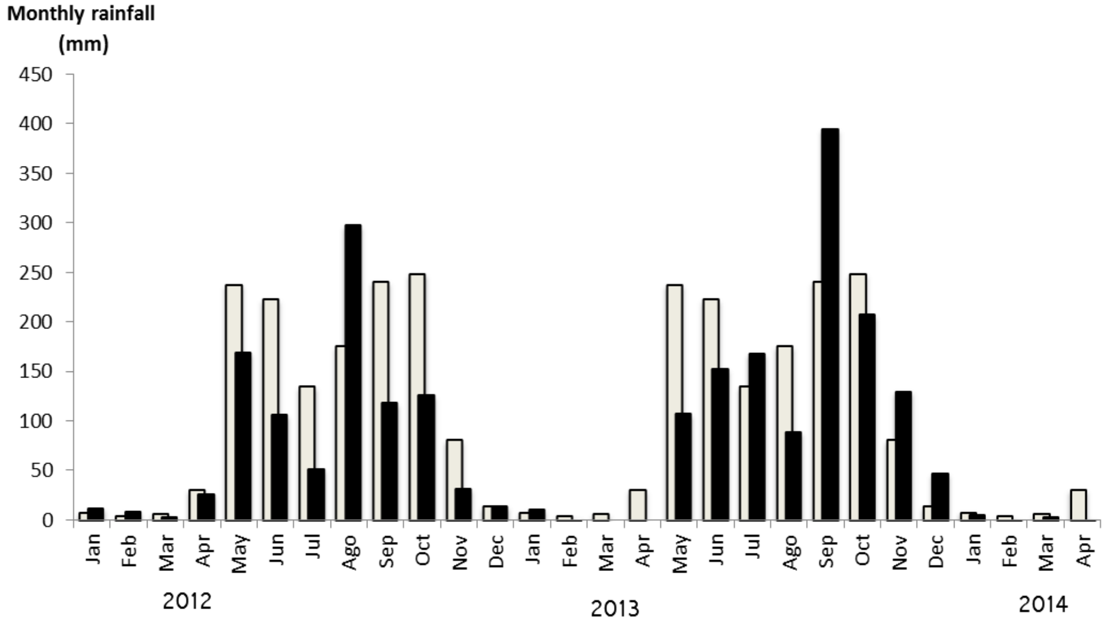

Fig 1.1. Monthly rainfall distribution from the climate station (in black) and long term mean annual rainfall (in white) in Masatepe, Nicaragua, over the period of study.

In the long-term research area in which the study was carried out, the 12-year old agroforestry experiment allowed analysis and comparison of the performance of coffee unshaded and shaded by a mixture of evergreen *Simarouba glauca* DC. and deciduous *Tabebuia rosea* Bertol. under sub optimal environmental conditions. Both shade tree species are widely utilized in Central America region for timber and other products but are poorly studied, and never before in coffee agroforestry systems.

At the study site, soils are characterized by the presence of a compact soil layer at intermediate and variable depth locally known as *talpetate*, formed by the cementing action of calcium carbonate on volcanic ash. The *talpetate* layer occurs in 15% of the soils of the Pacific coastal plain in Nicaragua and is quite common in different soils of Central America and Mexico. Tests crops of maize and sugar cane indicated that the presence of *talpetate* affected rooting conditions, the nutrients and the moisture availability and the potential for mechanization of the soils (Vogel and Acuña Espinales 1995). However, there is a lack of information about the effects of the *talpetate* on coffee root growing.

Such environmental conditions are representative of one site class that has been utilized for coffee cultivation in Nicaragua, in Central America and other regions highly susceptible to climate changes impacts in which water resources are forecast to diminish. Location of studies in agriculturally sub-optimal environments is important, as these are the conditions under which many farmers have to operate. The results may help farmers and researchers to better understand how to maximize coffee production with efficient water use in regions with similarly unfavorable environments for coffee cultivation.

1.3. OBJECTIVES

The central aim of this investigation was to evaluate water relations and use in full sun coffee compared to coffee shaded with deciduous *Tabebuia rosea* Bertol. and evergreen *Simarouba glauca* DC. which have been utilized as shade trees in Central America but have never been studied before in coffee agroforestry. The study also aimed to evaluate below ground interactions between coffee and shade tree species in the presence of a hard compact soil layer on soil water uptake and root system distribution.

1.3.1. Specific objectives

- To measure and compare coffee root distribution in full sun coffee and agroforestry.

- To assess *Tabebuia rosea* and *Simarouba glauca* root system spatial distribution and its influence on coffee root system development in agroforestry.

- To evaluate the influence of shade tree root system on coffee water uptake facilitation in a compact soil layer present in the study site locally called talpetate.

- To evaluate *Tabebuia rosea* and *Simarouba glauca* shade tree effects on coffee transpiration and soil surface evaporation rate in agroforestry compared to full-sun coffee.

- To measure and compare water loss by rainfall interception in coffee shaded by *Tabebuia rosea* and *Simarouba glauca* and full-sun coffee.

- To evaluate coffee, *Tabebuia rosea* and *Simarouba glauca* influences on water loss by evapotranspiration in sub optimal environmental condition and possible competition between coffee and shade tree.

1.4. HYPOTHESES

1.4.1. Root distribution and water use in the full sun coffee compared to coffee agroforestry

We hypothesized that coffee and tree roots explore different spatial niches; and that evergreen *Simarouba glauca* and deciduous *Tabebuia rosea* tropical timber tree species exhibit different root system behaviors that differentially influence the coffee root distribution. Overall, tropical timber tree species behavior (as distinct from shade tree species, typically leguminous) as coffee shade trees has been poorly investigated. Moreover, in the study area there is a compact soil horizon, locally called *talpetate*, which is typical of the soil conditions in the coffee cultivation Carazo region in Nicaragua. We hypothesized that under restrictive soil conditions, tree roots penetrate through the hard-pan and facilitate coffee water uptake throughout the soil profile. We also hypothesized that soil water uptake by coffee in agroforestry system depends on the shade tree root system characteristics and the rainfall distribution and intensity over the year.

1.4.2. Rainfall interception, stemflow and throughfall in coffee shaded by *Tabebuia rosea* Bertol. and *Simarouba glauca* DC.

We hypothesized that tree canopies modify water availability for coffee cultivation in an agroforestry system; and that rainfall partitioning in interception, stemflow and throughfall affects coffee water use in shaded system. Little is known about the importance of rainfall partitioning in coffee water use in agroforestry and no information was found about the influence of *Tabebuia rosea* and *Simarouba glauca* as shade trees on water loss by rainfall interception in coffee agroforestry compared to full sun coffee.

1.4.3. Water loss by plant transpiration and soil evaporation in coffee shaded by *Tabebuia rosea* Bertol. and *Simarouba glauca* D.C. compared to unshaded coffee in sub optimal environmental conditions

We hypothesized that deciduous *Tabebuia rosea* and evergreen *Simarouba glauca* timber tree species modify the water budget in different ways and thus their suitability as coffee shade trees in the prevailing sub optimal environmental conditions. We also hypothesized that water loss by plant transpiration and soil surface evaporation may lead to a competitive relationship between coffee and shade trees depending on tree species' characteristics, soil conditions and available water.

1.5. GENERAL OUTLINE OF THE THESIS

This dissertation was divided into six Chapters as follows: Chapter I which presents a general introduction including context of the research, objectives and hypotheses; Chapter II reviews the main topics related to water dynamics in agroforestry systems, water relations in coffee, shade tree performance and characteristics and the impacts of global climate change in coffee water use. Chapter III presents the topic Root distribution and water use in a coffee shaded with *Tabebuia rosea* Bertol. and *Simarouba glauca* DC. compared to full sun coffee in sub-optimal environmental conditions (published in Agroforestry Systems in 2015). Chapter IV discusses the partitioning of rainfall, in particular rainfall interception, stem flow and throughfall as affected by coffee, *Tabebuia rosea* and *Simarouba glauca* compared to full sun coffee while Chapter V discusses partitioning of soil water into plant transpiration and soil evaporation in unshaded coffee and coffee shaded by the timber tree species *Tabebuia rosea* and *Simarouba glauca*. The Chapter VI consists of a general discussion about the most important findings of the experiment and conclusions with recommendations for future research on the topic.

CHAPTER II

LITERATURE REVIEW

2.1. COFFEE WATER RELATIONS

Originally arabica coffee developed as an understorey shrub in Ethiopian tropical forests at altitudes of 1600–2800 m with an average temperature of around 25^{0}C and well distributed 2000 mm rainfall but with three or four consecutive dry months (Sylvain 1955). Only relatively recently has coffee been grown in the open condition (i.e. without tree shade), including regions closer to the equator in which two annual dry seasons may occur (Cannell 1985).

Most coffee growing areas (except countries near the equator) exhibit the same phenological cycle in which a period of water stress, induced either by dry soil or dry air, seems to be obligatory to prepare flower buds for blossoming. High concentration of endogenous abscisic acid (ABA) maintains the sexual structure of flower buds protected from dry season effects in a dormant state known as hydro-periodism (Alvim 1973; Crisosto *et al.* 1992). Studies have shown that buds need to experience a critical low level of water potential for flowering, approximately -1.2 MPa, which allows a rapid influx of water into the buds at the time of rainfall or irrigation. But too severe water stress and exposure to high temperature may cause abortion of flowers with impacts on coffee yields (Carr 2001).

The understanding of water relations in coffee is paramount for coffee cultivation since small changes in water availability at key periods of crop development may result in negative effects on coffee grown even without apparent signs of water deficit (Da Matta *et al.* 1993). Physiological aspects of coffee plants and their water requirements were first studied by Nutman (1937) and subsequently by many authors (Wormer 1965; Bierhuizen *et al.* 1969; Meinzer *et al.* 1990; Crisosto *et al.* 1992; Gutiérrez and Meinzer 1994; Tausend *et al.* 2000; Carr 2001; Da Matta *et al.* 2007) by using different techniques. Those findings were complemented by the contributions from Fanjul *et al.* (1985), Barradas and Fanjul (1986), Van Kanten and Vaast (2006), Gutierrez (2007), Siles (2007), Franck and Vaast (2009), Lin (2010) and Charbonnier (2013) among other authors who compared coffee water relations in shaded and unshaded environments. In the following paragraphs, I will try to order and resume this wealth of scientific information.

2.1.1. COFFEE TRANSPIRATION

Transpiration in a range of woody species has been determined by using heat as a tracer for sap movement. The methods commonly employed are the stem heat balance, trunk sector heat balance, thermal dissipation technique and heat-pulse method (Smith and Allen 1996). Gutiérrez *et al.* (1994a) successfully measured coffee sap flow by using stem heat balance in greenhouse and field experiments. Coffee transpiration was also measured by using the potometer method (Lin 2010). However, comparison between both techniques showed more accuracy in the measurements by the stem heat balance while the potometer method displayed operational difficulties and low precision in scaling up data for the plot level (Goulden and Field 1994).

A number of experiments have been conducted to determine which endogenous and exogenous factors govern transpiration. The results are somewhat contradictory. For example, field experiments showed that coffee was able to keep relatively high levels of transpiration when evaporative demand was high even under severe water deficit (Gutiérrez and Meinzer 1994). It was reported that transpiration rate of arabica coffee plants in greenhouse experiments remained at 80% of its maximum when soil water content was about 30%. Relative turgidity decreased from 92% to 80% when soil water declined from field capacity to wilting point (Bierhuizen *et al.* 1969). Other studies showed that transpiration started to decline only when soil moisture dropped to 20% (Nunes and Duarte 1969). The apparent independence of transpiration rate from the soil water content was also reinforced by other studies in which the low soil water availability over the dry season did not have any significant effect on reducing transpiration in coffee monoculture (Van Kanten and Vaast 2006).

The influence of the leaf area index, hydraulic architecture and properties of the water-conducting pathway in coffee transpiration has been demonstrated. A study in three coffee cultivars (Typica, San Ramon and Yellow Caturra) showed that the differences in daily transpiration rates seemed to be governed by the apparent hydraulic conductance of the soil-leaf pathway rather than the leaf area. Of the three cultivars studied Typica exhibited the highest rates of sapflow, the more open crown, the least vulnerability of hydraulic conductivity and the lowest value of the ratio of leaf area to sapwood area (Tausend *et al.* 2000). Conversely, another study on transpiration (T) as a component of evapotranspiration (ET) expressed as the ratio T/ET at different values of LAI showed that transpiration increased from 40% to 95% of ET while LAI increased from 1.4 to 6.7 in coffee grown in hedgerow configuration (Gutiérrez and Meinzer 1994).

Responsiveness to vapor pressure deficit (VPD) in coffee indicated that air humidity could play the major role in controlling stomatal aperture (Fanjul *et al.* 1985; Gutiérrez and Meinzer 1994). The influence of different micro environments with different temperatures and VPD on coffee transpiration depending on leaf position and location was demonstrated by simulations based on a three dimensional coffee canopy architecture by Dauzat *et al.* (2001). Typical values of stomatal conductance were found to be between 0.10 and 0.15 mol m^2 s^{-1} and maximum values were usually attained prior to midday followed by a steady decline during the afternoon (Gutiérrez *et al.* 1994b). Another study demonstrated high values of stomatal conductance in the early morning hours that started to decline at around 9 – 10 h with increasing in VPD (Barros *et al* 1997). Nevertheless, values of air saturation deficit at around 1.5 kPa led to a reduction in stomatal conductance in arabica coffee even in soil at field capacity (Carr 2001). A similar threshold of saturation deficit of air was observed in the dry period when coffee transpiration decreased and ceased to follow the reference evapotranspiration pattern either in full sun or in the tree-shaded environment (Van Kanten and Vaast 2006). Nevertheless, coffee water use and performance in different environmental conditions is still considered to be poorly understood.

2.1.2. COFFEE LEAF WATER POTENTIAL

Coffee growth and yield are determined by plant water balance but, plant water status varies constantly over time. The leaf water potential (LWP) is the driving force for the liquid water movement through the plant. Conceptually LWP is a function of flux rate and internal resistances and represents the thermodynamic expression of tissues water status. It is assumed that during the night hydraulic equilibration takes place so that before sunrise the water in the plant is in equilibrium with the soil water potential and water consumption is minimal, and at solar noon it is expected that water consumption reaches its highest level (Elfving *et al.* 1972).

Da Matta *et al.* (1993) proposed that the ability of coffee to retain high leaf water potential under dehydrating conditions was related to osmotic adjustment which is defined as a net increased solute concentration that serves to maintain turgidity and therefore it is expected to favor drought tolerance. It is accepted that, in some species, accumulation of osmotically active solutes such as proline, for example, has been considered as an adaptation to water shortage (Hare *et al.* 1998). Nevertheless, proline concentration in cultivar Catuai did not change the capacity of coffee plants to withstand drought. This amino acid (proline and others) accumulation was considered to be an injury response imposed by water limitation rather than a mechanism against drought stress (Mazzafera and Teixeira 1989). Moreover, osmotic adjustment is not a general trait observed in coffee genotypes. A study using five arabica coffee cultivars (Catuai, Guatemalan, Mokka, San Ramon and Yellow Caturra) in the field in drying soils showed great variation in LWP between the different cultivars and in the rates at which gas exchange activity declined. The most severe leaf water deficit was observed in Mokka cultivar which reached LWP of -2.60 MPa (±0.07) at midday and -1.65 MPa (±0.20) at predawn in drought condition (Meinzer *et al.* 1990). The study suggested that coffee leaf water potential maintenance was related to water use rates and soil water extraction efficiency in the different cultivars.

Coffee leaf water status maintenance has also been attributed to the ability of coffee plants to lower cellular wall elasticity under water limiting condition (Meinzer *et al.* 1990). However, osmotic and elastic adjustments and efficiency in water absorption and use may be not enough to couple with a gradual diminishing in soil water availability without an efficient stomatal control of transpiration (Da Matta 2004).

The somewhat contradictory results demonstrate that more investigation is needed on coffee water relations and plant water balance. The current knowledge is clearly not enough in order to improve coffee growth and yield with maximum efficiency in water use especially with the present tendency towards low water availability conditions as coffee cultivation increasingly takes place in areas of marginal climatic suitability.

2.2. CLIMATE IMPACTS ON COFFEE GROWTH AND YIELD

Drought episodes are considered to be the major environmental stress affecting coffee production. Drought stress affects the growth and the development of the plant in different ways over the coffee crop's phenological phases. Overall, severe drought stress disturbs the plant's metabolism with disruption of osmotic and ionic homeostasis and damage to cell membranes and proteins. In such conditions, the time factor is paramount for coffee crop survival and yield maintenance as drought stress usually develops slowly and increases in intensity the longer it lasts (Da Matta and Ramalho 2006; Camargo 2010).

Plant water deficit is accompanied by loss of turgor and wilting, cessation of cell enlargement, closure of stomata, reduction in photosynthesis and movement of water and nutrients to various parts of the plant with interference to many basic metabolic processes. The maintenance of cell turgidity is crucial for plants. Turgidity loss may indirectly affect photosynthesis through reduction of stomatal conductance.

The drought condition is often aggravated by both high solar radiation and high temperature. A decrease in CO_2 assimilation in *Coffea arabica* at temperatures above 24^0C was reported by Nutman (1937). Another study demonstrated that continuous exposure to temperatures above 23^0C accelerates fruit development and ripening often accompanied with loss of quality (Camargo 2010). Moreover, variations on the size of coffee beans within and between years depend on the plant water status during the period of fruit expansion occurring between 10-17 weeks after blossoming. Drought may reduce the size of beans, the number of fruiting nodes per tree and the number of fruits per node depending on its severity and timing. Some fruit shedding that occurs during the period of rapid fruit swelling may be aggravated by drought. Prolonged drought in the initial stages of bud development may result in the atrophy of set fruit (Carr 2001).

Also, prolonged dry environmental conditions reduce shoot extension and the area of individual leaves. Early leaf senescence is also stimulated in drought conditions. But, despite leaf abscission being a mechanism to avoid transpiration when water is limiting, coffee plants may delay or reduce leaf shedding as a strategy to save resources that otherwise would be used in restoration of leaf area in the rainy season (Carr 2001). The avoidance of leaf shedding is also important to maintain crop yield but, high solar radiation incidence and temperature may result in absorption of much more energy than that used in the photosynthesis process and cause overheating of leaves which can reach 40^0C in extreme cases. The excess of energy may potentially lead to reactive oxygen species production that can detrimentally oxidize photosynthetic pigments and proteins (Da Matta and Ramalho 2006). In response to such conditions, leaf water potential tends to decrease and a hydraulic signalization of the plant water status induces the biosynthesis of the stress hormone abscisic acid

(ABA) as a strategy for water loss control in the short-term. Therefore, stomatal conductance is reduced in order to maintain the plant water status.

Moreover, the relationship of the roots with shoots is also strongly affected by conditions of prolonged shortage of water. Reduction of shoot growth is one way that plants use to keep their water status stable and to reduce water loss to the atmosphere. As water flows from the higher to the lower water potential, root water potential decreases as a mechanism to maintain plant water status and avoid water flux from the root xylem to the soil solution by diminishing root hydraulic conductivity. At the same time the plant may invest in expansion of the root system to increase the soil volume explored and increase water uptake. Root system distribution and growth plays an important role in maintaining a favorable internal water status under water deficit conditions. Plants able to develop deeper root systems usually are more tolerant to drought. In dry conditions coffee roots may extend deeper and extract a greater quantity of soil water from deep layers. Studies on coffee root system characteristics indicated that the most efficient strategy to face dry conditions seems to be associated with a deeper root system rather than larger dry mass (Da Matta and Ramalho 2006).

Genotype selection in order to improve coffee yield in water-limited environments was found to be only partially successful due to the variability of rainfall and the polygenic nature of drought tolerance. A complementary approach involves the identification of traits that contribute to withstanding drought condition. Potential important traits may include water extraction efficiency, water use efficiency, hydraulic conductance, osmotic and elastic adjustment and modulation of leaf area. However, most of these traits are complex and poorly understood (Da Matta 2004).

There are a wide range of factors that influence coffee responses to drought and there is a need to improve the knowledge of coffee performance in sub-optimal environmental conditions which are characteristic of most marginal lands that have been used for coffee cultivation more recently, especially regarding the effects of climate changes.

2.3. WATER DYNAMICS IN COFFEE AGROFORESTRY

In agroforestry, water dynamics and use is affected by shade trees in different ways. For example, the trees' presence may influence water fluxes by changes in the microclimate under shade. In a study on coffee agroforestry in Mexico, the effect of Inga trees on buffering the maximum and minimum temperature and reducing the VPD in agroforestry compared to an open system was demonstrated. Daily maximum temperature reduction of 4 - 5^0C in the shade was reported (Barradas and Fanjul 1986).

Reduction of leaf temperature by shade trees also favors water use by coffee. Depending on the time of the day, season and leaf position within the coffee canopy, in coffee shaded with *Inga densiflora* leaf temperature was reported to be between 1 and 7^0C lower (Siles *et al.* 2009). A similar study demonstrated that coffee leaves without shade experienced air temperatures higher than ambient in the wet and dry season while in a shaded environment they were often lower (Muschler 1997). This temperature reduction is very important particularly in the tropics and marginal regions for coffee cultivation. Leaf temperature has a direct effect on the photosynthesis process for which the optimal rate is between 18^0C and 24^0C for arabica coffee (Da Matta 2004).

Comparison between coffee agroforestry and open systems showed that stomatal conductance was greater in shaded plants (Gutiérrez *et al.* 1994a; Vaast *et al.* 2005). The close correlation between stomatal conductance and net photosynthesis may result in carbon gain by the sunfleck effect in the shade (Fanjul *et al.* 1985). The spatial and temporal variability of net photosynthesis and transpiration was simulated (by using the MAESTRA model) in coffee agroforestry at a plot scale and showed that above-ground net primary productivity was not influenced by shade tree presence. Simulations showed greater light use efficiency in the shade compared to coffee in the full sun despite the reduction on photosynthetically active radiation under shade tree canopies (Charbonnier 2013).

The effect of different shade tree species on coffee water consumption was demonstrated in sub-optimal conditions in Costa Rica by Van Kanten and Vaast (2006). Coffee shaded by *Terminalia ivorensis* exhibited lower water consumption (538 mm p.a.) compared to that under *Eucalyptus deglupta* (689 mm p.a.) and under *Erythrina* *poeppigiana* (702 mm p.a.). Similar values of coffee water consumption (703 mm p.a.) were found in Mexico in coffee agroforestry with *Inga leptoloba* as shade tree (Jiménez and Goldberg 1982). Also, water use of coffee and shade tree combined resulted in greater whole system water consumption when compared to the full sun (Van Kanten and Vaast 2006).

Water loss by soil surface evaporation was measured in coffee agroforestry at different shade levels in Mexico by Lin (2007). It was demonstrated that the higher the shade cover the lower was the soil evaporation. Lower water loss by soil evaporation means there is more water available for plant water use. However, apart from this study no other soil evaporation measurements have been found in coffee agroforestry.

Another factor to consider is that in agroforestry, the water available for under-storey coffee may be limited by interception of rainfall by shade tree canopies. Partitioning of rainfall into throughfall, stemflow and interception was studied in coffee shaded with *Inga densiflora* in Costa Rica by Siles *et al.* (2010). It was demonstrated that total rainfall interception was slightly increased in the shade (11.4% of rainfall) compared to an open system (9.6% of rainfall). This result was related to a three-fold greater leaf area index of coffee than that of shade tree. The influence of leaf area index and pruning on rainfall interception was demonstrated in coffee associated with *Inga* spp in Mexico by Jaramillo and Chaves (1998) and with *Erythrina poeppigiana* in coffee agroforestry in Costa Rica by Imbach *et al.* (1989). Studies on interception by shade tree canopies are very important especially in dry environments in which rainfall water is a critical factor for coffee growth and yield but investigations on this rainfall interception in coffee agroforestry are few.

2.4. COFFEE AGROFORESTRY WATER BALANCE

The water balance is one of the most important tools to assess water partitioning and competition for water in agroforestry systems. The water balance by an ecosystem over a given period of time may be estimated by the equation:

$$P = (Et + \Delta S + I + R_{off}) - R_{on}$$

Where P=precipitation; Et=evapotranspiration; ΔS=change in soil water storage; I= Interception; R_{off}=run off; R_{on} = run on.

Evapotranspiration is the water transpired by plants plus the soil evaporation. Interception comprises the rainfall intercepted by the foliage and evaporated back to the atmosphere. ΔS is the variation in soil water content in the soil volume studied. Run off and run on may occur either over the soil surface or as sub-surface flow within permeable upper horizons, and percolation (drainage) down to a water table is also included in the run off term, as it is a loss to the system (Rutter 1963).

The water balance partitioning in evapotranspiration, throughfall, drainage and run off in a coffee agroforestry watershed in Costa Rica demonstrated that superficial run off was 50% lower than in the monoculture. The experimentation and modelling across hydrological and physiological approaches indicated the great potential of coffee agroforestry to reduce superficial displacement of sediments and to provide hydrological environmental services by the efficient mechanism of aquifer recharge and discharge (Gomez-Delgado *et al.* 2010). However, studies on hydrological performance in coffee agroforestry either at a plot or at a basin scale are few.

Coffee agroforestry water flux assessment by measuring rainfall interception, simulation of transpiration and percolation were determined in *Coffea arabica* associated with *Cordia alliodora* and *Erythrina poeppigiana* in Costa Rica by Imbach *et al.* (1989). Great variability in interception in *Coffea arabica* with *Erythrina poeppigiana* was demonstrated and significant differences between interception in both systems was found to be due to the effect of management, particularly shade tree pruning. Transpiration amounted to 42.2% of rainfall in *Coffea arabica* with *Erythrina poeppigiana* while with *Cordia alliodora* it was 36.5% probably due to the pruning effect. It was demonstrated that water loss by leaching in coffee agroforestry was comparable to that of a natural forest (Imbach *et al.* 1989).

A coffee agroforestry water balance by measuring rainfall interception, transpiration, runoff and change in soil water content allowed simulations of different climate scenarios. A potentially high risk of water stress in agroforestry was predicted when the dry season was extended by 4-6 weeks. It was reported that the length of the dry season appeared far more important than the annual volume of rainfall (Cannavo *et al.* 2011).

Very little information is available on all components of coffee agroforestry water balance by using reliable and comparable methods.

2.5. COFFEE SHADE TREE CHARACTERISTICS AND PERFORMANCE

There may be great shade tree diversity when coffee is planted in forest after clearing of the understorey but more commonly coffee agroforestry consists of one, two or more shade tree species, often specifically planted, and includes timber, leguminous or fruit trees. For instance, 77 different coffee shade tree species were reported in El Salvador (Escalante and Somarriba 2001), 24 in Nicaragua and 107 in Mexico (López-Gómez *et al.* 2008). In Costa Rica diversification diminished with the increasing of farm size and coffee management (Llanderal and Somarriba 1999).

Leguminous trees are by far the most prevalent shade tree in Mexican and Central American coffee agroforestry. Leguminous trees such as *Albizia*, *Inga*, *Leucaena*, *Erythrina* and *Gliricidia* spp. have been preferred by farmers as coffee shade tree in part to also produce firewood. Leguminous trees have the advantage of generally being tolerant of periodic pruning in order to avoid light competition. Also, legumes may enhance soil nutrition through their nitrogen fixation capacity (Muschler 1997; Beer *et al.* 1998). Studies in coffee agroforestry with *Erythrina poeppigiana* as shade tree showed an input of 34 kg ha^{-1} year^{-1} of nitrogen fixation compared to full sun coffee (Babbar and Zak 1994).

Despite the beneficial impact of these legume species, in sub optimal conditions for coffee cultivation in the south of Costa Rica it was reported that coffee was affected by the seasonal phenology of *Erythrina poeppigiana* when the shade trees completely lost their leaves during the dry seasons which coincided with the period when the buffering effect of shade was needed most (Vaast *et al.* 2007). This phenological characteristic led farmers to prefer evergreen to deciduous as coffee shade trees in the Guanacaste region in Costa Rica. On the other hand, deciduous trees may be useful in areas with sub-optimal rainfall to provide mulch to maintain soil moisture and minimize water use when they are leafless in the dry periods (Albertin and Nair 2004).

Concerning timber trees, *Eucalyptus*, *Terminalia*, *Cordia*, *Cedrela* and *Alnus* are among the most common genera utilized in Central America coffee zones. But, despite the high potential for diversification of production and increasing incomes for farmers by timber production, especially in periods of lower coffee prices, only a small number of species of timber trees are used in coffee plantations (Haggar *et al.* 2001; Somarriba *et al.* 2004). Studies on coffee agroforestry based on timber tree species showed that

Eucalyptus deglupta and *Terminalia ivorensis* were ecologically and economically viable options for sub optimal environmental conditions in Costa Rica (Vaast *et al.* 2007). In Latin America, particularly in Costa Rica, farmers have introduced *Terminalia amazonia* as a coffee shade tree instead of *Terminalia ivorensis* due to its more compact crown and better quality of wood (Dzib *et al.* 2006). In optimal environmental conditions in the Central Valley of Costa Rica, coffee associated with *Eucalyptus deglupta* experienced lower soil water content and suffered drought stress during the five months dry season in contrast to coffee in association with regularly pruned *Erythrina poeppigiana* or full sun coffee (Jimenez and Alfaro 1999). But overall there is a lack of knowledge about timber tree characteristics and performance in agroforestry in different environmental conditions, particularly plant behavior which varies with other associated plants, arrangement, management and environment (Huxley 1996).

Despite coffee accounting for the largest part of the system water use, shade tree water consumption may lead to a greater total water use in agroforestry when compared to monoculture. Studies on transpiration of *Inga densiflora* as a coffee shade tree demonstrated that it accounted for 40-50% of the total water use in the system (Siles 2007). Estimation of annual transpiration of evergreen *Eucalyptus deglupta* resulted in 210 mm p.a. while *Terminalia ivorensis* was 519 mm and *Erythrina poeppigiana* was 195 mm, which represented 23%, 49% and 21% respectively of the total system water use. Although *Eucalyptus deglupta* was considered a better shade tree species than *Terminalia ivorensis* due to its constant and lower shade level during the year, results indicated that in the medium term shade of both timber tree species improved coffee growth and increased productivity under the sub optimal conditions of the study site (Van Kanten and Vaast 2006).

Knowledge about shade tree characteristics and potential adaptation of environmental conditions is crucial to avoid competitive relationships with coffee in resources use in agroforestry. Management skills by farmers such as selection of the shade tree species, planting density, tree thinning and frequency of canopy pruning are very important to ensure that the level of shade is neither too high for adequate coffee growth and productivity nor too low for effective protection of coffee plants against adverse climatic conditions (Vaast *et al.* 2007). However, little information is available about tropical timber tree species in coffee agroforestry in sub optimal environmental conditions for coffee cultivation. Although widely used in agroforestry in Central

America no information was found about the characteristics of *Simarouba glauca* and *Tabebuia rosea* as coffee shade trees.

2.6. BELOW GROUND RELATIONSHIPS IN COFFEE AGROFORESTRY

The coffee root system distribution is characterized as being more concentrated in the upper first 30 cm of the soil profile and then to decrease with depth (Nutman 1933a; Guiscafre-Arrilaga and Gomez 1938). Also, a study using tracer techniques at different distances from the trunk showed greatest root activity near to the trunk to around 30 cm distance from the stem (Huxley *et al.* 1974). Coffee root growth was found to be highly variable depending on seasonal pattern, environmental and soil condition (Nutman 1933b; Franco and Inforzato 1946; Morales and Beer 1998). The lateral spread of surface roots was constrained by the influence of neighboring coffee trees. More than one coffee tree in the same station improved deep axial root growth as far as to 3.5 m while single trees did not extend deeper (Clowes and Logan 1985). In agroforestry coffee roots may be influenced by the shade tree root system but in turn may also affect tree root distribution. *Coffea arabica* associated with *Eucalyptus deglupta* in Costa Rica showed distinct root system spatial arrangement and contrary to expectations, coffee fine roots were sufficiently competitive to displace shade tree fine roots (Schaller *et al.* 2003).

Below ground interactions in agroforestry may define complementarity or competition in water use. Studies on fine roots in a sub optimal growing zone in Costa Rica in which *Coffea arabica* was shaded by *Eucalyptus deglupta* or *Terminalia ivorensis* demonstrated that *Terminalia ivorensis* was potentially a stronger competitor with coffee compared to *Eucalyptus deglupta* (Van Kanten 2003; Vaast et al. 2007) while in optimal environmental condition for coffee cultivation *Eucalyptus deglupta* as coffee shade tree presented no competitive relationship (Schaller *et al.* 2003). However, studies on coffee root behavior in agroforestry and shade tree root system performance in different environmental conditions are also few.

In restrictive soil conditions root distribution and water movement may be inhibited while in agroforestry tree roots can favor crop root penetration and water uptake. Studies demonstrated that in a rigid soil matrix, the channels created by old dead tree root are utilized by crops to acquire water from deeper soil layers (Schroth 1995; Udawatta et al. 2006). Studies in coffee root development in distinct soil types showed little effect by a hard pan on coffee root growth (Nutman 1933b). Apart from his work, the impacts of a restrictive soil layer on coffee root penetration have been poorly investigated.

2.7. GAPS IN THE KNOWLEDGE OF COFFEE AGROFORESTRY WATER RELATIONS

Robust information on coffee agroforestry is still limited, especially in water use and dynamics. Field experiments on coffee water use are relatively few, given the extensive cultivation and value of the crop. In agroforestry, considering the species diversity, management heterogeneity and variations in environmental conditions, assessment of coffee water performance is difficult to extrapolate. Modeling could provide a holistic approach by connecting inter-dependent process. However, the available information in coffee agroforestry water fluxes influenced by different shade tree species and environmental condition to integrate successful process-based models is limited. Very little information was found on tropical timber tree species as coffee shade trees despite the potential additional income for farmers. There is a lack of information on root system behavior of coffee and associated shade trees along climatic and soil gradients in order to assess potential competition for water under the effects of climate change. Very few studies were found on coffee agroforestry evapotranspiration. Most of them are incomplete and do not accounts with direct measurement of the components, as conducted in this study.

CHAPTER III

ROOT DISTRIBUTION AND WATER USE IN COFFEE SHADED WITH *TABEBUIA ROSEA* BERTOL. AND *SIMAROUBA GLAUCA* DC. COMPARED TO FULL SUN COFFEE IN SUB-OPTIMAL ENVIRONMENTAL CONDITIONS [a]

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Padovan, Vega-Jarquín, Costa, Brook and Rapidel designed research; Padovan, Cortez, Navarrete, Navarrete, Deffner, Centeno, Munguía and Barrios performed research; Padovan and Vílchez-Mendoza analyzed the data; Padovan, Brook and Rapidel wrote the paper.

ABSTRACT

Root niche differentiation for optimal exploitation of resources was found in an arabica coffee agroforestry system in Nicaragua. Rooting behavior was compared in both unshaded (FS) and shaded (AFS) coffee combined with two previously untested tropical timber species (deciduous *Tabebuia rosea* Bertol. and evergreen *Simarouba glauca* DC.). The predominant andisol presents a compacted soil layer (talpetate). Study was developed in sub-optimal environmental conditions for coffee cultivation

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(455 m.a.s.l., mean 27°C/year, 1300 mm rainfall/year, six months dry season) in Nicaragua.

Twelve and five trenches 200 cm deep were dug in AFS and FS respectively. Roots per unit area were counted on two perpendicular soil faces. Volumetric water was measured continuously over two years by using 45 reflectometers in different soil layers. The talpetate varied greatly in depth, thickness and physical structure.

Coffee fine roots were more abundant than tree roots and were concentrated in the shallower strata (0 – 80 cm) whilst tree roots proliferated more below 100 cm. The *Simarouba glauca* root system was denser below 100 cm than *Tabebuia rosea* root system. There was no meaningful difference in coffee root counts in FS and under *Tabebuia rosea*, but coffee root counts were higher near *Simarouba glauca trees*.

2012 and 2014 had mild dry seasons and whole profile soil water content was similar in FS and AFS, but in the 2013 severe dry period volumetric water and water uptake were lower in AFS than in FS. This indicates that the normal advantage of greater soil exploration in AFS was cancelled presumably due to continued water uptake by deep rooting trees whereas the FS still had available water.

Key words: coffee agroforestry; niche differentiation; talpetate; compact soil layer; soil water content.

3.1. INTRODUCTION

Roots are the connection between shoot requirements and soil resources in terrestrial plants. While structural roots form the anchorage for the plant and storage of carbohydrates, fine roots perform the function of resource acquisition. Water and nutrients uptake are related to the root system distribution pattern which is in turn influenced by genotype, environmental interactions and management (Nair 1984; Fitter 1996).

In agroforestry systems where crop and tree growth occur simultaneously, the root system distribution pattern of the different components is a determinant of complementarity or competition in resource use. An ideotype of a shade tree would be that it should possess a deep root system in order to take up water and nutrients that are not available for crops (Sanchez 1995; Cannell *et al.* 1996). In reality most tree species have dense root systems in the topsoil where nutrients are concentrated

(Schroth 1995). A global study of tropical tree rooting distributions showed that on average 26% of roots are in the upper 10 cm of the soil profile, 60% down to 30 cm and 78% in the top 50 cm (Jackson *et al.* 1996).

Comparison between pure tree stands and agroforestry showed that in the monocrop stands of hybrid walnut (*Juglans nigra* x *regia*) and poplar (*Populus euramericana*) fine root density decreased with depth while in the intercropped stand tree fine root density was displaced to deep soil layers (Mulia and Dupraz 2006). Other study demonstrated that maize confined the root system of apple tree (*Malus domesticus*) laterally and induced a greater vertical root development in intercropping compared to monoculture apple tree growth in Nebrasca (Yocum 1937).

Below-ground competition may be avoided by both selection of shade trees with appropriate rooting architecture and tree root management. Root pruning of trees provides a powerful management tool for manipulating competition although the interruption of bi-directional flow of water from deep soil horizons to lateral roots at the top layer and vice-versa may be a disadvantage (Ong *et al.* 2007). Root bi-directional flow may benefit shallow-rooted crops growing in drying soils if adjacent trees can provide water from depth by accessing groundwater and therefore, the coexistence between tree and crops may be facilitated (Roupsard *et al.* 1999; Smith *et al.* 2004).

Although the coffee root system is characterized by its concentration in the upper soil layers (Nutman 1934; Bull 1963; Huxley *et al.* 1974), coffee root extension and distribution are also highly influenced by environmental and soil conditions. In dry sites, coffee root distribution is skewed towards deeper soil layers, and this distribution is related to higher drought tolerance (Ramos and Carvalho 1997; Da Matta and Ramalho 2006).

In optimal conditions for coffee cultivation in Costa Rica, no competition for water was found when shaded with *Eucalyptus deglupta* (Schaller *et al.* 2003) or *Inga densiflora* (Siles *et al.* 2009). However, reports on coffee and tropical timber tree interactions in sub-optimal environmental conditions are few. This paper discusses soil exploration by coffee and shade tree roots in a mature agroforestry experiment comparing unshaded monoculture coffee (FS, "full sun") with adjacent agroforestry (AFS) plots, comprising coffee cultivated under mixed shade of two tree species.

The research described in this paper took place in a coffee agroforestry system in a location with a compacted soil horizon. Other work has demonstrated that compacted soil layers may limit water movement, root penetration and therefore, plant water uptake (Bennie 1996; Bengough *et al.* 2011). In such soil conditions, tree roots play an important role in facilitating water flow and crop root penetration (Nair 1984; Van Noordwijk *et al.* 1996). Voids left by partially decomposed tree roots may be utilized by crops to acquire water from deeper soil layers (Van Noordwijk *et al.* 1991). Moreover, root channels with live or decaying roots can increase saturated hydraulic conductivity by serving as conduits for preferential flow (Johnson-Maynard *et al.* 2002; Benegas *et al.* 2014).

For this study the hypotheses tested were that under soil conditions characterized by a compact layer, trees roots penetrate through the hard-pan and so facilitate coffee water uptake throughout the soil profile; that coffee and tree roots explore different spatial niches; and that evergreen and deciduous tropical timber tree species exhibit different root system distributions.

The study was conducted in sub-optimal conditions for arabica coffee cultivation, typified by a dry season with six months with rainfall < 50 mm, the presence of a compacted soil layer at intermediate and variable depth, and root exploration ultimately limited by a mineral compact layer at approximately 2 m depth. This experiment site is representative of the whole Carazo coffee growing region in Nicaragua. Location of such studies in agriculturally difficult environments is important, as these are the conditions under which many farmers have to operate.

3.2. MATERIALS AND METHODS

3.2.1. Site description

This study was carried out from November 2011 to May 2014 in an experiment located at Jardin Botánico, Masatepe, Department of Masaya, southern Nicaragua (11^0 53′ 54″ N, 86^0 08′ 56″ W) at a long term research site managed by the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), jointly with the Universidad Nacional Agraria (UNA), Federación Cooperativas de Ahorro y Crédito (CENECOOP-FEDECARUNA) and Instituto Nicaraguense de Tecnologia Agropecuaria (INTA). The experiment was established in 2000 and was described by Haggar *et al.* (2011).

The site is located at 455 m.a.s.l. which is considered to be rather low for arabica coffee cultivation. The mean annual temperature is 27^0C with only slight seasonal variation and mean annual rainfall is 1470 mm. From 85% to 97% of the total annual precipitation falls over the wet season (May-November) while a pronounced seasonal drought occurs from late November to mid-May (Vogel and Acuña Espinales 1995). Annual rainfall recorded was 968 mm and 1312 mm in 2012 and 2013 respectively.

In the study area the topography is flat and soils are predominantly characterized as andisols, which are derived from volcanic ejecta. These soils are typically deep, well drained and have high organic matter content, low bulk density, high allophane content and consequently a high phosphorus fixation capacity, high amorphous mineral content and high water retention capacity (FAO, 2001).

On this particular study site, however, soils are characterized by the presence of a hardened layer locally known as talpetate (Fig 3.1). Such layers occur in about 15% of the Nicaragua Pacific region. Its properties reflect both geologic and soil-forming processes and can be extremely variable. It ranges from soft, weathered material containing some harder rock fragments to a fairly continuous hard layer with rock-like properties. The texture varies from fine to sandy, with the latter often appearing stratified (Vogel and Acuña Espinales 1995).

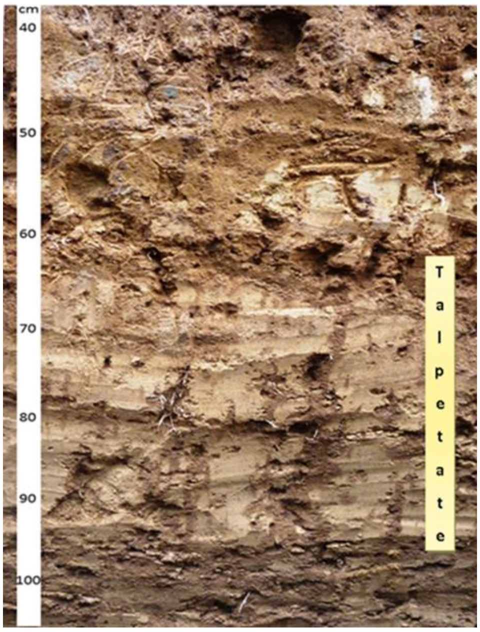

Fig 3.1. Talpetate layer in the soil profile with roots inside the fractures

At Masatepe, the talpetate layer is characterized by high aluminium and silicon contents which are retained in allophones after irreversible dehydrating to become a cemented material. This is usually associated with limitations to water movement and root growth. However, weaknesses or fractures that occur in the talpetate layer allow roots to access the deeper soil horizons (Vogel and Acuña Espinales 1995).

Besides the talpetate, in Masatepe, the soil profile consists of three other main layers distinguished by color: brown (uppermost layer), reddish (usually above the talpetate) and a yellowish, granular layer, under the talpetate. At 1.60 - 2.0 m depth, there is a dark granular compact layer, without organic content, where neither roots nor breaks were observed, so we did not explore below 2.10 m.

The bulk density varied from 0.62 g cm^{-3} (S.E.= 0.026) to 0.65 g cm^{-3} (S.E.= 0.039) on average in the shade and full sun plots, respectively, while in the talpetate layer it reached 0.72 g cm^{-3} in both systems. The mean organic matter content of the soil profile was 3.38% (S.E.=1.05) and 3.82% (S.E.=2.0) in the shade and full sun plots respectively. In the uppermost, brown layer organic matter content was found to be 8.75% (S.E.=0.10) in the shade system and 8.22% (S.E.=0.25) in the full sun, and decreased with depth. The pH (in H_2O) did not differ in both systems and ranged between 5.70 and 5.80 which is considered adequate for coffee cultivation. Management includes fertilization with 37.3 kg ha^{-1} of N, 48.8 kg ha^{-1} of P and 27.6 kg ha^{-1} of K as NPK per year. In addition 34.4 kg ha^{-1} of N as urea and 12 kg ha^{-1} of K as KCl are applied each year.

3.2.2. Experimental design

The experimental design consists of a full sun monocrop coffee (FS) plot (50.5 m x 28.5 m) as a pseudo replication and two adjacents coffee agroforestry system (AFS) plots (80.0 m x 40.0 m and 60.0 m x 23.7 m) in which data were collected in 2011 and 2013. For the current study, pseudo-replication occurred within the full sun treatment plot due to the poor set of coffee plants and problems with small floods in the real replication. However, it was considered appropriate for a process-based study such as this one. The *Coffea arabica*, variety "Pacas" was planted in 2000, at a density of 4000 plants ha^{-1}. Coffee spacing was 2 m between rows and 1.25 m between plants. Coffee plants were pruned selectively in accordance with standard agronomic practice. In the coffee agroforestry system plot *Coffea arabica* is associated with *Simarouba glauca* DC. (Simaroubaceae) and *Tabebuia rosea* (Bertol.) DC. (Bignoniaceae) planted as shade trees. The initial density of the mixed tree cover was 667 trees per ha with alternating rows of both species, but tree density was reduced over time, since 2000, in order to achieve an agronomically appropriate shade level. The mean density of *Tabebuia rosea* was 113 trees ha^{-1} and that of *Simarouba glauca* was 75 trees ha^{-1} over the period of the study (Fig 3.2). The experimental design was based on three hypothesized levels of competition for water in AFS compared to full sun coffee. The split-split plot design consisted of five incomplete blocks (whole plot) with four split plots (treatments): coffee monoculture, and in the coffee agroforestry system, coffee near *Simarouba glauca* trees, coffee near *Tabebuia rosea* trees and shaded coffee as far as possible from both tree species (around 4 m); and two split-split plots (soil profiles) for each treatment.

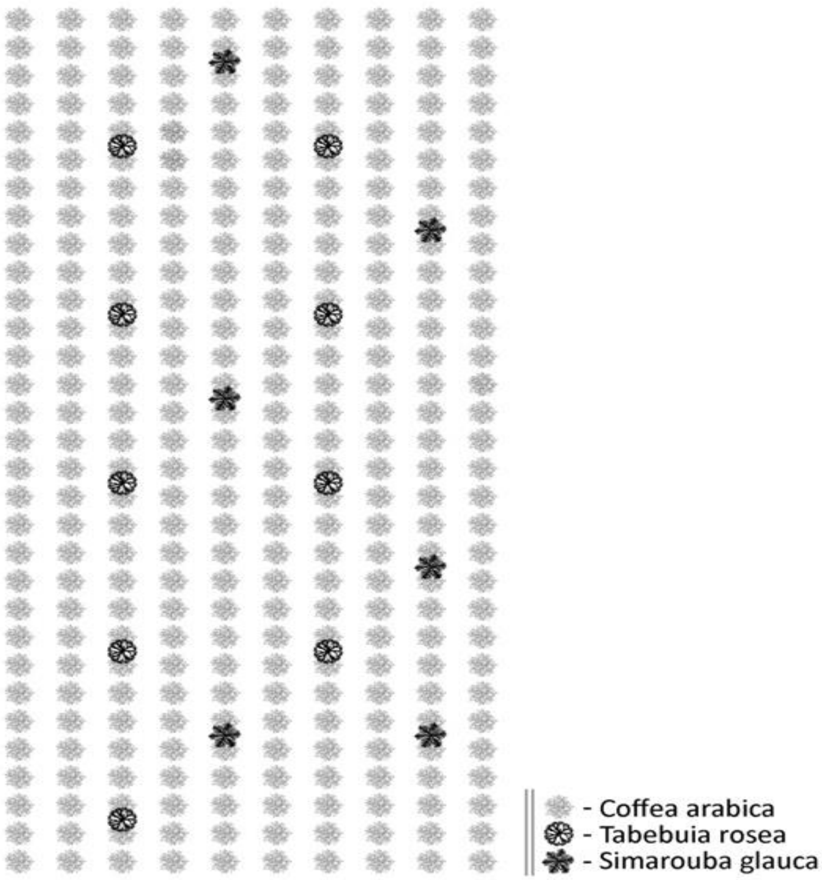

Fig 3.2. Schematic representation of the experimental design of (one quarter of) the shade plot with coffee, *Simarouba glauca* and *Tabebuia rosea* spatial distribution pattern over the period of the experiment.

3.2.3. Tree species studied

Simarouba glauca DC. is native to tropical and sub-tropical regions of Central America, Mexico and the Caribbean. It is an evergreen timber tree that grow successfully over a range of soil types and their deep root system enables efficient access to water year round (Brodribb *et al.* 2003). In the study area *Simarouba glauca* trees at age of 13 years reached in the average 17 m height with 25.5 cm DBH.

Tabebuia rosea Bertol. is native to Mexico, Central America, Venezuela and coastal Ecuador. Trees grow in a great variety of habitats, but prefer regions with high annual rainfall (between 1200 and 2500 mm). It has a deep root system and tolerates occasional waterlogging. It is a deciduous tree that sheds its leaves in the late dry season (CABI, 2013). In the study area *Tabebuia rosea* trees stood bare for about two months (April and May) in 2012 and for four months (from the end of February to the end of June) in the more severe dry season of 2013. By the end of the experiment trees reached 15.5 m height and 28.7 cm DBH on average in the experimental area.

3.2.4. Fine root distribution

Fine root distribution of trees and coffee plants was recorded by the root impact counting method (Tardieu 1988; Van Noordwijk *et al.* 2000). This method is based on the traditional profile wall method proposed by Thiel in 1892 that has been used with modifications by several authors (Bohm 1979). A root impact was considered to be any intersection of a root with the exposed vertical soil profile under study (Laclau *et al.* 2001). Fine roots were defined as root with diameters ≤ 2 mm. Three and six trenches were dug in the full sun and shade coffee respectively in November 2011while another two and six trenches were dug in unshaded and shaded coffee in November 2013. A total of five trenches in FS and twelve trenches in AFS were analyzed. Both trench faces were used for recording. No significant effects of time of recording were found on root distribution ($p>0.05$), so a mature, stable root system was assumed for analytical purposes. Ten profiles were analyzed in the full sun coffee plot and twenty four profiles in coffee agroforestry plots: eight profiles were 150 cm distant from *Tabebuia rosea* stems; eight profiles 150 cm distant from *Simarouba glauca* stems and the other eight as far as possible from any tree, but within the agroforestry plots. Trenches were located between the coffee rows and about 50 cm away and perpendicular from the coffee stems. Each trench was 200 cm deep and 60 cm wide. The soil profile was divided into 10 x 10 cm grid cells and the number of roots in each grid cell was counted. We used a small knife to gently remove the surrounding soil and expose the root ends. Roots of *Coffea arabica*, *Tabebuia rosea* and *Simarouba glauca* were distinguished from each other on the basis of color, smell and rigidity characteristics. The *Tabebuia rosea* roots were flexible and whitish while *Simarouba glauca* roots were rigid, easily broken and yellowish with more strong smell compared to *Tabebuia rosea* roots. The *Coffea arabica* roots had a clearer color in comparison to the tree roots, they were brittle and with a smell very characteristic.

3.2.5. Soil water content

We measured the changes in the soil water content during the two and a half years of our experiment: when the first trenches were dug, a total of 45 Time Domain Reflectometers (Campbell Scientific Inc. CS616, subsequently called TDR probes) were inserted into the soil of one of the trench walls, horizontally in the middle of each of the four soil layers reported above; thus, depths of insertion were variable. Once the probes were inserted the trenches were fulfilled. Horizontal location of each TDR soil profile was established so that it was representative of a reproducible cell (mid distance from the center of the coffee row and the center of the interrow). TDR probes were connected to dataloggers (CR 1000 with multiplexer, Campbell Scientific Inc.), scanned every minute and data were stored every 30 minutes during the whole experiment. Minimal disturbance soil samples of sufficient dimensions to insert a TDR probe were also extracted from each soil layer (two samples per layer). Progressive drying was measured simultaneously by TDR and by weighing, so that a calibration equation was available for each soil layer, following a protocol adapted from Udawatta *et al.* (2011). The volumetric soil water contents were then multiplied by the thickness of the soil layers in which each TDR probe was inserted to calculate the soil water content of each layer. All soil layer water contents were added to get the soil water content of the whole profile at each time step.

We then calculated water uptake for each trench per period of time. As a first step, the deepest TDR in each trench was examined. For the purposes of this paper we only selected periods when these deep TDR showed a consistent decrease or a stable signal throughout the period, indicating that water was not diffusing down from upper layers. We were thus able to discard periods when drainage out of the observed soil profile could have occurred. All periods with heavy rains had thus to be discarded (whole wet season in 2013, and almost all wet season in 2012, with the exception of a one month period in July-August when rainfall events were very low). The data retained covered 53% of the two-year experiment, in nine continuous periods ranging 25-60 days. Soil surface run-off and run-on was also discounted since no run-off was observed in the study area because the soil surface was horizontal. Moreover, andisols are renowned for their high infiltration rates.

We could then estimate evapotranspiration from the coffee systems from soil water content change: providing the assumptions of lack of drainage were accepted the water balance equation could be simplified to:

$$S1 - S2 + R = Et$$

Where: S_1 is the soil water stock in the soil profile at the beginning of the period (mm); S_2 is the soil water stock in the soil profile at the end of the period (mm); R is the accumulated rainfall during the period (mm); E_t is the evapotranspiration by the soil-plant system accumulated during the period (mm). Final data were expressed in $mm.day^{-1}$, calculated as the ratio between total evapotranspiration and the total number of days of the period.

Data analysis

General and mixed linear models were performed taking into account the hierarchical model in the split-split plot design (Pinheiro and Bates 2009). Roots were analyzed by variance analysis to compare root impacts between both data collection periods. Root spatial distribution was analyzed by co-variance analysis regarding the depth as co-variable. As residuals did not conform to a normal distribution, data were transformed into natural log (1+root impact). The model was also applied to analyze the effect of the talpetate on coffee root distribution by contrast analysis. The model took into account the logarithm of coffee root impacts in the treatments and the presence or absence of talpetate in replications by depth. Differences in soil water content between both the full sun and agroforestry system in the three dry periods studied were tested. The temporal series for both treatments were assumed in the model as a first order autoregressive function. Model assumptions were evaluated by residuals and predictors plots. Heterogeneous variances were modelled for treatments and years. All analyses were performed by using InfoStat software 2014 (Di Rienzo *et al.* 2014).

3.3. RESULTS AND DISCUSSION

3.3.1. Coffee and tree fine root distribution

Coffee root growth in deep layers was not significantly enhanced in the presence of tree roots ($p>0.05$), fine root growth being similar in full sun and in shaded coffee systems. Coffee roots reached 150 cm and 170 cm depths in the full sun and in agroforestry system respectively which suggest only a weak influence of tree roots on coffee root depth penetration (Fig 3.3).

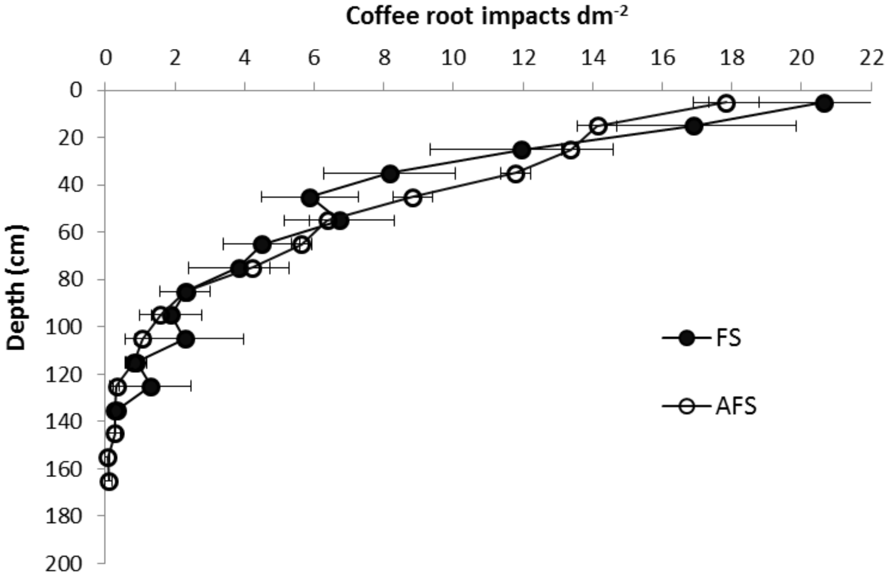

Fig 3.3. Coffee root impacts dm^{-2} in the soil profile in full sun coffee (FS) and coffee agroforestry (AFS) from the mean of ten soil profiles in FS plot and 24 in AFS. Errors bars represent the standard error of the mean.

Most roots were concentrated in the upper 30 cm of the soil profile where 56.9% coffee fine root impacts in the full sun and 50.6% in the shade occurred. However, coffee root distribution did differ between shade tree species. There were more coffee root impacts on average in the soil profile near *Simarouba glauca* than near *Tabebuia rosea* trees ($p=0.001$) (Fig 3.4). In the uppermost 30 cm, coffee root counts were approximately an order of magnitude greater than maximum tree root counts. In contrast to the coffee, shade tree root density was greater in deep soil layers than close to the soil surface, exhibiting niche differentiation between them and the shallower coffee roots (Fig 3.5).

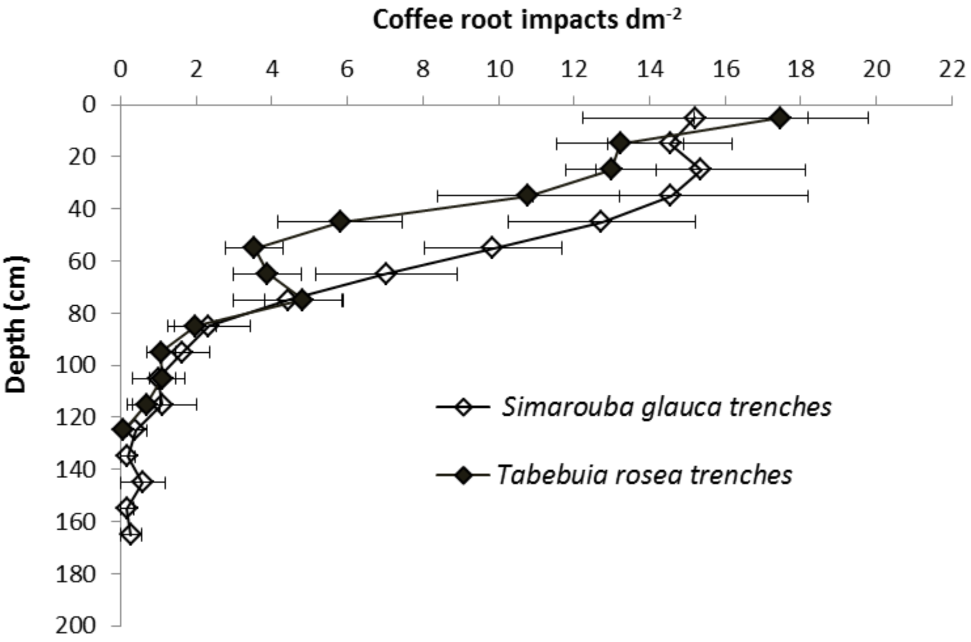

Fig 3.4. Coffee root impacts dm^{-2} in soil profiles near *Tabebuia rosea* and *Simarouba glauca* trees from the mean of eight soil profiles near each tree. Errors bars represent the standard error of the mean.

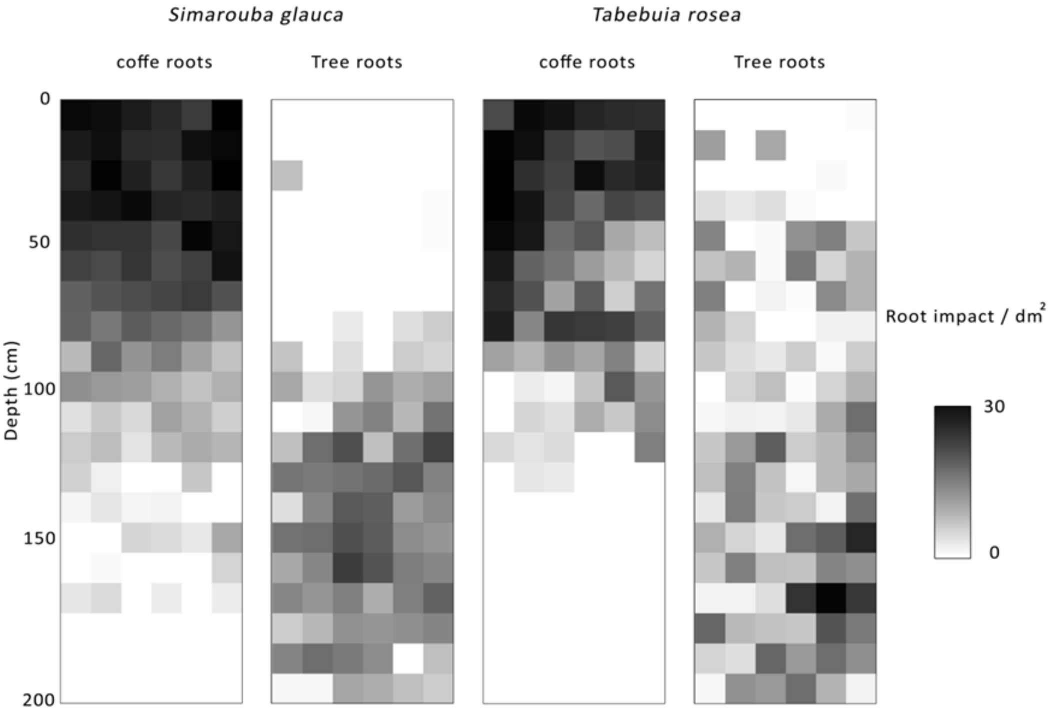

Fig 3.5. Niche differentiation of fine coffee roots and fine tree roots in the agroforestry system from the mean of 24 soil profiles in shade plots. Pictures represent the whole grids where roots were counted in 10cm x 10cm cells.

Roots of both tree species reached the dark, granular compacted layer at around 200 cm depth but penetrated no further. Tree root distribution pattern varied with species. In the deeper layers although both tree species showed higher root density below 110 cm depth, the *Simarouba glauca* root system was denser and more concentrated while *Tabebuia rosea* roots did not display such a distinct zonation in the soil profile ($p<0.0001$). Maximum fine root density of *Simarouba glauca* occurred at 165 cm depth and *Tabebuia rosea* exhibited a less distinct peak at 115 cm depth (Fig 3.6).

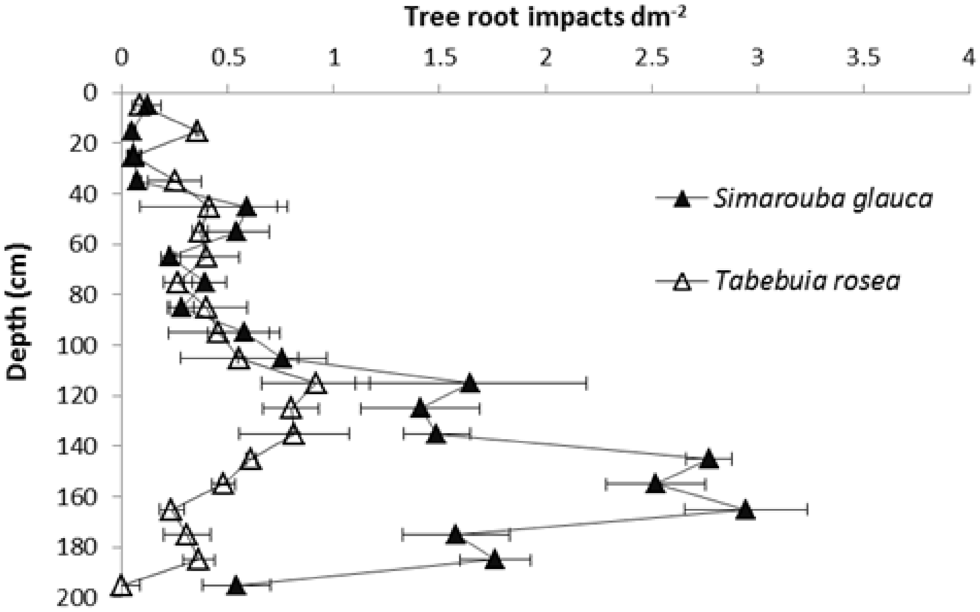

Fig 3.6. *Simarouba glauca* and *Tabebuia rosea* fine root distribution from the mean of 24 soil profiles in shade plots. Errors bars represent the standard error of the mean.

3.3.2. The effect of talpetate on coffee roots distribution

Field observations demonstrated that the depth of the talpetate layer varied between 20-170 cm and 20-150 cm in the full sun and in the shade plots respectively. The talpetate layer width was also highly variable ranging from 20 to 120 cm in the full sun and 30 to 80 cm in the shaded plots, although these differences were not significant between both systems. Also, there were sites where the tapetate layer was dense and compact and others where it was fractured at different levels regardless of the treatment. The bulk density and the organic matter content of the talpetate layer were not significantly different between the full sun and agroforestry systems or between the treatments ($p>0.05$). The bulk density ranged from 0.54 g cm^{-3} to 0.85 g cm^{-3}

while the organic matter varied from 0.5 % to 1.66 %. The presence of the talpetate layer had a significant effect (F=6.32; p=0.02) on coffee root growth. The contrast analysis of presence and absence of talpete on coffee root distribution by depth showed that coffee root impacts diminished in the presence of talpetate (0.55; S.E=0.03) compared to in the absence of talpetate (0.67; S.E.=0.04) regardless of the treatment. Vogel and Acuña Espinales (1995) also found limitations on root growth and agriculture development in soils with talpetate in comparison to soils without talpetate layer in Nicaragua.

3.3.3. Soil water content

Soil water content was a consequence of the rainfall inputs and its interactions with water uptake by plants and movement within the soil. Rainfall in 2011 was normal for the region, with relatively late rains in November (data not recorded locally). Total rainfall in the 2012 dry season was 57.2 mm with a maximum daily rainfall event of 16.8 mm. In 2012 (Fig 3.7), the rainfall in September to November was low, and the following dry season lasted almost six months, with only 23 mm rainfall overall.

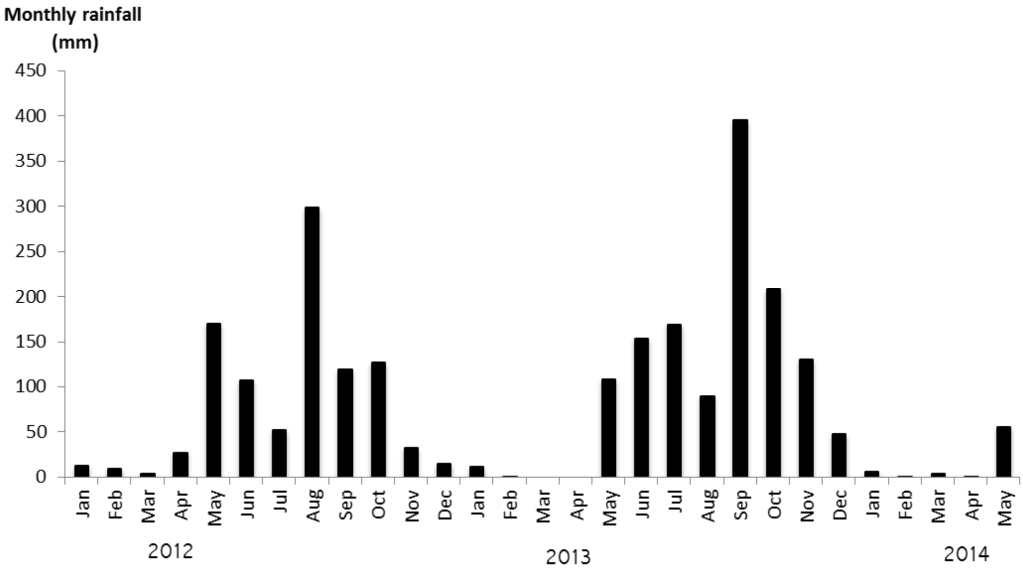

Fig 3.7. Monthly rainfall distribution from climate station, Masatepe, Nicaragua; February 2012 to May 2014.

The corresponding rainfall in late 2013 was much more abundant. Comparison between soil water content of both systems showed significant differences (F = 5.98; p = 0.0148) on the soil water content in the three periods studied (Fig 3.8).

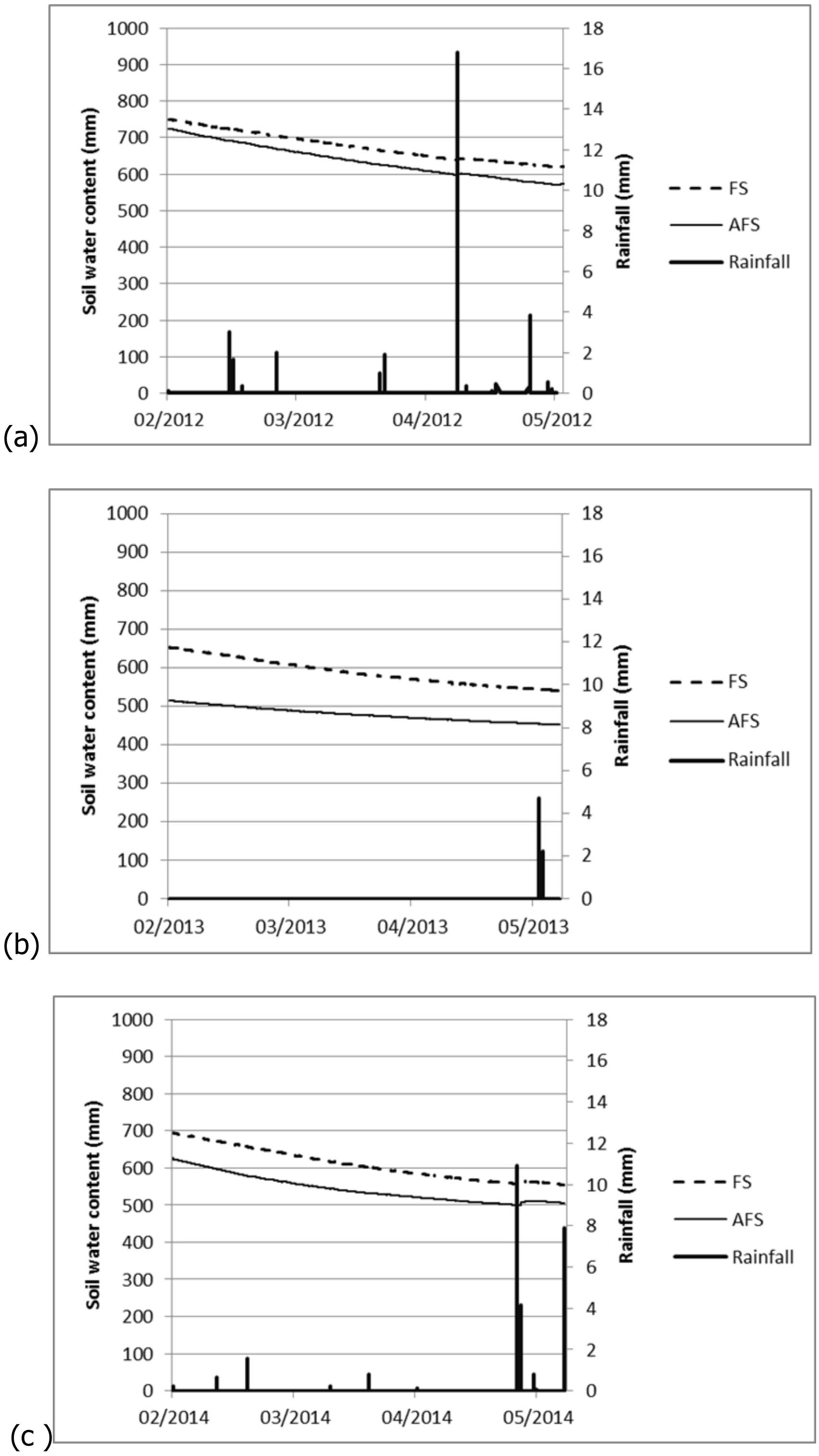

Fig 3.8. A comparison of soil water content in the whole soil profile (2000 mm) from the mean of three trenches in the full sun and six trenches in agroforestry in the (a) 2012, (b) 2013 and (c) 2014 dry periods.

The full sun coffee showed greater mean water content (561 mm; S.E.=20.2) over the whole soil profile than the agroforestry system (484 mm; S.E.=26.3) in the period of study. Comparison of temporal differences in soil water content of both systems showed that in 2012 soil water content was greater (584 mm; S.E.= 27.1) compared to 2013 (468 mm; S.E.=23.2). In 2014 slopes were similar to 2012 (516 mm; S.E.=33.9) indicating the same rates of water uptake (Fig 3.8a and 3.8c). However, in 2013 in AFS the slope was close to zero due to lower available water. The lowest values of water content during the observation period were registered at the end of the 2013 dry season in AFS when it reached 453 mm while in 2012 it was 572 mm and in 2014 506 mm (Fig 3.8b).

3.3.4. Soil water uptake

The comparison of daily water uptakes by both coffee systems from the soil profile is presented in Fig 3.9. We used only periods when drainage could be discounted. Soil water content data came from a total of nine soil profiles: three in the full sun coffee and six in the coffee agroforestry system. In the agroforestry system we found greater water consumption than in full sun coffee for most of the periods presented. However, at the end of the severe 2013 dry season ($p=0.07$) this condition seemed to be reversed. Both systems showed a very low rate of water uptake at the end, but data indicated that the coffee agroforestry system had lower soil available water than the full sun coffee (Fig 3.9). This indicates that in 'normal' dry seasons, water extraction rate in AFS was similar to FS and due to deeper tree root exploration, water content was lower. However, in the 2013 dry period, roots in AFS had extracted water to the point that soil water content was approaching a steady state, while there was still enough water in the FS soil to permit water uptake, albeit at reduced rate, to continue. Thus, only in very dry periods did the presence of tree roots exert competition to the point where coffee was no longer able to extract water.

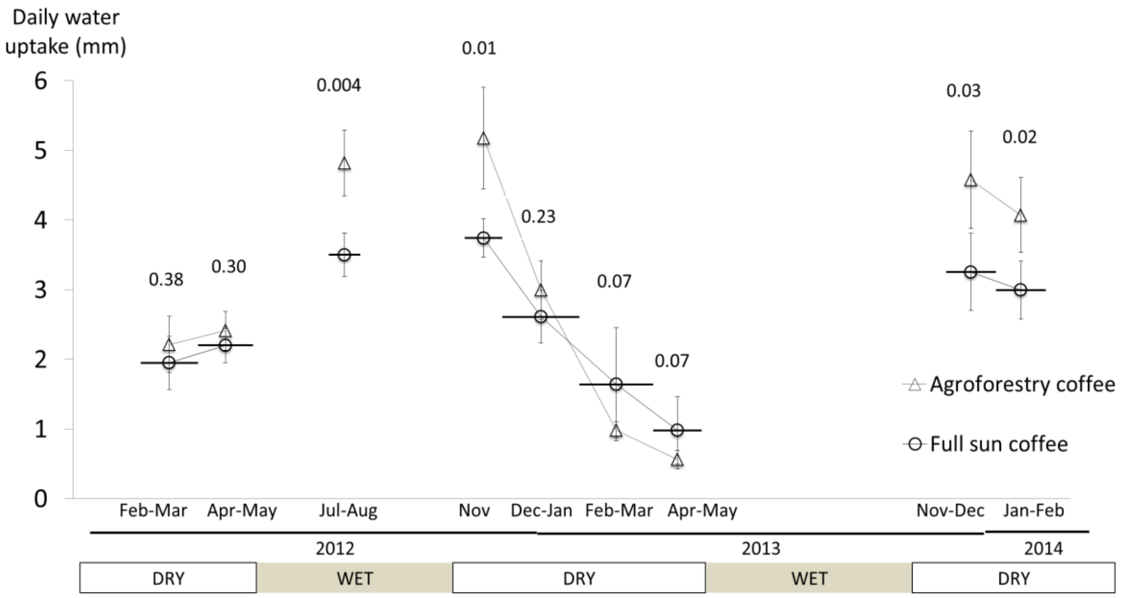

Fig 3.9. Comparison of soil water uptake by the two coffee cropping systems from the whole soil profile 2012 to early 2014. Horizontal bars represent the period lengths under consideration. Errors bars represent standard error of the mean. Probabilities for identical values figure above each comparison (T-test).

3.4. CONCLUSIONS

Root distribution may define competition or complementarity in resources use in agroforestry systems. In this investigation shallower coffee roots and deeper tree root distribution patterns suggest complementarity in soil water use throughout the soil profile. This root niche differentiation is desirable in agroforestry but is not often demonstrated.

However, coffee and tree root system distribution varied with tree species. *Simarouba glauca* presented denser root system in deep soil layers compared to *Tabebuia rosea* suggesting a facilitative relationship upon coffee root growth. Coffee and *Simarouba glauca* exhibited a clear niche differentiation whereby soil water and nutrients are likely to be extracted from different strata. The results reinforced the ecological hypothesis (Cannell *et al.* 1996) in which tree deep root system may improve soil resources use that are not available for crops.

We demonstrated that although coffee roots crossed the talpetate zone, there was some influence of this hard layer on restricting coffee root growth regardless of the treatment.

Soil water content was higher in the full sun coffee rather than the agroforestry in the whole soil profile in the dry seasons of the investigation period. At the beginning of both 2013 and 2014 dry seasons, the agroforestry coffee system was able to take up water at a greater rate from the soil profile, explained by a greater requirement by trees and a better exploration of the whole profile by roots.

But by the end of a severe dry season, as observed in 2013, the advantage of the better soil exploration was cancelled: it seems that soil water became almost exhausted during the dry season. By comparison, full sun coffee, which used less water at the beginning of the 2013 dry season, still had soil water left in the deeper layer when the dry season extended. This deep soil water was progressively used by the system, allowing a greater water use when compared to the agroforestry coffee.

Although more data would be required to distinguish the water uptake from coffee, both species of trees or the soil evaporation, we can hypothesize that there was a competition between trees and coffee for soil water uptake in atypically dry periods.

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CHAPTER IV

RAINFALL INTERCEPTION, STEMFLOW AND THROUGHFALL IN COFFEE SHADED WITH *TABEBUIA ROSEA* BERTOL. AND *SIMAROUBA GLAUCA* DC. COMPARED TO FULL SUN COFFEE

4.1. INTRODUCTION

Trees associated with crops may improve water use by diminishing water loss from soil evaporation (Jackson and Wallace 1999), by enhancing soil infiltration capacity and reducing runoff (Rao *et al.* 1998; Lunka and Patil 2016), by increasing retention of water in soil via higher organic matter content due to tree litter inputs (Beer 1987) and also by increasing water uptake from deep soil layers that otherwise could be lost by leakage (Cannell *et al.* 1996). However, trees may use a significant proportion of rainfall (Ong and Black 1994) and additionally may intercept and modify raindrop trajectories reducing the water that reaches the ground with impacts on crop growth and yield (Calder 1998).

Rainfall interception is recognized as an important component of water balance in agroforestry systems. The water inputs through gross rainfall may pass through the foliage and crop branches (throughfall) and add to soil water content; or flow down the leaves, branches and trunk to reach the ground (stemflow) or water may be kept on the leaf surface until it evaporates (interception) and so never reaches the soil. Because of the difficulties of directly measuring water loss by canopy interception it is estimated from the difference between the incident gross rainfall and the sum of throughfall and stemflow (Horton 1919; Rutter 1963). The rainfall interception process is influenced by both the climatic condition (rainfall intensity, wind speed, air temperature, solar radiation) and tree canopy parameters such as architecture and leaf area as well as the leaf and trunk surface characteristics (Crockford and Richardson 1990).

Throughfall has been shown to be the most important component of water input. Studies on rainfall interception by five tropical timber tree species in Panamá demonstrated that the average throughfall varied from 73.1% to 87.7% of the gross rainfall (Park and Cameron 2008). The influence of tree species on throughfall was also demonstrated in the Central Valley of California where values for pear and oak trees were 77% and 58% of the gross precipitation, respectively (Xiao *et al.* 2000). Also, it was found that throughfall rates increased with the distance from the tree trunks (Eschner 1967). This same general pattern was reported by different authors and is likely to be due to the typically greater canopy density near the stem. It could also be due to crown architecture whereby branches nearer the stem facilitate greater stem flow as a percentage of incident rainfall. Throughfall rate has been documented to closely match the rainfall pattern of the precipitation event (Rutter *et al.* 1971). Intense precipitation events may further increase the probability of branch drip and decrease stemflow volumes by overloading preferential flow paths on tree trunks, therefore enhancing throughfall (Crockford and Richardson 1990).

Overall, stemflow contributes little to precipitation reaching the ground when compared with throughfall. In the tropical environment, studies showed stemflow to be around 1% of gross rainfall and consequently it has been considered to be negligible (Marin *et al.* 2000). Nevertheless, stemflow has provided an important localized source of soil moisture and chemical inputs through the rainwater funneling process in which a spatial concentration of water and solutes occurs particularly at the base of tree trunks (Levia and Frost 2003). Stemflow input quantities into forest and agricultural soils are highly variable between and within types of vegetation cover.

In agroforestry systems both the tree and crop canopies affect rainfall distribution and the input to the soil surface. In coffee agroforestry great variability in rainfall interception from canopy surfaces has been demonstrated. Comparisons between coffee agroforestry with low and high shade density in India demonstrated that interception increased with shade density and varied from 9% to 16% of the gross rainfall for low and high shade levels, respectively (Gurav *et al.* 2012). High rates of interception were found in coffee agroforestry in optimal environmental conditions in Colombia with around 47% of gross rainfall in full sun (FS) and 54.5% in agroforestry (AFS) averaged for different shade tree species (Jaramillo 2003). A study in *Coffea arabica* shaded with *Erythrina poeppigiana* which was pruned periodically showed only 3.5% of the total rainfall was intercepted by the pruned shade tree (Calder 1998). The effect of rainfall amount on rainfall interception was demonstrated in coffee shaded with *Inga densiflora* in Costa Rica. It was found that interception loss reached values close to 75% for 1mm rainfall and 50% for rainfall around 5 mm while for rainfall greater than 30 mm interception decreased to 10% (Siles *et al.* 2010). Such variability in rainfall interception estimation in coffee agroforestry clearly indicates the need for further studies. To assess the water loss by interception from the system is of considerable interest, particularly in dry climates.

Although the process of retention and subsequent evaporation of water droplets on vegetation has been extensively studied in forests, it is still poorly understood and hardly taken into account in agroforestry systems. Those studies cited above undertaken on coffee agroforestry were insufficient to show consistent results for throughfall distribution or a pattern of stemflow in coffee and shade trees. The interaction between rainfall and vegetation characteristics is relevant for understanding water relations in coffee agroforestry taking into account the different environmental conditions. This chapter presents a comparison between rainfall interception in unshaded coffee and coffee agroforestry shaded with *Tabebuia rosea* and *Simarouba glauca* timber tree species in a coffee agroforestry system in Nicaragua. The objective is to contribute to better understanding of the effects of rainfall partitioning on the water balance of the coffee agroforestry system and the effects of the two tropical timber tree species on rainfall distribution.

4.2. MATERIALS AND METHODS

4.2.1. Site description and experimental design

The study was carried out in an experiment located at Jardin Botánico, Masatepe, Department of Masaya, southern Nicaragua (11^0 53′ 54″ N, 86^0 08′ 56″ W), a long term research site managed by the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), jointly with the Universidad Nacional Agraria (UNA), Federación Cooperativas de Ahorro y Crédito (CENECOOP-FEDECARUNA) and Instituto Nicaraguense de Tecnologia Agropecuaria (INTA). The experiment was established in 2000 and is described in Haggar *et al.* (2011). The site is located at 455 m.a.s.l. where mean annual temperature is 27^{0}C and mean annual rainfall is 1470 mm. In 2013 the annual rainfall recorded was 1312 mm. Of the total annual precipitation 85% to 97% falls during the wet season (May-November) while a pronounced seasonal drought occurs from late November to mid-May. In this study measurements were carried out after 28 rainfall events from 26 May to 11 October 2013 during three main periods: at the beginning (May-June), in the middle (July-August) and at the end (September-October) of the wet season.

The experimental design consisted of a full sun monocrop coffee (FS) plot (1440 m^2) and an adjacent coffee agroforestry system (AFS) plot (3200 m^2). In both systems *Coffea arabica* density was 4000 plants ha^{-1} throughout the experiment, 2 m between rows and 1.25 m between plants. Coffee was selectively pruned yearly in February after harvest.

In the coffee agroforestry system plot, *Coffea arabica* was associated with *Simarouba glauca* DC. (Simaroubaceae) and *Tabebuia rosea* (Bertol.) DC. (Bignoniaceae) planted as shade trees regularly mixed in the plantation. The mean density of *Tabebuia rosea* was 113 trees ha^{-1} and that of *Simarouba glauca* was 75 trees ha^{-1} over the period of the study. Three sub plots were established in the agroforestry system as pseudo-replicates, each one bounded by two *Simarouba glauca* trees and two *Tabebuia rosea* trees in the plot corners and the coffee plants within (mean area, 44.93 m^2 each). Tree specimens were representative of the average tree size in the plot. In the full sun plot coffee plants were randomly selected but stratified according to the range of coffee tree sizes.

4.2.2. Species studied

Coffea arabica L. (Rubiaceae) variety "Pacas" is a natural mutation of Bourbon discovered in 1949 in El Salvador on a farm belonging to a family named Pacas. This variety is known to be adapted to hot and dry environments. Its agro-ecological aspects were analyzed and compared to the other traditional varieties at the study site and it displayed good branching capacity, branch length and leaf production and a good yield potential in sub optimal environmental conditions (Blanco *et al.* 2003).

Simarouba glauca DC. is native to tropical and sub-tropical regions of Central America, Mexico and the Caribbean. In the study area this evergreen timber tree species reached about 17 m height, 25.5 cm DBH and canopy area of 41 m^2 with an average of 7.2 m canopy diameter. The stem has finely cracked and grey colored outer bark while the inner bark is creamy in color. Mean bark thickness was 0.92 cm in the study area over the experiment. This species is successful over a range of soil types and their deep root system enables effective access to water year round. It has large and waxy compound leaves approximately 20 cm in length comprising 12–16 oblong pinnae, each approximately 5 cm in length, in a dense rounded crown (Brodribb *et al.* 2003).

Tabebuia rosea Bertol. is native to Mexico, Central America, Venezuela and coastal Ecuador. Trees grow in a great variety of habitats, but thrive better in regions with annual rainfall between 1200 and 2500 mm. Trees require a dry period to initiate and enhance flowering and fruiting. It has a deep root system and tolerates occasional waterlogging (CABI 2013). It is a fairly fast growing tree. At the study site 12 year old *Tabebuia rosea* trees reached 15.5 m height and 28.7 cm DBH. The tree crown was wide with an average of 44 m^2 with irregular, stratified ramifications and only a few thick branches. Tree canopy diameter was about 7.4 m by the end of the experiment. Leaves are compound, digitate and long petiolate. Each leaf has five leaflets of variable size, the middle one being the largest. It is a deciduous tree that sheds its leaves in the late dry season (Gentry 2002). The bark can be grey to brown and may be vertically fissured. Mean bark thickness was 1.53 cm in the study area.

4.2.3. Rainfall

Rainfall was measured by an automatic weather station installed in the full sun plot. Sensors installed at 2.50 m height were connected to a dataloggers (CR1000 Campbell Scientific Instruments). Data were continuously collected every 30 minutes over the period of study. The weather station measured relative humidity and temperature (HMP50 Campbell Scientific Instruments) and also solar radiation (CS300 Campbell Scientific Instruments), wind speed (03101 Campbell Scientific Instruments) and rainfall with tipping bucket rain gauges (TE525MM/TE525M Campbell Scientific Instruments). Rainfall measurements were calibrated by using five manual rain gauges installed in the full sun system and as close as possible to the edge of the agroforestry system plot without being affected by the tree stratum. Throughfall and stemflow were measured for 28 rainfall events during the period of study, which summed 444.5 mm, corresponding to 33.8 % of the total annual rainfall in 2013 (1312mm). Measurements were done during 8 rainfall events from 26 May to 13 June; 11 rainfall events from 18 July to 6 August and over 9 events from 15 September to 11 October (Fig 4.1).

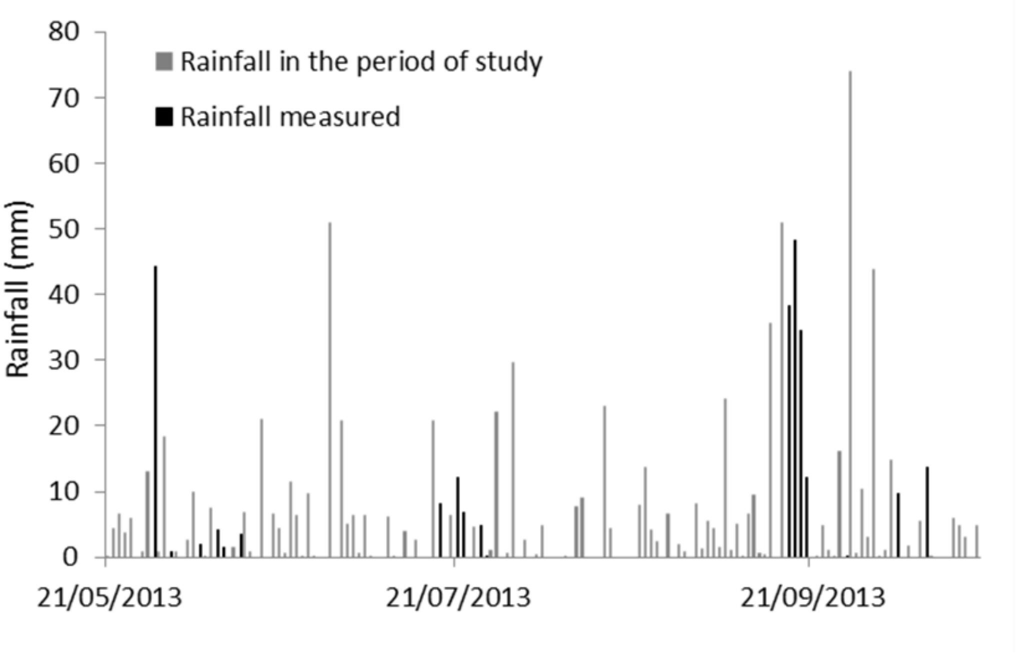

Fig 4.1. Daily rainfall events over the period of study and in the three periods measured: May-June, July-August and September-October 2013.

4.2.4. Leaf area index

Tree leaf area index (LAI) was calculated from hemispherical photographs taken by a Nikon Coolpix 4500 camera with a fish-eye lens oriented vertically upwards towards the tree canopy. Hemispherical photographs were analyzed by using the Gap Light Analyzer software (Frazer *et al.* 1999). Leaf area indices calculated from the hemispherical photographs were calibrated by destructive direct measurements that combined gravimetric and planimetric techniques (Jonckheere *et al.* 2004). Leaf area of the trees in the plots was calculated using tree density.

Coffee leaf area was measured on a sample of 18 and 30 coffee shoots in the full sun and AFS, respectively, over the period of study. The leaf area was calculated by using the equation established in the laboratory:

Leaf area (cm^2) = 0.7243 * length (cm) * width (cm)

The shoot leaf area (m^2) was obtained by multiplying mean leaf area of every 20th leaf by the total number of leaves per shoot. LAI of coffee in both systems was calculated by multiplying the average of shoot leaf area by shoot density per m^2.

The coffee and tree LAI data interpolation from measurements carried out at the beginning, the middle and at the end of the experiment allowed estimation of LAI for each rainfall event.

4.2.5. Stemflow

Coffee and tree stemflows were measured by using collars fitted and sealed on to the stem in an upward spiral in order to collect the flowing water. Collars were installed around six tree trunks each of *Tabebuia rosea* and *Simarouba glauca*. Collars were also installed around nine and 15 coffee stems in the full sun and agroforestry plots, respectively. Water collected by collars was conducted by a tube into a bucket with lid placed on the ground and measured daily. Daily stemflow per tree species calculated at the plot scale was based on tree species density. Coffee plant density was also used for stemflow estimation at the plot scale.

4.2.6. Throughfall

Throughfall was monitored under the canopy of nine and 15 coffee plants in the full sun and agroforestry respectively. Three rain gauges (made of PVC cylinders with edges which had been beveled) were placed at intervals from the coffee trunk (0.20 m, 0.60 m and 1.0 m) in a diagonal line at ground level (Fig 4.2).

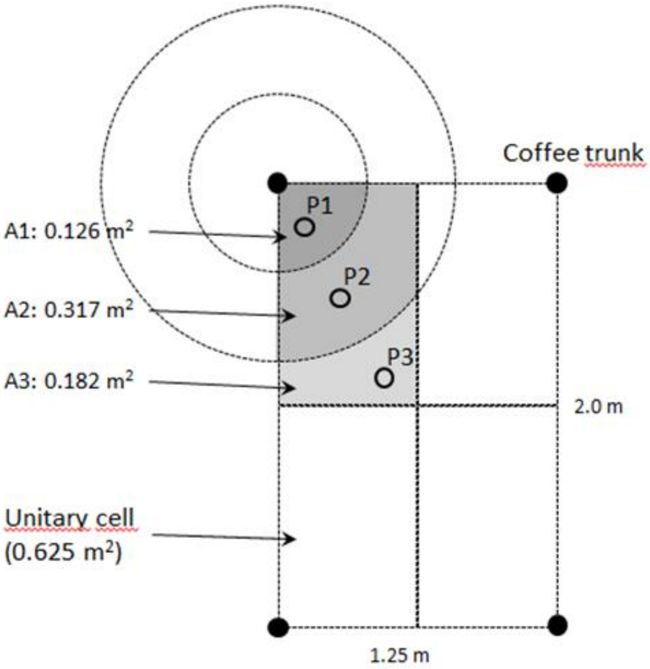

Fig 4.2. Rain gauge distribution for coffee throughfall monitoring in the full sun and shade plots.

The rainfall collected in each rain gauge was divided by the rain gauge section (0.0117 m^2) and throughfall was weighed for each distance by multiplying this throughfall by the area sampled by each gauge (m^2) divided by the area of the unitary cell. For coffee, this weighing was calculated geometrically and the result of the multiplication was divided by the total of a quarter of the area occupied by coffee tree (Fig 4.2). A total of 72 rain gauges were used for coffee throughfall measurements: 24 coffee plants equipped with three gauges. Throughfall was also monitored under six *Simarouba glauca* and in six *Tabebuia rosea* trees in the coffee agroforestry being two trees of each species within each one of the three sub plots in the shade. We used a total of 78 rain gauges regularly spaced in circles at 1.0, 2.5 and 5.5 m distant from the tree stems and above the coffee plant canopies (Fig 4.3). The sampling area of each rain gauge was calculated by using the classical Thiessen polygon technique (Tabios and Salas 1985). Placing rain gauges above coffee canopy height was necessary so that interception and throughfall could be partitioned into tree and coffee canopy components. The average volume of water measured in the morning after each rain event divided by the rain gauge section per unit area was used to calculate throughfall per tree. Throughfall was extrapolated for the whole plot based on tree density. Throughfall as a percentage of gross rainfall was calculated for a range of five rainfall event magnitudes (< 5 mm; 5-10 mm; 10-20 mm; 20-40 mm; >40 mm) occurring during the study periods.

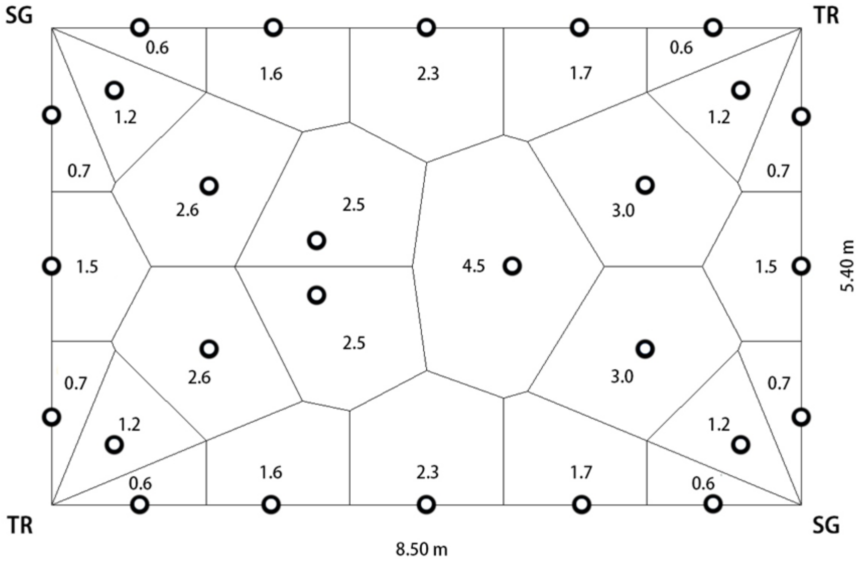

Fig 4.3. Rain gauge (circles) distribution for tree throughfall monitoring and spatial weighing for each gauge (m^2) calculated by the Thiessen polygon method in one out of three replications in the shaded plot.

4.2.7. Interception loss

Loss by canopy interception by coffee and trees was calculated by subtracting the measured daily throughfall and stemflow from gross rainfall based on the follow equation:

$L = R - (S + T)$

where: L= interception loss; R= Rainfall; S= Stemflow; T= throughfall (Rutter 1963; Gurav *et al.* 2012). Interception dynamics over the two-year period of experiment was obtained by modeling coffee and shade tree interception measurements as a function of rainfall (Gash 1979).

4.2.8. Statistical analysis

Data analysis was conducted by using InfoStat software (Di Rienzo *et al.* 2014). A general linear mixed model allowed determination of significant differences on throughfall, stemflow and interception between systems regarding LAI as a fixed effect. The influence of the distance from the coffee and tree trunks on throughfall was tested. Relationships between gross rainfall versus throughfall and versus stemflow were derived from curvilinear and linear regression analyses, and these are presented towards the end of the results section.

4.3. RESULTS

4.3.1. Leaf area index

Coffee LAI was greater in shaded coffee compared to FS over the monitoring period ($p<0.001$). As measurements were carried out during the growing season LAI tended to increase over the time. Changes in LAI of coffee in FS, in AFS and of *Tabebuia rosea* and *Simarouba glauca* over the experiment were presented in Table 4.1.

LAI of trees was significantly different between both tree species ($p<0.0001$) with mean values of 0.52 (S.E.=0.01) for *Tabebuia rosea* compared to 0.37 (S.E.=0.01) for *Simarouba glauca*. Deciduous *Tabebuia rosea* showed greater variation in LAI which is probably related to refoliation in the period studied while LAI of evergreen *Simarouba glauca* was more stable (Table 4.1).

Table 4.1. LAI of coffee in FS, coffee in AFS, *Tabebuia rosea* and *Simarouba glauca* in the three consecutive periods studied: May-June, July-August and September-October 2013. (Mean ± standard error).

	May-June	July-August	Sep-October
Coffee FS	1.95 ± 0.41	2.60 ± 0.48	3.41 ± 0.01
Coffee AFS	3.05 ± 0.15	3.73 ± 0.46	4.76 ± 0.01
Tabebuia rosea	0.25 ± 0.25	0.50 ± 0.18	0.78 ± 0.31
Simarouba glauca	0.33 ± 0.02	0.35 ± 0.04	0.41 ± 0.06

In AFS LAI of coffee and trees combined was 37% greater than LAI in FS coffee with mean total LAI of 2.66 (SE=0.03) and 4.26 (SE=0.02) over the monitoring period in FS and AFS, respectively.

4.3.2. Stemflow

Stemflow increased gradually over the three periods studied reaching greater values in the last period when most heavy storms occurred. Coffee stemflow was linearly related to rainfall in FS (R^2=0.99) and to tree throughfall (R^2=0.98) in AFS (Fig 4.4).

Coffee stemflow as a percentage of incident rainfall was greater in AFS compared to FS (p=0.0001). Stemflow varied between 1.3% and 1.6% of rainfall in FS and of tree throughfall in AFS respectively. Coffee stemflow as a percentage of gross rainfall in FS and tree throughfall in AFS for the five magnitudes of rainfall studied are presented in Table 4.2.

Table 4.2. Stemflow as a percentage of gross rainfall (or throughfall) in coffee FS, coffee AFS, *Tabebuia rosea* (TR) and *Simarouba glauca* (SG) for five magnitudes of rainfall over the period of study. SE is the standard error of the mean.

	Coffee FS		Coffee AFS		TR		SG	
	%	SE	%	SE	%	SE	%	SE
< 5 mm	0.8	± 0.14	1.9	± 0.37	0.9	± 0.25	0.6	± 0.16
5 - 10 mm	1.0	± 0.09	1.3	± 0.07	1.8	± 0.17	1.1	± 0.08
10 - 20 mm	1.4	± 0.07	1.6	± 0.05	2.4	± 0.07	1.4	± 0.08
20 - 40 mm	1.5	± 0.05	1.6	± 0.05	2.2	± 0.02	1.3	± 0.03
> 40 mm	1.6	± 0.02	1.8	± 0.02	2.1	± 0.02	1.3	± 0.02

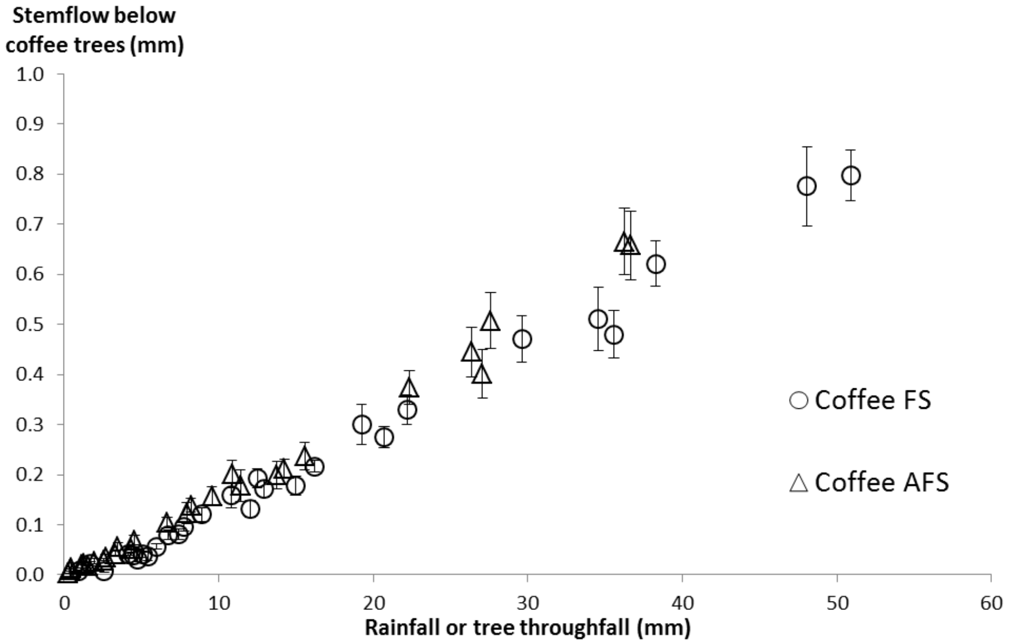

Fig 4.4. Coffee stemflow as a function of rainfall in FS and tree throughfall in AFS over the period of study. Vertical bars represent the standard error of the mean.

Tree stemflow varied with tree species and was greater in *Tabebuia rosea* compared to *Simarouba glauca* (p=0.0001) (Fig 4.5). Tree stemflow represented an average of 1.9% and 1.1% of gross rainfall for *Tabebuia rosea* and *Simarouba glauca,* respectively (Table 4.2). Differences may be related to variations on bark width and texture. The *Tabebuia rosea* bark was found to be thick (1.53 cm; SE=0.27), coarse and fissured while *Simarouba glauca* bark was thin (0.92 cm; SE=0.04) and smooth. Relationship between stemflow and rainfall was strong and positive for both shade tree species (R^2=0.98).

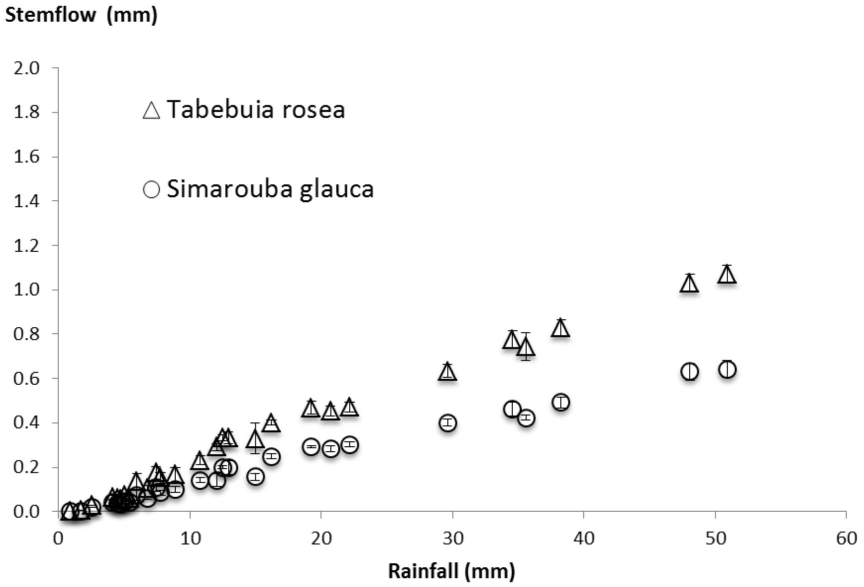

Fig 4.5. Tree stemflow as a function of rainfall over the period of study. Vertical bars represent the standard error of the mean.

4.3.3. Throughfall

Linear regression analysis showed strong and positive relationships between throughfall below coffee trees with gross rainfall in FS (R^2=0.99) and with tree throughfall below shade trees in AFS (R^2=0.98) (Fig 4.6).

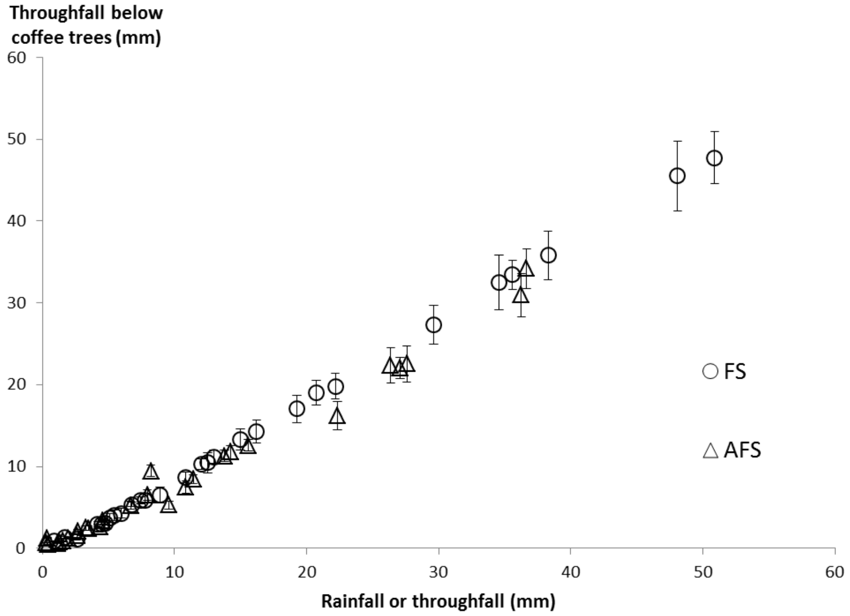

Fig 4.6. Throughfall below coffee trees in FS and AFS as a function of rainfall in FS and the tree throughfall in AFS over the period of study. Vertical bars represent standard error of the mean.

Differences between systems were not significant (p=0.08) for throughfall expressed as a percentage of gross rainfall being 65% and 69% in AFS and FS, respectively. In FS coffee throughfall as a fraction of rainfall tended to increase gradually with rainfall amount in unshaded coffee and ranged between 61% and 84% of gross rainfall for rainfall events up to 5mm and above 40 mm, respectively. In AFS coffee throughfall reached its maximum at 84% of rainfall when rainfall events were between 20-40 mm (Table 4.3).

Table 4.3. Throughfall as a percentage of gross rainfall (or throughfall) by coffee FS, coffee AFS, *Tabebuia rosea* (TR) and *Simarouba glauca* (SG) for five magnitudes of rainfall. SE is the standard error of the mean.

	Coffee FS		Coffee AFS		SG		TR	
	%	SE	%	SE	%	SE	%	SE
< 5 mm	61	± 2.0	53	± 2.0	31	± 1.0	27	± 1.0
5 - 10 mm	62	± 2.0	65	± 3.0	53	± 1.0	47	± 1.0
10 - 20 mm	71	± 2.0	78	± 3.0	72	± 1.0	66	± 1.0
20 - 40 mm	79	± 3.0	84	± 4.0	81	± 1.0	68	± 1.0
> 40 mm	84	± 5.0	75	± 4.0	80	± 1.0	68	± 2.0

The effect of the distance from the trunk on coffee throughfall was tested and this effect varied between systems (p<0.001) being greater in FS compared to AFS. The large differences in such effect on coffee throughfall between systems may be explained by greater foliage in the shade with 31% greater LAI compared to FS over the period of the experiment. Throughfall measured beneath coffee trees in FS was lowest at 0.20 m from the coffee stem with 35% of rainfall while at 0.60 m and 1.0 m distance from the coffee trunk was similar with 89% and 79% of incident rainfall, respectively (Fig 4.7). In AFS coffee throughfall expressed as a percentage of tree throughfall increased gradually with the distance from the coffee trunk and differences between distances were significant (p=0.01). Coffee throughfall represented 57%, 66% and 73% of tree throughfall at 0.20 m, 0.60 m and 1.0 m from the coffee trunk, respectively (Fig 4.8).

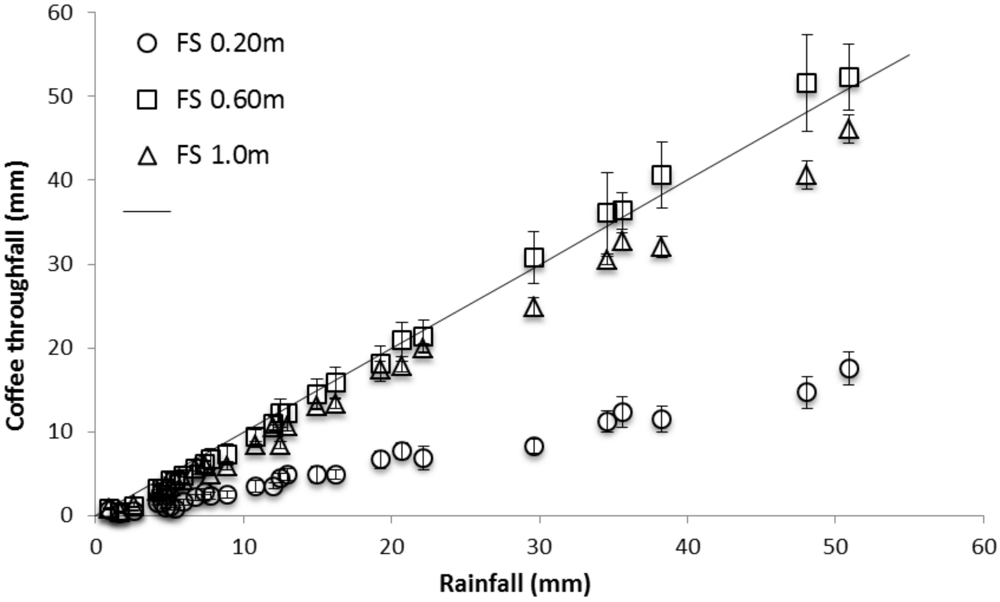

Fig 4.7. Throughfall below coffee canopies as a function of rainfall in FS at different distances from the coffee trunk (0.20, 0.60 and 1.0 m).

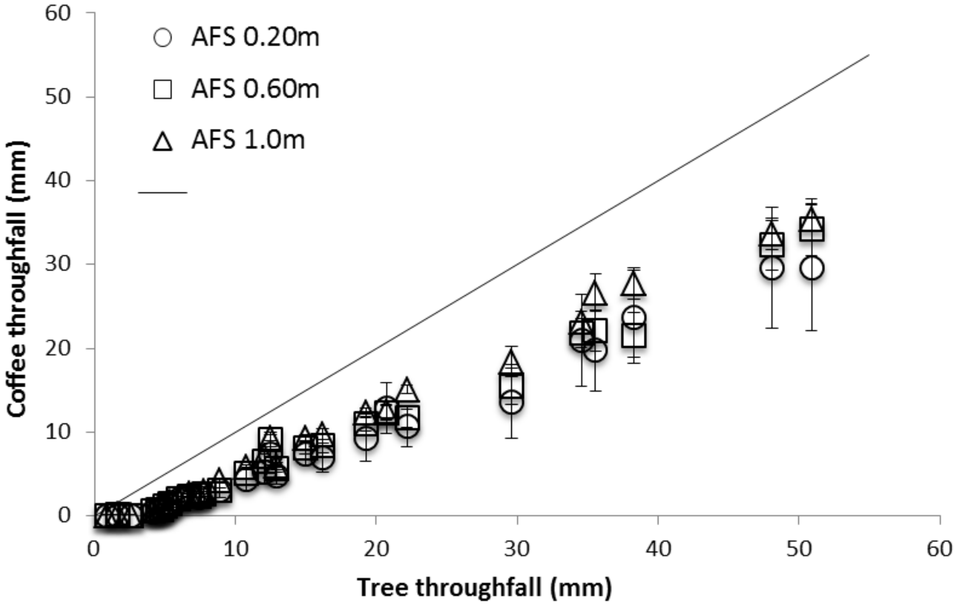

Fig 4.8. Throughfall below coffee canopies as a function of tree throughfall in AFS at different distances from the coffee trunk (0.20, 0.60 and 1.0 m).

Throughfall measured beneath shade tree canopies varied with tree species ($p<0.001$) being greater beneath *Simarouba glauca* trees compared to *Tabebuia rosea*. The ratio of tree throughfall to gross rainfall was 0.61 and 0.53 beneath *Simarouba glauca* and *Tabebuia rosea*, respectively. A positive and strong relationship was found between throughfall below both tree species and rainfall ($R^2=0.99$) (Fig 4.9). A general tendency of increasing in *Tabebuia rosea* and *Simarouba glauca* throughfall expressed as a percentage of gross rainfall was observed (Table 4.3).

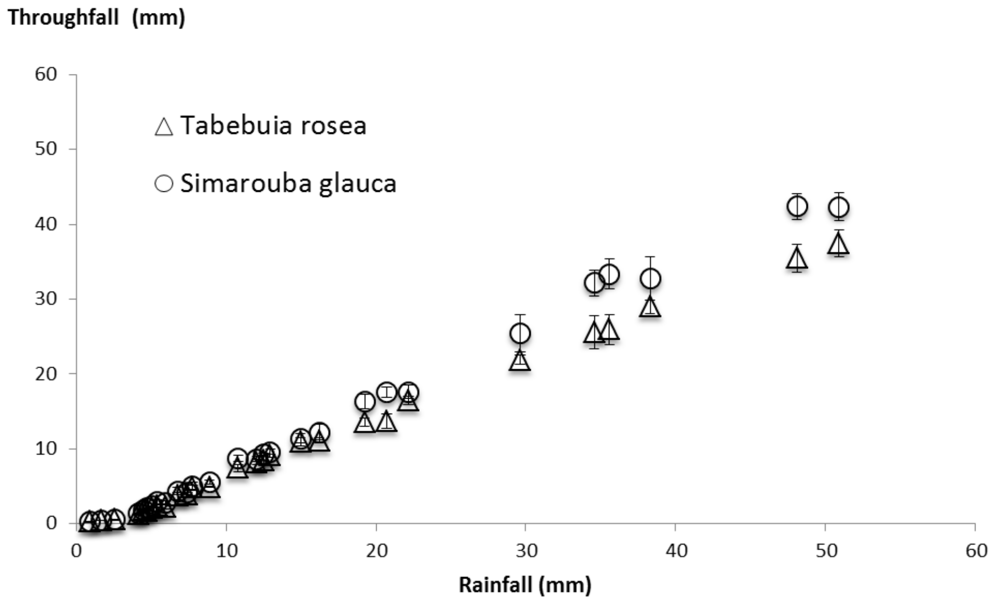

Fig 4.9. Mean tree throughfall beneath six *Tabebuia rosea* and six *Simarouba glauca* as a function of gross rainfall over the period of study. Vertical bars represent the standard error of the mean.

Throughfall beneath *Tabebuia rosea* was similar at distances from the tree trunk ($p=0.08$) (Fig 4.10) while beneath *Simarouba glauca* was similar at 2.5 m and 5.5 m and differed at 1.0 m distance from tree trunk (Fig 4.11). Tree throughfall as a percentage of gross rainfall represented 50%, 56% and 64% of rainfall at 1.0 m, 2.5 m and 5.5 m distance from *Tabebuia rosea* stem, respectively, while beneath *Simarouba glauca* throughfall was 55%, 65% and 69% of rainfall, respectively, for the same distances.

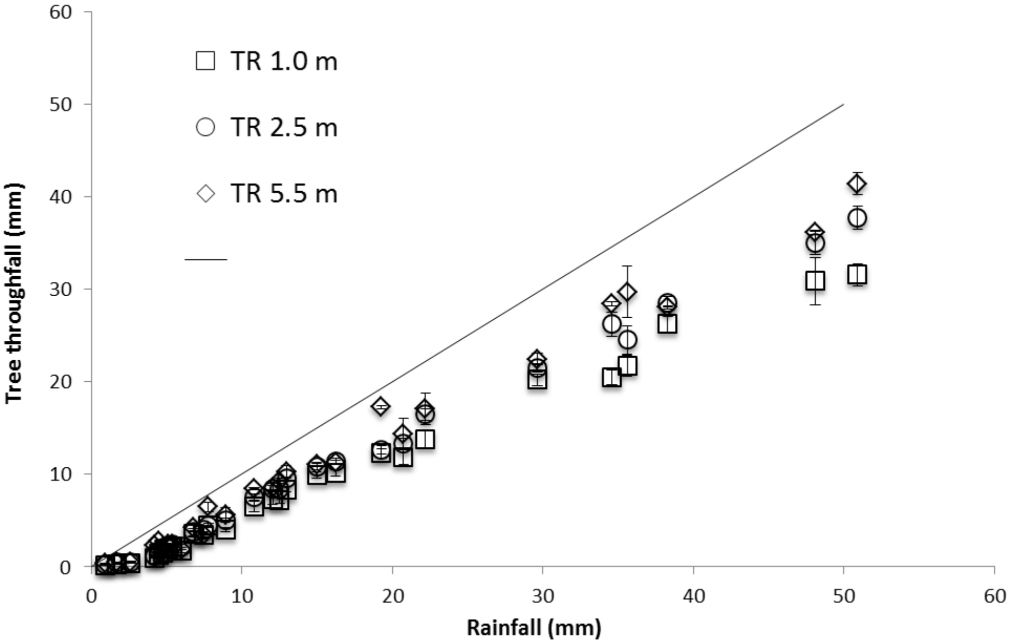

Fig 4.10. Spatial distribution of throughfall beneath *Tabebuia rosea* (TR) as a function of gross rainfall at different distances from the tree trunk (1.0 m, 2.5 m and 5.5 m).

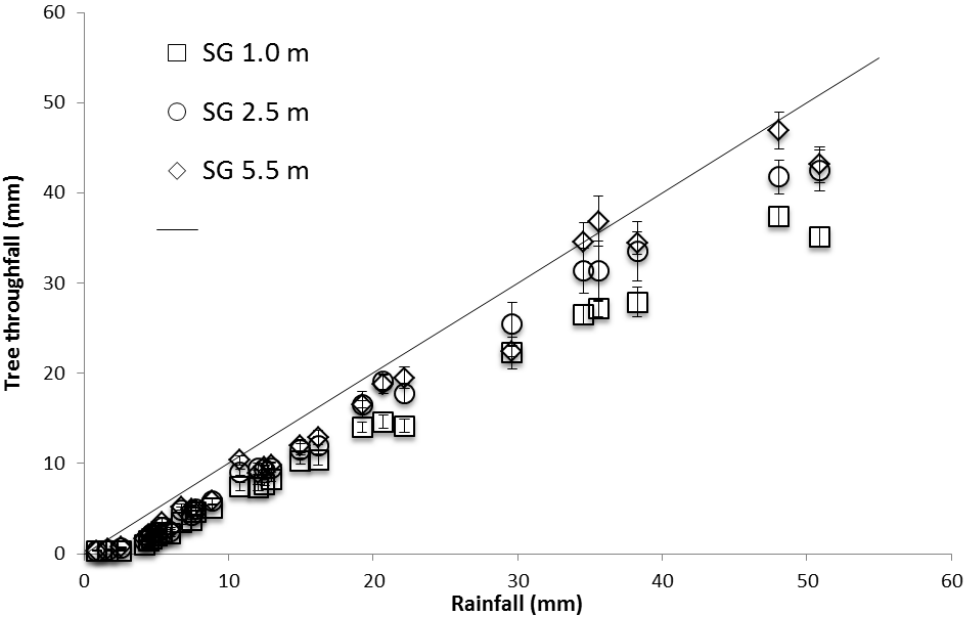

Fig 4.11. Spatial distribution of throughfall beneath *Simarouba glauca* (SG) as a function of gross rainfall at different distances from the tree trunk (1.0 m, 2.5 m and 5.5 m).

4.3.4. Rainfall interception

Water loss by interception by coffee plants as a proportion of rainfall was similar in both systems (p=0.17). Interception expressed as a percentage of rainfall represented 33% and 30% of gross rainfall in AFS and FS, respectively (Fig 4.12). However, coffee interception performed differently in both systems depending on rainfall size. Rainfall interception expressed as a percentage of rainfall tended to diminish gradually with increasing in rainfall amount in both systems (Table 4.4). Greater variability in rainfall interception in AFS compared to FS was likely due to the inherent variability in tree throughfall as a component of rainfall interception estimation in the shaded environment.

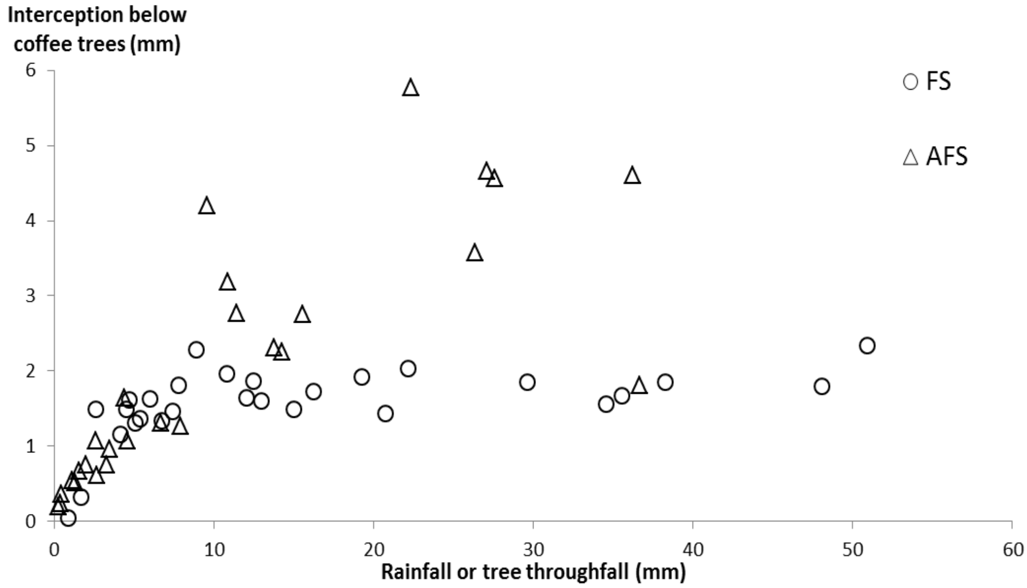

Fig 4.12. Rainfall interception by coffee trees in FS and AFS over the period of study.

Overall interception by shade trees varied with tree species (p<0.0001). Interception expressed as a fraction of rainfall represented 44% and 38% of incident rainfall by *Tabebuia rosea* and *Simarouba glauca* canopies, respectively, over the monitoring period (Fig 4.13). Interception by shade trees expressed as a percentage of gross rainfall was greater for small rainfall events below 5mm when reached 69% and 72% of rainfall in *Simarouba glauca* and *Tabebuia rosea* respectively (Table 4.4). The percentage of canopy interception loss diminished gradually with increasing in rainfall size and reached 18% and 30% of gross rainfall for big rainfall events above 40 mm, in *Simarouba glauca* and *Tabebuia rosea,* respectively (Table 4.4).

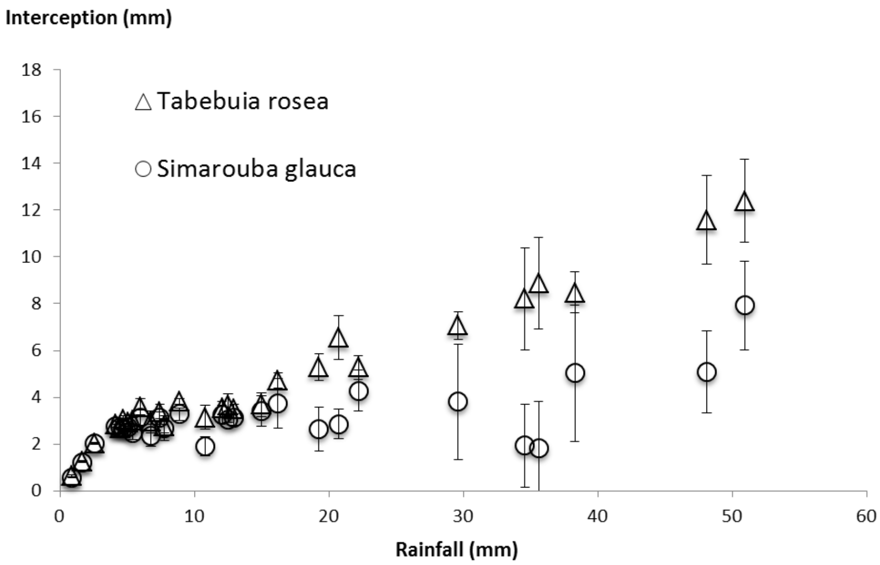

Fig 4.13. Interception by *Tabebuia rosea* (TR) and *Simarouba glauca* (SG) canopies as a function of rainfall. Vertical bars represent the standard error of the mean.

Table 4.4. Rainfall interception expressed as a fraction of rainfall or tree throughfall in coffee FS, coffee AFS, *Simarouba glauca* and *Tabebuia rosea* over the period of experiment.

	Coffee FS		Coffee AFS		SG		TR	
	%	SE	%	SE	%	SE	%	SE
< 5 mm	38	± 2.0	44	± 2.0	69	± 1.0	72	± 1.0
5 - 10 mm	37	± 2.0	34	± 3.0	46	± 1.0	51	± 1.0
10 - 20 mm	28	± 2.0	21	± 3.0	26	± 1.0	30	± 1.0
20 - 40 mm	20	± 2.0	15	± 4.0	18	± 1.0	30	± 1.0
> 40 mm	15	± 5.0	24	± 4.0	18	± 2.0	30	± 2.0

Globally rainfall partitioning in throughfall, stemflow and interception expressed as a percentage of gross rainfall (Table 4.5) showed that stemflow accounted for the minor proportion of rainfall while throughfall was the most important contribution for interception estimation. In agroforestry most rainfall interception was due to shade trees being greater by *Tabebuia rosea* (Table 4.5).

Table 4.5. Rainfall partitioning in throughfall, stemflow and interception expressed as a fraction of rainfall or tree throughfall in coffee FS, coffee AFS, *Simarouba glauca* and *Tabebuia rosea* over the period of experiment.

	Throughfall		Stemflow		Interception	
	%	SE	%	SE	%	SE
Coffee FS	69	± 3.0	1.3	± 0.1	30	± 3.0
Coffee AFS	65	± 3.0	1.6	± 0.2	33	± 5.0
Tabebuia rosea	53	± 1.0	1.8	± 0.2	44	± 1.0
Simarouba glauca	61	± 1.0	1.0	± 0.1	38	± 1.0

4.3.5. Rainfall interception modelling

Rainfall interception measurement and modelling were used in order to extrapolate the results obtained for the whole period of study. In agroforestry, rainfall interception modelling may consist in an important tool to predict the effects of water loss by coffee and shade tree canopies, particularly in water limiting condition for coffee cultivation. Coffee and tree daily interception values derived from throughfall and stemflow measurements were modelled as a function of incident rainfall or tree throughfall by using Michaelis-Menten equation:

$$I = \frac{Imax * R}{Km + R}$$

Where:

I is the interception

I_{max} is the maximum interception

R is the rainfall

k_m is the Michaelis-Menten constant

K_m is equal to the rainfall amount in which the interception is half of its maximum value. The model yields an asymptotic equation in which for low rainfall rates interception is proportional to rainfall and for rainfall rates above k_m values interception is equal to the interception maximum and is independent of rainfall rates. Thus, the model is based on two main variables: the rainfall and the maximum interception. Coffee interception modelled in FS showed that maximum interception was attained at 2.0 mm with k_m of 2.4 mm rainfall threshold (Fig 4.14) while in AFS maximum interception of 5.7 mm was obtained with K_m of 13 mm. Regarding the inherent difficult to accurately estimate interception in AFS due to the heterogeneous rainfall produced by the shade tree canopies effect we choose to adjust maximum interception by coffee in the shade. We used coffee LAI as a reliable reference rather than the rainfall obtained from tree throughfall. Thus, mean coffee LAI in AFS related to coffee LAI in FS in the period of measurements allowed obtaining 3.0 mm maximum interception.

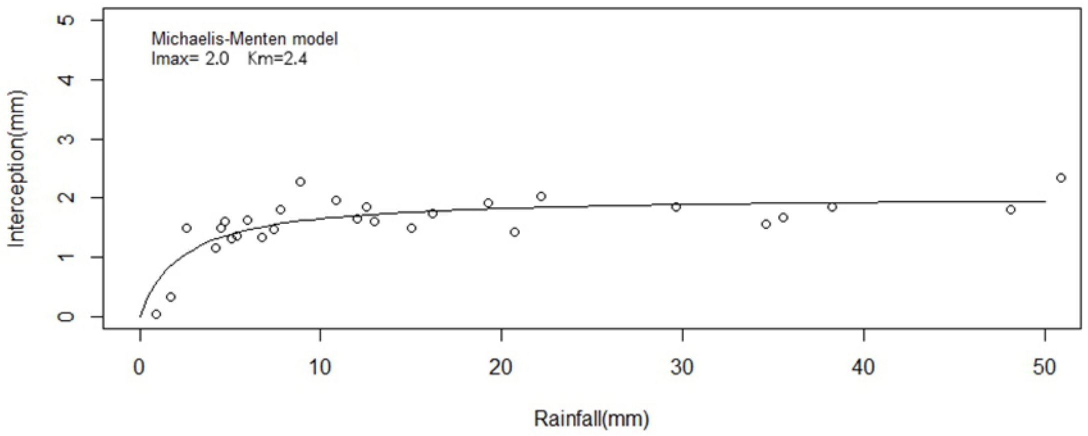

Fig 4.14. Interception measured and modelled by coffee tree canopies in FS.

The model fitted well for *Simarouba glauca* trees and reached maximum interception at around 4.6 mm with k_m of 4.5 mm rainfall (Fig 4.15). However, for *Tabebuia rosea* maximum interception was estimated at 25 mm with k_m of 64 mm, which is clearly unrealistic (Fig 4.16).

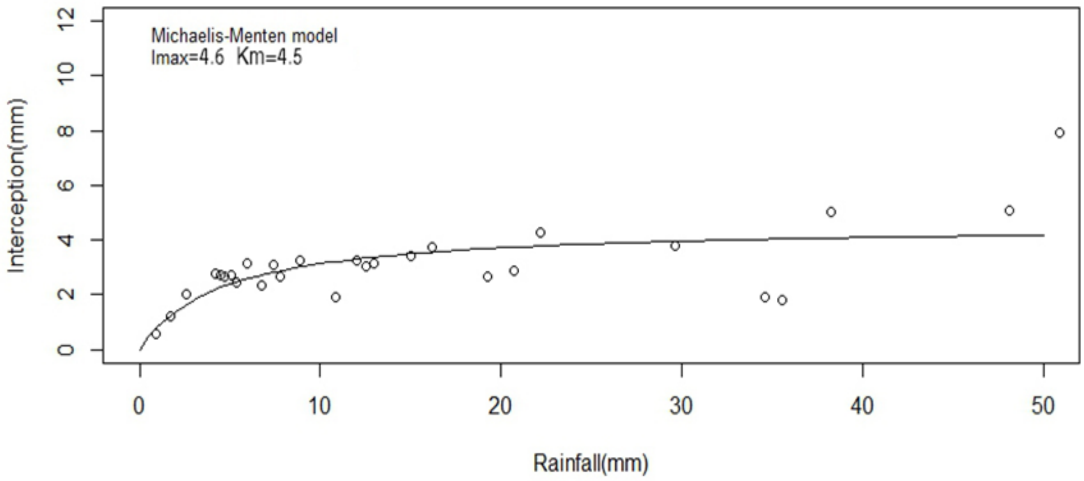

Fig 4.15. Rainfall interception measured and modelled by *Simarouba glauca* canopy.

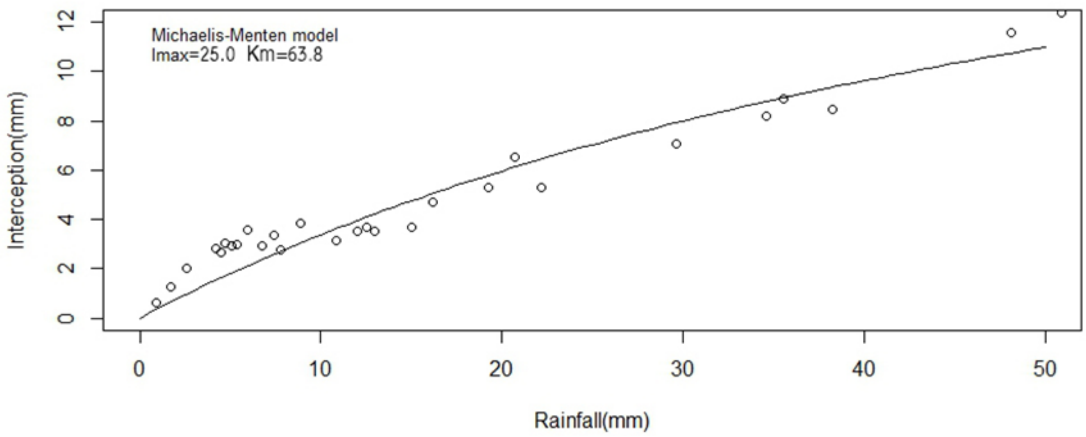

Fig 4.16. Rainfall interception measured and modelled by *Tabebuia rosea* canopy.

Coefficients from Michaelis-Menten equation (Table 4.6) were applied for coffee and tree interception modeling. In AFS coffee interception modeling took into account tree throughfall calculated from the difference between rainfall and the sum of tree interception and tree stemflow. Coefficients for tree stemflow modeling were obtained from stemflow measured in each tree species versus gross rainfall regression (Table 4.7). Tree interception and stemflow were up scaled to the agroforestry plot level by using tree density. Interception by trees and shaded coffee summed allowed the whole agroforestry system interception calculation.

Table 4.6. Coefficients for coffee FS, coffee AFS, *Tabebuia rosea* (TR) and *Simarouba glauca* (SG) interception (RI) by the equation: $I=a*b/a+b$

	I_{max}	K_m
Coffee FS	2.0	2.4
Coffee AFS	3.0	13.2
TR	25.0	63.8
SG	4.6	4.5

Table 4.7. Regression coefficients for *Tabebuia rosea* (TR) and *Simarouba glauca* (SG) stemflow (Sf).

	a	b	e
TR		0.022	-0.0118
SG		0.013	

The model applied to the whole set of rainfall events over the two-year period of observation allowed estimating changes over time of interception in both systems. Pearson correlation coefficients between interception measured and modelled was 0.76 and 0.90 in FS and AFS, respectively. Simulations showed that globally contrasting precipitation pattern observed between both years of study did not have an effect on rainfall interception ($p=0.22$). Differences between years were found when comparing interception in the wet seasons ($p=0.01$) rather than in the dry periods ($p=0.15$). Irrespective of the system, rainfall interception expressed as a percentage of rainfall represented 28% and 33% of rainfall in 2012 and 2013 wet seasons while in the dry represented 10% and 11% of gross rainfall in 2012 and 2013, respectively. Comparison between systems showed greater interception in AFS ($p<0.0001$) with 18% and 24% of gross rainfall in FS and AFS, respectively, over the period of the experiment. Rainfall interception as a percentage of rainfall in both systems by year and season is presented in Table 4.8.

Table 4.8. Interception as a percentage of gross rainfall over the dry and wet seasons in 2012 and 2013 in shaded (AFS) and unshaded (FS) systems.

Year	System	Season	Interception (%)	SE
2012	AFS	Dry	11	± 2.0
		Wet	33	± 2.0
	FS	Dry	10	± 2.0
		Wet	24	± 2.0
2013	AFS	Dry	12	± 2.0
		Wet	38	± 2.0
	FS	Dry	11	± 2.0
		Wet	27	± 2.0

4.4. DISCUSSION

4.4.1. Stemflow

This study demonstrated that the average coffee stemflow was quite low. Mean coffee stemflow was between 1.6% and 1.3% of gross rainfall or tree throughfall. Mean coffee stemflow was similar to previous studies in coffee shaded with *Eucalyptus deglupta* in Costa Rica in which stemflow was found to be 2% and 3% of rainfall in unshaded coffee and in coffee shaded with *Eucalyptus deglupta,* respectively (Harmand *et al.* 2007). On the other hand, our results did not agree with another study on coffee shaded with *Inga densiflora* growing in higher rainfall and optimal environmental conditions for coffee cultivation in Costa Rica, which reported values for coffee stemflow of 10.6% and 7.2% of gross rainfall (Siles *et al.* 2010). Variations in precipitation pattern, on stem area and stand density could contribute to explaining contrasting results. However, few studies are available on rainfall partitioning in coffee agroforestry and, in most of them, stemflow measurements are considered negligible thereby precluding comparisons.

Stemflow measured in shade trees was often greater down *Tabebuia rosea* tree trunks when compared to *Simarouba glauca* trees which could be attributed to the inherent species-specific differences in tree architecture, including bark texture and bark water storage capacity. However, flaky-barked species such as *Tabebuia rosea* was expected to display greater water-holding capacity and therefore, lower stemflow generation than smooth-barked *Simarouba glauca* (Crockford and Richardson 1990). This contradiction may be explained by the inherent difficulty of fitting collectors on a rough trunk with a watertight seal, and possible meteorological influences on water loss from collectors under great rainfall intensity. Our results for stemflow of 1.8% and 1.1% of rainfall for *Tabebuia rosea* and *Simarouba glauca* respectively were similar of that reported for *Inga densiflora* of 1.2% of gross rainfall in coffee agroforestry (Siles *et al.* 2010). Results were also similar to stemflow of 1.28% of gross rainfall found for *Inga* spp in coffee agroforestry in Colombia (Castaño and Jaramillo 1999). Our results in tree stemflow are also within the ranges reported for five tropical timber tree species in a Panamanian plantation which varied from 0.9% to 2.7% of rainfall (Park and Cameron 2008). Stemflow was found to be of 1.2% of gross rainfall in maize and *Grevillea robusta* in agroforestry system in semi-arid Kenya (Jackson 2000) while in a perennial polyculture in central Amazonia stemflow varied from 0.1% to 1.4% of rainfall for different tree species being similar of 1.8% of precipitation measured in a primary rainforest nearby the study site (Schroth *et al.* 1999). There is a large consensus that this component is relatively small. Further experiments and improvements on techniques for stemflow measurement are needed in order to get better accuracy of results. However, investing more resources on this component might not be the most efficient strategy to improve our understanding of water flows in agroforestry systems.

4.4.2. Throughfall

In this study, throughfall beneath coffee canopies as a percentage of incident rainfall varied from 69% to 65% in FS and AFS, respectively (p=0.08). This result may be influenced by lower LAI in unshaded coffee plants which could favor raindrops to pass through the coffee canopies in FS. Reduced LAI and canopy extension in coffee plants in FS compared to coffee bushes in AFS could also explain the great variability in coffee throughfall with distance from the coffee stem in the unshaded environment. In contrast greater canopy cover in the shaded coffee led to a lower influence of the distance from coffee trunk (especially near the trunk at 0.20 m and 0.60 m) on throughfall rates. Comparison with Harmand *et al.* (2007) findings showed greater throughfall of 82% in coffee under *Eucalyptus deglupta* as shade tree in their study while in this experiment coffee throughfall under the wider canopy cover of *Simarouba glauca* and *Tabebuia rosea* coffee, throughfall was 65% of incident rainfall. Despite the differences in coffee density and management, this may indicate the potential effects of different shade tree species on rainfall beneath tree canopies with some influence on drop characteristics that reach the crops (Calder *et al.* 1996; Jaramillo and Chaves 1998).

However, coffee throughfall in AFS was calculated in relation to throughfall across tree canopies. This throughfall, as contrasted with incident rainfall, is highly heterogeneous. In our calculation, we assumed that coffee bushes were representative of the whole plot, and received, as a mean, the average throughfall. If this assumption is not correct, and the coffee bushes used for measuring coffee throughfall were located closer to tree trunks than the average situation, then those particular bushes could receive less throughfall than the average, and throughfall percentage might be underestimated.

In this study tree throughfall showed greater values beneath *Simarouba glauca* shade tree which had lower LAI and smaller leaves compared to *Tabebuia rosea*. This result is in agreement to the tendency of lower canopy cover and small leaves to produce bigger throughfall as previously reported by Geisler *et al.* (2013) and by Goebes *et al.* (2015). Moreover, the waxed leaf surface characteristic of *Simarouba glauca* seemed to facilitate water passing through the canopy compared to the rough leaf surface of *Tabebuia rosea* which indicated that leaf traits may have some influence on throughfall and interception rates.

4.4.3. Interception loss

We demonstrated that in the agroforestry system, tree and coffee canopies combined led to a greater reduction of water availability for plant growth compared to FS likely due to 37% greater total LAI in the shade. However, most interception in AFS was found to be by shade tree canopy rather than by the coffee canopy despite greater coffee LAI which may suggest some influence of plant architecture and canopy cover extent on interception rates. Moreover, leaf traits such as broader leaves and roughness influenced greater water retention on the leaf surface of *Tabebuia rosea* when compared to smaller leaves of coffee and *Simarouba glauca*. A study by Germer *et al.* (2006) showed that interception can vary broadly due to different leaf traits for canopies with the same LAI.

Water loss by interception that is indirectly estimated from throughfall and stemflow measurements is highly dependent from how accurately both terms are measured. In this study bias on interception estimation, especially on *Tabebuia rosea* tree canopy and on coffee canopy in AFS, may be attributed to underestimation of both the stemflow and throughfall measurements. Bias was found especially during high rainfall events when rainfall water could have been splashed from the collectors which were not detected during the measurements. It is expected the most potential influence would be derived from throughfall measurements as this is the largest component in rainfall partitioning. Although the Thissen polygon technique applied in this study contributed to capturing the spatial variability of throughfall on a micro scale, adjustments towards a more regular pattern in the spatial arrangement of collectors rather than the orthogonal collector distribution could be recommended in future in order to minimize this potential source of error.

In this study simulations showed 24% of incident rainfall intercepted in AFS which was greater than interception of 3.5% of rainfall in coffee with *Erythrina poeppigiana* (periodically very severely pruned, virtually to stumps) and of 13.5% in coffee with *Cordia alliodora* (Imbach *et al.* 1989). Nevertheless, these figures come from a climate that is altogether very different from that of our study site, with many more rainfall events and a wetter climate. These differences could account, at least partly, for the differences in the percentage of intercepted rainfall. Our result was also greater than interception of 8.9% and 15.7% of gross rainfall found in coffee agroforestry with low (230 tree ha^{-1}) and high shade (390 tree ha^{-1}) levels reported by Gurav *et al.* (2012). The lower tree density (188 tree ha^{-1}) and greater interception in this study can be attributed to different shade tree characteristics, coffee agroforestry management and environmental condition.

This study showed daily interception of 0.61 mm (SE=0.05) in FS and 1.06 mm (SE=0.05) in AFS which was similar to daily interception of 0.63 mm and 0.66 mm in FS and 1.16 mm and 0.95 mm in AFS found by Cannavo *et al.* (2011). We demonstrated that in both systems most water loss by interception occurred in the wet seasons rather than the dry, when more rainfall water was available. Cannavo *et al.* (2011) showed similar values for interception as a percentage of gross rainfall in the dry season of 11.9% and 17.4% of rainfall while our study showed 10% and 11% of rainfall in FS and AFS, respectively. However, in the wet season our results were quite greater with 26% and 35% of total rainfall compared to 7.89% and 11.37% of rainfall in FS and AFS, respectively. Variations AFS may be related to uncertainties in throughfall measured in both the coffee and shade trees with effects on interception rate estimation.

We demonstrated that contrasting precipitation pattern over the both years of study did not have an effect on interception in the whole. Differences were observed in the wet seasons (p=0.01) and not in the dry periods (p=0.15). In 2013 wet season interception was greater than in 2012 wet season in both systems following the greater rainfall amount in the second year. Interception represented 24% and 27% of gross rainfall and 33% and 38% of rainfall in FS and AFS in 2012 and 2013, respectively. In the dry seasons simulations showed similar interception between years and systems which represented 10% and 11% of rainfall and 11% and 12% of rainfall in FS and AFS in 2012 and 2013, respectively.

4.5. CONCLUSIONS

This study demonstrated the substantial effect of *Tabebuia rosea* and *Simarouba glauca* shade trees on the reduction of amount of rainfall reaching the soil surface in a coffee agroforestry system. Interception of rainfall by the canopy was significant in the agroforestry system and could result in greater soil moisture deficits in a sub-optimal climatic environment such as experienced at this site. However, the proportion of rainfall intercepted was notably less during the dry season which is when soil moisture deficits had their most serious effects, compared to the wet season. The results reinforced the effect of shade tree species characteristics, canopy cover and rainfall variations on rainfall intercepted over the period of study.

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CHAPTER V

WATER LOSS BY PLANT TRANSPIRATION AND SOIL EVAPORATION IN COFFEE SHADED BY *TABEBUIA ROSEA* BERTOL. AND *SIMAROUBA GLAUCA* DC. COMPARED TO UNSHADED COFFEE IN SUB-OPTIMAL ENVIRONMENTAL CONDITIONS

5.1. INTRODUCTION

Coffee production is being threatened by increasing climate variability. Coffee shade has been suggested as a promising strategy to cope with the decline of available water and the increase of temperature in the context of global climate changes. Shade trees may buffer the effects of high temperature (Barradas and Fanjul 1986; Muschler 1997; Siles *et al.* 2009) and may increase water availability for plants use by reduction of soil erosion and runoff (Beer 1995; Gomez-Delgado *et al.* 2010). However, shade trees transpire and may thus increase the whole system water use depending on the shade tree species, management, soil and environmental conditions. Potential competition for water between coffee and shade tree is therefore, one of the main disadvantages of coffee agroforestry (Beer 1987).

The assessment of competition or complementarity in water use in agroforestry may be facilitated by evapotranspiration partitioning. Evapotranspiration comprises the processes by which water changes phase from a liquid to a gas: evaporation from the soil, transpiration through the stomata of plants and evaporation of water intercepted by plant canopies (Wilcox *et al.* 2003; Kool *et al.* 2014). These processes can be highly variable in space and time (Williams *et al.* 2004). Transpiration is considered as a productive flux because it is related to plant growth while soil evaporation and interception are regarded as being unproductive once it is lost to the atmosphere and is not used for plant biomass production (Liu *et al.* 2002).

The soil evaporation component may have a very important role in water conservation in agroforestry. Evaporation from the soil is principally from top soil where most fine roots are found. Shade trees may reduce radiation and temperature of the soil surface with decrease of water loss by soil evaporation (Ritchie 1971). The effects of increasing shade tree density on the gradual diminishing of soil evaporation was reported in coffee agroforestry by Lin (2007). Reduction of the soil evaporation component in agroforestry systems may increase water retained in the soil and thus the overall proportion of rainfall used by crop and trees through transpiration (Wallace *et al.* 1999).

Transpiration, as the dominant component of evapotranspiration (Lawrence *et al.* 2006; Xu *et al.* 2008) has been assessed and compared in coffee agroforestry and full sun coffee. Van Kanten and Vaast (2006) demonstrated that coffee transpiration was often greater in the full sun while the whole system water use was greater in the shade. Cannavo *et al.* (2011) showed that the higher water use by coffee and shade trees through transpiration plus water loss by interception resulted in lower drainage when compared to full sun coffee. However, despite water dynamics and use being significantly affected by shade trees little is known about whole system water use in coffee agroforestry since most studies are addressed to one or another evapotranspiration component. Studies that integrate soil surface evaporation and plant transpiration in coffee agroforestry with appropriate techniques for both components are few.

Here we studied the contribution of coffee and shade tree transpiration and soil evaporation to the total evapotranspiration in a coffee agroforestry system by measuring each component directly. We also compared the water consumption by deciduous *Tabebuia rosea* and evergreen *Simarouba glauca* grown as coffee shade trees. The results contribute to a better understanding of water allocation within the agroforestry system and coffee responses to moisture variability. This is important in order to identify shade trees ideotypes and possible management interventions which are more suitable for coffee agroforestry in the context of scarce water resources.

5.2. MATERIALS AND METHODS

5.2.1. Site description and experimental design

The study was carried out during 2012 and 2013 in an experiment located at Jardín Botánico, Masatepe, Department of Masaya, southern Nicaragua (11° 53′ 54″ N, 86° 08′ 56″ W) at a long term research site managed by the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), jointly with the Universidad Nacional Agraria

(UNA), Federación Cooperativas de Ahorro y Crédito (CENECOOP-FEDECARUNA) and Instituto Nicaraguense de Tecnologia Agropecuaria (INTA). The experiment was established in 2000, as described by Haggar *et al.* (2011).

The site is located at 455 m.a.s.l. which is considered to be rather a low altitude for arabica coffee (*Coffea arabica* L.) at this latitude. Mean annual temperature is 27^0C – above *C. arabica* comfort zone - and mean annual rainfall is 1470 mm. From 85% to 97% of the total annual precipitation falls over the wet season that lasts from May to November while a pronounced seasonal drought occurs from late November to mid-May (Vogel and Acuña Espinales 1995). Annual rainfall recorded during the experimental period was 968 mm and 1312 mm in 2012 and 2013 respectively.

Soils in the area are predominantly characterized as Andisols, which are derived from volcanic ejecta. These soils are typically deep, well drained and have high organic matter content, low bulk density, high allophane content and consequently a high phosphorus fixation capacity, high amorphous mineral content and high water retention capacity (FAO, 2001). On this particular study site, however, soils are characterized by the presence of a hardened layer locally known as talpetate. Such layers occur in about 15% of the Nicaragua Pacific region. Its properties reflect both geologic and soil-forming processes and can be extremely variable (Vogel and Acuña Espinales 1995).

Soil bulk density of the whole soil profile varied from 0.62 g cm^{-3} (S.E.=0.026) to 0.65 g cm^{-3} (S.E.=0.039) on average in the shade and full sun plots, respectively, while in the talpetate layer it reached 0.72 g cm^{-3} in both systems. The mean organic matter content of the soil profile was 3.8% (S.E.=2.0) and 3.4% (S.E.=1.05)in the shade and full sun plots respectively. In the uppermost, brown layer organic matter content was found to be 8.7% (S.E.=0.10) in the shade system and 8.2% (S.E.=0.25) in the full sun, and this decreased with depth. The pH (in H_2O) did not differ in both systems and ranged between 5.70 and 5.80, which is considered acceptable for coffee cultivation. Management includes fertilization with 37.3 kg ha^{-1} of N, 48.8 kg ha^{-1} of P and 27.6 kg ha^{-1} of K as NPK compound fertilizer per year. In addition 34.4 kg ha^{-1} of N as urea and 12 kg ha^{-1} of K as KCl are applied each year.

As a consequence of the original layout of the experiment within which the experimental plots used in this study are located, the design consists of a full sun monocrop coffee (FS) plot (1440 m^2) and an adjacent coffee agroforestry system (AFS) plot (3200 m^2). Sub-plots for sampling were established within these main plots, as pseudo-replicates. In the coffee agroforestry system plot *Coffea arabica* is associated with a mix of *Simarouba glauca* DC. (Simaroubaceae) and *Tabebuia rosea* (Bertol.) (Bignoniaceae) planted as shade trees. Tree spacing was originally 4 m x 4 m, alternating both species (Haggar *et al.* 2011), but tree density has been reduced over the time by thinning to achieve a shade level appropriate for coffee production. The mean density of *Tabebuia rosea* was 113 trees ha^{-1} and that of *Simarouba glauca* was 75 trees ha^{-1} over the period of the study. Coffee density throughout of the experiment was 4000 plants ha^{-1}, spacing being 2 m between rows and 1.25 m between plants in both the agroforestry and full sun coffee. Coffee plants were pruned periodically in accordance with standard agronomic practice.

5.2.2. Species studied

The species *Coffea arabica* L., *Tabebuia rosea* Bertol. and *Simarouba glauca* DC. studied in this Chapter had been already described in the previous Chapters. The main characteristics of both timber tree species are presented in the Table 5.1.

Table 5.1. Main characteristics of the two shade tree species in the study site: *Tabebuia rosea* and *Simarouba glauca*, over the period of the experiment.

	Tabebuia rosea Bertol.	*Simarouba glauca* DC.
Distribution	Central America, Mexico, Venezuela and coastal Ecuador	Tropical and sub-tropical regions of Central America, Mexico and the Caribbean
Density (tree ha^{-1})	113	75
Phenology	deciduous	evergreen
Leaf morfology	compound leaves, digitate and long petiolate. Each leaf has five leaflets of variable size	compound leaves 20 cm in length comprising 12–16 oblong pinnae, each approximately 5 cm in length
Leaf texture	rough	waxy
Leaf area (m^2)	55 ± 10.6	62 ± 21.3
LAI	0.62 ± 0.12	0.46 ± 0.2
Bark depth (cm)	1.5 ± 0.27	0.92 ± 0.04
Bark texture	fissured	smooth
DBH (cm)	28.7 ± 0.41	25.5 ± 0.23
Heigh (m)	15.5 ± 0.20	17 ± 2.43
Crown diameter (m)	7.4 ± 0.65	7.2 ± 0.3
Crown area (m^2)	44.4 ± 7.8	41.2 ± 3.24
Root distribution	randomly distributed in the soil profile	more concentrated in deep soil layers

5.2.3. Climate

Two automatic weather stations were installed in the full sun and shade plots. Sensors installed at 2.50 m height were connected to dataloggers (CR1000, Campbell Scientific Inc.). Data were collected every 30 minutes from February 2012 to December 2013. Both weather stations measured relative humidity and temperature (HMP50, Campbell Scientific Inc.) and the full sun plot weather station additionally measured solar radiation (CS300, Campbell Scientific Inc.), wind speed (03101, Campbell Scientific Inc.) and rainfall (TE525MM/TE525M, Campbell Scientific Inc.). Reference evapotranspiration was calculated based on the FAO Penman-Monteith equation (Allen *et al.* 1998) using data from the automatic weather station installed in the full sun plot. Rainfall measurements from the automatic station were calibrated by monitoring five manual rain gauges in the study area.

5.2.4. Soil water content

Changes in the soil water content were continuously measured during 2012 and 2013 by using time domain reflectometer (TDR) probes (Campbell Scientific Inc. CS616) that were connected to dataloggers (CR 1000 with AM 16/32B multiplexer, Campbell Scientific Inc.). These were installed horizontally, being inserted from 15 cm to 190 cm into the walls of 200 cm deep pits, which were then back-filled. Distance between TDR probes depended on the characteristic soil layer depths which were quite variable in the study area. A total of nine pits (three in the full sun plot and six in the AFS plot) were equipped with these TDR probes, located one in each soil layer down to 200 cm depth (four to six TDR per pit). Data were scanned every minute and stored every 30 minutes. Minimal disturbance soil samples of sufficient dimensions to insert a TDR probe were also extracted from each soil layer (two samples per layer). In the laboratory, the progressive drying was measured simultaneously by TDR and by weighing, so that a calibration equation was available for each soil layer, following a protocol adapted from Udawatta *et al.* (2011). The volumetric soil water contents of the layers in which each TDR probe was inserted were then multiplied by the thickness of each layer to calculate the soil water content at each time step.

5.2.5. Coffee and tree leaf area index

Leaf area of coffee plants were measured in the dry (February and April) and wet seasons (July and November) over 2012 and 2013. To calculate the leaf area of the coffee plants we measured an average of 30 typical coffee shoots in the full sun plot and 35 in AFS. Shoots were purposively selected by stratifying the whole shoot population using their height and diameter in both stands. In order to estimate total leaf area of each sampled shoot, we counted the total number of leaves, and measured length and width of every 20th leaf. The area of measured leaves was calculated by using an equation established by direct measurement of leaf area in the laboratory:

Leaf area = 0.7243 * length * width

Leaf area of each shoot was then calculated by multiplying the number of leaves by the mean leaf area. LAI of the coffee plots were estimated by multiplying the mean leaf area of the shoots by coffee population density and by the mean number of shoots per coffee plant. We measured coffee leaf area four times per year in 2012 and 2013 in the wet (July and November) and the dry (February and April) seasons.

Tree leaf area was calculated by using the hemispherical photograph technique on four trees of each species four times per year (February, April, July and November) in 2012 and 2013. Hemispherical photographs were taken by using a Nikon Coolpix 4500 digital camera with a fisheye lens which permitted the taking of vertically upward photographs of the tree canopy. Images were analyzed by the Gap Light Analyzer software (Frazer *et al.* 1999) and adjusted to the crown size (681 pixels for *Tabebuia rosea* and 1000 for *Simarouba glauca*). In order to correct for the effect of branch traces in the images, hemispherical photographs of leafless *Tabebuia rosea* canopy in the dry season were used. The effect of the distance between lens and tree crown was corrected by multiplying the number of the pixels of the image by the square of the distance between lens and crown.

To calibrate this indirect method, we selected four individuals of each species and applied the procedure previously described to take hemispherical photographs and calculate the resulting black pixels. We then felled those trees and harvested all their leaves. Three samples of 100 leaves were randomly taken from the bulk leaves of each tree, and their area was measured by using a scanner (planimeter LI 3000) close to the field. This planimeter was calibrated by measuring the area of a subsample of leaves using a calibrated planimeter LI 3100 (*Simarouba glauca* R^2=0.9785; *Tabebuia rosea* R^2=0.9031). The leaf area and dry weight of each sample allowed the calculation of the average of specific leaf area of sample by the equation:

$SLA = LA_s / DW_s$

Where: SLA=specific leaf area; LA_s=leaf area of sample; DW_s=total dry weight of sample.

The fresh weight of all leaves in the tree the remaining leaves of each tree was measured, its moisture content was measured on a sub sample (around 20%) and total leaf area of each felled tree was then derived from total dry weight and SLA. Leaf area of each tree (LA_t) was calculated by the equation:

$LA_t = DW_t * SLA$

Where: LA_t = tree leaf area; DW_t = tree leaf dry weight; SLA = specific leaf area

To ensure the exploration of a wide range of total leaf area for each species, we felled the trees at different times. We adjusted the linear regression between direct and indirect leaf areas for *Tabebuia rosea* ($R^2 = 0.899$) and *Simarouba glauca* ($R^2 = 0.724$), and used the regression equation to calculate leaf areas of the trees of our experiment (which we did not fell) during the whole two year period of our experiment. Tree leaf area for each species was then calculated based on the mean of each tree measurement date and tree density.

5.2.6. Coffee and tree transpiration

Coffee sap flow was measured in the dry (February and April) and wet seasons (July and November) in 2012 and 2013 by using the stem heat balance method (Dynagage/Dynamax, Inc.) in four coffee shoots at a time in each plot (but moving them from bush to bush to avoid heat damage). This method was successfully tested previously in the laboratory against direct measurement of water loss in potted coffee plants by Rapidel and Roupsard (2009). Coffee shoots were selected from the average of the stem diameters in both stands which was 2.94 cm and 3.07 cm in the full and shade coffee respectively. SGB 19, 25 and 35 gauges were connected to a CR 10 X datalogger (Campbell Scientific Inc.) and coffee shoots were monitored over an average period of six consecutive days, four times per year in 2012 and 2013. Coffee stems were protected against external heat and water ingress by thermal shields. The heat source was turned off at night in order to protect the stems from overheating. Data were collected every 15 minutes. Leaf specific transpiration for each shoot was calculated by dividing the water flow ($L.d^{-1}$) per shoot leaf area that was measured simultaneously. Coffee transpiration was up scaled to the plot level (mm.d^{-1}) by using LAI.

Tree sap flow rates were continuously measured over 2012 and 2013 by using the thermal dissipation technique (Granier 1985; Granier 1987) in four trees of each species. Trees were selected taking into account the average of diameters in the plot, which were 25.8 cm and 23.5 cm for *Tabebuia rosea* and *Simarouba glauca* respectively. The set of probes (one continuously heated by a constant electrical source and another as a non-heated reference probe) were inserted horizontally into tree stems (22 mm deep at 2.5 m height above the ground) with a vertical separation between probes of 15 cm. The heated probe was connected to a 137 mA potentiometer (continuous current). Trunks were insulated 1 m above and below the probes. The natural thermal gradient between the probes were measured when sensors were run with the heaters off for 10 days in March 2012. The temperature gradient between the probes was recorded on a datalogger CR 800 (Campbell Scientific Inc.) every 30 minutes from February 2012 to December 2013. The sap flow was calculated by multiplying the flow density by the conducting section area (Smith and Allen 1996). Regression analysis by using measurements of conductive cross sectional sap wood area and the DBH from the same four trees of each species in the plot allowed the calculation of coefficients to estimate the conducting section for *Tabebuia rosea* (R^2=0.69) and *Simarouba glauca* (R^2=0.89) from the total trunk section. As the probe length was close to the sapwood thickness it was assumed that flow rate was constant over the whole sap wood cross section (Vertessy *et al.* 1995).

Calibration of thermal dissipation probes was undertaken by measuring the sap flow of the same trunk using the stem heat balance method (Dynagage/Dynamax, Inc.) over eight days in different periods in 2012 and 2013. Gauges (SGA 150) were connected to a datalogger CR 800 (Campbell Scientific Inc.) and data were recorded every 15 minutes. For each species the coefficient α for the Granier equation was adjusted by optimization to reduce the sum of squares of the differences between the thermal dissipation and the stem heat balance measurements from different periods. Mean tree transpiration of each species was multiplied per *Tabebuia rosea* and *Simarouba glauca* density to obtain transpiration in the AFS plot.

5.2.7. Leaf water potential

Coffee Leaf Water Potential (LWP) at predawn - PLWP and at midday – MLWP was measured and compared in FS and AFS by using a portable pressure chamber (Scholander *et al.* 1965). The measurements were taken over a three consecutive day period, four times per year, being two during the dry season (February and April) and two in the wet season (July and November) in 2012 and 2013. Four mature and fully expanded leaves were selected at random in the upper third of the bushes of three coffee plants in each plot. The measurements were performed in the field immediately after cutting the leaves, before sunrise for PLWP and between 12:00 and 12:30 for MLWP.

5.2.8. Soil evaporation

Measurements were carried out by using seven and eight weighing lysimeters in the FS and AFS respectively, over the 2012 (April to June) and 2013 (June to November) rainy seasons and continuing into the 2014 dry season (February to April). Lysimeters were made from PVC tubes (15.7 cm internal diameter and either 20 or 30 cm length) adapted from Jackson and Wallace (1999). These were filled by soil with minimal disturbance and replaced into the holes (Daamen *et al.* 1995). A mesh was attached at the bottom of the tubes in order to allow excess water to drain. We used a barrier made by zinc foil (28 mm) all around the threshold of the lysimeter and the internal soil wall to avoid soil falling inside the hole when the lysimeters were removed for the weighing process. Lysimeters were located in the row between coffee plants at a distance of 0.62 m from the trunks and in the inter row 1.0 m from the coffee trunks in both plots. Lysimeters were weighed every morning before 07.00h using a portable electronic balance (0.1 g resolution). Periods for analysis were selected taking into account an interval of at least 24h after a rainfall event even if relatively small in order to avoid potential errors in measurements and the on-going drainage process that could be mistaken for evaporation. The effect of the lysimeters tube length was also analyzed.

The Ritchie model (Ritchie 1972) was used to extrapolate these measurements of soil evaporation rate over the whole period of study in FS and AFS. The model considers soil evaporation to occur in two phases: 1) a constant rate stage which depends on the radiative energy that reaches the soil surface; 2) a falling rate stage in which soil evaporation depends on upward water movement in the soil profile dependent on soil hydraulic properties. The first phase calculation was determined by potential evaporation estimated by the Penman equation (Penman 1963) with inputs from a FS weather station and assumed to be the same over the adjacent AFS plot. Soil evaporation calculation was based on the equation:

$Es1 = Rns * \Delta /(\gamma + \Delta) * 0.408$

Where:

Rns=net radiation at the soil surface ($MJ.m^{-2}$);

Δ=slope of the saturation vapor pressure curve at mean air temperature ($kPa\ K^{-1}$);

γ = constant of the wet and dry bulb psychrometer equation ($kPa\ K^{-1}$).

Net radiation and LAI were used as inputs for net radiation at the soil surface calculation in FS and AFS at the first stage, following Ritchie (1972). The coefficients of the Ritchie model were then calibrated to minimize the sum of squares of errors between measured and calculated evaporation rates.

5.2.9. Data analysis

Variance analysis was performed to compare the influence of the systems, seasons and tree species on soil water content in the treatments by using a general linear mixed-effects model (R, lme4 package). The same model was utilized to assess and compare coffee and tree transpiration as a function of years, systems and seasons as well as the effect of the interactions of variables. The model was also applied to compare statistical differences in LWP. Soil evaporation was also analyzed as a function of LAI, lysimeters location, systems and seasons. Lysimeter size effects on soil evaporation measurements were also tested. Analysis were carried out by using InfoStat software (Di Rienzo *et al.* 2014).

5.3. RESULTS

5.3.1. Climate

Total annual rainfall was 968 mm in 2012 being about 34% lower than the long-term mean annual rainfall of 1470 mm in that region. The 2012 dry season lasted from the beginning of January until middle May with a maximum daily rainfall event of 16.8 mm and a total rainfall of 57.2 mm. The subsequent 2012 wet season provided lower than normal precipitation and was followed by the 2013 dry season which lasted almost six months, with only 23.5 mm rainfall overall. Total rainfall in 2013 was 1312 mm, 11% lower than the long term mean.

The reference evapotranspiration (ET_0) fluctuated with variations in meteorological factors which changed with the season pattern. Daily reference evapotranspiration, calculated with inputs from the automatic weather station installed in the FS plot, was similar between years ($p=0.06$) but differed between seasons ($p<0.0001$) with means 3.8 $mm.d^{-1}$ (S.E.=0.05) and 3.3 $mm.d^{-1}$ (S.E.=0.04) in the dry and wet seasons, respectively. Maximum reference evapotranspiration of 5.39 $mm.d^{-1}$ was achieved in 2012 dry season (Fig 5.1). Vapor pressure deficit (VPD) was found to be similar between FS and AFS ($p=0.47$). VPD did not vary between years ($p=0.08$) but differed with seasons ($p<0.0001$) (data not shown). VPD was 0.40 kPa (S.E.=0.01) and 0.78 kPa (S.E.=0.01) averaged in the wet and dry seasons, respectively. Minimum VPD was found in AFS in 2012 wet season with 0.01 kPa whilst maximum values reached 1.38 kPa in FS and 1.35 kPa in AFS in 2012 dry season.

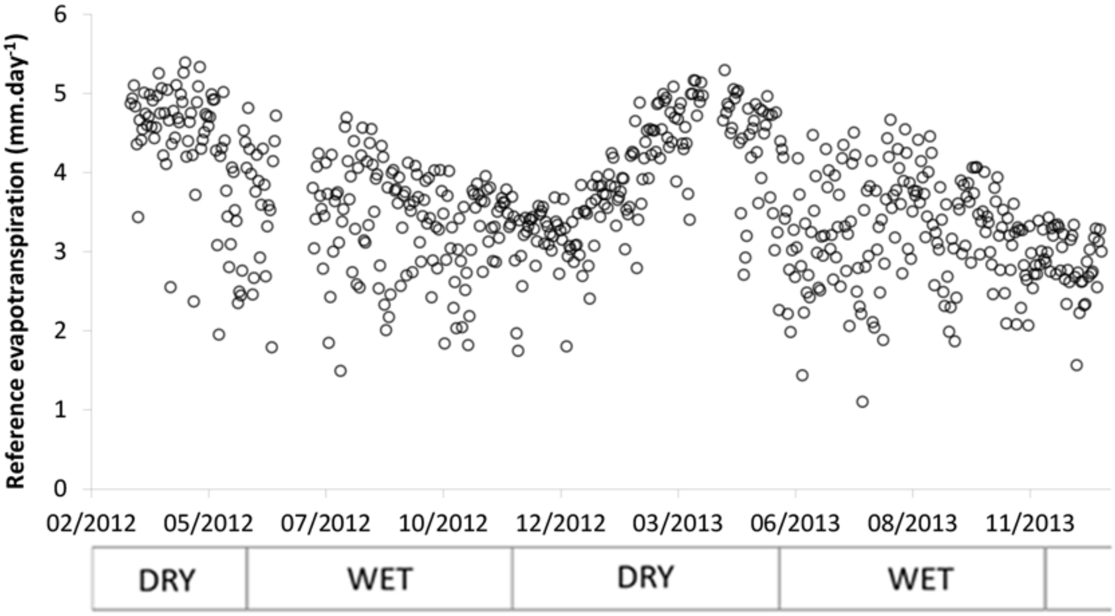


Fig 5.1. Daily reference evapotranspiration in the dry and wet seasons over the period of the experiment.

5.3.2. Soil water content (SWC)

Mean SWC from three and six trenches in FS and AFS, respectively, averaged over the 2000 mm soil profile over the whole year, was greater in 2012 (731mm; S.E.=3.8) compared to 2013 (690mm; S.E.=3.9) (Fig 5.2). Comparing treatment effects, soil water content in the whole profile was almost always lower in AFS when compared to full sun coffee ($p<0.05$) except for a short period at the end of 2013 wet season when mean soil water content reached its maximum (1000 mm). The minimum value of SWC was recorded at the end of 2013 dry season when it reached 452 mm in AFS which represented 12% lower soil water than in FS during the same period (Fig 5.2).

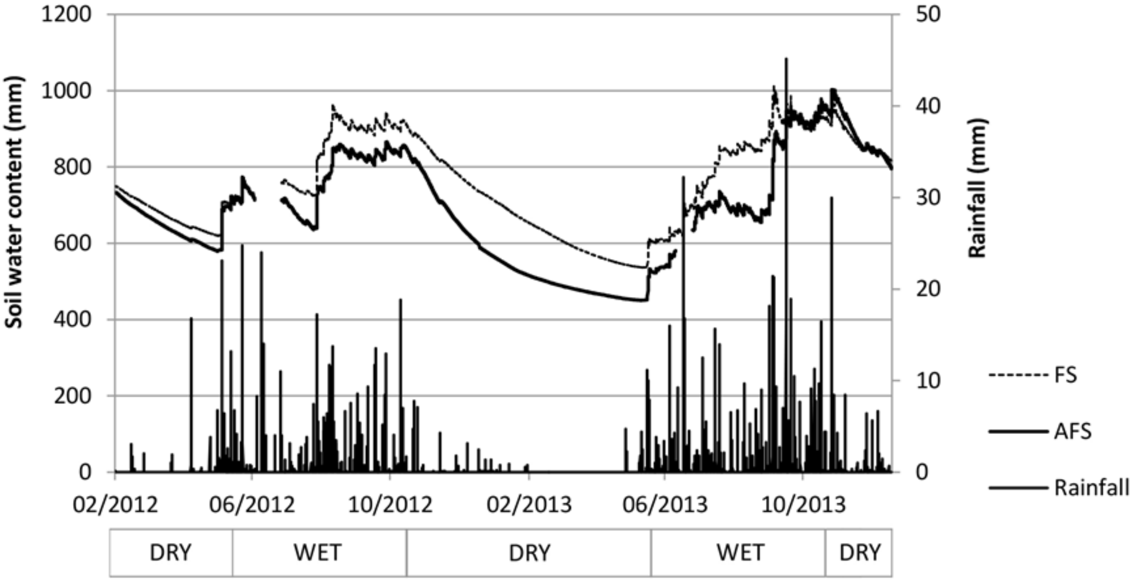


Fig 5.2. Mean soil water content (from three profiles in FS and six profiles in AFS) in the whole soil profile (0-2.0 m) and rainfall over the period of the experiment.

5.3.3. Coffee and tree leaf area index

LAI of coffee plants was always greater in AFS compared to FS ($p<0.001$), being 2.39 (S.E.=0.10) and 3.57 (S.E.=0.10) in FS and AFS respectively. Coffee LAI seasonal patterns showed a strong decrease during the whole length of the dry periods and afterwards increasing in the wet seasons in both systems, although this increase was much delayed after the harsh dry period of 2013. Mean coffee LAI ranged from 2.88

(S.E.=0.05) to 5.01 (S.E.=0.07) in the dry and wet seasons respectively in shaded coffee while in FS it varied from 1.68 (S.E.=0.02) in the dry to 3.73 (S.E.=0.12) in the wet seasons (Fig 5.3). LAI was little influenced by plant defoliation due to the coffee rust epidemics caused by *Hemileia vastatrix* in Central America over the period of the experiment. Mean annual incidence of coffee rust measured by CATIE in the study area over the experiment was 1% and 8% in FS and AFS respectively in 2012 while in 2013 was 2% in both systems (data not published), thus the effect was considered negligible.

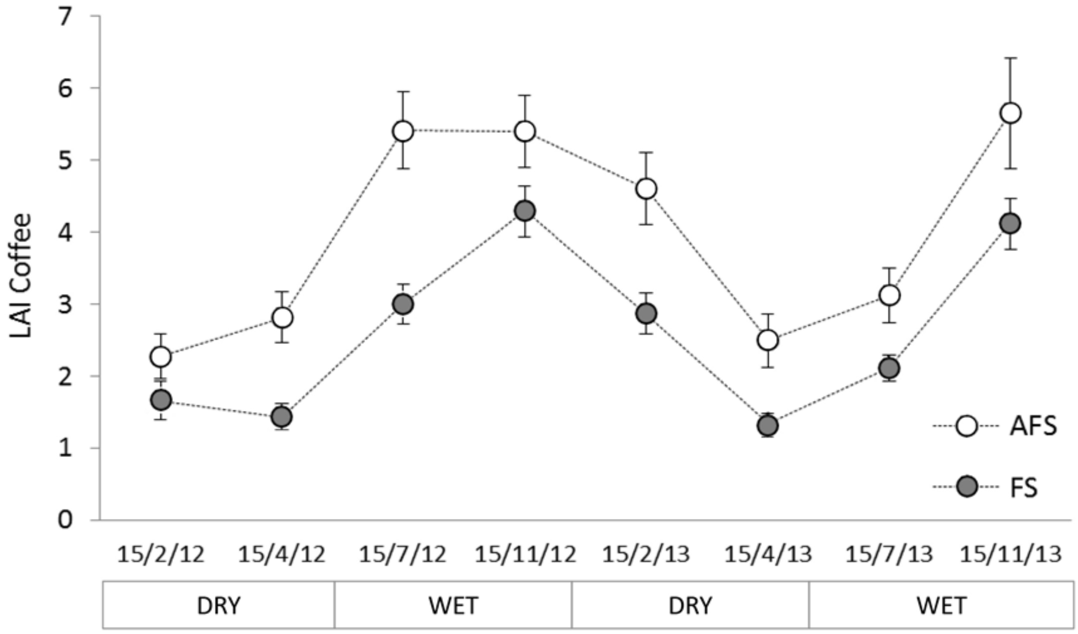


Fig 5.3. Coffee leaf area index in the dry (February – April) and wet seasons (July – November) in AFS and FS over 2012 and 2013. Vertical bars represent the standard error of the mean.

Tree LAI varied with shade tree species, ranging on average from 0.46 (S.E.=0.003) for *Simarouba glauca* to 0.70 (S.E.=0.02) for *Tabebuia rosea*. Tree LAI of both species also varied with the seasonal dynamics ($p<0.001$). In deciduous *Tabebuia rosea* LAI dropped to zero in April with mean LAI ranging between 0.13 (S.E.=0.10) in the dry to 1.12 (S.E.=0.09) in the wet seasons (Fig 5.4). In evergreen *Simarouba glauca* LAI remained more stable with mean of 0.44 (S.E.=0.004) in the dry while in the wet it was 0.48 (S.E.=0.01).

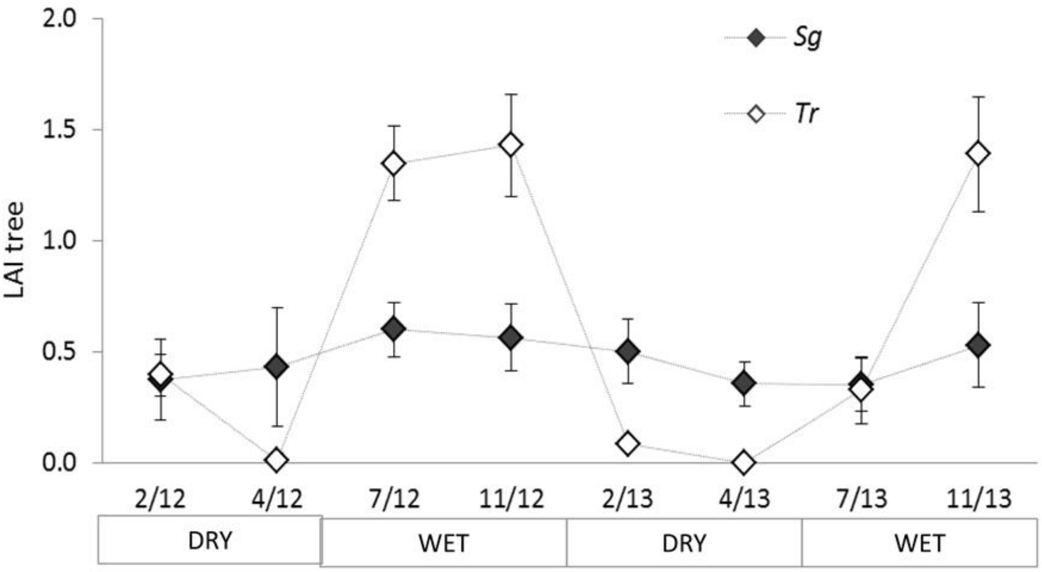
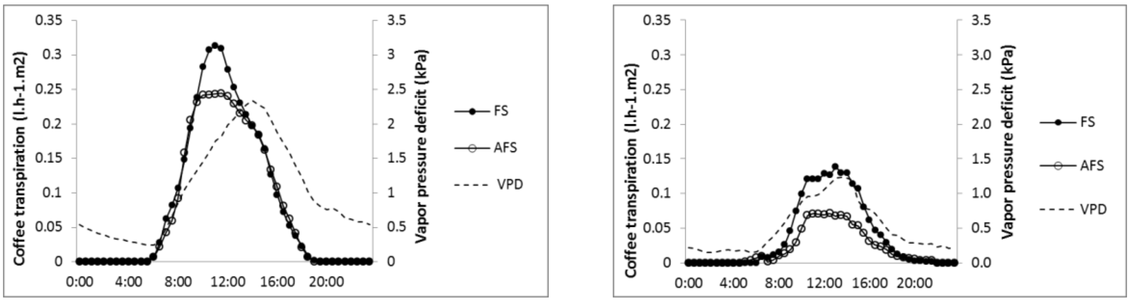


Fig 5.4. *Tabebuia rosea* and *Simarouba glauca* leaf area index in the dry (February – April) and wet seasons (July - November) in 2012 and 2013. Vertical bars represent the standard error of the mean.

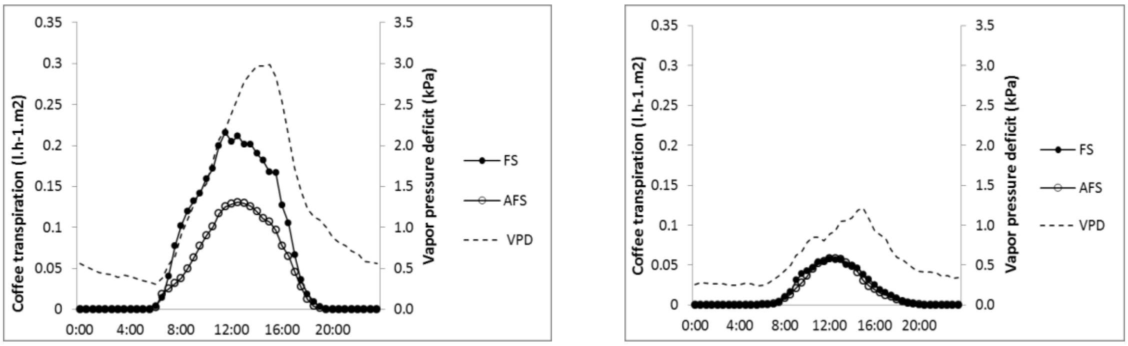
5.3.4. Coffee and tree transpiration

Coffee transpiration on a leaf area basis differed between systems ($p<0.001$) and was often greater in FS (0.78 L.d^{-1}m^{-2} S.E.=0.02) compared to AFS (0.60 L.d^{-1}m^{-2} S.E.=0.02) averaged over the period of study. Seasonal pattern influences on coffee transpiration in FS and AFS were compared by using a generalized linear mixed model. Coffee transpiration was typically greater ($p<0.001$) in the dry periods (February and April) compared to the wet periods (July and November) in both systems likely due to greater evaporative demand in dry conditions. In AFS mean coffee transpiration rate varied from 0.44 L.d^{-1}m^{-2} (S.E.=0.02) to 0.59 L.d^{-1}m^{-2} (S.E.=0.02) and in FS from 0.56 L.d^{-1}m^{-2} (S.E.=0.03) to 0.81 L.d^{-1}m^{-2} (S.E.=0.03) in the wet and dry seasons respectively. Coffee transpiration was influenced by changes in water availability in the two years studied ($p<0.001$). Lower water supply had the effect of reducing coffee transpiration per unit leaf area to 0.53 L.d^{-1}m^{-2} (S.E.= 0.02) in 2013 compared to 0.80 L.d^{-1}m^{-2} (S.E.=0.02) in 2012 .

Over the time course of a day a comparison of coffee transpiration in both systems showed a tendency to an earlier and longer peak in AFS in dry conditions. In 2012 dry season in AFS coffee transpiration reached a peak at 10:00 that was then constant until 12:00 when it started to decline while in FS the peak was reached at 11:00 and declined at 11:30 in 2012 dry season (Fig 5.5 a). In 2013 dry season coffee transpiration in AFS was stabilized around 11:30 until 13:30 while in FS transpiration declined rapidly after the peak (Fig 5.5 c). Mean coffee transpiration reached maximum values of 0.31 $L.h^{-1}.m^{-2}$ in FS and of 0.24 $L.h^{-1}.m^{-2}$ in AFS in 2012 dry season with VPD of 1.7 kPa and 1.3 kPa respectively. In the 2013 hard dry season although the highest values of 2.9 VPD were recorded, the maximum transpiration rate was reduced to 0.21 $L.h^{-1}.m^{-2}$ and 0.13 $L.h^{-1}.m^{-2}$ in FS and AFS respectively (Fig 5.5 c), probably due to the effect of low soil water availability. In the wet season coffee transpiration rate tended to diminish in both systems. In 2012 transpiration followed the trend of evaporative demand (1.23 kPa) (Fig 5.5 b) while in 2013 despite the similar VPD (1.21 kPa) transpiration was reduced probably by the lower soil water availability (Fig 5.5 d). Coffee transpiration maximum values reached 0.13 $L.h^{-1}.m^{-2}$ and 0.07 $L.h^{-1}.m^{-2}$ in FS and AFS in the 2012 wet season while in 2013 it was around 0.05 $L.h^{-1}.m^{-2}$ in both systems.


a) Dry season 2012

b) Wet season 2012


c) Dry season 2013

d) Wet season 2013

Fig 5.5. Typical diurnal trends in coffee transpiration on a leaf area basis from mean of four coffee trees each in FS and AFS over five consecutive days in the 2012 dry (a) and wet season (b) and 2013 dry (c) and wet season (d).

When up scaled to the plot level, coffee transpiration was greater in AFS likely due to the influence of 33% greater coffee LAI in the shaded environment (Fig 5.6). Mean coffee transpiration varied between 1.43 mm (S.E.=0.24) and 2.74 mm (S.E.=0.13) and between 1.32 mm (S.E.=0.25) and 1.34 mm (S.E.=0.14) in the dry and wet seasons in 2012 and 2013, respectively, in the FS plot while in AFS mean coffee transpiration ranged between 1.81 mm (S.E.=0.42) and 2.32 mm (S.E.=0.30) and between 1.65 mm (S.E.=0.15) and 1.80 mm (S.E.=0.24) in the dry and wet seasons in 2012 and 2013, respectively.

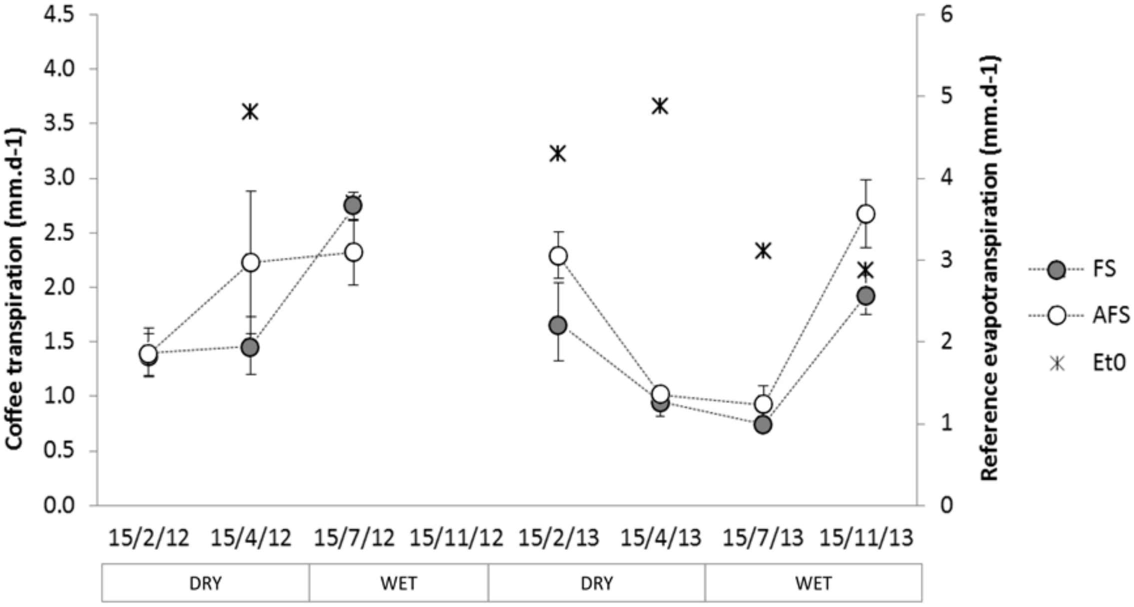


Fig 5.6. Plot level mean daily coffee transpiration (mm d $^{-1}$) in FS and AFS and reference evapotranspiration in the dry (Feb-April) and wet seasons (July-Nov) in 2012 and 2013. Bars represent the standard error of the mean.

Tree transpiration varied with shade tree species, seasonal pattern and environmental conditions. Tree transpiration rate differed between years ($p<0.0001$) with mean transpiration per tree of 45 L.d^{-1} (S.E.=2.33) in 2012 and reduced to 26 L.d^{-1} (S.E.=3.14) in 2013 as a probable effect of lower soil water content. Deciduous *Tabebuia rosea* transpiration was highly influenced by seasonal pattern when compared to evergreen *Simarouba glauca*. *Tabebuia rosea* daily transpiration ranged from 86 L.d^{-1} (S.E.=5.08) in the wet season (July-November) to 31 L.d^{-1} (S.E.=3.59) in the dry season (February-April) while *Simarouba glauca* displayed more constant water consumption that varied little, from 25 L.d^{-1} (S.E.=1.59) to 29 L.d^{-1} (S.E.=1.26) in the wet and dry season respectively. Tree transpiration on a plot basis followed the reference evapotranspiration in the wet but not in the dry seasons likely due to the water availability influence (Fig 5.7).

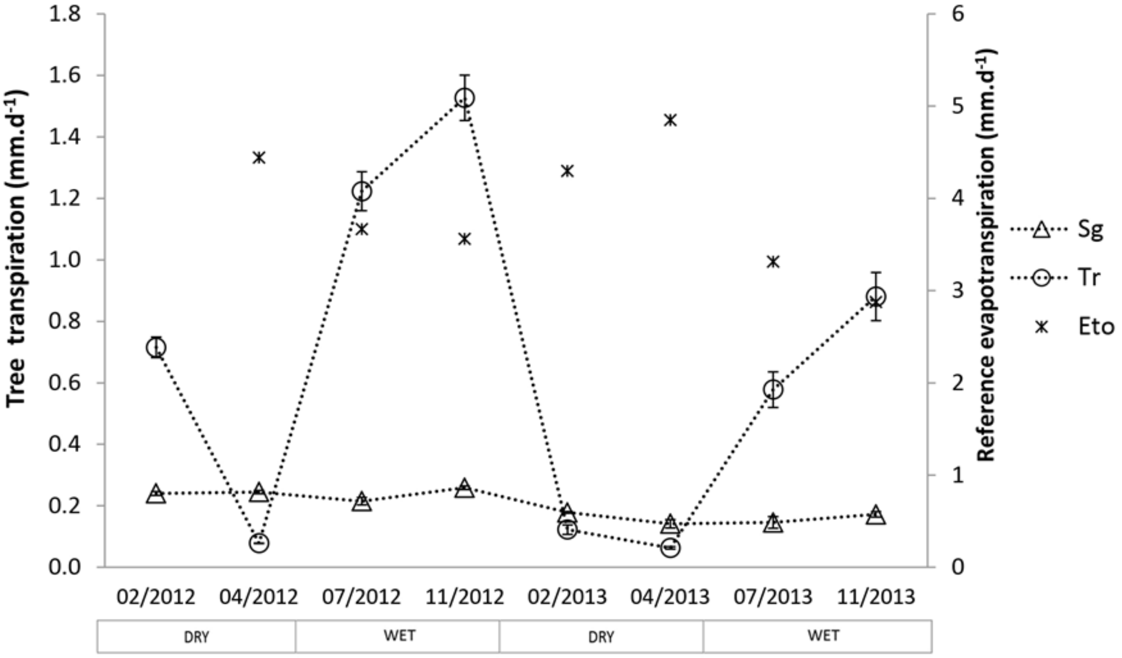
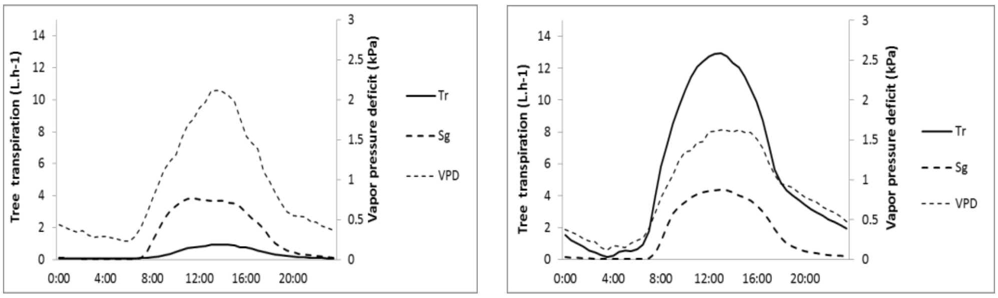


Fig 5.7. Plot level mean tree transpiration and reference evapotranspiration in the dry (Feb-April) and wet seasons (July-Nov) in 2012 and 2013. Bars represent the standard error of the mean

Comparison between daily *Tabebuia rosea* and *Simarouba glauca* water consumption from mean transpiration of five consecutive days measured each 30 minutes showed that in the wet seasons tree transpiration tended to follow the atmospheric demand (Fig 5.8 b and 5.8 d). *Tabebuia rosea* reached its maximum transpiration rate with 12.9 L.h^{-1} and 11.7 L.h^{-1} while *Simarouba glauca* reached maximum 4.3 L.h^{-1} and 3.2 L.h^{-1} in 2012 and 2013 wet seasons when VPD ranged from 1.6 kPa and 0.9 kPa respectively. However, in the dry seasons despite of the greater VPD which reached between 2.1 kPa and 2.8 kPa, transpiration fell to 0.90 L.h^{-1} and 0.60 L.h^{-1} in *Tabebuia rosea* and to 3.84 L.h^{-1} and 1.49 L.h^{-1} in *Simarouba glauca* in 2012 and 2013 respectively (Fig 5.8 a and 5.8 c). As a deciduous tree species *Tabebuia rosea* daily transpiration showed great difference between both years and seasons while evergreen *Simarouba glauca* did not. At the plot level *Tabebuia rosea* mean daily transpiration rate varied between 0.30 mm.d^{-1} (S.E.=0.05) and 1.03 mm.d^{-1} (S.E.=0.05) in the dry and wet season, respectively, while *Simarouba glauca* transpiration did not change between seasons with an average of 0.20 mm.d^{-1} (S.E.=0.01) (Fig 5.8).

a) Dry season 2012 b) Wet season 2012



c) Dry season 2013 d) Wet season 2013

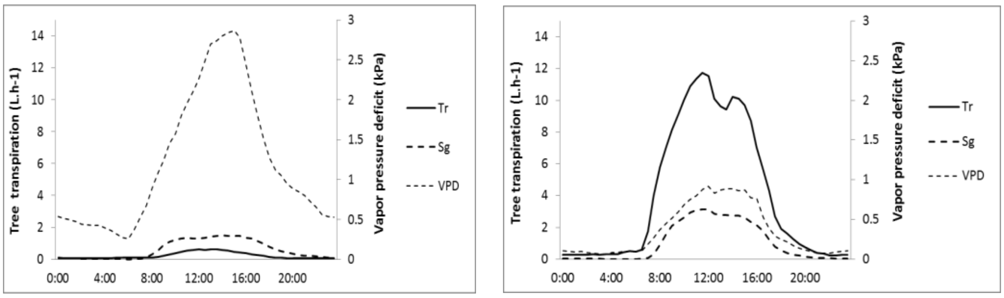


Fig 5.8. Diurnal patterns of transpiration (L.h^{-1}) by *Tabebuia rosea* and *Simarouba glauca* trees and VPD (kPa) from mean of five consecutive days in the 2012 dry (a) and wet seasons (b) and in the 2013 dry (c) and wet seasons (d).

5.3.5. Soil evaporation

Evaporation from the soil surface was greater in the wet compared to the dry seasons with mean of 2.22 mm.d-1 (S.E.=0.06) and 0.58 mm.d-1 (S.E.=0.05) in the wet and dry seasons respectively (Fig 5.9).

In the dry seasons (April 2012 and March-April 2014) rainfall events were light and sparse and soil water content in the uppermost soil layer showed little variation in both systems with mean of 0.38 $m^3.m^{-3}$ (S.E.=0.004). Soil surface evaporation varied from 0.53 $mm.d^{-1}$ (S.E.=0.04) to 0.45 $mm.d^{-1}$ (S.E.=0.04) in FS and AFS respectively, but, differences between systems were not significant (p=0.55). The influence of rainfall events on soil evaporation in the dry season was demonstrated on the slope variation comparing April 2012 with March-April 2014 drying events (Fig 5.9). Evaporation in April 2012 came after a large storm (19.6 mm) in the previous four days while by the middle of March-April 2014 scattered and small rains that occurred previously to the measurements did not have the same effect on soil evaporation rates. During the dry seasons great atmospheric demand had no influence on soil evaporation rate and no difference was found related to location of lysimeters in the row or interrow (p=0.15) (Fig 5.10). The ratio of actual to reference evaporation was 0.10 on average in the dry while in the wet periods it was 0.67. In wet conditions such as May-June in 2012 and May-November 2013 soil evaporation showed greater rates in FS compared to AFS (p=0.001). Mean soil evaporation was 2.50 mm d^{-1} and 1.98 mm d^{-1} in FS and AFS, respectively. In contrast to the dry monitoring periods, lysimeters location at the row or the interrow had a significant effect on soil evaporation in the humid period (p=0.01) (Fig 5.10).

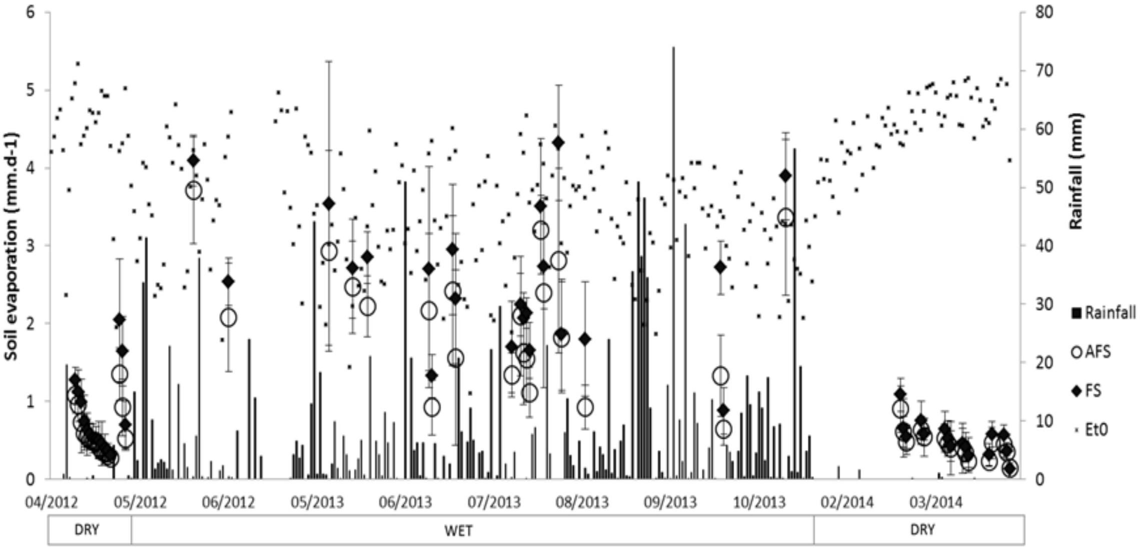


Fig 5.9. Soil evaporation ($mm.d^{-1}$) from lysimeters in FS and AFS from April 2012 to April 2014. Vertical bars represent the standard error of the mean. Daily rainfall (right axis) and ET0 (left axis) are indicated as references.

Irrespective of the systems mean daily evaporation ranged from 2.41 mm.d^{-1} (S.E.= 0.11) to 2.02 mm.d^{-1} (S.E.=0.12) in the interrow and row location, respectively (Fig 5.10). Soil evaporation over the whole two-year measurement period was calculated by fitting the Ritchie soil evaporation model (Ritchie 1972) to our measured data (Fig 5.11). The relationship between soil evaporation measured and modelled was linear with R^2=0.62 and R^2=0.44 in AFS and FS respectively (Fig 5.12 and 5.13). Simulations showed that water loss by soil evaporation was far from negligible and represented 44% and 12% of incident rainfall in wet and dry season, respectively.

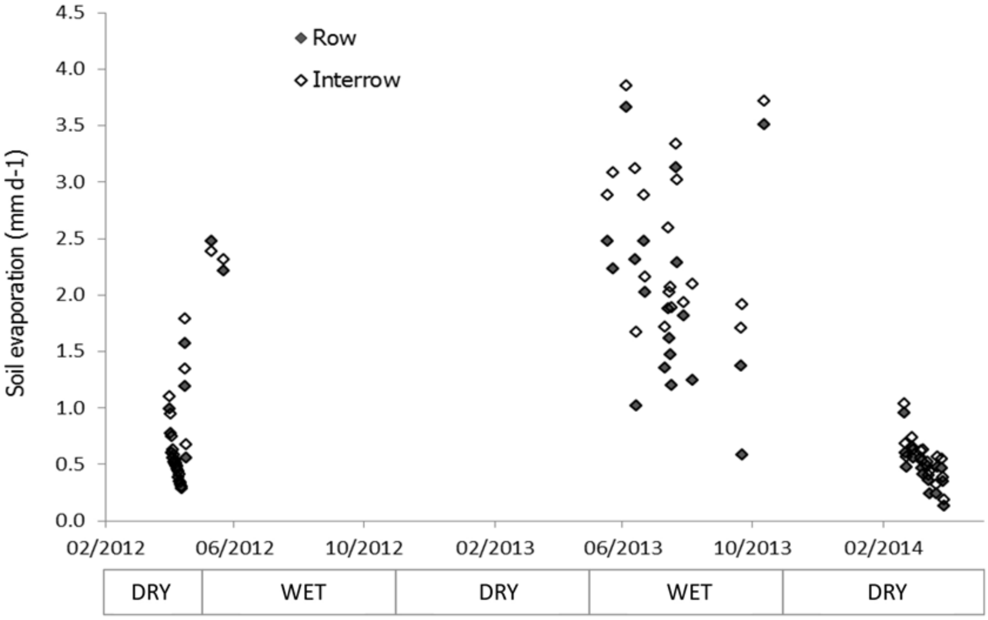


Fig 5.10. Daily soil evaporation from lysimeters located in the row or interrow over the dry monitoring periods in 2012 and 2014 and over the 2013 wet period.

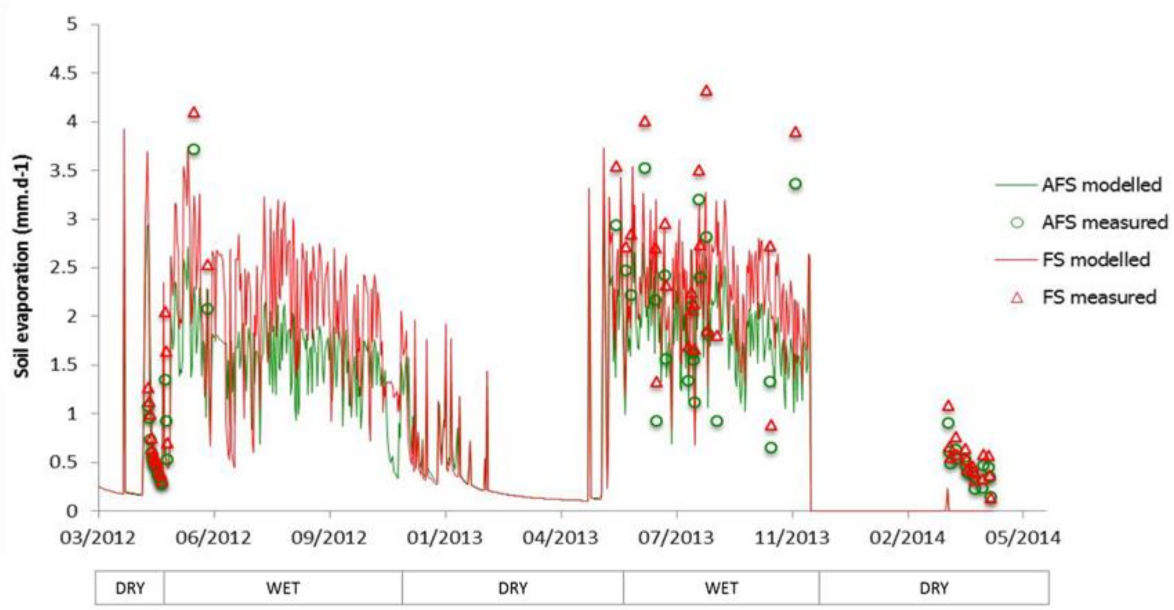


Fig 5.11. Daily soil evaporation rate measured and modelled by Ritchie soil evaporation model, in FS and AFS from April 2012 to April 2014. LAI data are required to compute Ritchie model; therefore, we could not perform the calculation between December 2013 and March 2014.

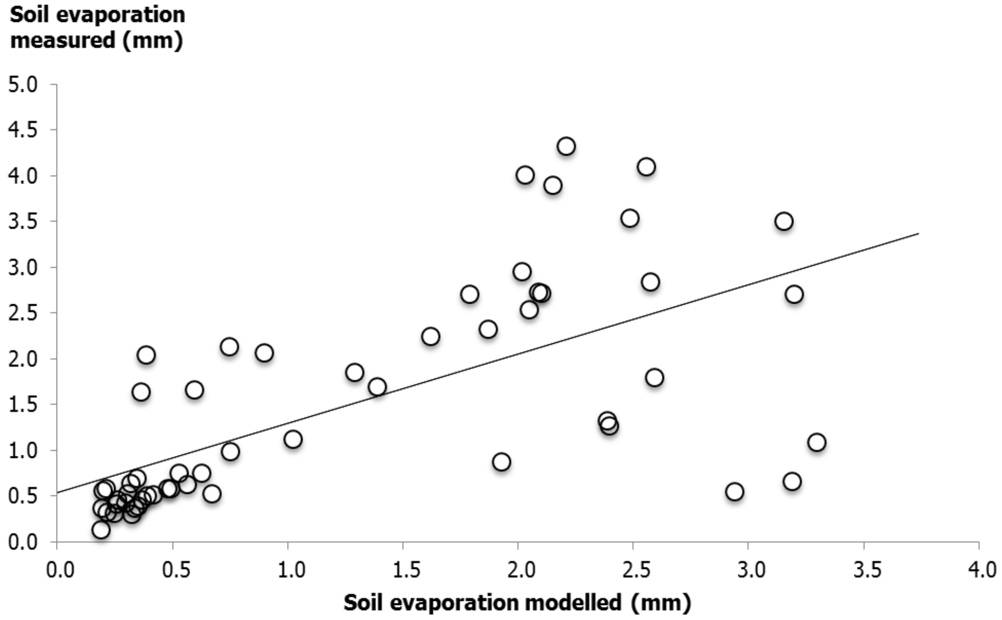


Fig 5.12. Soil evaporation measured and modelled in FS coffee. Regression equation: y=0.759x + 0.5385; R^2=0.44

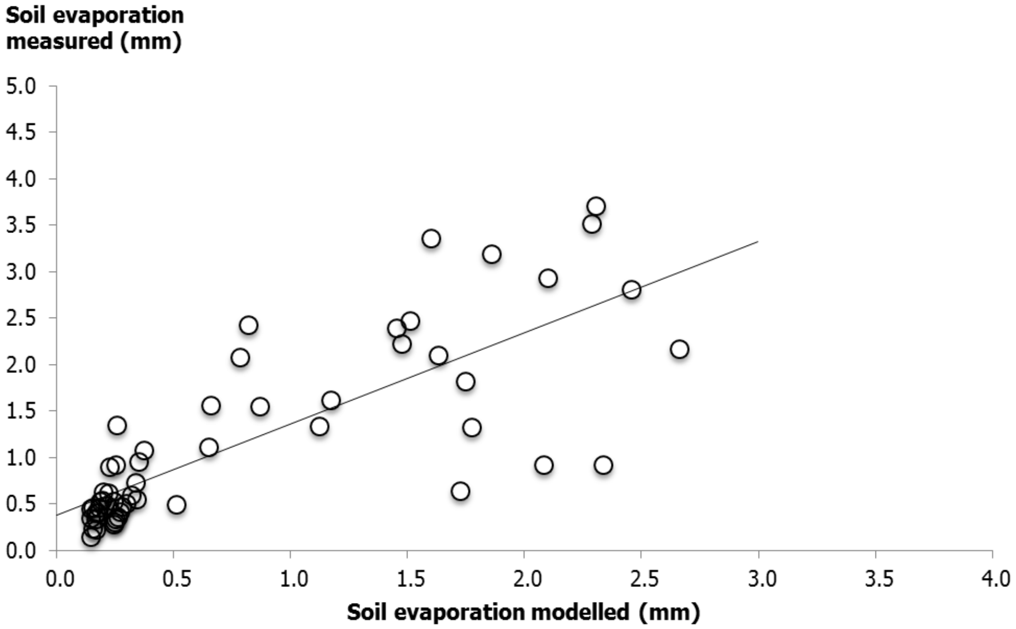


Fig 5.13. Soil evaporation measured and modelled in AFS. Regression equation: y= 0.9804x + 0.3857; R^2=0.62

5.3.6. Coffee leaf water potential (LWP)

Predawn leaf water potential (PLWP) differed between years (p=0.0002) being greater in 2012 following the greater soil water availability. Mean PLWP was -0.20 MPa (S.E.=0.07) in 2012 while in 2013 reached an average of -0.57 MPa (S.E.=0.07). The influence of the available water on PLWP was demonstrated by the high correlation coefficient of 0.94 between PLWP and soil water content (SWC). In the dry periods mean PLWP was -0.74 MPa (S.E.=0.06) while in the wet seasons it was -0.12 MPa (S.E.=0.06) (Fig 5.14).

Midday leaf water potential (MLWP) was also influenced by the seasonal pattern ($p<0.0001$) with mean MLWP of -1.60 MPa (S.E.=0.06) and -0.64 MPa (S.E.=0.05) in the dry and wet seasons, respectively. By the end of 2013 severe dry season MLWP reached its lowest values with -2.04 MPa in FS and -2.33 MPa in AFS. MLWP tended to be more negative when vapor pressure deficit (VPD) was larger and the SWC was limited, which corresponded to high correlation coefficients of -0.90 and 0.97 between MLWP and VPD and between MLWP and SWC, respectively.

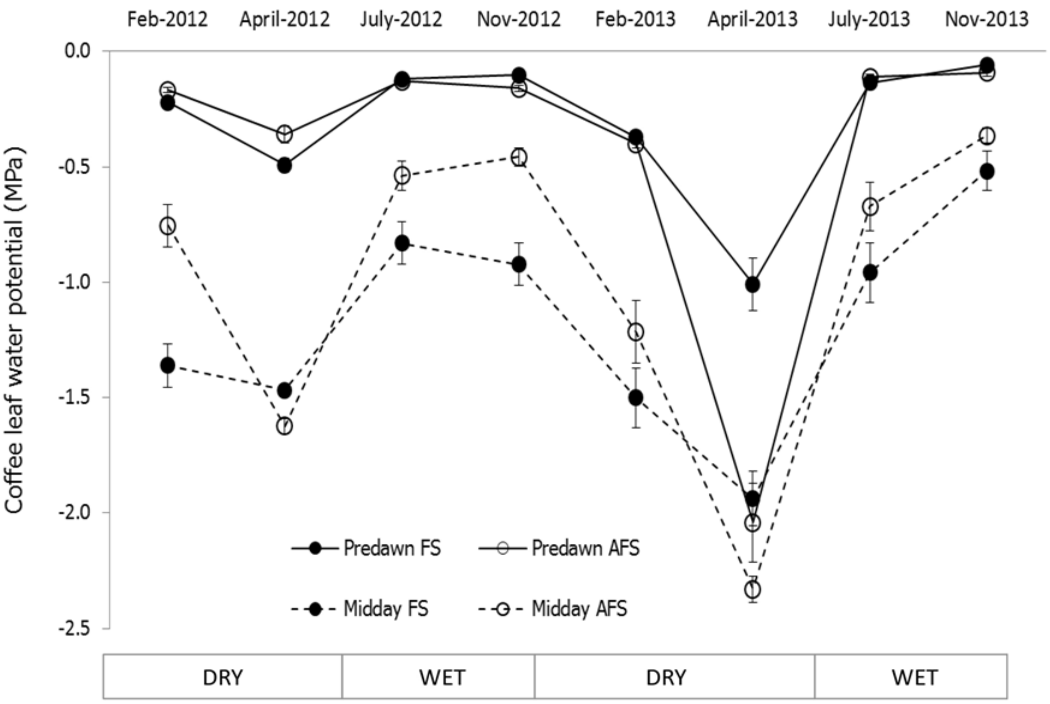


Fig 5.14. Mean coffee leaf water potential at predawn and midday from three days consecutive measurements in the dry (February and July) and wet seasons (July and November) in 2012 and 2013. Bars represent the standard error of the mean.

5.3.7. Total evapotranspiration

On average total evapotranspiration was greater in coffee agroforestry compared to full sun coffee (p=0.004) (Table 5.2). Mean evapotranspiration rate was 3.89 mm.d-1 (S.E.=0.28) and 2.80 mm.d-1 (S.E.=0.28) in AFS and FS respectively. With respect to seasonal effects, evapotranspiration was estimated for both systems in February (middle of dry season), April (end of the dry season), July (middle of wet season) and November (end of the wet season) in 2012 and 2013. Due to missing data on coffee transpiration in November 2012 we decided to exclude the total evapotranspiration estimation in that period (Table 5.2).

Table 5.2. Total evapotranspiration calculated from transpiration plus soil evaporation on a plot basis (with the standard error of the mean) and as percentage of total evapotranspiration in FS and AFS in February, April and July in 2012 and in February, April, July and November in 2013.

	Transpiration				Soil Evaporation				Evapotranspiration	
	FS		AFS		FS		AFS		FS	AFS
	(mm.d-1)	%	(mm.d-1)	%	(mm.d-1)	%	(mm.d-1)	%	(mm.d-1)	(mm.d-1)
Feb 2012	1.40 ± 0.22	68	1.38 ± 0.19	69	0.65 ± 0.22	32	0.63 ± 0.21	31	2.05 ± 0.44	2.01 ± 0.40
April 2012	1.46 ± 0.26	88	2.55 ± 0.66	92	0.21 ± 0.003	12	0.22 ± 0.005	8	1.67 ± 0.27	2.77 ± 0.66
July 2012	2.74 ± 0.13	58	3.76 ± 0.37	70	1.96 ± 0.27	42	1.63 ± 0.09	30	4.69 ± 0.39	5.39 ± 0.47
Feb 2013	1.68 ± 0.36	91	2.59 ± 0.23	94	0.18 ± 0.002	9	0.18 ± 0.002	6	1.86 ± 0.36	2.77 ± 0.23
April 2013	0.95 ± 0.14	89	1.22 ± 0.10	91	0.12 ± 0.0004	11	0.12 ± 0.0004	9	1.07 ± 0.14	1.34 ± 0.10
July 2013	0.75 ± 0.10	25	1.65 ± 0.25	46	2.24 ± 0.22	75	1.96 ± 0.20	54	2.99 ± 0.31	3.61 ± 0.46
Nov 2013	1.93 ± 0.18	49	3.73 ± 0.40	68	2.00 ± 0.18	51	1.79 ± 0.22	32	3.93 ± 0.36	5.52 ± 0.62

In the partitioning of evapotranspiration, transpiration was the most important contributor to water loss compared to soil evaporation in both systems. Transpiration accounted for 83% and 69% of evapotranspiration while soil evaporation represented 17% and 30% in AFS and FS respectively. Evaporation from the soil surface represented 50% and 33% of total evapotranspiration in the wet season while in the dry season it was reduced to 20% and 12% in FS and AFS respectively. Transpiration varied from 67% to 50% and from 88% to 80% of evapotranspiration in the wet and dry seasons in AFS and FS respectively.

Transpiration partitioning in AFS demonstrated that coffee transpiration was typically the greatest fraction compared to tree transpiration (Table 5.3). On average coffee transpiration comprised 75% of the total transpiration in AFS while *Tabebuia rosea* and *Simarouba glauca* each represented 17% and 8% of the total.

Table 5.3. Transpiration partitioning in AFS with coffee, *Tabebuia rosea* and *Simarouba glauca* transpiration rate in mm.d^{-1} and in percentage of the total transpiration in the system. Standard errors of the means are in brackets.

	Coffee		*Tabebuia rosea*		*Simarouba glauca*		AFS Transpiration
	mm.d^{-1}	%	mm.d^{-1}	%	mm.d^{-1}	%	mm.d^{-1}
Feb 2012	1.38 ± 0.19	59	0.71 ± 0.03	30	0.24 ± 0.006	10	2.33 ± 0.22
April 2012	2.22 ± 0.65	87	0.08 ± 0.001	3	0.25 ± 0.005	10	2.55 ± 0.66
July 2012	2.32 ± 0.30	62	1.22 ± 0.06	32	0.22 ± 0.01	6	3.76 ± 0.37
Feb 2013	2.29 ± 0.21	88	0.12 ± 0.02	5	0.18 ± 0.003	7	2.59 ± 0.23
April 2013	1.01 ± 0.09	83	0.06 ± 0.004	5	0.14 ± 0.01	12	1.22 ± 0.10
July 2013	0.92 ± 0.17	56	0.57 ± 0.06	35	0.15 ± 0.02	9	1.65 ± 0.25
Nov 2013	2.67 ± 0.31	72	0.88 ± 0.08	23	0.17 ± 0.01	5	3.73 ± 0.40

Also, coffee transpiration as a proportion of the total transpiration of the system tended to great values when *Tabebuia rosea* water requirements were low in the dry periods (April 2012 and February-April 2013) which characterized a complementarity relationship over time.

5.4. DISCUSSION

5.4.1. Coffee water use

Coffee water consumption on a leaf area basis was 23% greater in FS compared to AFS. On the other hand, at a plot scale we found coffee transpiration 15% greater in AFS likely due to 33% greater leaf area index in shaded coffee. Also, in the study area measurements by CATIE showed shade level between 53% and 67% of full irradiance over the period of experiment. Mean 60% of shade level had an effect on attenuation of stomatal limitation with greater coffee transpiration rates related to FS. This is consistent with other study in which comparison of different shade levels in optimal coffee growing condition in Costa Rica, in lower climatic stress condition than this study site, demonstrated that shade level of up to 55% was beneficial for coffee gas exchange maintenance at the leaf scale (Franck and Vaast 2009). Irrespective of shade level, the same trend of greater coffee transpiration rate in AFS was previously reported by Van Kanten and Vaast (2006) for coffee associated with timber tree species *Eucalyptus deglupta* or *Terminalia ivorensis* or with leguminous *Erythrina poeppigiana* when compared to FS system. Our results showing greater coffee water use on a leaf area basis in the open system was found to be similar to another study on coffee shaded with *Inga densiflora* in Costa Rica in which FS coffee transpiration was about 20-45% greater than in AFS (Cannavo *et al.* 2011).

In this study coffee transpiration was driven by both the atmospheric demand and soil water availability. Contrasting precipitation in the two consecutive years of study allowed comparison of coffee transpiration behavior in both years. In 2012, when soil water was not so limiting, coffee transpiration tended to follow air saturation deficit in the wet and dry season as demonstrated in Figure 5.5. Restriction of coffee transpiration was observed under VPD values of 1.7 kPa in FS in the dry season, probably, as a mechanism to prevent water stress. The close relationship between transpiration and atmospheric parameters has been previously demonstrated (Fanjul *et al.* 1985; Gutiérrez and Meinzer 1994) and coffee transpiration inhibition at a similar threshold of VPD = 1.5 – 1.6 kPa was reported by Van Kanten and Vaast (2006) and by Gutiérrez and Meinzer (1994). The general independence of coffee leaf transpiration from soil moisture was demonstrated when a decrease in transpiration rate was recorded only when 80% of the soil water in the rooting zone had been depleted (Nunes and Duarte 1969).

We demonstrated that in the second year, over the severe dry season, lower transpiration rate occurred despite the high solar radiation (1015 $W.m^{-2}$) and high vapor pressure deficit (2.9 kPa) which suggest a response to low soil moisture that seems to have become the predominant limiting factor of transpiration. We also demonstrated that in the 2013 hard dry season, coffee leaf water potential declined to its lowest level when reached -1.94 MPa and -2.33 MPa at midday in FS and AFS, respectively. The same order of magnitude of -2.55 MPa was found for zero turgor in *Coffea arabica* cultivar reported by Meinzer *et al.* (1990) in drought conditions. The lowest levels of leaf water potential and decline of coffee water use found in AFS during the restrictive soil water condition in 2013 dry season was associated with high level of water stress in coffee plants. This result indicated competition for water between coffee and shade trees in such environmental conditions.

5.4.2. Shade tree water consumption

In the agroforestry system most water use was due to coffee plants rather than shade trees. This was probably a consequence of the greater coffee LAI and coffee density compared to the trees. Coffee water use represented 75% of the whole water transpired in AFS while deciduous *Tabebuia rosea* shade trees accounted for 15% and evergreen *Simarouba glauca* for 8%. The *Tabebuia rosea* water consumption pattern was determined by leaf phenology, soil water availability and environmental conditions. The positive and strong correlation between LAI and transpiration rate (R^2=0.80) reinforced the effect of leaf phenology on *Tabebuia rosea* water consumption patterns. Despite of lower transpiration in the dry periods (February-April) *Tabebuia rosea* transpiration on a plot basis reached mean 0.30 mm.d^{-1} being even greater (p=0.02) than *Simarouba glauca* transpiration that was 0.19 mm.d^{-1} averaged in the period. Very low rates were observed in April when most of trees were leafless. But, *Tabebuia rosea* remained completely leafless for only short periods of about 2-3 weeks in April 2012 and 5-8 weeks during the 2013 severe dry season. Potential reduction in water loss over the dry season was compensated for by greater water consumption in the late dry seasons to achieve full leaf expansion which characterized *Tabebuia rosea* as a water spender compared to *Simarouba glauca* tree. *Tabebuia rosea* daily transpiration rates varied from 1.22 mm.d^{-1} (S.E.=0.06) to 0.45 mm.d^{-1} (S.E.=0.04) and from 0.67 mm.d^{-1} (S.E.=0.10) to 0.09 mm.d^{-1} (S.E.=0.01) in the wet and dry seasons in 2012 and 2013 respectively. Moreover, the deciduous *Tabebuia rosea* root system randomly distributed in the soil profile, as presented in Chapter III, indicated possible competition for water in the dry periods in the upper soil layer where most coffee roots are concentrated. This study demonstrated that such a competitive relationship was minimized during the "normal" dry periods because most *Tabebuia rosea* water requirements occurred in the wet seasons and did not coincide with the greatest periods of coffee water consumption that was in the dry. Simultaneous periods of great water requirements by deciduous *Tabebuia rosea* and of low water use by coffee plants suggested a complementarity in water use over time between coffee and shade tree. However, competition between coffee and shade tree was observed in periods of low water input supply as the 2013 severe dry season.

Conversely, evergreen *Simarouba glauca* may be considered as a water conserver with lower and more stable water consumption pattern over the course of the experiment compared to *Tabebuia rosea*. Exception was found in lower *Simarouba glauca* water use in 2013 severe dry season when maximum transpiration rate declined to 1.49 L h^{-1} compared to 3.84 L h^{-1} in 2012 dry season. Overall, mean *Simarouba glauca* daily transpiration rate ranged from 0.19 mm.d^{-1} (S.E.=0.01) to 0.22 mm.d^{-1} (S.E.=0.01) in the wet and dry season respectively. Although the seasonal differences in *Simarouba* *glauca* transpiration rate were not statistically significant, previous studies showed the tendency of increasing transpiration rates as the dry season progressed in evergreen timber trees such as *Eucalyptus tetrodonta* and *Eucalyptus miniata* (Grady *et al.* 1999). Similar findings were reported for *Acacia mangium* in Panama likely as a response to the exploration of deep sources of soil water (Kunert *et al.* 2010). *Simarouba glauca* was characterized by denser and concentrated root system in deep soil layers (below 1.10 m depth) with a clear root niche differentiation to coffee roots as reported in Chapter III. This description of evergreen *Simarouba glauca* water use pattern and spatial below ground arrangements is supported by findings of Meinzer et al. (1999) in which species with small seasonal variability in leaf fall, was able to exploit deeper soil layers with increasing drought condition. Also it is worth to recall that in this investigation, *Tabebuia rosea* and *Simarouba glauca* water uptake and consumption must have been influenced by being limited to no more than 2.0 m soil depth exploration, below which point no roots were found.

5.4.3. Soil surface evaporation

This study demonstrated that shade trees had an effect on reducing water loss from soil surface evaporation. Shade trees were responsible for a decrease of 31% in soil evaporation compared to the open system. The same tendency of reduction on evaporation rate in the shade was demonstrated in a sub humid climate in Kenya in which soil evaporation in agroforestry was reduced by 35% when compared to bare soil (Wallace *et al.* 1999). Another study in a *Grevillea robusta* agroforestry system in Kenya showed that beneath shade tree soil evaporation was reduced to 39% of the rainfall compared to 55% without any canopy (Wallace *et al.* 1997). In coffee agroforestry, comparison between different canopy cover levels showed a reduction in soil surface evaporation with increasing canopy cover (Lin 2010). However, literature on water loss measurements by soil evaporation in coffee agroforestry system is sparse thereby any comparison with other studies was limited. Soil water evaporation takes place from where most coffee fine roots occur with a potential effect on coffee water use which is of considerable importance, especially in dry environments (Beer 1987). This study demonstrated that in dry periods despite the great potential evaporation of 4.7 mm low mean soil evaporation was observed (from 0.25 $mm.d^{-1}$ to 0.38 $mm.d^{-1}$). These rates were similar to findings of Wallace (1991) in arid lands where the evaporation rate of 0.5 $mm.d^{-1}$ was much less than potential evaporation of 3.8 mm. In wet condition greater evaporation from soil surface compared to the dry periods was also reported by Zhang et al 2008 and by Yunusa *et al.* (2004). We demonstrated that in the environmental condition studied soil water evaporation was far from negligible. Water loss by soil evaporation varied from 0.31 mm d^{-1} (S.E.=0.02) to 1.76 mm d^{-1} (S.E.=0.03) while coffee water use by transpiration ranged from 1.59 mm.d^{-1} (S.E.=0.05) to 2.49 mm.d^{-1} (S.E.=0.09) in the dry and wet seasons respectively. Similar orders of magnitude for coffee transpiration were reported by Van Kanten and Vaast (2006) however simultaneous measurements of soil evaporation are rare.

5.4.4. Total evapotranspiration

Total evapotranspiration was greater in AFS compared to FS as reported previously in coffee with *Inga densiflora* in optimal condition for coffee cultivation in Costa Rica (Cannavo *et al.* 2011). Evapotranspiration partitioning into plant transpiration and soil surface evaporation demonstrated that transpiration comprised the most important component in both systems. Transpiration represented 69% and 83% of the total evapotranspiration in FS and AFS respectively. Studies in a coffee orchard in Brazil showed similar proportions of transpiration to evapotranspiration of about 65% (Flumignan *et al.* 2011). Plant transpiration as a dominant source for total evapotranspiration was reported in other studies (Yepez *et al.* 2003; Williams *et al.* 2004; Xu *et al.* 2008) however in coffee agroforestry information is lacking and comparisons are limited. Our results demonstrated that in agroforestry most water consumption was due to coffee and not by shade trees. The effect of shade trees water use did not result in water stress for coffee cultivation until the 2013 severe dry season occurred. In the 2013 water limiting conditions coffee transpiration was reduced to 54% and 35% in AFS and FS respectively compared to the dry season in the previous year. This study showed the effect of shade trees on diminishing water loss by evaporation, particularly during the wet periods. This may result in more water being available for transpiration that potentially could be used for coffee growth and to improve yield, which is quite important in a sub-optimal environment such as at Masatepe. In drought condition evaporation from the soil surface was at its minimal rate of 0.04% to the total evapotranspiration and similar in FS and AFS. The same tendency of small or negligible fraction of soil evaporation to the evapotranspiration in drought condition was similarly reported in arid and semiarid environments (Williams *et al.* 2004) due to breakdown of soil hydraulic conductivity at the surface.

5.5. CONCLUSIONS

This study demonstrated that in sub optimal conditions for coffee cultivation agroforestry was a better water user when compared to a non-shaded coffee system since most of soil water was used for coffee transpiration and not by shade trees or lost by evaporation from the soil surface.

Our results indicate that even in these sub optimal environmental conditions soil water was not usually a constraint for coffee water consumption in agroforestry. Complementarity in water use over time was demonstrated between coffee and *Tabebuia rosea* whilst complementarity in root system distribution and soil water uptake was observed between coffee and *Simarouba glauca* tree. This supports the idea of complementarity of coffee and shade trees over most of the period of study.

Competition in water use between coffee and shade trees was observed in a severe dry season when water input supply was not enough to avoid coffee water stress in agroforestry due to coffee plus shade tree water requirements.

Evergreen *Simarouba glauca* characteristics such as taking up water from deeper soil layers and the lower and more constant water consumption pattern seemed to be more suitable as coffee shade tree when compared to deciduous *Tabebuia rosea* in sub optimal conditions for coffee cultivation.

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CHAPTER VI

GENERAL DISCUSSION AND CONCLUSIONS

6.1. Study site and experimental design

We had the opportunity to study a mature coffee agroforestry experiment established in 2000 in sub optimal conditions for coffee cultivation in Masatepe, Nicaragua. Such sub optimal conditions consisted of:

- Mean annual temperature of 27^0C that is above *Coffea arabica* comfort zone and 455 m.a.s.l. which is considered to be rather low for *Coffea arabica* cultivation at this latitude;
- Mean annual rainfall of 1470 mm with a 6 month long dry season (which on average receives only 9% of the annual rainfall). Over the two years of study the contrasting mean annual precipitations of 968 mm in 2012 and 1312 mm in 2013 provided the chance to assess water dynamics and use in a normal and an abnormally dry conditions;
- Soil accessible to roots was limited to 2 meters depth, after which a pan constituted by coarse volcanic ejecta impeded root penetration. Additionally, a hardened layer (talpatete) crossed this accessible two-meter layer and further impaired root growth.

The original experiment consisted of three replicates of all treatments, as described by Haggar *et al.* (2011). Nevertheless, for the measurement of hydrological variables in this study, we selected only one full sun coffee plot, due to the poor establishment of coffee plants and problems with small floods in the other two replications. Thus, our experimental design consisted of a full sun monocrop coffee (FS) plot (1440 m^2) and an adjacent coffee agroforestry system (AFS) plot (3200 m^2) in which pseudo replications were located. In the coffee agroforestry system plot *Coffea arabica* was associated with *Simarouba glauca* DC. (Simaroubaceae) and *Tabebuia rosea* (Bertol.) DC. (Bignoniaceae) planted as shade trees. Tree spacing was originally 4 m x 4 m with 625 trees ha^{-1} alternating both species in all rows, but tree density had been reduced over time in order to achieve an agronomically appropriate level of shade under mature trees. Tree spacing was 8 m x 8 m over the period of the experiment. *Tabebuia rosea* mean density was 113 trees ha^{-1} and that of *Simarouba glauca* was 75 trees ha^{-1}.

Coffee density throughout the experiment was 4000 plants ha^{-1}, spacing being 2 m between rows and 1.25 m between plants. Coffee plants were pruned periodically in accordance with standard agronomic practice.

The root study experimental design consisted of a full sun monocrop coffee (FS) plot and two adjacent coffee agroforestry system (AFS) plots in which data were collected in 2011 and 2013. Evapotranspiration and rainfall interception studies were only done in one agroforestry plot due to equipment limitations, and we utilized pseudo-replications in both the full sun and the agroforestry plots. This design was considered appropriate for this process-based study.

For the evapotranspiration study the experimental design allowed us to assess the three hypothesized levels of competition for water in AFS compared to full sun coffee: coffee near *Simarouba glauca* trees, coffee near *Tabebuia rosea* trees and shaded coffee as far as possible from both tree species. Interception losses in trees and coffee bushes were studied in three sub plots established in the agroforestry system each one bounded by two *Simarouba glauca* trees and two *Tabebuia rosea* trees and including the coffee plants within. They were compared to interception losses in coffee bushes in the full sun treatment plot.

6.2. Complementarity and competition for water in coffee shaded with *Tabebuia rosea* and *Simarouba glauca* in sub optimal environmental condition

6.2.1 Below-ground interactions

One of the main goals of coffee and tree combination in agroforestry is to make better use of available soil water and improve overall productivity. However, in water-limiting conditions, the potential competition for water may impair the effectiveness of the agroforestry system. Competition can be avoided when coffee and tree root systems are able to exploit water from distinct soil horizons (Cannell *et al.* 1996; Ong *et al.* 1996). In this study most of the coffee roots were concentrated in the upper 30 cm of the soil profile and a minority reached a maximum depth of 150 cm and 170 cm depth in FS and AFS respectively. Coffee root growth was similar between systems which indicated little effect of shade tree root system on enhancing coffee root growth, as hypothesized. Also, in this investigation shallower coffee roots and deeper *Simarouba glauca* root distribution patterns suggested potential for complementarity in soil water use throughout the soil profile. Although both shade tree species showed greater root density below 110 cm depth *Simarouba glauca* and *Tabebuia rosea* root systems behaved differently. *Tabebuia rosea* roots were present in the whole soil profile while *Simarouba glauca* roots were denser and concentrated in the deeper layers. Coffee and *Simarouba glauca* root system exhibited a clear niche differentiation whereby soil water was likely to be extracted from different strata. However, deep rooted trees and spatial difference in coffee and tree roots distribution by themselves are not enough to guarantee complementarity of resources use. A deep source of water is required depending on water availability and soil condition. Moreover, species effects could have influenced coffee and tree root systems partitioning. In a mature system with such coffee and shade tree spatial distribution as at the study site, an effect of the root system of the dominant species over the other may occur. In a mixed shade tree species this domination relationship may be observed between both shade tree species and or between shade tree and coffee roots. Vertical distribution of coffee and eucalyptus root systems in agroforestry studied by Schaller *et al.* (2003) demonstrated that coffee roots were competitive enough to displace the shade tree roots. However, in order to check species-specific characteristics of the shade trees utilized in our study a pure stand of *Simarouba glauca* and also of *Tabebuia rosea* in the same environmental conditions would be necessary.

In this particular study site, soil is characterized by the presence of a hardened layer of volcanic ash locally known as talpetate. This layer was extremely variable ranging from soft, weathered material containing some harder rock fragments to a fairly continuous hard layer with rock-like properties. It also varied in depth below the soil surface and in thickness of the layer. Although there was some influence of this hardened layer in restricting water movement, fractures enabled water and roots to cross the talpetate and infiltration to the deeper strata occurred. However, root growth, and soil water uptake was limited to two meters depth due to a much denser layer of compacted volcanic ash at that depth. The water stored in the soil was affected by 34 % and 11% lower rainfall in 2012 and 2013 respectively compared to the long-term mean annual rainfall of 1470 mm in that region which is considered low for coffee cultivation. Extended dry seasons lasted up to six months with 57.2 mm and 23 mm rainfall overall in 2012 and 2013 respectively, during which coffee and trees depended on stored soil water only. Limitations in both the depth of rooting zone and the soil water availability had great effect on coffee and tree water use over these prolonged dry periods. In a deeper soil, tree roots would normally go further down in order to get water from deep layers. Conversely, the time course of soil water content showed that in the dry periods water uptake tended to decrease earlier in AFS when compared to FS owing to the effect of shade trees. In 2013, during the very dry season, the coffee and tree water requirements were greater than the soil water stock in the 2 m of soil profile, which was insufficient to avoid the high level of water stress suffered by coffee.

6.2.2 Coffee water use

In the sub optimal environmental conditions studied coffee water use on a leaf area basis was 25% greater in FS than in AFS. As a LAI-dependent process (Taugourdeau *et al.* 2014), transpiration was found to be influenced by the seasonal variation being smaller when coffee was fully leaved and greater when leaf shedding occurring, over the dry periods. Other studies have shown that transpiration on a leaf area basis tend to increase in response to defoliation (Meinzer and Grantz 1991; Tausend *et al.* 2000). In the dry periods, fewer leaves distributed in the coffee plant crown provided low shade cast by neighbouring leaves and therefore, high solar radiation and temperature with humidity alteration at the leaf surface may occur, which favoured greater leaf transpiration compared to the wet periods. In the shaded environment high radiation and temperature were minimized which resulted in a lower leaf to air water vapour pressure deficit and therefore, lower leaf transpiration rates compared to FS. Greater coffee LAI in the shade did not result straightforwardly in greater leaf-level transpiration rate likely due to leaves overlapping in the dense coffee crown with low leaf surface and due to low photosynthetically active radiation under shade tree canopies. Moreover, as the leaf transpires, water vapour tends to humidify the air nearby the leaves reducing evaporative demand and transpiration rates.

However, coffee water consumption on a land area basis was greater in AFS compared to FS due to higher vegetative growth of coffee plants in shaded environment with 33% greater coffee LAI in agroforestry. The same trend of greater coffee LAI and transpiration per hectare in AFS was demonstrated by Van Kanten and Vaast (2006) in sub optimal environmental conditions in Costa Rica in which coffee was associated with different shade tree species (*Erythrina poeppigiana*, *Eucalyptus deglupta* or *Terminalia ivorensis*).

Coffee water use could be influenced by plant defoliation due to the coffee rust epidemics caused by *Hemileia vastatrix* that occurred in Central America in the period of the experiment. However, mean annual incidence of coffee rust measured by CATIE in the study area over the experiment was 1% and 8% in FS and AFS respectively in 2012 while in 2013 was 2% in both systems (data not published). But those rates may be considered low compared with the disease incidence of 32% in Nicaragua in the same period (Avelino *et al.* 2015). The overall low incidence may be related to agronomic practices and the monitoring routine in the study site that allows early detection and control of coffee rust. Higher coffee rust incidence in shade may be explained by buffering effect on temperature and radiation with increasing leaf wetness which favours the *Hemileia vastatrix* infection (Avelino *et al.* 2004). Another study also showed worse coffee rust occurrence in shade system (Staver *et al.* 2001). Despite the management influence, climate anomalies were found to be the most important factor of influence of the disease in the region over the period of study (Avelino *et al.* 2015). Overall, the climate conditions also seemed to be the most influence on coffee water use in the period of study with little effect from the coffee rust in the experiment results.

In this study, the influence of soil water availability in coffee transpiration was demonstrated by the contrast precipitation pattern in the two consecutive years of the experiment. In the first year, coffee transpiration tended to follow air saturation deficit in both the wet and dry seasons. This close relationship between transpiration and atmospheric parameters had been previously demonstrated (Fanjul *et al.* 1985; Gutiérrez *et al.* 1994b). In contrast, in the 2013 severe dry season lower transpiration rates occurred despite the high radiation (1015 W.m^{-2}) and high vapour pressure deficit (2.9 kPa) as a response to very low plant available soil water that became the predominant limiting factor of transpiration. The high level of water stress was indicated by coffee leaf water potential that reached -1.94 MPa at midday in FS and -2.33 MPa in AFS. The general independence of coffee transpiration on soil water availability was demonstrated by Nunes and Duarte (1969) thereby our results suggest that the lower levels of transpiration in the harsh dry period may be associated with a high level of soil water depletion that induced water stress of coffee plants. Also, the lowest levels of leaf water potential and decline of coffee water use found in AFS in the 2013 restrictive soil water conditions indicated possible competition for water between coffee and shade trees in those unusual circumstances.

6.2.3 Shade tree water use

We demonstrated greater water consumption in agroforestry compared to coffee monoculture. However, the highest contribution to water use in agroforestry was due to coffee rather than shade trees. Deciduous *Tabebuia rosea* shade tree accounted for 17% and evergreen *Simarouba glauca* for 8% of the whole water transpired in the system. In the study site deciduous *Tabebuia rosea* water use pattern was mainly controlled by the degree of foliation ranging from 1.22 $mm.d^{-1}$ (S.E.=0.06) to 0.45 $mm.d^{-1}$ (S.E.=0.04) and from 0.67 $mm.d^{-1}$ (S.E.=0.10) to 0.09 $mm.d^{-1}$ (S.E.=0.01) in the wet and dry seasons in 2012 and 2013, respectively. A strong and positive relationship (R^2=0.80) between *Tabebuia rosea* mean transpiration rate and LAI reinforced the conclusion that the water consumption pattern was affected by phenology. Deciduous tree species may be advantageous as coffee shade tree providing further light availability during dry periods and therefore, enhancing floral induction with effects on increasing fruit load (Beer *et al.* 1998). However, potential benefits from light inputs and reduction in the water use by *Tabebuia rosea* over the dry periods was overcome by the great water consumption in the late dry seasons to achieve full canopy expansion. *Tabebuia rosea* may be characterized as a water spender when compared to evergreen *Simarouba glauca*. Also, this study demonstrated that most water consumption by *Tabebuia rosea* occurred over the wet seasons which did not coincide with great water use by coffee that was during the dry periods. In this case, deciduousness favoured a complementarity in water use over time between coffee and shade tree. However, in a limited water supply condition as the severe dry season in the study site, deciduousness represented a competitive factor due to great shade tree water use which accentuated the low soil water available for coffee. This may constitute a good reason for deciduous *Tabebuia rosea* not being a good choice as coffee shade tree in sub optimal environmental condition for coffee growth. Water requirements by *Tabebuia rosea* that was determined by leaf phenology, soil water availability and environmental conditions contrasted with the tendency for lower and more stable water consumption by *Simarouba glauca* over the course of the experiment.

Evergreen *Simarouba glauca* water use was similar throughout the period of study. Mean *Simarouba glauca* daily transpiration rate ranged from 0.19 $mm.d^{-1}$ (S.E.=0.01) to 0.22 $mm.d^{-1}$ (S.E.=0.01) in the wet and dry season respectively likely due to the influence of greater evaporative demand over the dry period. Another study showed the tendency of increasing transpiration rates as the dry season progressed in evergreen timber trees such as *Eucalyptus tetrodonta* and *Eucalyptus miniata* (Grady *et al.* 1999). *Simarouba glauca* was characterized by a denser and more concentrated root system in deep soil layers (below 110 cm depth) with a clear root niche differentiation from coffee roots as we demonstrated in Chapter III. Most water uptake from deep soil layers was reinforced by the lower soil water content below 0.4 m of the soil profile found near *Simarouba glauca* when compared to *Tabebuia rosea*. Also, evergreen *Simarouba glauca* water use pattern and spatial belowground arrangement are supported by findings of Meinzer *et al.* (1999) in which species with small seasonal variability in leaf fall were able to exploit deeper soil layers with increasing drought conditions. The influence of drought on water use by evergreen timber tree as a coffee shade tree was reported in Costa Rica regarding *E. deglupta* (Jimenez and Alfaro 1999). These authors showed rapid water depletion and great competition with coffee in water limiting condition over a five month dry season while another study in high precipitation conditions showed no competition for water between coffee and trees (Schaller *et al.* 2003). Our study site, located in conditions where water can be limiting to coffee growth is clearly similar to the first case, where competition for soil water between coffee and shade trees was demonstrated during the drier year.

6.2.4. Shade tree effects on coffee production in sub optimal environmental condition for coffee cultivation

We did not measure coffee production in this experiment. Thus, in order to assess the shade tree effects on coffee yields we used the results of measurements carried out by the Centro Tropical de Investigación y Enseñanza (CATIE) at the study site, during the period of study and over the 10 years previous to this experiment. Despite the greater coffee LAI and the higher coffee transpiration rates demonstrated in the shade, coffee production was 25% lower in AFS compared to FS from averaged data of the 10 years period. This result may be explained by the shade effect on reduction of the number of nodes per branches, on inhibiting flower bud formation and, therefore, on diminishing fruit load previously reported by various authors (Cannell 1985; Carr 2001; Da Matta 2004). Globally, the effect of shade tree on coffee production has been variable depending on the shade density and environmental condition. Da Matta (2004) proposed, as a general rule, that the more the sub-optimal condition for coffee grown the site is, the greater would be the benefits from shade for coffee production. This is somehow related to the stress gradient hypothesis (Bertness and Callaway 1994) in which facilitative and competitive interactions will vary inversely across abiotic stress gradients with positive and facilitative interactions being more common in conditions of high abiotic stress. In the sub optimal coffee growing condition studied, lower coffee production in the second year of study, compared to the mean coffee produced over the period of study, seemed to be an effect of the lower precipitation, rather than the mean shade level being 60% of full irradiance averaged over the experiment. In optimal environmental condition for coffee in Costa Rica, with less climatic stress condition than this study, shade cover up to 55% was found to favor the coffee fruit set maintenance (Franck and Vaast 2009). In a study in optimal conditions for coffee cultivation in Mexico, a positive effect was reported on yield within a range of 23% and 38% of shade cover whilst under shade up to 48% coffee yield was maintained and decreased under shade cover above 50% (Soto-Pinto et al. 2000). Great variation in results reported indicates the need for further studies regarding the wide source of influence beyond shade density on coffee production in agroforestry system.

The lower coffee yield in AFS was compensated by greater productivity of the whole system. Cumulative coffee green bean yield measured by CATIE over 2004-2013 (exception for missing data in 2009) consisted in 78,298 kg ha^{-1} and 58,736 kg ha^{-1} which corresponded to cumulative values of US$ 36.445,00 and US$ 26.538,00 [b] (adjusted for each year regarding local annual inflation index in the period)[c] in FS and AFS, respectively. By the end of the same period, timber production consisted in 601 m^3 ha^{-1} from both the *Tabebuia rosea* and *Simarouba glauca* shade tree species in the study site (Cruz Castillo 2014), which was estimated in US$ 174/m^3 [d]. The current tree density in the study site generated a shade density of 60% averaged over the period of study that would permit at least 10% of timber tree utilization with minimal impacts on coffee yield. Thus, it would allow obtaining at about US$ 10.421,00 from timber which summed to the coffee yield inputs would mean 1.4% greater incomes in AFS compared to FS coffee, in that site conditions. Further financial advantages from wood could be accounted by adding the firewood amount produced in the shade system (not recorded). Moreover, studies have demonstrated strong effect of shade on coffee bean size and coffee quality improvements (Muschler 1997; Vaast *et al.* 2005; Vaast *et al.*

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[b] from historical data on annual coffee prices paid for growers - export value – available in International Coffee Organization: http://www.ico.org/new_historical.asp?section=Statistics

[c] Available in: www.indexmundi.com/pt/nicaragua

[d] from roundwood (non-coniferous tropical) exports value regarding Costa Rica as a reference available in International Tropical Timber Organization: http://www.itto.int/annual_review_output/

2006) which may enhance incomes in sub optimal condition for coffee cultivation, such as at the study site, due to the better prices in the coffee market. Moreover, it is very probably less risky to have incomes from diversified sources, and those sources combined have less variability than separately. Although the need of more detailed information in order to have the economic balance of both systems compared, data indicated better financial performance in AFS in the site conditions studied. Another study comparing coffee yields in the shade and in the open in Nicaragua by Clemens and Siman (1993) showed coffee yields of 315-630 kg h^{-1} in shaded traditional technology while in the open sun with high input technology was 1,365-2,730 kg h^{-1}. However, they reported that the balance between the profit and the total costs regarding fertilizers and pesticides resulted in 73% and 28% of rate of return for shaded coffee and for coffee in the open sun, respectively. The great variability in shade tree canopy cover, coffee cultivars, the age of coffee stand, system management and biophysical environments precludes comparison on coffee yield and the whole system production between this experiment and other coffee agroforestry systems.

6.3. Water dynamics and use in coffee agroforestry in sub optimal conditions

6.3.1. Evapotranspiration partitioning

Coffee growth and yield are directly related to the hydrological process in which a very small proportion of the water absorbed by plants is used in the photosynthesis and therefore, in coffee production. Most of water budged is lost by transpiration, soil evaporation, rainfall interception, runoff and infiltration. In agroforestry, coffee and tree interactions affects the water flux in all its components. In this study, evapotranspiration which includes soil surface evaporation plus coffee and shade trees transpiration, as the main component of the water balance, was directly measured in agroforestry and full sun coffee.

We also measured rainfall interception, in which precipitation is captured by the vegetation canopy and subsequently evaporated. Our results demonstrated the effect of coffee and shade tree canopies combined on diminishing the water that reaches the soil in agroforestry. We found that mean annual interception was 24% of gross rainfall in agroforestry compared to 18% in FS. However, it was relatively difficult to compare our results with those of other authors, due to few studies in coffee agroforestry and the huge variations in interception data reported. Our results were found to be high when comparing to other study with conditions relatively similar to this investigation site with interception of 15.5% and 8.9% of rainfall (Siles et al. 2010; Cannavo et al. 2011). Interception calculation is derived from the difference of rainfall and the sum of stemflow and throughfall, thereby different sources of error may be present. Bias was found on interception estimation, particularly in *Tabebuia rosea* tree canopy and in coffee canopy in AFS that may be attributed to underestimation of both the stemflow and throughfall measurements. Throughfall, as the largest component in rainfall partitioning seemed to be the major potential influence on the results. However, errors from stemflow measurements, equally hard to measure accurately, should not be discounted, especially during the big rainfall events. Also, we hypothesize that the spatial representativity of rain gauges related to the actual structure of the plantation may be another possible source of bias. A more regular pattern in the rain gauges spatial arrangement rather than the orthogonal distribution used in this experiment could be recommended in order to minimize this potential source of error, but new measurements will be required to test this hypothesis. Also, in this study interception was monitored only over a short period of 28 rainfall events during 2013 wet season, thereby a properly extrapolation of the data for the whole period of experiment was limited.

After being intercepted on the leaves and the bark of trunks and branches, rainfall water is evaporated. It is unlikely that much of this evaporation takes place on the day of the interception, process that could explain the high interception capacity of shade trees: it usually rains during the afternoon, and evaporation diminishes strongly during the night. On the other hand, when this water evaporates, it clearly decreases the net radiation reaching the ground surface, and thus the potential for transpiration or evaporation. That is, adding interception to transpiration or evaporation as components of the water balance is, at least in part, a double counting, from the point of view of the energy balance. It seems that the reality of this double counting depends on the height of the vegetation: in forest trees, the water accumulated by rainfall interception on the leaves evaporates much faster as compared to the transpiration rate; therefore, the double counting is limited. In smaller vegetation, as could be considered the coffee layer in our experiment, the evaporation is much slower and double counting could be an issue (Rutter 1975).

Evapotranspiration partitioning showed that transpiration was the greatest contribution in water consumption in both systems. We demonstrated that transpiration accounted for 83% and 69% of evapotranspiration while soil evaporation represented 17% and 30% in AFS and FS respectively. A similar order of magnitude was found in coffee monoculture in Brazil in which, transpiration and soil evaporation accounted for 65% and 35% of total evapotranspiration, respectively (Flumignan et al. 2011). However, in coffee agroforestry, studies regarding whole evapotranspiration components directly measured are lacking. Most studies of transpiration reliably measured in coffee agroforestry do not take evaporation from the soil surface into account.

Transpiration, which is of high relevance because is directly linked with growth and yield, was found to be greatly dependent on the leaf area. In this study, transpiration and coffee and tree leaf area were measured over short periods that included some days, in the dry and wet seasons, in 2012 and 2013. However, we did not measure leaf area over periods that lasted two-four months, in which great variability of climate conditions should have affected coffee and tree leaf area and therefore, transpiration rates, which was difficult to recover by modelling.

Our results demonstrated that although transpiration constituted the largest component of total evapotranspiration, soil surface evaporation represented a significant term and should be neglected neither in research nor in management of coffee. Soil surface evaporation was 19% greater in FS compared to AFS. Mean daily soil evaporation was 2.59 mm (S.E.=0.16) and 2.10 mm (S.E.=0.14) in FS and AFS, respectively. The significant effect of LAI on evaporation rate was demonstrated ($p<0.0001$). We also demonstrated that soil evaporation depended a lot on rainfall distribution, as was expected from existing studies in other cropping systems. Soil evaporation was greater in periods of scattered rainfall, due to great evaporation in the first phase after each rainfall compared to periods of large and infrequent rainfall. The lower evaporation rate found in the dry periods despite of higher evaporative demand was similar to findings of Wallace (1991) in arid lands, and may be explained by relatively low rates of water movement toward the surface in unsaturated soil. Indeed, in the dry periods soil evaporation was similar in the row or interrow in both systems while in the wet period differences on lysimeters location was found. In the wet period water loss by soil surface evaporation was always greater in the interrow rather than in the row, despite of the system.

This study showed that shade trees associated with coffee optimized soil water consumption by increasing productive water use as transpiration. Moreover, lower soil evaporation rate in agroforestry compared to full sun coffee may result in less waste of water to the atmosphere that could be available for crop and tree transpiration. The influence of seasonal pattern on plant transpiration and soil evaporation was demonstrated. Results demonstrated that, in the sub optimal condition for coffee cultivation, the dry periods favoured greater evaporative demand with increasing transpiration and at the same time reduction in water loss by soil surface evaporation due to low soil water availability.

6.3.2. Evapotranspiration by directly and indirect estimation compared

In this experiment, evapotranspiration estimates in AFS and FS systems was obtained by two independent approaches: 1) Direct estimates of evapotranspiration by direct measuring soil evaporation and plant transpiration (coffee and shade trees), as presented in Chapter V; 2) Indirect estimates of evapotranspiration by measuring changes in the water stock of the soil profile through Time Domain Reflectometry (TDR) probes monitored in different layers of the soil profile in both systems, as explained in Chapter III.

1) Evapotranspiration was estimated by direct measurement of the main components of water balance such as soil surface evaporation and transpiration of coffee in FS and of coffee and trees in AFS.

$ET = SE + \sum T$

Where: SE = soil surface evaporation; $\sum T$ = transpiration of coffee or coffee and tree.

2) Evapotranspiration was indirectly estimated by measuring changes in soil water stock of the soil profile by using Time Domain Reflectometers - TDR probes (CS616 - Campbell Scientific Inc.). Evapotranspiration was estimated regarding the assumption of lack of drainage and was simplified by the equation:

$S1 - S2 + R = Et$

where: S1 is the soil water stock in the soil profile at the beginning of the period (mm); S2 is the soil water stock in the soil profile at the end of the period (mm); R is the accumulated rainfall during the period (mm); Et is the evapotranspiration by the soil-plant system accumulated during the period (mm).

Water consumption comparing evapotranspiration estimation by directly measurements of soil evaporation and plant transpiration; and by evapotranspiration estimated from changes in soil water stock, was found to be of very similar order of magnitude in both systems over the periods studied in spite of the different sources of data and methods utilized in both studies. The similarity of the outcomes and the accuracy of methods and procedures utilized in both approaches reinforced the reliability of the results obtained (Fig 6.1).

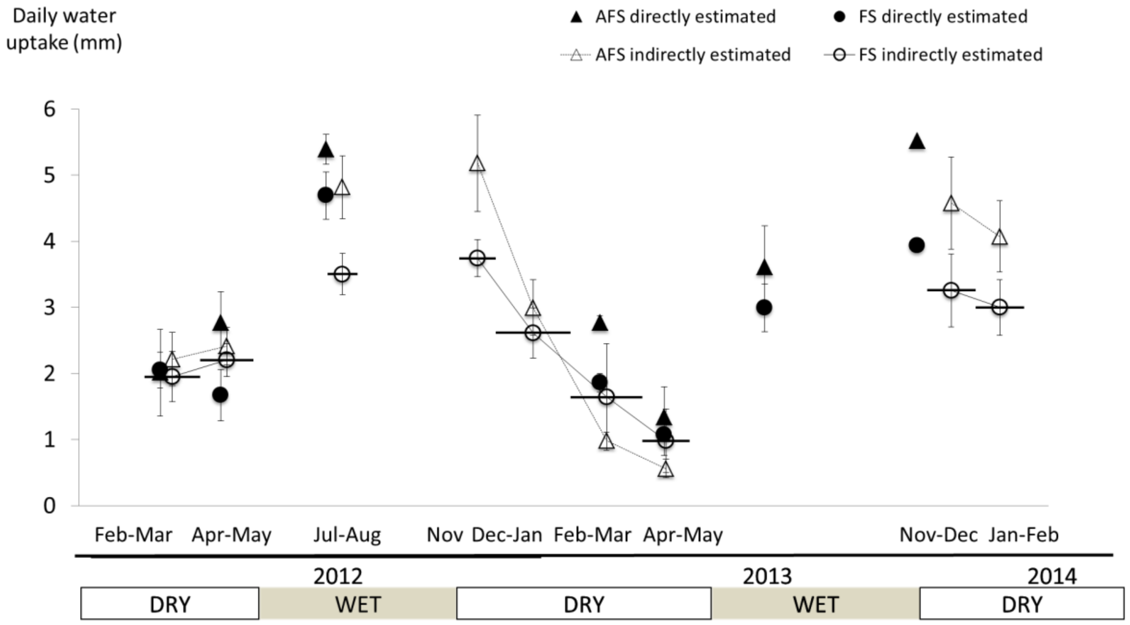

Fig 6.1. Daily soil water uptake directly estimated (by soil evaporation and plant transpiration measuring) and indirectly estimated (by changes in the soil water stock) in FS and AFS and reference evapotranspiration over the period of study. Vertical bars represent the standard error of the mean.

We observed that on the whole, water uptake tended to be most influenced by soil water availability than the evaporative demand. Reference evapotranspiration was greater in the dry compared to the wet seasons. However, maximum values of daily water consumption were observed in the wet seasons in both years which suggested that soil water was the main driver of water consumption in both systems in the sub optimal environmental condition studied. Most water uptake in the wet seasons was influenced primarily by leaf area index of coffee and trees which was greater in the wet than in the dry seasons.

We demonstrated that in AFS water uptake was greater while coffee yield was lower compared to FS due to the effect of water use of shade trees and coffee combined. However, enough water availability (although lower than ideally required by coffee cultivation) and deeper root distribution pattern of shade tree did not represent a risk for coffee cultivation in AFS for most of the period of study. In 2012 precipitation was 34% lower than the mean annual rainfall of 1470 mm in the region and an extended and severe dry season occurred in 2013. In such conditions water uptake was very low in both systems and as an effect of coffee and shade tree combined water uptake tended to decrease earlier in AFS and competition for water occurred. This study demonstrated that in these drought conditions coffee transpiration reached its lowest values and coffee leaf water potential indicated a high level of water stress in the agroforestry system.

These results suggest that in the sub optimal environmental conditions studied where the rooting zone was limited to 2 m depth, temperature was high and rainfall was low for coffee cultivation, agroforestry could be a risk in the context of climate change. In such conditions further studies are required to improve design and management in order to minimize competition for water between coffee and shade tree.

6.4. GENERAL CONCLUSIONS

In the sub optimal environmental conditions for coffee cultivation in which this study was done, water was not limiting for most of the period of study and *Tabebuia rosea* and *Simarouba glauca* shade trees could take up water from deep layers reducing competition with coffee which suggest a complementary relationship.

Some complementarity of soil water exploration over the whole soil profile was demonstrated by shallower coffee roots and deeper shade tree root distribution pattern. Desirable root niche differentiation was demonstrated between coffee and *Simarouba glauca* tree that favoured water use from deep layers not available for coffee and that otherwise could be lost by deep drainage.

This study demonstrated that in the sub optimal condition for coffee cultivation most of water was used by transpiration that accounted for 77% and 67% of total evapotranspiration in AFS and FS. Evapotranspiration partitioning showed that water loss by evaporation from soil surface was far from negligible and represented 23% and 33% of total evapotranspiration in AFS and FS respectively. In agroforestry coffee had the greater contribution to the total transpiration and not the shade trees. Greater transpiration and lower evaporation from the soil surface in agroforestry compared to full sun coffee suggest greater effectiveness in water use in shaded environment regarding the system as a whole but not necessarily for the coffee.

In this study a serious shade tree effect in constraining coffee water consumption was observed over the 2013 severe dry season when transpiration was stabilized and coffee leaf water potential reached its lowest value (-2.33 MPa) which suggested a high level of water stress and a high level of competition between coffee and shade trees.

Our results showed that the effect of shade tree species on coffee water consumption differed with tree species characteristics. We found a temporal differentiation in water use pattern between coffee and deciduous *Tabebuia rosea* which mitigate potential competitive relationship for most of the period of experiment. We also observed a spatial niche differentiation between coffee and evergreen *Simarouba glauca* root systems. Evergreen *Simarouba glauca* water use pattern such as taking up water from deeper soil layers and the lower and more constant water consumption seemed to be more suitable as coffee shade tree when compared to deciduous *Tabebuia rosea* in sub optimal conditions for coffee cultivation.

Results obtained about changes in soil water stock estimation from water loss measurements when compared with results from direct measurement of changes in soil water stock were consistent indicating that methods utilized in this investigation were reliable and suitable for the coffee agroforestry water balance in the study site conditions.

6.4.1. TESTING THE RESEARCH HYPOTHESES

6.4.1.1. Root distribution and water use in coffee shaded by *Tabebuia rosea* and *Simarouba glauca* compared to full sun coffee in sub optimal environmental conditions.

- Trees had no significant influence on coffee root distribution and no difference was found between coffee root system in agroforestry and full sun coffee.
- Coffee roots crossed the compacted soil layer but the restrictive soil conditions had a negative influence on coffee root growth regardless of the system.
- Coffee root growth was greater near *Simarouba glauca* rather than *Tabebuia rosea*.

- Evergreen *Simarouba glauca* and deciduous *Tabebuia rosea* exhibited different root systems behaviour. *Simarouba glauca* and coffee exhibited greater root niche differentiation than Tabebuia rosea and coffee, suggesting complementarity relationships.
- Coffee water uptake was severely restricted in agroforestry compared to full sun coffee over the 2013 severe dry season.

6.4.1.2. Rainfall interception, stemflow and throughfall in a coffee shaded by *Tabebuia rosea* Bertol. and *Simarouba glauca* DC.

- We confirmed that shade tree canopies modified water availability for coffee cultivation in agroforestry system.
- Shade tree characteristics such as leaf area and leaf traits had some influence on the amount of rainfall that reached the soil surface.
- Most of rainfall partitioning was distributed as throughfall.
- We confirmed negligible amount of stemflow in coffee and shade trees when compared to throughfall and rainfall interception.

6.4.1.3. Evapotranspiration in a coffee shaded by *Tabebuia rosea* and *Simarouba glauca* timber tree species compared to unshaded coffee in sub optimal environmental conditions.

- Transpiration comprised the major fraction of evapotranspiration in both systems.
- Agroforestry showed greater transpiration and lower soil evaporation when compared to full sun water use. Coffee transpiration was the greater contributor to the total transpiration in agroforestry.
- We confirmed the hypothesis that water loss by evaporation from the soil surface was reduced by the effect of shade trees associated with coffee crops, even in dry seasons when only evergreen *Simarouba glauca* maintain its leaves.
- Deciduous *Tabebuia rosea* and evergreen *Simarouba glauca* affected soil water budget in different ways. *Tabebuia rosea* exhibited great and highly variable pattern of water consumption compared to *Simarouba glauca*.
- In sub optimal conditions for coffee cultivation a complementarity relationship between coffee and *Tabebuia rosea* and *Simarouba glauca* as shade tree was demonstrated. The hypothesis on competition between coffee and shade tree was confirmed only at the atypically severe dry periods.

6.5. CONSIDERATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH ON COFFEE WATER RELATIONS IN AGROFORESTRY

Understanding of water dynamics and use by coffee and shade tree is determinant of successful coffee agroforestry design especially in water limiting environments. It is known that in arid and semi-arid environments agroforestry may be not the best option due to greater water consumption by the whole system. In the humid tropics knowledge of the hydrological processes and interactions with different crops and tree species are limited. Studies of water relations in coffee agroforestry are rare and could become more required in the future with climate change.

This study demonstrated that water loss by rainfall interception on the canopies surface is of relevant importance in the coffee agroforestry water balance in sub optimal environmental condition. Despite the great quantity of literature available on the topic little was found in coffee agroforestry. Also, available studies did not include all components for rainfall interception. Due to the inherent difficulty of measuring rainfall partitioning, studies have shown great variability in interception with different environmental conditions and shade tree species. Thus, consensual estimates of interception in coffee agroforestry are still lacking. Regarding a methodological approach we could recommend careful attention to throughfall and stemflow measurements under big rainfall events. Accuracy of results would require a revision in the rain gauges spatial distribution towards a more regular sampling pattern. The tree canopy characteristics and the rainfall interception effects on available rainfall water for coffee should be taken into account by farmers as criteria for shade tree species definition, especially in conditions of limiting water.

Soil surface evaporation as one of the most important components of water balance has been poorly investigated in agroforestry systems. Most of the studies on soil surface evaporation are related to arid and sub arid environments. The shade tree effects on soil evaporation in tropical environment have rarely been studied and very few are available in coffee agroforestry. In the study site conditions soil surface evaporation represented a significant term in the system water loss and should not be neglected in the management decisions. Thus, further research is needed in coffee agroforestry regarding seasonal pattern, different arrangements and environmental conditions in order to identify how to improve whole system water use by maximal reduction of water loss by soil evaporation.

The study of root system spatial distribution was found to be an important tool to assess below ground interactions and potential complementarity or competition in agroforestry. Coffee and shade tree root systems evaluated in this study demonstrated the root niche differentiation between shallower coffee roots and *Simarouba glauca* root system that dominated deeper soil layers. This result, previously rarely demonstrated in coffee agroforestry suggested complementarity in water use between both species. However, given the dynamic characteristic of root systems and possible dominant root systems influence it would be important to check species-specific characteristics or behavioural effects on such distribution. Also, in a mature agroforestry system such as at the study site, in which average shade tree spacing was about 8 m, root competition between tree species could be expected, thereby we suggest a study of both coffee and shade tree root system by growing tree species separately and in agroforestry systems in the same environmental condition.

This study reinforced the strategic role of agroforestry on diminishing water loss by soil evaporation and enhancing soil water available for coffee growth and yield. The sub optimal condition for coffee cultivation studied is similar to a wide range of coffee farms all over the world which are predicted to fail as coffee land producer in the next decades. In such water-limiting condition suitable shade tree characteristics and functional traits would contribute to improve the system water use. The contrasting performance of deciduous and evergreen shade tree species on water consumption was demonstrated. Leaf traits were determinant on the water loss by rainfall interception from the shade tree canopies and therefore, on available soil water for coffee growth and yield. We also demonstrated that root system characteristics indicated competition or complementarity in water uptake between coffee and shade tree. However, given the heterogeneity and complex nature of the agroforestry systems, trait-based approaches and process-based models development are required in order to better understand the ecological processes and mechanisms that govern interactions between crops, trees and environment and also predict system behaviour in the current context of global climate change.

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