Competitive Interactions Between *Coffea arabica* L. And Fast-Growing Timber Shade Trees

By

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Dedication

To the memory of my father Wim and my brother Ricky.

To my mother Ninon, who taught me how to persevere.

To the environment and the people in Pérez Zeledón,
who kept me motivated in my work.

"Pasensi na wan bita bon, ma en froktu switi fu nyan."

(*Surinamese proverb*)

"Patience is a bitter tree, but its fruit are sweet to eat."

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Biography

Rudi van Kanten is a national of Suriname, born on June 1965. He concluded his elementary and high school education in Paramaribo and obtained his Agronomical Engineering degree at the Federal University of Viçosa (Minas Gerais, Brazil) in 1989. He was employed at the Ministry of Agriculture (1989 – 1992), in charge of extension planning, project formulation and the organisation of educational events. In 1994 he obtained his Masters degree in Agroforestry at CATIE. He was employed as Production Manager at CARIFRUITS Ltd., a fruit producing and processing company, from 1995 – 1998 and as Operation Manager at the Regional Project on the Eradication of the Carambola Fruit Fly in South America, a project operating in four countries, from 1998 – 1999. In 1999 he initiated his doctoral studies at CATIE with emphasis on Agroforestry, which were completed in 2003 under the CATIE – UWB joint PhD program. His current professional interests include production and conservation ecology, in applied science and transfer of technology to farmers, scholars and general public.

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Key words: agroforestry, *Eucalyptus deglupta* Blume., fine root length density (*RLD*), sap flow, *Terminalia ivorensis* A. Chev.

Summary

Early *Coffea arabica* associations with timber shade trees *Eucalyptus deglupta* or *Terminalia ivorensis* and service tree *Erythrina poeppigiana* were studied on-farm in Costa Rica (640 m a.s.l.; rainfall 3516 mm yr^{-1}). *Terminalia ivorensis* stem diameter, crown projection and shading were higher than for *E. deglupta*. Coffee plant growth was higher in uniformly than in locally fertilised plots, and higher under *E. deglupta* but was not influenced by timber shade tree proximity. Coffee produced more berries under *E. deglupta*. Coffee and timber tree fine roots (diameter < 2.0 mm) predominated in the coffee fertilisation strip compared with on the opposite side or in coffee inter-rows. Coffee *RLD* (fine root length density) was evenly distributed in 20 cm topsoil but tree *RLD* predominated in the first 10 cm. Coffee and *E. deglupta RLD* increased progressively from 2 to 5-year-old associations, with coffee *RLD* concentrating close to the coffee trunks and tree *RLD* in the inter-rows. Interspecies nutrient competition was low although *T. ivorensis* was the potentially stronger competitor with coffee and coffee the stronger competitor than trees. Daily coffee water uptake was lower under timber trees than in full sun or under *E. poeppigiana*. Both coffee and tree transpiration was restricted in the dry period by an air vapour pressure deficit (*VPD*) threshold level, while the plants followed the photosynthetic photon flux density and *VPD* pattern in the wet season. Daily water uptake ranged from 0.38 – 1.73 litre m^{-2} of foliar area for coffee and from 47 – 104, 44 – 119 and 13 – 90 litre per tree for *Eucalyptus deglupta*, *T. ivorensis* and *Erythrina poeppigiana*, respectively. In the dry period there was evidence of water competition between shade trees and coffee plants. *Eucalyptus deglupta* was a more promising timber shade tree to be associated with coffee than *T. ivorensis*.

Kanten van, RF (2003) Interacciones competitivas entre *Coffea arabica* L. y árboles maderables de rápido crecimiento. Tesis de PhD, CATIE – UWB Joint Doctoral Program, Turrialba, Costa Rica, 165 p.

Palabras claves: agroforestería, *Eucalyptus deglupta* Blume., flujo de savia, longitúd de raíces finas por volumen (*RLD*), *Terminalia ivorensis* A. Chev.

Resumen

Se estudiaron asociaciones jóvenes de *Coffea arabica* con árboles de sombra (*Eucalyptus deglupta*, *Terminalia ivorensis* o *Erythrina poeppigiana*) en una finca en el Sur de Costa Rica (640 m s.n.m. y 3516 mm año^{-1} de precipitación). El diámetro del tronco, la proyección de la copa y el nivel de sombra fueron mayores en *T. ivorensis* comparado con *E. deglupta*. El crecimiento de los cafetos con fertilización uniforme fue mayor que en los con fertilización localizada y en la asociación con *E. deglupta*, pero no hubo influencia de la proximidad del árbol de sombra maderable. Los cafetos bajo sombra de *E. deglupta* produjeron más frutos. Las raíces finas de los cafetos y árboles maderables (diámetro < 2,0 mm) prevalecieron en la banda de fertilización de los cafetos en comparación con el lado opuesto de la banda o entre callejones. La longitud de raíces finas por volumen (*RLD*) de los cafetos se distribuye equitativamente en los 20 cm del suelo superficial, pero la *RLD* de árboles prevaleció en los primeros 10 cm de profundidad de suelo. De manera progresiva se incrementó la *RLD* de los cafetos y de *E. deglupta* en las asociaciones con edades de 2 a 5 años; en los cafetos se concentró cerca de sus troncos y en los árboles se concentró entre los callejones. La competencia ínter-específica por nutrimientos fue baja, aun cuando *T. ivorensis* fue el competidor potencial más fuerte, mientras que los cafetos fueron los competidores más fuertes. El consumo diario de agua por los cafetos fue similar en cafetos a pleno sol o bajo sombra, pero con magnitudes menores bajo la sombra de los maderables. La transpiración de los cafetos y los árboles fue restringida por altos valores de diferencia de presión de vapor (*DPV*) en la época seca, mientras seguía el patrón de la radiación fotosintéticamente activa y la *DPV* en la época lluviosa. Para los cafetos, el consumo diario de agua variaba entre 0,38 – 1,72 litros m^{-2} de área foliar de los cafetos y para los árboles entre 47 – 104, 44 – 119 y 13 – 90 litro por árbol, respectivamente para *Eucalyptus deglupta*, *T. ivorensis* y *Erythrina poeppigiana*. En la época seca hubo evidencia de competencia por agua entre árboles y cafetos. *E. deglupta* fue un árbol maderable de sombra más prometedora para la producción de café que *T. ivorensis*.

Kanten van, RF (2003) Interações competitivas entre *Coffea arabica* L. e árvores madeireras de rápido crescimento. Tese de PhD, CATIE – UWB Joint Doctoral Program, Turrialba, Costa Rica, 165 p.

Palavras chaves: agrossilvicultura, *Eucalyptus deglupta* Blume., fluxo de sávia , longitude de raízes finas por volume (*RLD*), *Terminalia ivorensis* A. Chev.

Resumo

Foram estudadas as associações jovens de *Coffea arabica* com sombra de árvores (*Eucalyptus deglupta*, *Terminalia ivorensis* ou *Erythrina poeppigiana*) em uma propriedade rural da região sul de Costa Rica (640 m a.n.m. e 3516 mm ano^{-1} de precipitação). O diâmetro do tronco, a projeção da copa e o nível de sombra foram maiores para *T. ivorensis* comparado com *E. deglupta*. O crescimento das plantas de café com fertilização uniforme foi maior que naquelas com fertilização localizada e foi maior na associação com *E. deglupta*, entretanto não houve influência pela proximidade da árvore madeirera de sombra. As plantas de café sob sombra de *E. deglupta* produziram mais frutos. As raízes finas das plantas de café e das árvores madeireras (diâmetro < 2.0 mm) prevaleceram na faixa de fertilização das plantas de café em comparação com o lado oposto da faixa ou entre as fileiras de plantas de café. A longitude de raízes finas por volume (*RLD*) das plantas de café se distribuiu uniformemente nos 20 cm do solo superficial, contudo, a *RLD* das árvores prevaleceu nos primeiros 10 cm de profundidade do solo. De maneira progressiva, houve um incremento da *RLD* das plantas de café nas associações com *E. deglupta* com idades de 2 a 5 anos; nas plantas de café houve uma concentração perto de seus troncos e nas árvores se concentrou entre as fileiras. A competição inter-específica por nutrientes foi baixa, ainda que *T. ivorensis* foi o maior competidor em potencial com o café, enquanto que o café foi maior competidor que as árvores. O consumo diário de água pelas plantas de café foi similar nas plantas de café a pleno sol ou sob sombra, mas com magnitudes menores sob a sombra das árvores madeireras. A transpiração das plantas de café e das árvores foi restringida pelos altos valores do déficit de pressão de vapor (*DPV*) na época seca, enquanto seguía o movimento da radiação fotossintéticamente ativa e a *DPV* na época chuvosa. Para as plantas de café, o consumo diário de água variou entre 0,38 – 1,72 litros m^{-2} de área foliar de café e para as árvores entre 47 – 104, 44 – 119 e 13 – 90 litros por árvore, respectivamente para *Eucalyptus deglupta*, *T. ivorensis* e *Erythrina poeppigiana*. Na época seca evidenciou-se a competição por água entre árvores e plantas de café. *E. deglupta* foi uma árvore madeirera mais promissora para a produção de café que a da *T. ivorensis*.

List of abbreviations and acronyms

A_S	Cross sectional area of the sap conducting wood (cm^2)
alt	Altitude
Anova	Analysis of variance
bd	Coffee basal diameter (cm) measured at 15 cm above soil surface
CASCA	Coffee Agroforestry Systems in Central America (INCO-dev No. ICA4-2001-10071) Project
CIRAD	French development-oriented agricultural research organisation
c_s	Specific heat capacity of sap ($J\ g^{-1} \times °C$)
DBH	Tree stem diameter (cm) at 1.3 m breast height
ETo	Daily evapotranspiration (mm)
F_m	Mass flow rate of sap ($g\ s^{-1}$)
F_S	Sap flow ($l\ h^{-1}$)
Facc	Accumulated sap flow ($l\ day^{-1}$)
G	Timber tree stand basal area ($m^2\ ha^{-1}$)
ht	Coffee plant height (cm)
Ht	Tree height (m)
ICAFE	Costa Rican Coffee Institute
K	Dimensionless parameter in Granier's empirical equation (1987)
LA	Leaf area (m^2)
m a.s.l.	Altitude in meters above sea level
N	Number of intercepts (Tennant's intercept method (1975))
Pin	Electric power supplied to a stem heat balance gauge heater (W)
PPFD	Photosynthetic photon flux density ($\mu mol\ m^{-2}\ s^{-1}$)

PY	Estimated coffee yield per plant (g) or per hectare (kg ha^{-1})
Q_{flow}	Heat uptake by the moving sap stream (W)
Q_r	Rate of vertical heat loss by conduction (W)
Q_s	Energy storage per unit of time within the heated stem section (W)
Q_v	Rate of vertical heat loss by conduction (W)
R	Total fine root length (cm)
RDW	Fine root dry weight (mg)
RH	Relative air humidity (%)
RLD	Fine root length per volume (cm cm^{-3}; root diameter < 2 mm)
RY	Real coffee yield per plant (g) or per hectare (kg ha^{-1})
SNK	Student-Newman-Keuls test
SOM	Soil organic matter
SRL	Specific fine root length (root length to weight ratio assuming constant root density; cm mg^{-1})
T	Temperature (°C)
TÖB	Tropical Ecological Supporting project of the German Government
V	Sap flow velocity (m s^{-1})
VPD	Air vapour pressure deficit (kPa)

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1. Introduction

This dissertation is based on three papers included as chapters 3, 4 and 5 and referred to (in the other chapters) by their Roman numerals, e.g., Paper I.

1.1. Problem statement

Coffee (*Coffea arabica* L.) is a perennial plant originally from a cool, shady environment in forests in South-eastern Sudan, South-western Ethiopia, and Northern Kenya. As an understorey crop, the plant grew in an environment with a temperature range between 15 and 24 °C, well-distributed rainfall (1600 – 2000 mm yr^{-1}), and a dry season lasting three to four months (Maestri and Barros 1977, Smith et al. 1992, Carr 2001). The evergreen plant sheds a small part of its leaves during the dry season. Orthotropic (vertical) shoots produce plagiotropic (horizontal) branches, where fruits originate from inflorescenses developed from the buds at each node on the plagiotropic branches produced in the previous year. Each plagiotropic branch node usually produces flowers only once and pruning has to be performed to renew vegetative tissue, thereby ensuring a continued supply of flowering nodes (Cannell 1985). Commercial varieties range in height between two and three meter and the plants are submitted to pruning cycles every three to five years.

Coffee is one of the most important agricultural crops and export commodities in Central America. In Costa Rica, coffee has been grown traditionally in the Central Valley (alt. 1100 – 1400 m a.s.l.) on fertile volcanic soils and under suitable agroecological conditions (mean temperature < 24° C and mean annual rainfall < 2000 mm). Coffee plantations have expanded to less optimal areas such as Pérez Zeledón, Southern Costa Rica, since the fifties and sixties (Ramírez 1987). This area, now one of the principal coffee growing regions of the country, is characterised by an altitude lower than the optimum (mainly 600 – 800 m a.s.l.), excessive rainfall (> 2900 mm yr^{-1}) and high average temperatures (> 23.5 °C). Coffee plantations were established predominantly on unfertile Ultisols which were formerly dedicated to the cultivation of cash crops (maize (*Zea mays*) and beans (*Phaseolus vulgaris*)), the cultivation of sugar cane (*Saccharum officinarum*) or breeding of cattle (Mata and Ramírez 2002). In Pérez Zeledón, agroecological conditions are unsuitable for coffee in full sun and it is usually associated with N-fixing non-timber trees such as *Erythrina poeppigiana* (Walp.) O.F. Cook. (Neill 1993). When service trees

are replaced by fast-growing timber trees, labour for tree pruning may be reduced and profitability of the system increased. Timber trees may diversify farmer's income, thereby mitigating the consequences of fluctuating or decreasing world coffee prices (Galloway and Beer 1997).

The shade uniformity in a coffee plantation, and the fact whether or not the shade tree sheds its leaves in the dry season (Willey 1975) must be considered in evaluation of coffee–shade tree systems. Tree shade reduces coffee plant stress and influences upon the quantity and quality of light, the distribution and total amount of moisture in the system, the diurnal range of ambient air temperature, and leaf and soil temperatures. The intensity of coffee flushing (i.e., the periodic production of young shoots and leaves) leaf size, thickness, and the number of stomates per leaf are directly related to shade levels. This also affects coffee productivity, coffee bean weight, size and quality (Cannell 1971, Willey 1975, Guyot et al. 1996, Kimemia and Mburu 1988, Huxley 1999, Muschler 2001). In Southern Costa Rica, coffee production is characterised by one production cycle per year. High berry production in one year which demands more photo-assimilates for fruit formation is followed by a lower production the next year when the plants increase the supply of photo-assimiliates to their vegetative parts (Cannell 1975). Another benefit of the tree shade is that it reduces the fluctuations in the bi-annual coffee production cycle.

Fast-growing timber trees may compete significantly for natural resources (the complex of water, light, and soil nutrients) when associated with coffee plants (Beer et al. 1998), especially when established simultaneously. Competition in an agroforestry system with two components can be defined as the interaction between the two species, which reduces growth and production of one or both of the species (Anderson and Sinclair 1993). Increased acquisition of the limiting resource will always be accompanied by increased use of the limiting resources. Therefore, the best opportunities for complementarity exist if a shortage of one particular resource is clearly limiting plant growth, but other resources are under-utilised and available (Cannell et al. 1996).

Information is needed on the growth and production performance of both system components in simultaneously established coffee – shade tree associations. While it has been shown that under conditions of high resource availability, associations between coffee

and fast-growing timber trees such as *Eucalyptus deglupta* Blume. do not lead to excessive competition from trees with the coffee plants (Schaller et al. 2003b), other evidence suggests that excessive tree competition may occur under drier conditions (Jiménez and Alfaro 1999) and possibly also under conditions of lower nutrient supply. In different coffee–shade tree associations, the complex of competition factors may influence growth and production of the system components differently. In case of timber trees, the effect of the association on the tree species (timber production and quality) is of interest.

Belowground competition can be characterised by root competition, and in the present context, the phenomenon where a timber tree root system reduces the access of the coffee root system to nutrients and water, either by taking them up for its own consumption or by impeding the development of the coffee root system (Schroth 1995). Root competition can be quantified by evaluating the presence of fine roots of both of the involved species.

In general, coffee floral initiation is fastest during the dry period (low soil water availability) and blossoming and rapid shoot growth are triggered by rains (Cannell 1985), a plant-water relationship called hydro-periodism (Alvim 1977). In most cases, water is considered to be the most limiting resource in crop or forest tree physiological processes (Boyer 1982, Kramer 1986). During the period of rapid fruit expansion of coffee, water must be freely available to ensure large, high-quality yields (Carr 2001, Vaast et al. 2002). Sap flow measurement of coffee plants in full sun monoculture, under shade trees, and of the associated trees permits estimation of transpiration and hence water consumption of both species to determine possible interspecies water competition as well as the periods when plant water use of the different involved species is elevated. Little information is available on sap flow in *C. arabica* in full sun (Gutiérrez and Meinzer 1994a, b; Gutiérrez et al. 1994) or under artificial shade (Fahl et al. 2000) and none has been found on coffee – shade tree plantations where coffee plant water use might be affected by different shade levels and the water consumption of the tree species.

1.2. Objective

The present research (Papers *I*, *II* and *III*) focuses on early coffee and timber tree growth in simultaneously established plantations, root dynamics and water use during the wet and dry seasons. Interactions between the dwarf and highly productive *C. arabica* cv. "Costa Rica

95" and fast-growing timber trees *E. deglupta* and *Terminalia ivorensis* A. Chev. were studied in a recently established agroforestry trial with different fertilisation schemes which also included plots of *E. poeppigiana*. This on-farm experiment on the Verde Vigor S.A. commercial coffee farm in Southern Costa Rica (Figure 1) had the advantage of being more realistic than an on-station trial. The main disadvantage was that the research objectives could not always be reconciled with farm management practices.

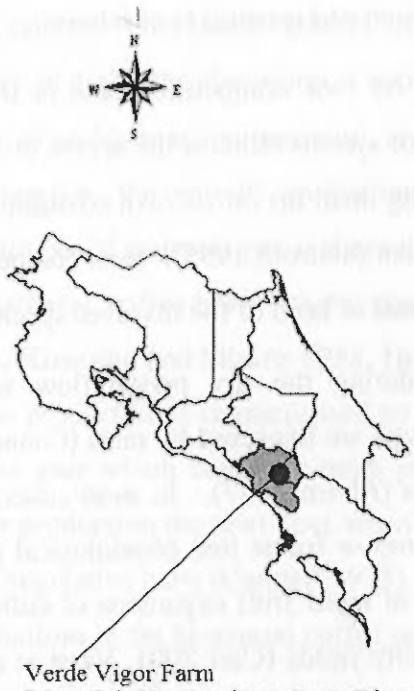

Figure 1 Site location of the on-farm experiment in Southern Costa Rica.

Source: Adapted from Renderos (2002)

In Paper *I*, early growth of *E. deglupta* or *T. ivorensis* as well as growth and production of *C. arabica* plants in coffee – timber tree associations were monitored. Five different distances of coffee plants to their nearest timber shade tree were studied and an estimation of coffee berry production was compared with actual production in 2001 to assess its reliability as a yield indicator.

Paper *II* studied root competition during the rainy and dry seasons in young coffee–shade tree associations (less than five years old) according to different depths and positions with respect to the homogenous distribution of fertilisers. Fine root length density of *C. arabica*

and trees (diameters < 2.0 m), specific fine root length and fine root dry weight of the timber tree species were calculated for depths 0–10, 10–20 and 20–40 cm close to the coffee trunk within and outside of the fertilisation band, and between coffee rows. The relationship between coffee and tree fine root distribution and their response to locally distributed coffee fertilisation was studied both in the on-farm experiment (*C. arabica* with *E. deglupta* or *T. ivorensis*) and in a pseudo-chronosequence in commercial plantations of *C. arabica* and *E. deglupta* with varying ages (two, three, four and five years).

Paper *III* investigates simultaneous measurement of sap flow in *C. arabica* and its associated trees *E. deglupta*, *T. ivorensis* or *E. poeppigiana* according to the constant heat balance principle. Coffee and tree sap flows were compared in wet and dry periods, and correlated with light availability, air temperature, air vapour pressure deficit and soil humidity. The daily water consumption per hectare for each system was also estimated.

The study was funded by the Tropical Ecology Support Program (TÖB) of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), which was aimed to improve management of tropical production systems through applied research. The sap flow equipment was funded by CIRAD (French development-oriented agricultural research organisation) and the Scientific and Cultural Centre of the French Embassy in Costa Rica. The project was hosted by CATIE which provided research and logistical support with the help of the CASCA project funded by the European Commission (Inco-dev No. ICA4-2001-10071). The farm collaborated in management, inputs and labour supply. The regional ICAFE (the National Coffee Institute of Costa Rica) office in Pérez Zeledón provided logistical support and advise on coffee management. A prior outcome of the same TÖB project has been a study on living grass barriers in coffee–timber tree plantations (Schaller et al. 2003a, b).

1.3. Hypotheses

- Coffee timber shade trees (*E. deglupta* and *T. ivorensis*) which receive additional tree fertilisation have greater height, stem diameter and crown projection, and the two timber species have different growth rates.

- Coffee plant response is a function of the proximity of the nearest timber shade tree (*E. deglupta* or *T. ivorensis*) and of treatments with or without additional tree fertilisation.
- Coffee height and basal diameter is higher in the plots with uniformly than locally applied coffee fertilisation.
- Coffee berry production is different under *Eucalyptus deglupta*, *T. ivorensis* or *Erythrina poeppigiana* shade trees.
- Estimation of coffee berry production based upon counting of eight branches is a reliable indicator of coffee yield.
- Coffee and timber tree fine root distribution and interactions can be influenced through fertiliser distribution.
- Coffee / timber tree (fine root length density) *RLD* ratios differ between fertilised, unfertilised and inter-row positions.
- Coffee and tree *RLD* increase in the zone exactly in the middle between coffee rows in older plantations.
- Sap flow in coffee plants and shade trees (*Eucalyptus deglupta*, *T. ivorensis* or *Erythrina poeppigiana*) is lower during the dry season than that during the wet season.
- Sap flow measured in coffee plants and shade trees is correlated with soil volumetric water contents and microclimatic conditions.

2. Literature review

2.1. *Coffea arabica* agroforestry systems

Arabica coffee, family Rubiaceae, derived its species' name from Arabia where Europeans first saw the plant in Yemen (Willson 1999). Coffee became widely accepted in Europe in the 18th century (Matthee 1995) and European botanical gardens played an important role in spreading coffee to tropical America in that century. The first coffee plants arrived in Suriname in 1713, found their way to French Guyana and arrived in Brazil, in 1727. A single plant, introduced in Martinique in 1721, led to the introduction of coffee to other parts of the Caribbean and Latin America (Smith et al. 1992). Nowadays, Brazil is the largest coffee producer with Colombia just being replaced by Vietnam as the world second largest coffee producers (CEPAL 2002).

The two most grown varieties in Costa Rica are Caturra, a mutant of the Bourbon variety, and Catuaí, a hybrid variety (Mundo Novo x Caturra), both introduced from Brazil. As an alternative to face coffee rust (*Hemileia vastatrix* Berk & Br), ICAFE selected the highly resistant hybrid dwarf cultivar Costa Rica 95 out of the Catimor T8600 series (Caturra x Timor hybrids). As compared to Caturra and Catuaí, Costa Rica 95, with notably darker leaves, has a low plant stature like Caturra but with shorter branches, allowing closer planting distances (Aguilar 1995, ANACAFE 1998, Bertrand et al. 1999). The variety has a higher production than Caturra and Catuaí (Aguilar 1998), presents a precocious harvest and depends on a high fertilisation scheme to maintain its high production. Costa Rica 95 is neither resistant to coffee berry disease (*Cercospora coffeicola* Berk & Cook), a disease which is strongly related to the physiological state of the plant, nor to *Meloidogyne* spp. and *Pratylenchus* spp. nematodes, but responds very well to acid soils with high aluminium levels. Like the other coffee varieties, the plant is susceptible to Anthracnose (*Colletotrichium coffeanun* Noack) and *Mycena citricolor*, two diseases which can cause serious economical losses and are combated with agrochemical use (Aguilar 1995, Bertrand et al. 1999).

In sub-optimal climatic zones (alt. < 1000 m a.s.l.), *C. arabica* needs to be grown under shade. Tree shade reduces oscillations in the biannual coffee production (cyclic yield pattern) in regions such as Costa Rica, extends the crop's productive life, and reduces

agrochemical use due to lesser incidence of weeds, diseases and pests. Trees also provide soil mulch and may improve nutrient cycling if tree roots explore the soil deeper than the coffee roots. Disadvantages may be, extra labour needed for tree pruning (especially non-timber trees), damaging of coffee plants due to tree pruning, thinning, or harvesting, allelopathic tree effects on the crop, and tree competition for soil nutrients and / or water (Willey 1975, Beer 1987, Ong 1996, Willson 1999, Kho 2000).

Apart from their fast growth, the following characteristics should be used to select timber tree species that can be successfully associated with coffee (Beer 1987):

- compatibility with the crop with minimal competition for water, soil nutrients and above and below ground growing space,
- a small diameter, low density crown to reduce wind effects, permit relatively high shade tree densities without reducing light levels below critical values for the crop, and minimise crop damage when individual trees are harvested,
- self-pruning and the ability to form a straight unforked stem in open-grown conditions,
- absence of major disease or insect susceptibility which could lead to sudden defoliation, and
- a rooting system not susceptible to wind throw.

In agroforestry, farmers will often prioritise the management of the crop component, and the trees are likely to be left to fend for themselves. Control of competition, both above and below ground, will be greatly modified by choosing the right species, planting density and plant arrangement (Huxley 1999). The trees create above and below ground microenvironment zones varying over time that comprise the growing space available to the crops (Van Noordwijk and Purnomosidhi 1995, Kho 2000, Smith 2000).

One of the benefits of tree shading is that it may increase the fraction of available water used by transpiration through decreasing soil evaporation. Potential benefits from shade are likely to depend on tree spacing and age, canopy structure, incident radiation, shading intensity and the photosynthetic pathway of the understorey crop (Ong et al. 2000).

Ong (1996) uses a simplified tree-crop interaction equation derived from hedgerow intercropping research data, with relatively easily measurable variables:

$$I = F - C + M + P + L \ . \qquad [1]$$

Crop yield is a function of the benefit of tree pruning on soil fertility and microclimate of the soil surface (F); the crop yield reduction due to inter-specific, tree-crop competition (C); the consequences of above ground changes in air temperature, light, humidity and wind speed (M); the consequence of changes in soil physical properties (P); and the reduction or avoidance of nutrient or water losses (L). For agroforestry systems with perennial crops, modelling is rather complicated.

Wilson (1988) used a competitive balance index (C_b) [Eq. 2] and a competitive intensity index (C_i) [Eq. 3] to express the effect of the interactions between plant components (e.g., yield, roots, shoots) of two crop species (grasses, legumes or weeds):

$$C_b = \log_e \times \frac{w_{ab} / w_{ba}}{w_{aa} / w_{bb}} \qquad [2]$$

$$C_i = \frac{w_{aa} + w_{bb}}{w_{ab} + w_{ba}} - 1 \qquad [3]$$

where w is dry weight per original plant; a and b are the two components (species / varieties) investigated; w_{aa} is the weight of component a in monoculture; w_{bb} the weight of component b in monoculture; w_{ab} weight of a growing in association with b; w_{ba} weight of b growing in association with a. The models however, do not respond to variations in planting densities.

Models representing root / shoot interactions, growth and functioning, and interactions with the above and below ground environment require considerable physiological understanding and parameterisation which may be beyond the scope of agroforestry (Gregory 1996a).

2.2. Examples of shade tree species associated with C. arabica

2.2.1. Eucalyptus deglupta

Eucalyptus deglupta Blume. (Myrtaceae), is a fast-growing tree species of low tropical humid forests originating from Papua New Guinea, parts of the Indonesian archipelago and the Philippines. This self-pruning tree (in planting distances < 5 m) can

reach heights of 35 – 60 m and *DBH* (tree stem diameter at 1.3 m breast height) of 50 – 200 cm in its native state. It may already produce flowers in the second year. In Central America, the species has been reported to grow well at altitudes below 1200 m a.s.l. with annual rainfalls exceeding 1000 mm. The mean rainfall in the tree's natural habitat is between 2500 – 3500 mm yr^{-1}, whereas 5000 mm yr^{-1} is indicated as the upper limit (Turnbull and Pryor 1984, CATIE 1994, Eldridge et al. 1994).

Young trees have to be protected from weed competition during establishment. At spacing > 5 m between trees, vigorously growing lateral branches may need to be pruned. In forestry plantations, initially spaced at 3 x 3 m, *E. deglupta* presents a well defined self-pruning. In Central America, leaf-cutting ants *Atta* spp. are a primary plague of young trees while termites are reported to be a major pest for adult trees both in Australia and Central America (Turnbull and Pryor 1984, CATIE 1994, Sánchez 1994, Chavarría 1997, Schaller et al. 2003b). Due to its light open crown with medium sized leaves, the tree species is suitable as a shade tree in agroforestry systems.

Forestry plantations, initially with 1111 trees ha^{-1}, can be thinned by 60% (including mortality) when average tree height reaches 7 – 8 m and once again by 60% when average tree height reaches 13 – 15 m thus leaving a final harvestable pure tree stand of 180 – 200 trees ha^{-1}. For agroforestry plantations, a maximum of 100 trees ha^{-1} is recommended which corresponds to tree distances between 8 – 12 m (CATIE 1994).

In Central America, annual height increments above 3.5 m were obtained in sites with well-drained loam – sandy to sandy soils. In Costa Rica, 16-year-old trees reached 30 m heights and 33 cm *DBH* and 20-year-old trees were observed with 50 m height and 85 cm *DBH*. (CATIE 1994). Growth rates on suitable sites may reach between 25 – 40 m^3 ha^{-1} yr^{-1} over 15 years (Eldridge et al. 1994).

Wood can be used as fibre for pulp or fuel and after treatment for posts, poles, construction, scantling, flooring and furniture (Turnbull and Pryor 1984, CATIE 1994, Eldridge et al. 1994).

2.2.2. *Terminalia ivorensis*

Terminalia ivorensis A. Chev. (Combretaceae), is a transitional moist evergreen forest/moist semi-deciduous forest, large pioneer species, originally from West Africa (extending continuously from Guinea to West Cameroon). The tree tends to shed its leaves during the dry season and is sensitive to water stress. However, this species can withstand an annual rainfall of < 1300 mm yr^{-1} and a dry season exceeding 4 – 5 months. It grows up to maximum altitudes of 1200 m a.s.l. Fruit bearing starts at 5 – 6 years and the winged seeds are wind dispersed (Bonaparte 1967, Lamb and Ntima 1971, Swaine and Hall 1983, Dupuy and Mille 1993, Norgrove and Hauser 2000).

Within the insect pests, Boateng (1992) names fruit- and shoot borers, defoliators, sucking pests and termites. There are some fungi such as *Nectria* spp. causing cancer and gummosis.

Swaine and Hall (1983) reported that *T. ivorensis* plantations in Ivory Coast and Ghana experienced such great mortality that after 30 years, very few trees remained alive. Since no causal pathogen could be isolated, they hypothesized that this species is not normally long-lived despite the large size it sometimes attains. Boateng (1992) relates the dieback to a number of causes such as a prolonged drought, the action of the *Endothnia* sp. fungus, nutrient imbalance, site factors, fire and most likely the negligence of thinning.

T. ivorensis in plantations can achieve a height of 30 m in 20 – 30 years. One tree reached 36.5 m in height and a *DBH* of 240 cm after only 22 years (Lamb and Ntima 1971).

For planting purpose bagged plants are preferred over stumped plants (Dupuy and Mille 1993). The same authors suggest tree thinning of a 700 trees ha^{-1} pure stand. The first thinning is recommended when the dominant height reaches 11 m, reducing the stand to 50%. The second after the mean diameter has reached 20 cm and stand basal area (*G*) 11 m^2 ha^{-1}, reducing the density to 175 stems ha^{-1}. Finally, the third one, bringing density down to 70 stems ha^{-1} when the mean diameter has reached 40 cm and the *G* 12 m^2 ha^{-1}.

The good general-purpose timber is used in building, as roofing shingles, in the panelling industry, in furniture making and sometimes used as fuel-wood (Chudnoff 1979, Boateng 1992, Dupuy and Mille 1993).

2.2.3. Erythrina poeppigiana

Erythrina poeppigiana (Walp.) O.F. Cook. (Papilionaceae), is a fast-growing tree which originates from the Andean foothills from Venezuela to Bolivia and was introduced to Central America and the Caribbean in the nineteenth century as a coffee and cocoa shade tree. It is now one of the most common coffee shade trees in Costa Rica (Neill 1993) that reaches heights of 30 m in non-pruned conditions and is generally found in elevations ranging from 150 to 1900 m a.s.l. and annual rainfall between 1000 – 3000 mm, tolerating dry seasons up to six months. The species can be propagated by cuttings and is easily recognisable by its conical prickles in the bark of the trunk and branches and alternate leaves with three leaflets and large, cup shaped stipels. The inflorescence is racemose and the relatively large flowers with orange petals are adapted to pollination by nectarivorous birds.

Rapid plant growth and sprouting, high biomass production, easy propagation from cuttings and the ability to withstand regular pruning combined with its multipurpose character (shade, nitrogen fixation, green manure) make the tree an interesting low-cost management option for coffee farmers in terms of inputs (Glover and Muschler 1993, Russo 1993).

2.3. Roots and competition

Roots are responsible for tree anchoring, soil development, soil organic matter (*SOM*) turnover, water and nutrient acquisition, and synthesising plant-growth-substances (Jackson 1983, Bledsoe et al. 1999, Atkinson 2000) and are an essential component in carbon, nutrient or water cycling studies in plant environments (Fairley and Alexander 1985, Fogel 1985, Jackson et al. 1996).

Plants can exploit soil heterogeneity by root proliferation, and changes in nutrient uptake rates, or the frequency of mycorrhizal infestation (Jackson and Caldwell 1993). Root systems tend to cluster, leaving vacant spaces to be utilised or re-utilised at a later stage. Individual roots or small clumps of fine roots compete when their depletion zones (the space around a root in which available nutrients or water are consumed) for particular resources overlap. The amount of soil nutrients extracted depends on the rooting characteristics such as root length density (*RLD*), root diameters and the size of the root system, the crop demand, the type of nutrient and the available nutrient pool, soil

diffusivity coefficients and plant water availability. Nutrient extraction is determined by soil diffusion and mass flow processes and the combination and interaction of factors determine a unique level of competition for each nutrient, assuming higher competition for elements with little soil interaction such as N in comparison with elements more strongly associated with soil minerals and organic matter such as P (Gillespie 1989, Gregory 1996b, Huxley 1999, Bengough et al. 2000). The clustering trend of roots weakens the validity of water and nutrient uptake models that assume that roots are evenly distributed, and might lead to overestimation of root presence (Gregory 1996a). Furthermore, Tardieu et al. (1992) concluded in a simulation study on root-soil water movement for a regularly distributed, clustered and strongly clustered root pattern that the soil resistance tends to increase and therefore the water uptake tends to decrease for clustered roots.

The ability of a root system to expand depends on the stimuli of root apices and the ability of the root system to respond to environmental stress. The balance between terminal extension growth and lateral branching of existing roots initially helps define the root architecture, which sets the limits within which a particular species can exploit the soil (Huxley 1999).

Roots can be divided into fine roots (diameter < 2 mm) and structural roots. Fine roots, the primary pathway for water and nutrient uptake (Jackson et al. 1997), account for 5 – 10% of total root dry weight or 3 – 5% of total dry weight biomass (Huxley 1999). In general, specific root length i.e. the root length to weight ratio assuming constant root density (*SRL* in cm mg^{-1}) is highest in young root systems and in those growing under low nutrient supplies. Assuming constant root density, *SRL* is largely determined by root diameter, and so it may seem more sensible to measure this variable directly. For most species, *SRL* is highest in low fertility soils (Fitter 1985).

Root distribution and density within the soil profile are primarily genetically determined, but it is also a response to soil type, moisture, nutrient availability, organic matter distribution and soil management. Sub-optimal production occurs when species with limited response plasticity are present in conditions where maximum response to the constraining factors is required. Environmental resources such as light, water and soil nutrients are the functional factors to which the plant will adapt and / or respond (Myers et

al. 1994). On the other hand, the soil profile is explored differently by different root systems, promoting root growth soil horizons where the roots experience the best water and nutrient conditions. In poor soils, trees tend to develop long root systems, which penetrate large soil volumes rapidly. In better soil conditions the development of ramifications with numerous short roots (e.g. mycorrhizae) is promoted, leading to an exploitation of available moisture and nutrients (Person 1983).

Jackson et al. (1996) analysed 250 root studies covering 11 terrestrial biomes to provide a database for use in assessing soil C distributions and in examining the effect of roots on C, H_2O, and nutrient fluxes between soil, plants and atmosphere. A global average indicated 30% of roots in the top 10 cm of soil, 50% in the top 20 cm and 75% in the top 40 cm soil layer. Large variations occurred between the different biomes. Tundra vegetation had as much as 60% of their roots in the upper 10 cm of soil while desert plants had only 20% of their roots in this same layer. The root / shoot ratio varied as well, ranging from values of 0.1 for managed croplands and values from 4 – 7 for tundra, grasslands and cold-deserts. Root densities were as high as 40 kg m^{-3} in sclerophyllous shrublands and tropical evergreen forests and as low as 5 kg m^{-3} in deserts and croplands.

Deep roots (taproots, sinker roots and obliquely descending lateral roots) need to be considered as well in the development of ecosystem models since they are of functional significance in ecosystem water fluxes, and for carbon and nutrient cycling (Nepstad et al. 1994, Canadell et al. 1996, Jackson et al. 1997, Jackson et al. 1999). In a review of root depth studies covering 253 woody and herbaceous species in 11 biomes, Canadell et al. (1996) report a record observation in a tropical Savannah with sandy soils in central Kalahari, Botswana where *Boscia albitrunca* tree roots were observed at a depth of 68 m during well drilling activities. In the Amazonian forest, Nepstad et al. (1994) found tree roots reaching up to 18 m depth, being responsible for absorbing up to 75% of the absolute total amount of plant-available soil water which was located below 2 m depth during a survey in a severe dry season with only 95 mm rainfall in a 5.5 month period. This was exactly the part of the soil which had been ignored by the vegetation-atmosphere models used for that region.

Root characteristics across plant species vary apparently independently of shoot characteristics. If water or soil nutrients are in short supply within the plant, the root system will get a larger share of the carbohydrate supply within the plant and will increase in size relative to the shoot or even in an absolute sense. When light (or CO_2 supply) is limiting plant production, the shoot will increase in size relative to the root system (Van Noordwijk et al. 1996).

Trenching (Van Noordwijk et al. 1996) or the establishment of living grass barriers can reduce root competition from trees (Schaller et al. 2003a). A combination of water stress and soil disturbance in the topsoil layers by cultivation or trenching can greatly modify how (and sometimes when) tree roots occupy this zone (Huxley 1999).

The level of tree-crop root presence, an indicator of competition, can be quantified by the half-distance between roots (r) [Eq. 4], assuming higher competition for lower r values (Gillispie 1989):

$$r = \frac{1}{(\pi \times RLD)^{1/2}} . \qquad [4]$$

One particular factor that can increase tree competition with crops is the activity of superficial rooting systems of young trees that might be especially competitive in the establishment phase of the agroforestry system (Smith 2000).

Root competition is the phenomenon where one root system reduces the access of another root system to nutrients and / or water, either by absorbing them for its own consumption or by impeding the development of the associated root system (Schroth 1995). Tree root systems are dynamic and flexible and they react to environmental and management conditions; for example, fertilisation might increase the presence of tree roots according to the requirements of specific agroforestry situations where fertilisation and mulching of the topsoil may favour the formation of shallow tree roots in that layer.

Desirable tree root characteristics vary from system to system. For certain conditions limited lateral root extension and low fine root presence in the topsoil might be desired for low competitiveness, whereas high root mass and turnover rates in the topsoil might be desired for high carbon inputs (Schroth 1995). Trees with high fine root presence in the

subsoil and deep root systems might be required for efficient nutrient cycling, as they bring available nutrients from the deeper layers to the surface via litter fall (Schroth 1995, Van Noordwijk and Purnomosidhi 1995, Van Noordwijk et al. 1996, Rowe 1999).

Two strategies to diminish tree-crop interactions might be selecting tree species with low root competitiveness or tree species with a root distribution complementary to that of the crops. Regarding the first strategy, it should also be considered whether reduction of leaching and soil enrichment with organic matter are important objectives which will not be fulfilled by choosing species with low root competitiveness (Schroth 1995). The second strategy refers to the ability of species combinations to coexist and utilise different niches (Anderson and Sinclair 1993).

To avoid negative interactions in agroforestry systems, tree species which provide the desirable functions of tree roots in the field at minimum cost should be identified. Information is required about the distribution and dynamics of tree roots under different site and management conditions, their competition with different crops and their effects on soil fertility (Schroth and Lehman 1995).

Several authors described coffee rooting systems in detail (Guiscafré-Arrilaga and Gómez 1940 and 1942, Franco and Inforzato 1946, Suárez de Castro 1953, Garriz 1978 and Cuenca et al. 1983). No particular coffee root system type has been identified since root distribution depends on both the genetic constitution and environmental conditions such as soil type and aeration, fertilisation and water availability (Franco and Inforzato 1946), as well as the presence of other plants. The "typical" root system of transplanted coffee plants consists of primary roots no deeper than 0.5 m (Franco and Inforzato 1946), 4 – 8 axial roots, lateral roots near the surface up to 3.0 m from the coffee trunk, lateral roots in deeper zones (also up to 3.0 m), feeder-bearers and the feeders or fine roots (Nutman 1933). Little information is available on rooting patterns of the three associated tree species in the present study.

2.4. Measurement of fine root parameters.

2.4.1. Root studies

Tree-crop below ground interactions are much less understood than visible above ground interactions and questions need to be answered concerning the lateral and vertical root extension, mycorrhizal associations, root turnover in relation to above ground phenophases, the periods during which extension growth occurs, the space tree roots are occupying, and nutrient and water absorption (Rao et al. 1993, Huxley 1999). Information about below ground interactions has lagged seriously behind other research topics (Huxley 1999).

The majority of root studies have been performed on annual crops or trees in temperate forests. Much of current agroforestry root research has been concentrated on alley cropping systems (Hauser 1993, Rao et al. 1993, Schroth and Zech 1995, Jonsson et al. 1988, Jones et al. 1998, Lehman et al. 1998). For woody perennials and other tree-crop mixtures in agroforestry there is yet little information and knowledge on the rooting pattern of newly introduced tree species, looking closely at the development of roots during the first few years of development might contribute to the understanding of agroforestry systems (Gregory 1996a, Huxley 1999).

Root systems in field situations are difficult to study, primarily because they are spatially and temporally complex and because available methods for their study are labour-intensive and destructive (Bledsoe et al. 1999).

Branching structures of the system can be quantified by describing root geometry and topology. The production of fine roots is partially determined by the root system architecture (Fitter 1985). Quantitative information on root morphology is essential for an understanding of their importance in the ecosystem. As in situ root physiology studies improve, the ability to integrate all portions of the plant flow path can yield important physiological insights and improved mechanistic understanding of plant-water relations, enabling predictions on ecosystem processes, the water balance and biosphere-atmosphere interactions (Jackson et al. 2000). On the other hand, absence of information on root system functioning would preclude research from being able to effectively design and manage agroforestry and other systems (Atkinson 1996).

The ideal root study provides data to compare total root biomass, fine roots alone, coarse roots, the distribution of root length and surface area with depth, the proportion of live and dead roots, and root distribution for ecosystems and individual species (Jackson et al. 1996).

Limitations to compare root data between different studies might be due to one or more of the following (Persson 1983, Jackson et al. 1996):

- sampling was carried out on few occasions during the study,
- fine-root biomass includes an unknown amount of dead roots,
- the number of replicate samples was insufficient to detect significant differences between samplings,
- the estimated quantitative variables (e.g. the number of root tips, root length) are not directly convertible into changes in root weight, and
- the root fragments were not classified into species or diameter-fractions.

Methods to study root parameters, such as biomass, length surface area, and volume, include: (i) Excavation of soil following coarse tree roots which might involve heavy equipment, (ii) Quantitative soil pits, (iii) Fractal branching patterns (Van Noordwijk and Purnomisidhi 1995, Van Noordwijk et al. 1996, Ong et al. 1999, Ozier-Lafontaine et al. 1999, Rowe 1999, Oppelt et al. 2001), (iv) Serendipitous events in which nature or mankind expose root systems of large trees, (v) Wall profile or trench methods (Bledsoe et al. 1999), (vi) Root windows, including larger walls and trenches, (vii) The pinboard ("fakir bed") method (Oliveira et al. 2000), (viii) Soil in-growth cores (Fahey et al. 1999 , Oliveira et al. 2000), (ix) Minirhizotrons (Gregory 1996b, Ephrat et al. 1999, Fahey et al. 1999, Smit et al. 2000), (x) Isotope techniques with ^{3}H, ^{14}C, ^{15}N, ^{35}S and ^{32}P as the most commonly used radioisotopes (Thomas et al. 1998, Huxley 1999, Rowe 1999, Binham et al. 2000), (xi) Computer-Assisted Tomography (CT) and Magnetic Resonance Imaging (MRI) (Asseng et al. 2000), (xii) DNA sequence variation (Jackson et al. 1999, Jackson et al. 2000), and (xiii) ground-penetrating radar (GPR) (Butnor et al. 2001).

2.4.2. Soil coring

Soil cores can be described as the classic method to harvest roots for studying root length, weight and diameter (Oliveira 2000). The most widely used core length is 10 cm and the diameter of the core varies between 4 – 8 cm (Photo 1 illustrates the "Göttingen" auger (diameter 8 cm) employed in the present study). The method, pointed out by Bengough et al. (2000) as being the most accurate for *RLD*, has great value due to its simplicity and has been extensively used by many researchers over many years (Persson 1983, Bledsoe et al. 1999). A clear disadvantage of the technique is its destructibility as well as the total amount of time needed for root harvest, washing, sorting and counting / image analysis, especially because many sub-samples are needed.

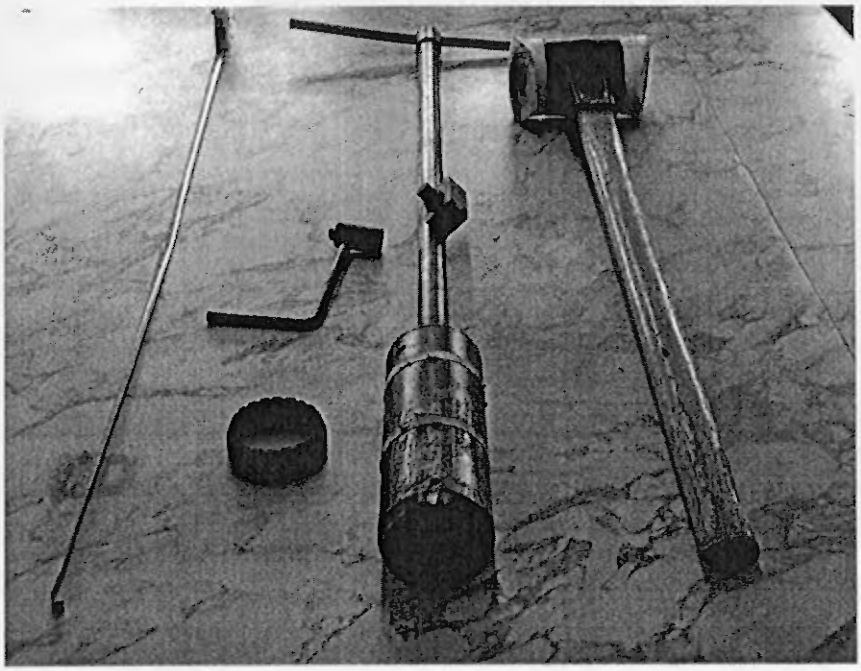

Photo 1. "Göttingen" auger (1.25 m long; cylinder internal diameter 8 cm and height 25 cm), with hammer, spare crown and shaft to expel soil cores.
Photo R. van Kanten.

In systems with crops in rows, Oliveira et al. (2000) advise stratified sampling within and between rows. As in above ground measurements, the number of replications (soil samples) adopted by different authors varies from three to ten per experimental unit. Serious biases may be introduced if the average value for all samples is assumed to be the

average for the field. For tree related sampling, the use of equidistant sampling spots in concentric circles around the tree trunk results in a fairly uniform coverage of the area occupied by the tree roots. This system was used by Weller (1971) using 10 sampling spots for each of the five concentric circles around the tree trunk incrementing in diameter from 1 to 5 m. The high amounts of samples needed per tree, the difficulty to trace concentric circles in the field and the fact that a higher percentage of the soil surface (m^2) is sampled in the circles close to the tree are a limitation of the method.

2.4.3. Root separation

Photo 2. Root washing installation with 1.0 and 0.5 mm sieves.
Photo by R. van Kanten.

Separation of live and dead roots is a difficulty that cannot be underestimated. Most soils contain large quantities of *SOM* fragments, which are difficult to separate from fine roots. Research with fresh samples and hand sorting *SOM* from roots relies on visual clues. The first stage is gently washing soil cores either automatically (e.g. root elutriator) or by hand (such as done in the present study; Photo 2), using a series of sieves and a gentle stream of water, since high water-flows easily damage fine roots (Oliveira et al. 2000). The root hydro pneumatic elutriator (Smucker et al. 1982) works well for many types of soils,

but soils of high organic matter content, present problems in the separation of roots from *SOM* (Bledsoe et al. 1999). In a study of sieve size effects on root length measurement of *Z. mays* and *Grevillea robusta*, Livesly et al. (1999) determined that a 0.5 mm sieve could recover 73 – 96% of the specific root length obtained by using a 0.25 mm sieve. The authors state that sieve size determination should also depend on the objectives of the study and the amount of available resources. Fine roots, for example, which passed through the 0.5 mm and were recovered by the 0.25 mm sieve contributed to only 6% of the total measured root biomass. According to Bengough et al. (2000) root losses during washing can reach up to 30%.

Once free from soil particles, roots should be separated from debris and organic matter. This is a tedious, time consuming process and Bledsoe et al. (1999) recommend to allocate a standard site-specific time period per sample for this activity before proceeding to the actual fine root sorting. In a study with sorghum and two tree species in a semi-arid region of Northeast Nigeria, Jones et al. (1998) decided to discard samples from the 0 – 10 cm soil layer for further analysis. The amount of litter in these samples made separation of roots impracticable and the authors found no visual evidence of substantial amounts of live tree and sorghum roots, a consistent finding with other dry season root profile studies.

Live roots are generally less dark in colour, turgid, and not easily broken, and the cortex and periderm are not easily separated. They also can be identified according to the association with mycelia (Fogel 1985). Dead roots are generally brittle, dark brown or black, wrinkled and easily broken off (Persson 1983, Bledsoe et al. 1999). In some cases, however, the distinctions might not be clear. In preliminary studies, Schroth and Lehman (1995) for example, encountered difficulties on distinguishing *Gliricidia sepium* and *Calliandra calothyrsus* fine roots from weed and maize roots with sufficient precision. In the same study, living and dead *Senna siamea* roots could not be distinguished based on visual or mechanical criteria.

2.4.4. Root length measurement

Root length measurement can either be done by the line intercept method or by image analysis which is a computerised development of the former. In the line intersect method of Tennant (1975) roots are placed in a film of water in a transparent tray with a

grid paper (e.g., 1 x 1 cm squares) underneath. With the help of a (5 – 10 x) magnifying glass and a hand counter, roots which cross an intercept line are counted once, and roots which touch the same intercept more than once (e.g. a root lying exactly on the intercept) are counted twice. Correct interpretation of intercepts is critical. Root material has to be separated well on the tray to avoid overlapping and underestimation of root length in total fine root length (R; in cm) calculation [Eq. 5]:

$$R = \frac{11}{14} \times N \times G \qquad [5]$$

where N is the number of intercepts and G the Grid unit values. G's of 0.3928, 0.7857, 1.5714 and 2.3571 correspond to ½ x ½, 1 x 1, 2 x 2 and 3 x 3 cm grid squares, respectively.

Tennant (1975) calibrated the line intersect method using root length ranges of 0 – 300, 75 – 700, 275 – 1100 and 600 cm – outside test range, respectively for ½ x ½, 1 x 1, 2 x 2 and 3 x 3 cm grid squares based on counting times of 5 – 6 minutes maximum and coefficients of variation of 5% or less.

In the image analysis method, fresh roots are placed in a film of water (to facilitate root distribution) in a tray; roots are scanned and length and surface are calculated from algorithms (Bledsoe et al. 1999). There are several root-scanning software programs available such as Regent Instrument's "WinRHIZO™" and Louisiana State University's Agricultural Centre's "G-ROOT." Bouma et al. (2000) emphasise the importance of reporting the details of the scanning protocol for comparative reasons because obtained results might be influenced by: staining period (where applied), maximum root density, scanning resolution and transformation threshold (the brightness value at which the scanning program decides whether a scanned pixel belongs to a root or the background). Light coloured roots (e.g. grass roots) may need to be stained prior to scanning.

2.5. *Plant water use*

Plants use water in biochemical reactions, as a solvent, to maintain turgor and for transpiration (Jackson et al. 2000). Water movement in the roots and the stem can be measured and quantified volumetrically (Fernández et al. 2000), indicating plant water

availability and enabling an estimation of the degree of water competition between different plant species growing in the same environment. If measured for a sufficient long period, the quantity of sap flow upward through the stem must equal transpiration of the leaves (Swanson 1994).

Reich and Borchert (1984) report a high correlation between rates of tree development and seasonal variation in tree water status, but only an indirect correlation between tree development and environmental water availability. During the January – April dry season, Meinzer et al. (1999) studied ten different tropical, deciduous or evergreen tree species in a tropical moist forest in Panama (9°09' N, 79°51' W) which were found to be exploring soil water at different depths, according to the tree species. Smaller trees as compared to taller trees tended to explore water in deeper soil layers.

Ideally sap flow should be measured in plant roots, near the base of the trunk (stem), at branch level and complemented with measurements of stomatal conductance in individual representative leaves (Andrade et al. 1998, Green and Clothier 1999). However, practical considerations might limit the measurement to the stem. Especially in small trees, the mass flow rate near the base of the stem is essentially equivalent to transpiration, with little effect of stem storage compartments which can cause a considerable lag period between fluctuations in transpiration and fluctuations in sap flow near the base of the stem (Andrade et al. 1998). Sap flow measurements considered to be equivalent to the plant transpiration rates can be counter checked with the Penman-Monteith model (Allen et al. 1998). Daily rates of water use can be estimated and soil moisture contents can be related to root presence in different systems (Green and Clothier 1999).

Sap flow measurement consists of the measurement of transpiration rates for whole plants, individual branches or tillers by techniques which measure the sap-ascending rate in the plant system. The method is easily being automated using a data logger, and is amongst others useful to study plant water relations and tree energy budgets. It is relatively more easily executed in comparison with other methods to determine transpiration such as stomatal conductance and deuterium tracing (Wiltshire et al. 1995, Smith and Allen 1996, Grime and Sinclair 1999) and might be the only alternative for measuring tree transpiration in complex heterogeneous terrain (Hatton et al. 1995). Besides this, stomatal conductance

on its own underestimates the real transpiration rate and was found to be less influential on transpiration in three coffee cultivars than hydraulic and crown architecture of the studied coffee plants (Tausend et al. 2000).

A thermal tracer technique which measures sap flow is the constant heat balance method (divided into methods for plant stems and methods for tree trunks) (Swanson 1994, Smith and Allen 1996, Fernández et al. 2000). The stem heat balance gauge comprises of a flexible heater, typically a few centimetres in width (Photo 3), which is wrapped around the stem and enclosed in a layer of cork, a layer of foam insulation and an aluminium-coated PVC weather shield (Photo 4). A known electrical power supplied to the heater (P_{in} in W) is partitioned into Q_v (the rate of vertical heat loss by conduction in the stem), Q_r (the radial heat loss by conduction) and Q_{flow} (heat uptake by the moving sap stream) [Eq. 6]:

$$P_{in} = Q_v + Q_r + Q_{flow} \qquad [6]$$

Some researchers divide Q_v into Q_d (downward) and Q_u (upward). Weibel and De Vos (1994) also consider Q_s energy storage per unit of time within the heated stem section, alleging that its neglecting might contribute substantially to the error. P_{in}, Q_v and Q_r (Figure 2) are measured to determine Q_{flow} [Eq. 6], to be converted into the mass flow rate of sap F_m (g s^{-1}) calculated by [Eq. 7]:

$$F_m = \frac{2 \times Q_{flow}}{c_s \times (\Delta_a T + \Delta T_b)} \qquad [7]$$

where c_s is the specific heat capacity of sap and (ΔT_a + ΔT_b) / 2 the increase in sap temperature across the heater, assuming that heating of the sap is radially uniform.

To make good contact between stem surface and heater or thermocouples, gauges should be installed on straight sections of the stem without swelling or lumps. If gauges are to remain for several months, it should be ensured that deformations on the growing stem and appearance of adventic roots do not occur through this process (Smith and Allen 1996).

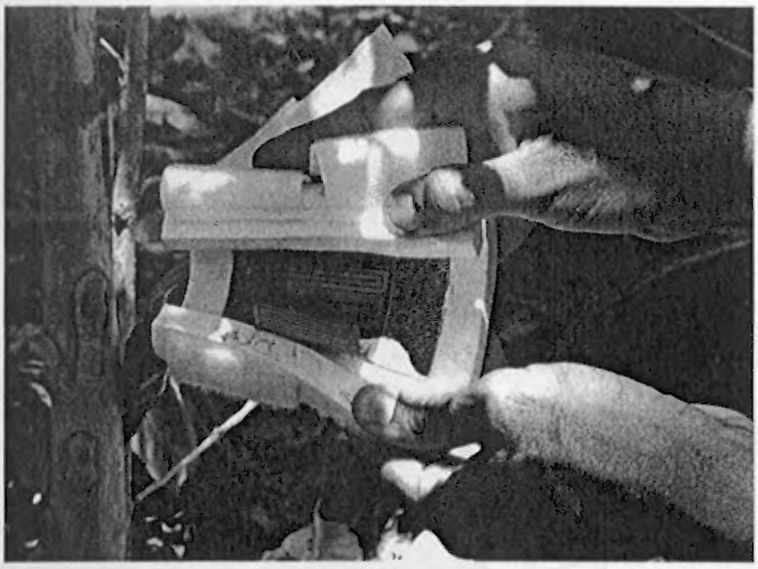

Photo 3. SGB25-ws gauge with view of the heater element and cork isolation, ready for placement on a cleaned coffee stem.
Photo P. Vaast.

Photo 4. SGB25-ws gauge installed on a coffee trunk protected with foam collar o-rings with plastic-tack sealer on the top of the upper ring.
Photo P. Vaast.

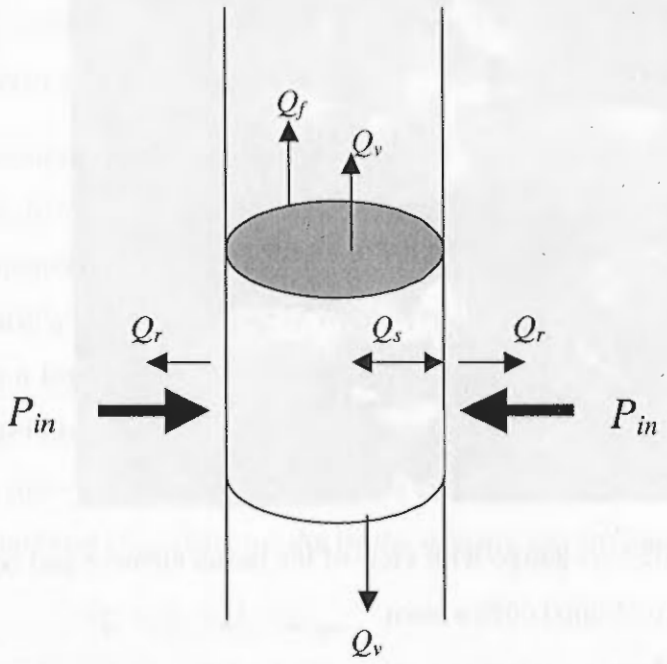

Figure 2 The constant power stem heat balance principle: different forms of heat loss Q_f, Q_r, Q_s and and Q_v are in balance with electrical power supplied to the heater P_{in}. Source: Adapted from Smith and Allen (1996).

The thermal dissipation method is an empirical method developed by Granier (1985) where a pair of probes is introduced in the tree trunk's sap conducting xylem or sapwood (Photo 5) to measure a temperature difference between the upper heated probe and the lower reference probe. Maximum temperature difference is assumed to occur when sap flow is zero and higher sap flow causes more heat dissipation of the heated probe and consequently a lower temperature difference between the probes (Granier 1987, Swanson 1994, Smith and Allen 1996). The probes are protected against the weather (Photo 6). The anatomical features important in measuring sap flow are: (1) the type of tracheary elements; (2) the diameter of individual tracheary elements; (3) the spatial distribution of functioning elements within a given growth ring; (4) the total number of growth rings containing functioning tracheary elements; and (5) the radial width of sapwood. Three types of conducting tissue can be distinguished: ring porous, diffuse porous and coniferous (or non-porous) wood (Swanson 1994). In diffuse porous trees, such as the trees in the present study, sap moves through vessels scattered throughout the functioning sapwood.

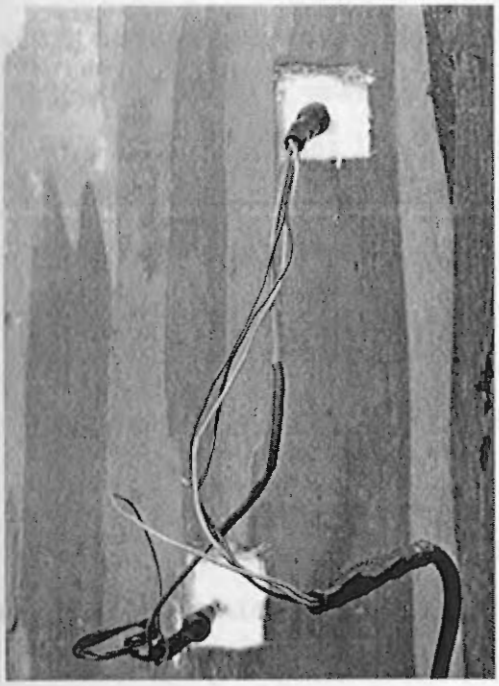

Photo 5. "Granier" probes (heated probe above, reference probe below) installed on *Eucalyptus deglupta*.

Photo R. van Kanten.

Photo 6. Zinc protection and weather shield on *Terminalia ivorensis*.

Photo P. Vaast.

For the heat balance method, Grime and Sinclair (1999) investigated errors in sap flow measurement, recommending gauge installation well away from the soil surface, with additional insulation below the standard weather-shield and the use of a conical shade above the gauge to prevent direct insolation and water ingress via stem-flow during rainfall. Instead of turning off the heating source during night hours, its power input can be reduced, assuring accurate resolution of low sap flow rates at night. Under field conditions the heated segment may experience large changes in T when ambient T and/or transpiration change rapidly, and, due to thermal inertia of the stem, there is a lag in the response of the gauge.

Over the years different units have been used for sap flow measurements. The sap flow nomenclature employed in this study is according to recommendations of Edwards et al. (1996) concerning a unified nomenclature for sap flow measurements.

For sampling and scaling from plant to stand, estimated sap flow should be expressed per leaf area or sap wood area (Smith and Allen 1996) such as for the coffee plants and the trees in the present study, respectively. Sap flow is influenced by a complex of factors including soil water availability, meteorological parameters such as radiation, vapour pressure deficit and air temperature and the status of the plants in terms of leaf temperature, leaf water potential and stomatal conductance (Wormer 1965, Bierhuizen et al. 1969, Dagg 1976, Maestri and Barros 1977, Fanjul et al. 1985, Barradas and Fanjul 1986, Meinzer 1993, Gutiérrez and Meinzer 1994a, Gutiérrez et al. 1994, Rapidel 1995, Mosquera et al. 1999, Dauzat 2001).

Chapter 3, 4 and 5 contain papers I, II and III, respectively. The results and discussion, conclusions and recommendations are presented in chapter 6.

PAPER I

Growth and production of *Coffea arabica* L. and fast-growing timber trees in associations in Southern Costa Rica.

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Submitted to Agroforestry Systems

Abstract

Simultaneously established 1 to 4-year-old coffee (*Coffea arabica*) associations with *Eucalyptus deglupta*, *Terminalia ivorensis* (timber trees) or *Erythrina poeppigiana* (service tree) were monitored on-farm (9°15' N; 83°29' W; alt. 640 m a.s.l.; annual rainfall 3516 mm and mean T 25.7°C). The split-plot design counted with 4 replications, with timber tree species with or without supplementary tree fertilisation as main treatments, *E. poeppigiana* as the control (main treatment) and uniformly or locally distributed coffee fertilisation as the sub-treatments. *T. ivorensis* stem diameter, crown projection (m^2) and shading were higher than for *E. deglupta*. Coffee plant height (cm) and basal diameter 15 cm above soil surface (mm) were higher in the uniformly than in the locally fertilised plots and higher in the two timber tree associations than in the *E. poeppigiana* control. Proximity to timber trees did not affect coffee development. *E. deglupta* can be suggested as the more suitable timber tree species to be associated with coffee. Predicted yield (*PY*) for locally fertilised sub-plots, based upon a pre harvest evaluation of eight selected branches per plant (36 plants per plot), was fitted to real coffee berry yield (*RY* in kg) with a quadratic model [$RY = 0.00098\ PY^2 + 0.4029\ PY$, $r^2 = 0.9474$ ($p < 0.001$)]. Predicted yield was not different between treatments but actually harvested coffee under *E. deglupta* was higher than under *T. ivorensis* or *E. poeppigiana*.

Key words: coffee plant distances, competition, predicted coffee yield

1. Introduction

Coffee (*Coffea arabica* L.) is one of the most important agricultural crops and export commodities in Central America (Galloway and Beer, 1997). This species was originally found in the Ethiopian highlands (alt. 1600 – 2800 m a.s.l., 6° – 9° N and 34° – 40° E) with mean temperatures of about 20° C and well distributed rainfall between 1600 – 2000 mm $year^{-1}$, with a 3 to 4-month dry season (Maestri and Barros, 1977). Optimal photosynthesis of *C. arabica* is registered below a maximum temperature of 24 °C. Close to the equator, coffee produces two berry yields per year (Jaramillo and Valencia, 1980) but further North in Costa Rica, only one harvest occurs per year; i.e., high production, which demands more fotoassimilates in one year, is followed by lower production the next year when the plant increases the supply of fotoassimiliates to vegetative parts (Cannell, 1975).

Traditionally coffee has been grown in the Costa Rican Central Valley (alt. 1100 – 1400 m a.s.l.) on fertile volcanic soils and optimum agroecological conditions. Use of all suitable land in combination with increasing land pressure from other sectors (urban constructions, industry, tourism) forced the activity, since the fifties – sixties, to less optimal areas such as Pérez Zeledón, in the Southern part of the country (Ramírez, 1987). This area, now the principal coffee-growing region of the country, is characterised by an altitude lower than the optimum (mainly 600 – 800 m a.s.l.), and too high rainfall (> 2900 mm yr^{-1}) and temperature (> 23.5 °C). Coffee plantations were established predominantly on unfertile Ultisols which were formerly dedicated to the cultivation of cash crops such as maize (*Zea mays*) and beans (*Phaseolus vulgaris*), sugar cane (*Saccharum officinarum*) or cattle breeding areas.

In this region, agroecological conditions are unsuitable for coffee in full sun and it is associated with shade trees, mainly N-fixing non-timber trees such as *Erythrina poeppigiana* (Walp.) O.F. Cook. (Papilionaceae), one of the most common shade trees in Costa Rican coffee plantations. This deciduous tree drops its leaves shortly before the rainy season, resprouting within a month. Regular pruning of the tree adds green manure to the system; an interesting low-cost management option for coffee farmers (Glover and Muschler, 1993) though labour costs may become a limitation in the case of Costa Rica (Tavares et al., 1999). When *E. poeppigiana* is replaced by fast-growing timber trees,

labour for tree pruning may be reduced and profitability of the system increased. Timber trees may stabilise farmer's income, mitigating the consequences of fluctuating or decreasing world coffee prices (Galloway and Beer, 1997). *Eucalyptus deglupta* Blume. (Myrtaceae) is an evergreen self-pruning tree species which grows well at altitudes below 1200 m a.s.l. with annual rainfall exceeding 1000 mm. In Costa Rica, the tree can reach heights of 30 m and stem diameters (at 1.3 m breast height [*DBH*]) of 33 cm at age 16 years (CATIE, 1994; Eldridge et al., 1994). *Terminalia ivorensis* A. Chev. (Combretaceae) is a semi-deciduous tree species, which grows up to maximum altitudes of 1200 m a.s.l., drops its leaves during the dry season and is sensitive to water stress (Lamb and Ntima, 1971; Dupuy and Mille, 1993). *Terminalia ivorensis* in plantations can achieve a height of 30 m in 20 – 30 years (Lamb and Ntima, 1971).

The uniformity of the shade in a coffee plantation is of importance, as well as tree leaf shedding in the dry season (Willey, 1975). Tree shade reduces coffee plant stress and influences the quantity and quality of light, the distribution and total amount of moisture in the system, the diurnal range of ambient air temperature, and leaf and soil temperature. The intensity of coffee flushing (i.e., the periodic production of young shoots and leaves), as well as leaf size, thickness and the number of stomates per leaf are directly related to shade levels. Trees may also positively influence nutrient cycling and availability, topsoil water status, weed, disease and pest incidence, the degree of the fluctuations of bi-annual coffee production and coffee bean weight, size and quality (Cannell, 1971; Willey, 1975; Kimemia and Mburu, 1988; Huxley, 1999; Muschler, 2001). On the other hand, fast-growing timber trees may compete significantly for growth resources (water, light, soil nutrients) when associated with coffee plants (Beer et al., 1998), especially when established simultaneously.

The present study focused on early growth of the fast-growing timber trees *E. deglupta* or *T. ivorensis*, with or without supplementary tree fertilisation, and on the growth and production of *C. arabica* plants associated with these timber trees or with the non-timber tree *E. poeppigiana*. Different distance categories of coffee plants to their nearest timber tree were studied in an agroforestry experiment established on a commercial coffee farm in Southern Costa Rica, with an *E. poeppigiana* association as the control treatment.

Estimated pre-harvest coffee berry production was projected against actual production in 2001 to verify its reliability as a yield indicator.

2. Materials and methods

2.1. Site description

The study was conducted from May 1999 until March 2002 on the commercial Verde Vigor S.A. coffee farm (9°15' N; 83°29' W; alt. 640 m a.s.l.), situated in Southern Costa Rica. The site has a tropical rainy climate (Amw, Köppen classification), corresponding to a Tropical Wet Forest life zone (Holdridge 1967), annual rainfall of 3516 mm (1998 – 2002) and annual mean temperature of 25.7 °C (1986 – 1997). From January until March there is a pronounced dry season and from the beginning of May until the end of December a wet season. Monthly rainfall (mm) was monitored for May 1998 – May 2002 (Figure 1).

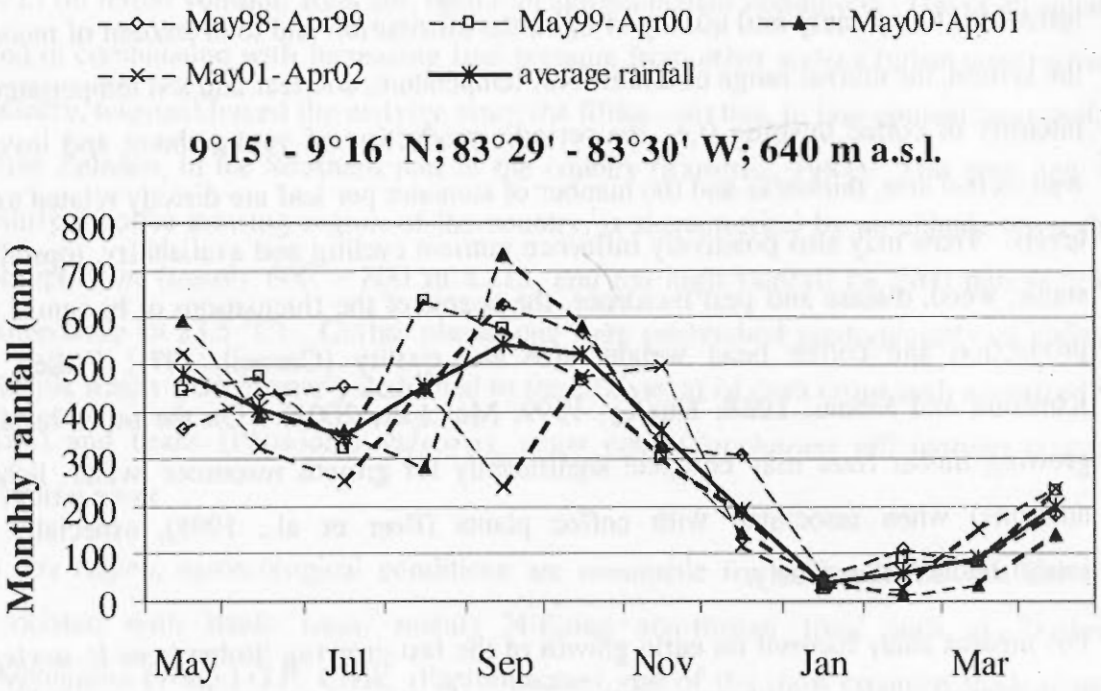


Figure 1 Monthly rainfall in a *Coffea arabica*-shade tree trial (*Eucalyptus deglupta*, *Terminalia ivorensis* or *Erythrina poeppigiana*) established in May 1998 in Southern Costa Rica.

Soils were classified as Ustic Palehumult (USDA classification) and based on analyses in 1998 and 1999, had average pH (H_2O) 5.1; soil exchangeable acidity 0.66 cmol l^{-1}; K, Ca and Mg of 0.16, 3.63 and 0.13 cmol l^{-1}, respectively; and P 7.7, Cu 3.6, Fe 239.7, Mn 5.8, and Zn 0.5 mg l^{-1}, respectively. P, K and Zn were below critical levels of 12.0 mg l^{-1}, 0.20 cmol l^{-1} and 3.0 mg l^{-1}, respectively (Bertsch 1995). The combination of the sum of bases (K + Ca + Mg = 3.9 cmol l^{-1}) below 5 cmol l^{-1}, and soil exchangeable acidity (0.66), higher than 0.5 cmol l^{-1}, suggested that low soil fertility was the limiting factor (Mata and Ramírez 2002). Soil bulk density (December 2001) was determined gravimetrically for depth layers 0 – 15, 15 – 30, 30 – 60, 60 – 90 and 90 – 120 cm was 0.91, 0.84, 0.91, 0.93 and 0.98 g cm^{-3}, respectively, using four core samples per depth. Low fertility (which however was balanced by high fertilisation rates during the experiment), water stress in the dry season, air temperatures above the photosynthetic optimum for coffee and high rainfall characterise the site as sub-optimal for coffee cultivation.

2.2. Plantation management

The experiment was established on former sugar cane (*S. officinarum*) fields which were cleared with fire and ploughed to about 50 cm depth. The sugar cane fields had been subjected to prolonged chemical weed control and had experienced soil compaction. Fertiliser (amounts and formulae) and liming were applied according to the commercial farm management's recommendations (Table 1). Weed management was performed manually with machetes, mechanically with brush-cutters and by regular herbicide applications (Paraquat, Glyphosate, Terbuthylazine) with manual or motorised knapsack sprayers. The latter activity was reduced drastically after the year 2000 when the farm management was forced to reduce its operating costs due to prolonged low coffee bean prices. Other coffee spraying activities included foliar application of zinc, insecticides, fungicides and of nematicides to the soil surface. Coffee harvests started in the year 2000 with measurements per plant, on two occasions between September and November. However, quantification of the 2000 harvest was interrupted when the farm harvested without notifying on the third occasion. The 2001 harvest (October – December 2001) was completely recorded.

Table 1. Fertilisers applied from May 1998 until May 2002 in a *Coffea arabica*–shade tree trial in Southern Costa Rica.

Year	Species	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Mg (kg ha^{-1})	S (kg ha^{-1})	B (kg ha^{-1})	Ca (kg ha^{-1})
1998	*C. arabica*	65.2	10.8	74.2	32.4	34.8	0.0	
	Trees[1)]	0.0	6.7	0.0	0.0	0.0	0.0	
1999	*C. arabica*	188.1	5.6	82.3	39.2	18.5	3.0	647.8
	Trees[1)]	19.3	0.8	11.2	3.4	3.0	0.4	
2000	*C. arabica*	99.5	0.0	332.4	92.5	105.5	1.9	357.5
	Trees	21.1	0.0	27.9	8.6	9.1	0.1	
2001	*C. arabica*	112.5	8.2	77.8	22.5	45.6	2.5	850.0
2002	*C. arabica*	54.4	4.0	37.6	10.9	22.0	1.2	

[1)] Tree (*Eucalyptus deglupta* or *Terminalia ivorensis*) fertilisation only until 2000.
[2)] Liming had been applied broadcasted.

E. deglupta was pruned once per year in the first two years removing lateral branches up to 3 m height. On several occasions during the first two years, *T. ivorensis* trees were submitted to phytosanitary pruning, removing infested lateral branches up to 3 m height to control the *Nectria* sp. fungal disease, an activity which was complemented with spraying of inorganic (copper oxide) and organic (Benzamidazol) fungicides. To reduce excessive shade to nearby coffee plants, lateral *T. ivorensis* branches were removed up to 4 m trunk height, until 2001. In September 1999, the 1-year-old *E. poeppigiana* trees were pruned for the first time and in the years 2000 and 2001, twice a year, in May and August. Two, three or four evenly orientated (cardinal points) branches, developed at 1.8 – 3.0 m height, were pruned to 1 – 2 m length to make tree stands and crown projections uniform. All vertical growing, unhealthy and other unwanted *E. poeppigiana* branches were removed. Pruned branches and leaves were distributed evenly on the soil surface in the *E. poeppigiana* plots after all branches had been chopped to less than 1 m sections.

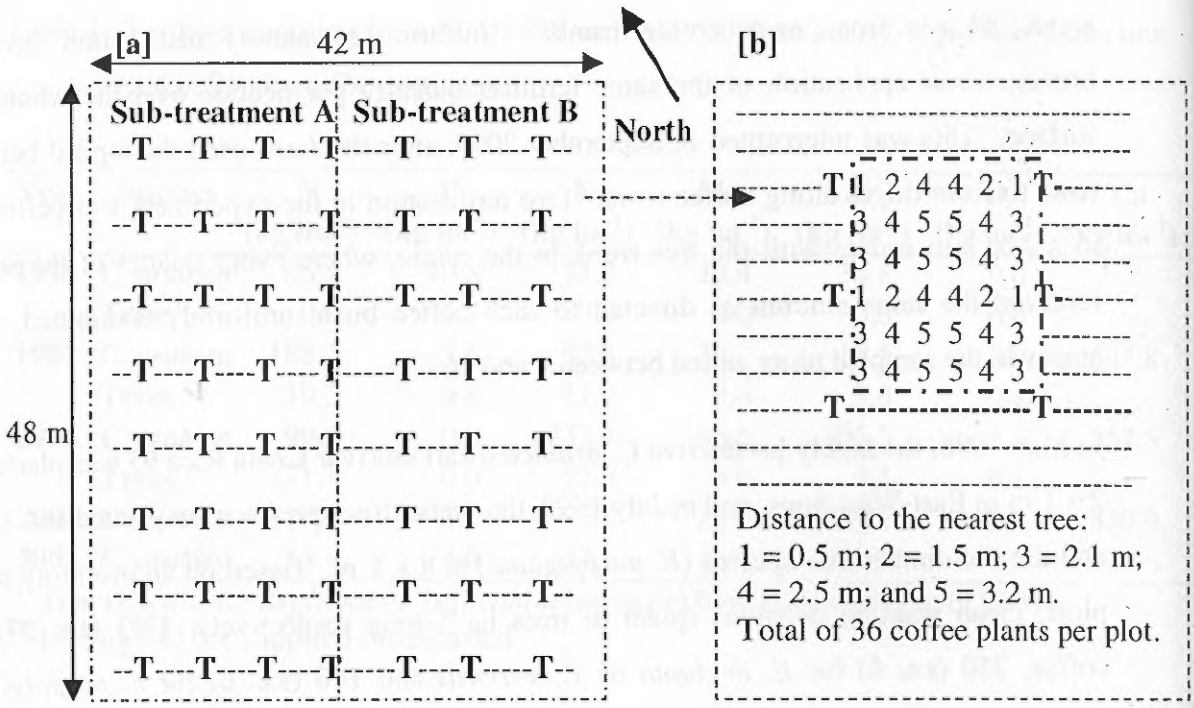
2.3. Experiment

The original design was established as a randomised complete block split-plot design with four replications. Timber tree species (*E. deglupta* and *T. ivorensis*), with or without supplementary tree fertilisation, and a coffee – *E. poeppigiana* (service shade tree) control formed the main treatments. Localised or uniformly distributed coffee fertilisation were the sub-treatments (split-plots). Localised distribution involved applying fertiliser up-slope

about 20 cm from each coffee trunk. Uniform (broadcast) distribution involved homogeneous application of the same fertiliser quantity per hectare over the whole plot surface. This was interrupted in September 2000, after the farm used the topsoil between rows to form ridges along coffee rows. Tree fertilisation in the experiment was performed in a 2 x 2 m square with the tree trunk in the centre, where every quarter of the square received the same amount as directed to each coffee bush, uniformly distributed. The slopes in the sampled plots varied between 4 and 26%.

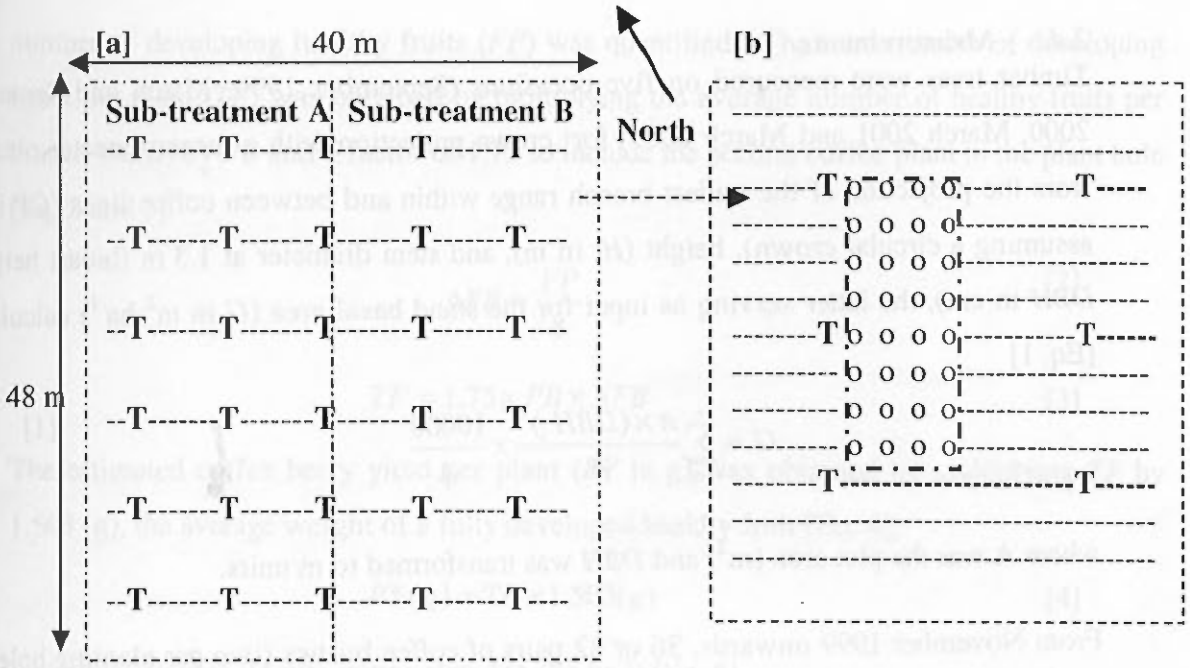
In May 1998, the highly productive *C. arabica* dwarf cultivar Costa Rica 95 was planted at 2 x 1 m in East-West lines, and in July 1998, the timber tree species were planted at 6 x 6 m and the non-timber tree species (*E. poeppigiana*) at 8 x 8 m. Based on an inventory of all plots, mean planting densities (plant or trees ha^{-1}) were respectively, 4723 (s.e. 37) for coffee, 250 (s.e. 6) for *E. deglupta* or *T. ivorensis* and 146 (s.e. 6) for *E. poeppigiana*. *E. deglupta* seedlings where cultivated in a nursery on the farm from seeds from the CATIE seed bank, source BL034, batch 034/95B, RN CR 042, proceeding from Charrarra, Cartago, Costa Rica (lat. 09°49' N; alt. 1000 m a.s.l.; mean T 21 °C; mean rainfall 1969 mm yr^{-1}). *T. ivorensis* seedlings were obtained from a local nursery with seeds from the CATIE seed bank, source Experiment 38, procedence Florencia Sur, CATIE, Turrialba, Costa Rica (lat. 09°53' N; alt. 600 m a.s.l.; mean T 22 °C; mean rainfall 2460 mm yr^{-1}). *E. poeppigiana* cuttings were obtained from a 2-year-old pure stand from a farm near the experiment.

In every split-plot, a coffee evaluation plot was established, consisting of six rows of six coffee plant holes (each plant hole normally contained two coffee bushes) for the timber tree treatments and eight rows of four coffee plant holes for the treatment with *E. poeppigiana* (Figures 2 and 3).



T fast-growing timber tree (*Eucalyptus deglupta* or *Terminalia ivorensis*; 6 x 6 m)
--- *C. arabica* lines (coffee planted at 1 x 2 m). Every coffee line with trees is separated by two coffee lines without trees, not indicated in figure 2a.

Figure 2 Tree and plant distribution in a *Coffea arabica*–timber tree plot [2a] and a coffee sub-plot [2b] in Southern Costa Rica.



T *E. poeppigiana* (8 x 8 m)

--- *C. arabica* lines (coffee planted at 1 x 2 m). Every coffee line with trees is separated by three coffee lines without trees, not indicated in figure 3a.

o Total of 32 *C. arabica* plants per coffee sub-plot

Figure 3 Tree and plant distribution in a *Coffea arabica–Erythrina poeppigiana* plot [3a] and a coffee sub-plot [3b] in Southern Costa Rica.

2.4. Measurements

Timber trees were measured on five occasions (September 1999, March and September 2000, March 2001 and March 2002) for: crown projection with a mean diameter obtained from the projection of the widest branch range within and between coffee lines (*CP* in m^2 assuming a circular crown), height (*Ht* in m), and stem diameter at 1.3 m (breast height = *DBH* in cm), the latter serving as input for the stand basal area (*G* in m^2 ha^{-1}) calculation [Eq. 1]

$$G = \sum_{i=1}^{n} \frac{\pi \times (DBH_i)^2}{4} \times \frac{10000}{A} \qquad [1]$$

where A was the plot area (m^2) and *DBH* was transformed to m units.

From November 1999 onwards, 36 or 32 pairs of coffee bushes (two per planting hole), in timber and non-timber tree plots, respectively, were measured in May and November (beginning and end of the rains, respectively) for height (cm) of the highest orthotropic stem, and basal diameter (*bd* in mm) 15 cm above soil surface of the orthotropic stems. In the timber tree treatments, plants in the coffee sub-plots were organised into five categories based on the five possible distances to the nearest tree (0.5; 1.5; 2.1; 2.5; and 3.2 m; Figure 2). According to the category, the 36 coffee plants in a sub-plot were ranked as 4 plants each at 0.5 and 1.5 m, 8 plants each at 2.1 and 3.2 m, and 12 plants at 2.5 m distance from the nearest shade tree.

Coffee berry yield was estimated in 12 evaluation plots (416 coffee bushes) i.e., in the locally fertilised coffee sub-plots in the two timber tree treatments (*E. deglupta* or *T. ivorensis*), without supplementary tree fertilisation, and in the *E. poeppigiana* (control) treatment (four repetitions of each). In July 2001, 4 months after flower-anthesis, the 36 coffee plant holes (32 in the case of the *E. poeppigiana* treatment) in each evaluation plot, including re-planted seedlings, were numbered and measured for height (*ht* in cm) of the higher plant which ranged from 38 - 195 cm. Based on the total number of nodes on the main stem of the higher plant (*NS*), which ranged from 18 – 53, the plants were categorised in seven groups (group I: 18 – 23 nodes; and subsequent groups incrementing by five additional nodes). The number of productive branches (*PB*) per plant was registered and on eight selected branches, systematically distributed down through the crown, the total

number of developing healthy fruits (*FP*) was quantified. The total number of developing fruits per plant (*TF*) was obtained by multiplying the average number of healthy fruits per branch (*AFB*) by *PB* and a factor of 1.75 to include the second coffee plant in the plant hole [Eq. 2 and 3].

$$AFB = \frac{FP}{8} \quad [2]$$

$$TF = 1.75 \times PB \times AFB \quad [3]$$

The estimated coffee berry yield per plant (*PY* in g) was obtained by multiplying *TF* by 1.503 (g), the average weight of a fully developed healthy fruit [Eq. 4].

$$PY(g) = TF \times 1.503(g) \quad [4]$$

Individual plant yield was extrapolated to (kg ha^{-1}) [Eq. 5]

$$Yield(kg \cdot ha^{-1}) = \frac{NP}{NS} \times YS \times 0.001(kg \cdot g^{-1}) \quad [5]$$

where *NP* was the number of coffee plants ha^{-1}, *NS* the number of plants per sub-plot (36 or 32, respectively for coffee under timber trees or under *E. poeppigiana*) and *YS* the sum of the estimated berry yield (g) per individual plant per sub-plot. Actual coffee berry yield (*RY* in kg ha^{-1}) was recorded for locally and uniformly fertilised coffee sub-plots in the treatments without supplementary tree fertilisation for the year 2001, repeating the procedure with equation 5 where *YS* is the sum of the actual harvested berries (g) for the plants per sub-plot.

2.5. Analytical methods

Data were analysed with SAS release 8 (SAS Institute Inc., Cary, NC, USA, 1999). Shade tree stand basal area (*G*) was calculated per treatment and measuring date. Timber tree growth parameters (height, *DBH*, *G* and *CP*) or coffee plant growth parameters (height and *bd*) were analysed with a split-plot analysis of variance (with measuring dates as sub-treatment). Differences were traced with a Tukey test ($p < 0.05$). Mean coffee height and *bd* per distance category and sub-treatment were analysed with an analysis of variance and a Duncan test to detect differences between distance categories for each measuring date. Predicted coffee berry yields (*PY*; based on counting of eight branches per plant) in the

locally fertilised plots and real coffee berry yield (*RY*) in the locally and uniformly fertilised plots in the treatments without supplementary tree fertilisation were submitted to analyses of variance. The relationship between *PY* and *RY* (for the locally fertilised plots) was evaluated with correlation and regression analysis (linear and quadratic models were tested) and differences were tested with a t-test.

3. Results and discussion

3.1. Tree growth

For both timber tree species, *CP* (Figure 4) started to increase notably 20 months after out planting. After about 29 months, *T. ivorensis* crowns started overlapping each other; for *E. deglupta* this occurred after 35 – 38 months suggesting the need for early thinning even though spacing was 6 x 6 m. Tree height increases (close to 3 m yr^{-1} for the first three years) slowed after the measurements at 32 months with no differences between treatments. *DBH* (and consequently *G*) and *CP* growth of *T. ivorensis* were higher than for *E. deglupta* ($p < 0.05$) but there was no obvious effect of supplementary tree fertilisation.

Sánchez (1994) compared 2 – 4-year-old *E. deglupta* (spacing 3.1 x 3.1 m) in Costa Rica (Table 2) associated with coffee against pure stand trees (spacing 2.7 x 2.7 m). The former system presented lower height / *DBH* relations (i.e., higher inversion in diameter growth and consequently a more attractive option for commercialisation due to shorter rotations as compared to tall thin trees): associated trees benefited from coffee fertilisation and supplementary tree fertilisation had no effect on tree growth. Height and *DBH* values of the pure stand at ages 30 and 48 months, where narrowly spaced trees were forced to grow in height, were higher than the values in the present experiment at ages 32 and 44 months.

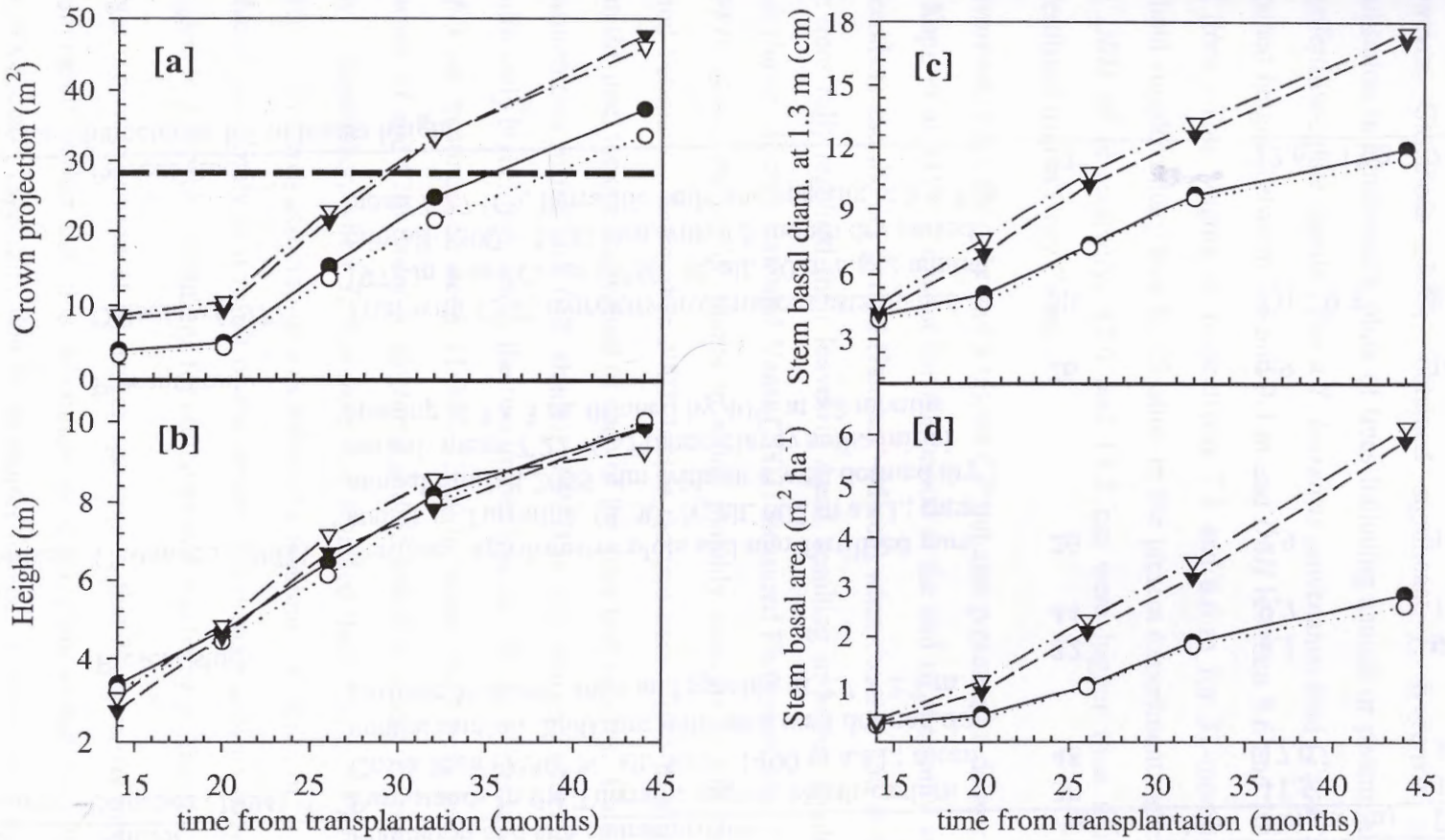


Figure 4 Mean crown projection (CP), height, stem diameter at 1.3 m breast height (*DBH*) and stem basal area (n = 120) for *Eucalyptus deglupta* (non fertilised trees = open circle; fertilised trees = closed circle) or *Terminalia ivorensis* (non fertilised trees = open triangle; fertilised trees = closed triangle) shade trees in a *Coffea arabica* trial Southern Costa Rica. The horizontal dotted line [4a] indicates the point where tree crowns (6 x 6 m spacing) meet and the trees should be thinned.

Table 2. Comparisons for early *Eucalyptus deglupta* and *Terminalia ivorensis* growth values.

Species	Author	Plantation and site characteristics	Age (months)	Height (m)	DBH[1)] (cm)
E. deglupta	Sánchez (1994)	Pure stands in the Turrialba region, North-eastern Costa Rica (9°50' N; alt. 500 – 1400 m a.s.l.; mean annual rainfall 2600 mm without a well defined dry period); Volcanic soils and spacing at 2.7 x 2.7 m.	30	11.5	10
			48	17.0	13
	Present study		32	8.1	9.6
			44	9.7	11.7
T. ivorensis	Castañeda (1981)	Fertilised agroforestry plots and non-fertilised pure stands in Turrialba, (9°50' N; alt. 602 m a.s.l.; mean annual rainfall 2055 mm without a well defined dry period; mean *T* 22 °C; Franco-clayey soils; initial spacing at 3 x 3 m, thinned by 40% at 22 months	26	7.9	10.1
	Present study		26	6.9	10.5
	Delaunay (1977)	Trial with 13 *T. ivorensis* provenances established in 1972 in Ivory Coast (5°50' N; alt. 80 m a.s.l.; annual rainfall 1300 – 1400 mm with a 5 month dry period; mean *T* 27 °C), Ferralitic soils and spacing at 8 x 3 m	30	7.0 – 9.3	8.6 – 10.5
	Present study		32	12.6 – 13.2	7.8 – 8.6

[1)] Tree stem diameter at 1.3 m breast height

Castañeda (1981) reported mean heights of 7.9 m and mean *DBH* of 10.1 cm for 26-month-old *T. ivorensis* trees in the Turrialba region (Table 2) as compared to average values of 6.9 m height and 10.5 cm *DBH* for 26-month-old trees in the present experiment. However, Castañeda (1981) obtained significant *T. ivorensis* growth response to fertilisation in agroforestry plots of trees including annual or perennial crops as compared to unfertilised pure stands. For a *T. ivorensis* provenance trial (Table 2), Delaunay (1977) obtained heights between 7.0 and 9.3 m and *DBH* between 8.6 and 10.5 cm for 30-month-old trees. Tree heights of respectively 7.8 and 8.6 m for 32-month-old trees with and without supplementary tree fertilisation in the present experiment matched the same range but *DBH* of respectively, 12.6 and 13.2 cm were higher than those obtained in the unfertilised trial in Ivory Coast.

T. ivorensis trees not only had a higher *CP* but also presented a denser crown, as observed by Kapp et al. (1997), except for the period at the end of the rainy season (November – December) and the dry period (January –March) when the tree had shed part of its leaves. The trees fully regained their leaves in April, resulting in higher shade levels than below *E. deglupta*. Kanten van and Vaast (2003) measured Photosynthetic Photon Flux Density (*PPFD*) above the coffee plants in 4-day monthly sessions in the study site, during the period February – September 2002, beside the tree trunks (0.5 m distance) and at 2.5 m from the tree, for one individual of each of the three tree species. Data was compared with measurements in full sun (0% shade). *PPFD* in full sun and under *E. poeppigiana* was significantly higher than under the two timber species. Shade percentages based on average *PPFD* per treatment between 11:00 – 13:00 h., when daily peak values occurred, varied between 37 and 67% under *E. deglupta* and 55 and 83% under *T. ivorensis* for the period May – September, when *T. ivorensis* had regained their leaves. *PPFD* measured in the coffee–*T. ivorensis* association was below the required 300 μmol m^{-2} s^{-1} for photosynthetic coffee plant activity as a result of the denser *T. ivorensis* crowns in May and June. This suggests less suitable conditions for coffee growth and berry production.

Larger crown expansion at an earlier age implies that *T. ivorensis* meets the coffee shade requirements earlier but this advantage is quickly converted into the disadvantage of excessive shade, especially due to its denser foliage. Continuation of the trend of faster *DBH* and *G* increments for *T. ivorensis* while maintaining the same height growth as

E. deglupta indicate an earlier harvest time; i.e., a shorter rotation and therefore, regarding the timber component of the system, a more attractive financial option for the farmers. This demonstrates why the system should be evaluated as a whole (e.g., coffee and timber production).

Anzola (unpublished data) obtained an average *T. ivorensis* Leaf Area (*LA*) 2.9 times greater than the average *E. deglupta LA* (189 $\pm$ 22.2 vs. 65 $\pm$ 11.6 m^2 $tree^{-1}$) using photo images of 15 individuals per species in the study site in June 2002. The irregular crown shape of *T. ivorensis*, with lateral branches growing in several strata, compared to the conical uniform *E. deglupta* crown might have biased *CP* measurements in the present study, since these were based on the largest branch width in two perpendicular directions. *DBH* is a more reliable tree growth parameter.

Timber tree stand basal area (*G* in m^2 ha^{-1}) can be related to the yield of the associated crop, as has been done by Nissen and Midmore (2002) for *Eucalyptus* spp. and *Paraserianthes falcataria* associated with annual crops. However, coffee has a biannual cyclic berry production pattern, and the present study, coffee fruit production data could not be related to *G*, possibly due to incomplete data for the 2000 coffee harvest.

3.2. Coffee growth and production

Over the period May 1999 – March 2002 (age 1 to 4 years), coffee bush height increased steadily to the typical maximum for this variety (2.0 m). Coffee *bd* increments slowed after age 2 years (Figure 5). Quadratic regressions (r^2 always above 0.90) gave a good fit to coffee height and *bd* curves. Plants in the uniformly fertilised coffee sub-plots were higher ($p < 0.05$) than those in the locally fertilised coffee sub-plots pointing to uniform fertilisation as the more efficient way to make nutrients available to coffee. In the two *E. deglupta* treatments, coffee height and *bd* were consistently higher than in the other three treatments. In turn, coffee under the two *T. ivorensis* treatments was consistently higher and had greater *bd* than under *E. poeppigiana* (control) ($p < 0.05$). Better coffee growth under *E. deglupta* can be attributed to less competition for water, soil nutrients and/or light.

Neither coffee nor timber tree growth was different in the plots with or without supplementary tree fertilisation, indicating that root competition was not reduced by

providing the trees with an additional nutrient source. However, it should be noted that tree fertilisation was discontinued when the trees reached an age of 27 months.

Two of the coffee–*E. poeppigiana* plots suffered accentuated soil erosion and several coffee plants which had poor growth, and were unlikely to become productive, had to be replaced. These coffee plants were diagnosed with deformed main roots; probably a result of inadequate nursery – transplantation practices. Soil water content in 0 – 30 cm profile of the coffee–*E. poeppigiana* association was significantly higher than in the two coffee–timber tree associations between December 2001 and June 2002 (Kanten van and Vaast, 2003). Jiménez and Alfaro (1999) obtained similar findings in a dry period in the Costa Rican Central Valley. They found higher water contents in the 0 – 60 cm soil profile in a coffee–*E. poeppigiana* association and coffee in full sun as compared to a coffee–*E. deglupta* association. The coffee–*E. poeppigiana* plots with stunted coffee plants and the difference in tree planting distance (8 x 8 m versus 6 x 6 m) hindered comparisons in the present study.

According to a 1998 survey of 30 farmers in the same region, comparing 14 coffee shade timber tree species (Tavares et al., 1999), *E. deglupta* was preferred above *T. ivorensis* because the latter required pruning labour costs to eliminate lateral branches to avoid excessive shading of the coffee crop even when the trees were young. An analysis over the whole timber tree cycle including timber harvest, however, could lead to another conclusion regarding the more (economically) attractive timber tree species to be associated with coffee. In the experiment, coffee shade below *E. poeppigiana* was considerably lower due to the fact that the trees were spaced at 8 x 8 m as compared to 6 x 6 m for the timber trees and *E. poeppigiana* was submitted to heavy pruning twice a year for shade regulation and green manure production. During the January – March dry period, coffee plants in *T. ivorensis* or *E. deglupta* shade consumed less water than plants in *E. poeppigiana* shade or in full sun (Kanten van and Vaast, 2003) indicating competition of the timber species for water with the coffee bushes in the dry season.

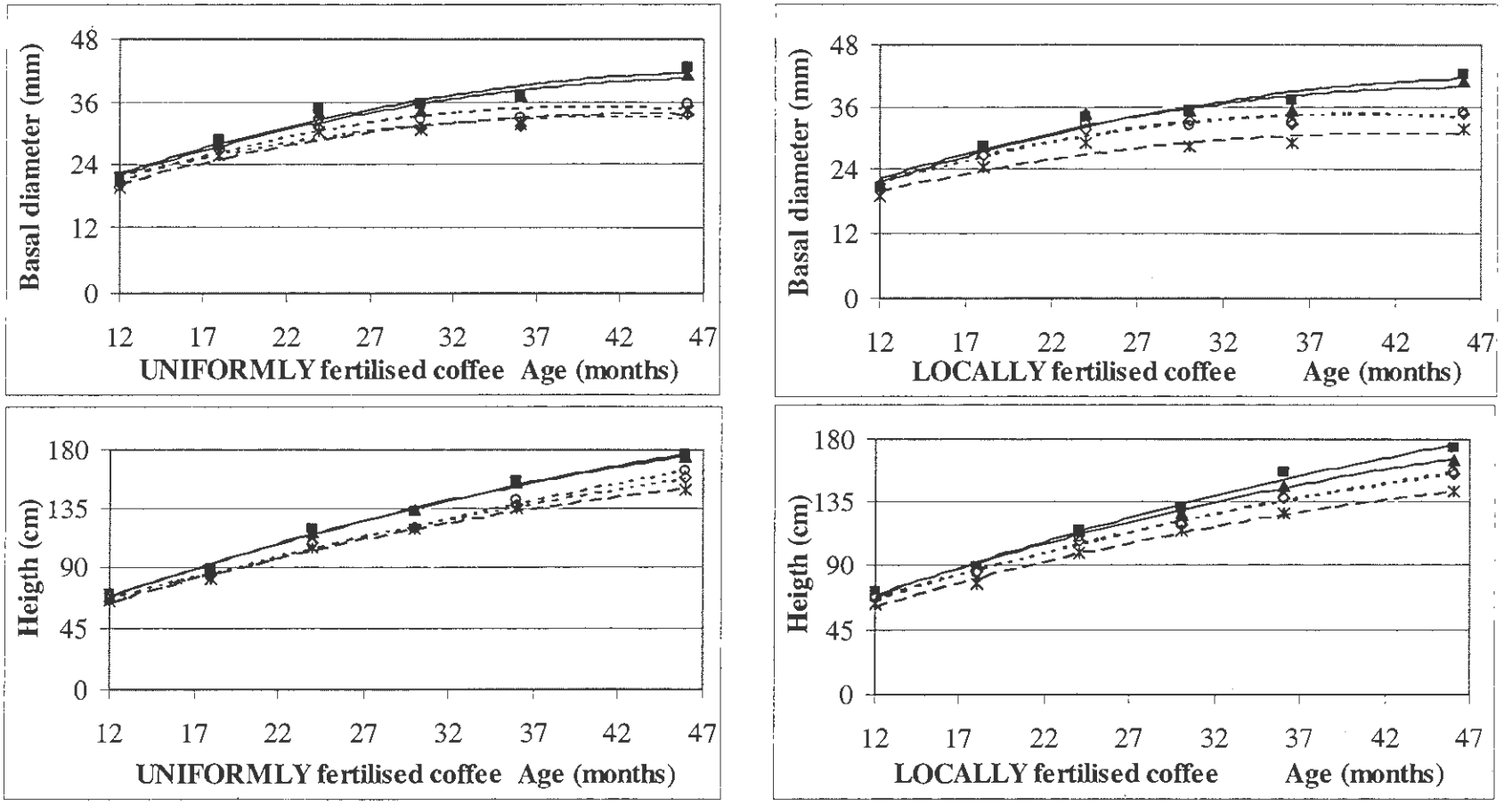


Figure 5 Mean height and basal diameter 15 cm above soil surface for uniformly and locally fertilised *Coffea arabica* plants associated with shade-trees in Southern Costa Rica. Treatments: unfertilised *Eucalyptus deglupta* ▲; fertilised *E. deglupta* ■; unfertilised *Terminalia ivorensis* ◊; fertilised *T. ivorensis* ○; *Erythrina poeppigiana* *. Symbols are linked with quadratic regression lines $r^2 > 0.90$.

In July 2000 in the study site, Aguilar et al. (2001) measured around 55 % shade below *E. deglupta* and around 80% shade below *T. ivorensis*. Higher shade under the 22-month-old *T. ivorensis* trees resulted in a higher number of non-productive coffee branches as compared to those below *E. deglupta* or in full sun. This was confirmed by Angrand et al. (2003) who evaluated coffee growth and flowering in 2002 in the same plots. Higher shade promotes larger leaf surface area (Cannell, 1971) but this parameter was not measured either by Aguilar et al. (2001) nor by Angrand et al. (2003). High shade levels below the *T. ivorensis* trees, even at an age when tree crowns were overlapping, confirms the disadvantage of excessive coffee shading by this species.

No differences in coffee growth parameters of any practical significance were found with respect to distance from the timber trees (Table 3). Schaller et al. (2003) drew the same conclusion for 4 to 5-year-old coffee (variety Catimor 5175)–*E. deglupta* associations in the Turrialba region in Costa Rica, with tree effect on coffee plants at 1.5 and 5.5 m distance. Nutrient concentrations (N, P and K) in coffee leaves were also not different for the two mentioned distances. A similar development of the coffee at different distances from the nearest tree is a favourable selection criterion for shade trees.

A root study between July 2001 – March 2002, at 0 – 20 cm depth in the timber tree treatments without supplementary tree fertilisation, with sampling in the coffee fertilisation strip, in the strip on the opposite side of the plants or in the coffee inter-rows (Kanten van et al. 2003), revealed low competition between species and combined coffee and tree fine Root Length Density (*RLD*; root diameter < 2 mm) always below 5 cm cm^{-3}. Lower coffee / *T. ivorensis RLD* ratios than coffee / *E. deglupta RLD* ratios suggest that fine roots of this timber tree species displace coffee fine roots; i.e., *T. ivorensis* is more likely to compete for nutrients with the coffee bushes than *E. deglupta*.

Table 3. Mean *Coffea arabica* height (*ht*) and basal diameter 15 cm above soil surface (*bd*) in associations with *Eucalyptus deglupta* or *Terminalia ivorensis* in Southern Costa Rica.

Age		Distance of *C. arabica* plants to the nearest timber-tree									
		0.5 m (n = 64)		1.5 m (n = 64)		2.1 m (n = 128)		2.5 m (n = 192)		3.2 m (n = 128)	
Months	C. arabica *in*	*ht* (cm)	*bd* (mm)	*ht* (cm)	*bd* (mm)	*ht* (cm)	*bd* (mm)	*ht* (cm)	*bd* (mm)	*ht* (cm)	*bd* (mm)
12	**E. deglupta**	72(1.8)[1)]a[2)]	22(0.6)a	70(1.7)a	21(0.6)a	69(1.3)a	21(0.4)a	68(1.0)a	21(0.4)a	68(1.2)a	21(0.4)a
	T. ivorensis	63(1.4)b	21(0.5)ab	65(1.6)ab	20(0.6)a	67(1.0)ab	21(0.4)a	68(0.9)a	21(0.3)a	68(1.0)a	21(0.4)a
18	***E. deglupta***	93(1.7)a	30(0.7)a	89(1.8)a	28(0.7)a	90(1.2)a	29(0.5)a	89(1.0)a	30(0.4)a	88(1.3)a	29(0.5)a
	T. ivorensis	79(1.5)b	26(0.6)b	81(1.6)b	26(0.6)b	84(1.1)a	28(0.4)a	87(0.9)a	28(0.4)a	87(1.1)a	28(0.5)a
24	***E. deglupta***	122(2.1)a	36(0.8)a	117(2.0)ab	35(0.7)a	117(1.5)ab	34(0.6)a	116(1.1)b	35(0.4)a	115(1.4)b	35(0.6)a
	T. ivorensis	103(1.9)c	29(0.7)c	105(2.0)bc	31(0.8)bc	108(1.4)ab	32(0.5)ab	111(1.1)a	33(0.5)a	112(1.3)a	34(0.6)a
30	***E. deglupta***	136(2.1)a	37(0.9)a	131(1.9)a	35(0.8)a	132(1.6)a	35(0.7)a	132(1.1)a	35(0.5)a	132(1.4)a	36(0.6)a
	T. ivorensis	118(2.1)a	31(0.7)a	118(1.9)a	32(0.9)a	121(1.3)a	33(0.6)a	121(1.2)a	33(0.5)a	122(1.3)a	33(0.6)a
36	***E. deglupta***	155(2.2)a	39(0.9)a	151(2.1)a	36(1.0)a	154(1.9)a	36(0.7)a	154(1.4)a	37(0.5)a	155(1.7)a	38(0.7)a
	T. ivorensis	143(2.5)a	32(0.8)a	140(2.5)a	32(0.9)a	140(1.8)a	33(0.6)a	142(1.5)a	34(0.5)a	141(1.7)a	33(0.6)a
46	***E. deglupta***	177(2.6)a	43(0.9)a	170(2.5)a	41(1.1)a	174(1.9)a	42(0.7)a	173(1.5)a	42(0.6)a	175(1.9)a	43(0.7)a
	T. ivorensis	165(3.0)a	35(0.8)a	161(3.2)a	35(0.9)a	162(2.2)a	36(0.6)a	163(1.7)a	36(0.5)a	159(2.1)a	35(0.7)a

[1)] Mean (standard error) [2)] different letters in the same row (corresponding to the same variable) indicate differences ($p < 0.05$) by the Student-Newman-Keuls test

Studying 2 to 5-year-old *C. arabica–E. deglupta* associations in pseudo-chronosequence nearby the experiment, Kanten van et al. (2003) observed a trend of higher *E. deglupta RLD* in the inter-rows against higher coffee *RLD* close to the coffee plants in the 0 – 20 cm topsoil. This coincided with findings of Schaller et al. (2003) studying 4 to 5-year-old *C. arabica–E. deglupta* associations. Apart from complementary exploitation by tree and coffee roots these latter authors concluded a trend of vertical partitioning of roots (tree roots between 0 – 10 cm and coffee roots between 10 – 20 cm soil depth) and high competitiveness of the coffee plants in a scenario of high availability of soil resources (frequent fertilisations).

Predicted coffee berry yield values, based on evaluation of eight branches, presented a correlation coefficient (r^2) of 0.95 with actual coffee yield (Figure 6) when fitted with a quadratic model [Eq. 6]:

$$RY = 0.00098PY^2 + 0.4029PY \qquad r^2 = 0.9474 \quad (p < 0.001) \qquad [6]$$

RY and *PY* for the three treatments did not differ significantly when submitted to a t-test, respectively for coffee under *E. deglupta* ($p < 0.0922$), *T. ivorensis* ($p < 0.3669$) and *E. poeppigiana* ($p < 0.2537$).

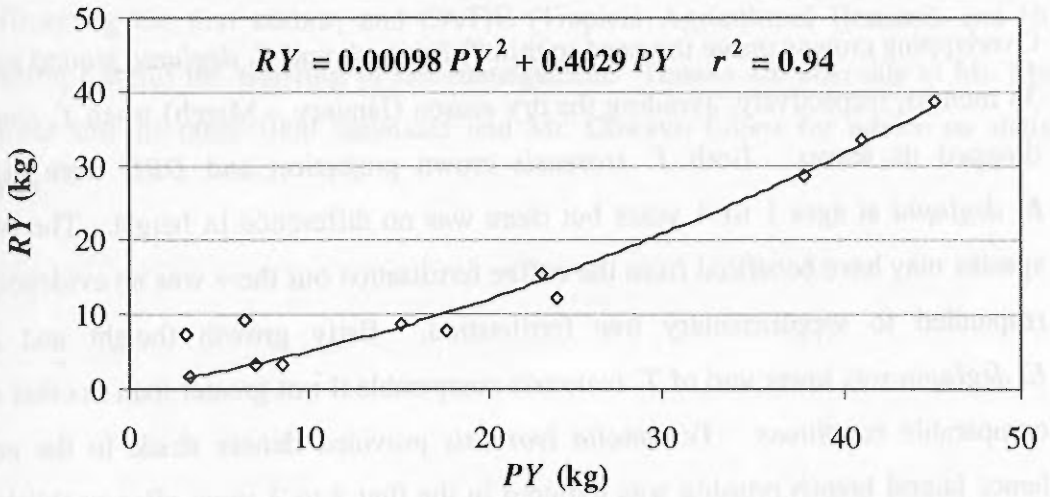


Figure 6 Estimated *Coffea arabica* berry yield based upon pre-harvest counts on eight branches (PY) vs. actual harvested berry yield (RY) for 3-year-old plants (October – December 2001) in associations with *Eucalyptus deglupta*, *Terminalia ivorensis* or *Erythrina poeppigiana* shade trees in Southern Costa Rica.

Predicted coffee berry yield averages of 4374 (s.e. 830), 3261 (s.e. 767) and 2762 (s.e. 733) kg ha^{-1} for coffee under *E. deglupta*, *T. ivorensis* and *E. poeppigiana* plots, respectively, were not significantly different from each other. Coffee berries were harvested on five occasions between 11 October and 06 December 2001 with the peak harvest occurring on the third (33%) and fourth (27%) collection. Real coffee berry yields were not different for uniformly or locally fertilised coffee bushes. Contrary to the predictions, *RY* in the locally fertilised sub-plots of 5095 (s.e. 925) kg ha^{-1} for coffee under *E. deglupta* was greater than that for coffee under *T. ivorensis* and *E. poeppigiana* with 2327 (s.e. 726) and 2807 (s.e. 833) kg ha^{-1}, respectively. This same trend was maintained in the uniformly fertilised sub-plots with values of 5790 (s.e. 717), 2567 (s.e. 547) and 2171 (s.e. 726) kg ha^{-1} for coffee under *E. deglupta*, *T. ivorensis* and *E. poeppigiana*, respectively. Taking into account the biannual coffee production cycle, the present results should be checked with at least another annual yield cycle. Furthermore, coffee yields within the treatments can be expected to vary over years. Coffee with less shade, such as the coffee under *E. poeppigiana* in the experiment, is expected to produce higher fluctuations between yields and to the plantation is expected to be exhausted at an earlier age as compared to more intense shaded coffee (Cannell 1975, Muschler 2001).

4. Conclusions

Overlapping crowns prove the need to thin *T. ivorensis* and *E. deglupta* around ages 30 and 36 months, respectively, avoiding the dry season (January – March) when *T. ivorensis* has dropped its leaves. Both *T. ivorensis* crown projection and *DBH* were higher than *E. deglupta* at ages 1 to 4 years but there was no difference in height. The two timber species may have benefited from the coffee fertilisation but there was no evidence that they responded to supplementary tree fertilisation. Early growth (height and *DBH*) of *E. deglupta* was lower and of *T. ivorensis* comparable if not greater than in other studies in comparable conditions. *Terminalia ivorensis* provided denser shade to the coffee and hence lateral branch pruning was required in the first 2 to 3 years after establishment. In the associations with *E. deglupta*, coffee plants reached greater height and *bd* values than in the other treatments over the 4-year measurement period. Coffee plants under *T. ivorensis* shade grew faster than those below *E. poeppigiana*; the control treatment with wider spaced

shade trees submitted to pruning twice a year which provided inadequate shade. However, there were no obvious effects of proximity of timber shade trees on coffee growth.

Uniformly fertilised coffee plants outperformed locally fertilised coffee plants in terms of coffee height and *bd* growth. Estimated coffee bean yield, based on an evaluation of eight branches per plant, predicted the actual harvested bean yield ($r^2 = 0.9474$; $p < 0.001$) but at least two years of data are needed to calibrate coffee bean yield predictions. Actually harvested coffee under *E. deglupta* was higher than under *T. ivorensis* and *E. poeppigiana.*

Lower shade level, and higher coffee plant growth and production points to *E. deglupta* as the more promising of the two timber species to be associated with coffee. Nevertheless, it would be recommended to study the associations over a longer time, including long-term trade-offs by the tree component (green manure production, timber) and coffee bean quality.

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PAPER II

Distribution and seasonal dynamics of fine roots in *Coffea arabica–Eucalyptus deglupta* or *Terminalia ivorensis* plantations in Southern Costa Rica.

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To be submitted to Agroforestry Systems

Abstract

Fine root dynamics (root diameter < 2.0 mm) were studied on-farm in a tropical rainy climate (9°15' N; 83°29' W; alt. 640 m a.s.l.) in associations of *Coffea arabica* with *Eucalyptus deglupta* or *Terminalia ivorensis* and in a pseudo-chronosequence of nearby *C. arabica–E. deglupta* associations, aged respectively, two, three, four and five years. Cores (internal diameter 8 cm) were taken in the 0 – 40 cm soil profile on one occasion (two years after out-planting) and subsequently in the following year in depth layers 0 – 10 and 10 – 20 cm, during and at the end of the rainy season, and during the dry season. Fine root density of coffee (spaced at 1 x 2 m) and timber shade trees (spaced at 6 x 6 m) was greater in the coffee fertilisation strip as compared to unfertilised areas close to the plants or in the inter-rows. Coffee fine roots were more evenly distributed in the topsoil (0 – 20 cm) whereas tree fine roots were mostly found in the first 10 cm. Although the two tree species had approximately the same fine root length density (*RLD*), lower coffee / tree *RLD* ratios in *T. ivorensis* suggest that this shade tree is potentially the stronger competitor with coffee. Coffee and tree fine root density for 0 – 10 cm measured during the rainy season increased progressively from 2 to 5-year-aged associations and coffee *RLD* increased relatively more than *E. deglupta RLD* in the 4 and 5-year-aged plantations suggesting that contrary to expectations, coffee fine roots were displacing tree fine roots.

Key words: coffee / tree *RLD* ratios, competition, pseudo-chronosequence, root length density (*RLD*), specific root length (*SRL*)

1. Introduction

Shaded coffee (*Coffea arabica* L.) plantations are of considerable importance in low elevation areas (< 1000 m a.s.l.) of Costa Rica. Traditionally, shade in this zone has been provided by nitrogen-fixing non-timber trees such as *Erythrina poeppigiana* (Walp.) O.F. Cook (Papilionaceae), which can improve nutrient cycling and have proven value in low external input systems (Nair, 1993). When these service trees are replaced by fast-growing timber trees, labour for tree pruning may be reduced and profitability of the system increased; timber trees may stabilise farmers' income, mitigating the consequences of fluctuating or decreasing world coffee prices. Fast-growing timber trees, however, may potentially also compete with the coffee plants (Beer et al., 1998). While it has been shown that under conditions of high resource availability, associations between coffee and fast-growing timber trees such as *Eucalyptus deglupta* Blume. (Myrtaceae) do not lead to excessive competition (Schaller et al., 2003), other evidence suggests that excessive competition may occur under drier conditions (Jiménez and Alfaro, 1999) and possibly under conditions of lower nutrient supply.

In the present context, root competition can be defined as the phenomenon whereby a timber tree root system reduces the access of the coffee root system to soil nutrients and / or water, either by taking them up for its own consumption or by impeding the development of the coffee root system (Schroth, 1995). No particular root system type for coffee has been identified since root distribution depends on both the genetic constitution and environmental conditions such as soil type and aeration, fertilisation and water availability, as well as the presence of other plants (Franco and Inforzato, 1946). The "typical" root system of transplanted coffee plants consists of primary roots no deeper than 0.5 m (Franco and Inforzato, 1946), 4 – 8 axial roots, lateral roots near the surface up to 2.4 m from the coffee trunk, lateral roots in deeper zones, feeder-bearers and the feeders or fine roots (Garriz, 1978). According to Smith (2000), young trees which are still confined to the shallow-rooting zone can compete strongly for nutrients with the associated crops in agroforestry systems. Sanford and Cuevas (1996) report several cases of dense root mats in the upper 20 cm soil layer of established tropical forest types. Schaller et al. (2003), working on a site without a dry season, confirmed an earlier report by Morales and Beer

(1998), working on a seasonally dry site, that the fine roots of *E. deglupta* shade trees predominate in the 0 – 10 cm soil layer while coffee fine roots predominate in the succeeding 10 – 20 cm layer. In the present study it was hypothesized that root distribution and interactions depend on nutrient availability, and thus can be influenced through fertilizer distribution. Root competition was compared in evenly aged, recently established coffee–shade tree associations (less than five years old) at different depths and different positions with respect to fertiliser distribution. Roots were sampled during the rainy and dry seasons in a sub-optimal coffee region (640 m a.s.l.; high annual rainfall > 2900 mm) with a pronounced three-month dry season. Fine root length density of *C. arabica* and trees (root diameters < 2.0 mm), as well as specific fine root length and fine root dry weight of the timber tree species were calculated for depths 0–10, 10–20 and 20–40 cm close to the coffee trunk (within and outside of the fertilisation band) and in coffee inter-rows. The relationship between coffee and tree fine root distribution and fine root response to locally distributed coffee fertilisation, was studied both in an on-farm experiment of *C. arabica* with shade trees *E. deglupta* or *Terminalia ivorensis* A. Chev. (Combretaceae) and in pseudo-chronosequence of commercial, 2, 3, 4 and 5-year-old *C. arabica* and *E. deglupta* plantations.

2. Materials and Methods

2.1. Site description

A preliminary study was conducted from June – September 2000 and the main study as well as a pseudo-chronosequence from July 2001 – March 2002 on the commercial Verde Vigor S.A. coffee farm (9°15' N; 83°29' W; alt. 640 m a.s.l.), situated in Southern Costa Rica. The site has a tropical rainy climate (Amw, Köppen classification), corresponding to a Tropical Wet Forest life zone (Holdridge, 1967) with annual rainfall of 3516 mm (1998 – 2002) and annual mean temperature of 25.7 °C. The pronounced dry season was from January until March and the wet season from the beginning of May until the end of December. During the main and the pseudo-chronosequence study (July 2001 – March 2002), rainfall totalled 2236 mm, which was 18% less than the rainfall over the same months averaged for the previous three years.

Soils were classified as Ustic Palehumult (USDA classification) and based on analyses in 1998 and 1999, had average pH (H_2O) 5.1; soil exchangeable acidity 0.66 cmol l^{-1}; K, Ca and Mg of 0.16, 3.63 and 0.13 cmol l^{-1}, respectively; and P 7.7, Cu 3.6, Fe 239.7, Mn 5.8 and Zn 0.5 mg l^{-1}, respectively. P, K and Zn were below critical levels of 12.0 mg l^{-1}, 0.20 cmol l^{-1} and 3.0 mg l^{-1}, respectively. Soil bulk density (December 2001), determined gravimetrically for depth layers 0 – 15, 15 – 30, 30 – 60, 60 – 90 and 90 – 120 cm was 0.91, 0.84, 0.91, 0.93 and 0.98 g cm^{-3}, respectively, using four core samples per depth.

The site is classified as a sub-optimal coffee-growing zone; i.e., high temperatures, seasonal water stress and poor soils (the latter balanced by high fertilisation rates).

2.2. Plantation management

2.2.1. Experimental site

All plots in the preliminary and main study (experimental site) were established on former sugar cane (*Saccharum officinarum*) fields which were cleared with fire and ploughed to about 50 cm depth prior to planting coffee bushes and trees. The sugar cane fields had been subjected to chemical weed control and had experienced soil compaction. In May 1998, coffee *Coffea arabica* cv. "Costa Rica 95" was planted at 2 x 1 m (2 plants per planting hole) in East-West lines, and in July 1998, the timber tree species were planted at 6 x 6 m. The trees were initially fertilised in the planting hole with 60 g of P_2O_5. *E. deglupta* seedlings where cultivated in a nursery on the farm from seeds from the CATIE seed bank, source BL034, batch 034/95B, RN CR 042, proceeding from Charrarra, Cartago, Costa Rica (09°49' N; alt. 1000 m a.s.l.; mean T 21 °C; mean rainfall 1969 mm yr^{-1}). *T. ivorensis* seedlings were obtained from a local nursery with seeds from the CATIE seed bank, source Experiment 38, procedence Florencia Sur, CATIE, Turrialba, Costa Rica (09°53' N; alt. 600 m a.s.l.; mean T 22 °C; mean rainfall 2460 mm yr^{-1}).

Fertiliser amounts and formulae were applied according to the commercial farm management's recommendations (Table 1). Lime was applied broadcast in the whole experiment. Weed management was performed manually with machetes, mechanically with brush-cutters and by regular herbicide applications (Paraquat, Glyphosate, Terbuthylazine) with manual or motorised knapsack sprayers. Other coffee spraying activities included foliar application of zinc, insecticides, fungicides and soil applications of

nematicides. Coffee harvests started in the second year after establishment. *E. deglupta* were pruned once per year in the first two years removing lateral branches up to 3 m trunk height. On several occasions, *T. ivorensis* were submitted to phytosanitary pruning, removing infested lateral branches up to 3 m trunk height to control a fungal disease (*Nectria* spp.). To overcome excessive shade of coffee plants, lateral *T. ivorensis* branches were removed up to 4 m trunk height, until 2001.

Table 1. Fertilisers applied from May 1998 until May 2002 in a *Coffea arabica*–shade tree trial in Southern Costa Rica.

Year	Species	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Mg (kg ha^{-1})	S (kg ha^{-1})	B (kg ha^{-1})
1998	*C. arabica*	65.2	10.8	74.2	32.4	34.8	0.0
	Trees[1)]	0.0	6.7	0.0	0.0	0.0	0.0
1999	*C. arabica*	188.1	5.6	82.3	39.2	18.5	3.0
	Trees	19.3	0.8	11.2	3.4	3.0	0.4
2000	*C. arabica*	99.5	0.0	332.4	92.5	105.5	1.9
	Trees	21.1	0.0	27.9	8.6	9.1	0.1
2001[2)]	*C. arabica*	112.5	8.2	77.8	22.5	45.6	2.5
2002[3)]	*C. arabica*	54.4	4.0	37.6	10.9	22.0	1.2

[1)] Tree (*Eucalyptus deglupta* or *Terminalia ivorensis*) fertilisation only until 2000.
[2)] Half of the fertilisation in July 2001, after the first root sampling session.
[3)] Fertilisation in May 2002, after the last root sampling session.

During the preliminary study, mean coffee (age 24 months; n = 36) basal diameter (*bd*), 15 cm above soil surface, and mean height were 34.8 (s.e. 0.5) mm and 114 (s.e. 1.4) cm for the associations with *E. deglupta* and 31.6 (s.e. 0.5) mm and 107 (s.e. 1.2) cm for those with *T. ivorensis*, respectively.

In the main study, mean coffee plant (age 48 months; n = 36) *bd* and height were respectively, 41.0 (s.e. 0.6) mm and 166 (s.e. 1.6) cm for the associations with *E. deglupta* and 34.7 (s.e. 0.7) mm and 155 (s.e. 2.0) cm for those with *T. ivorensis*.

2.2.2. Pseudo-chronosequence study

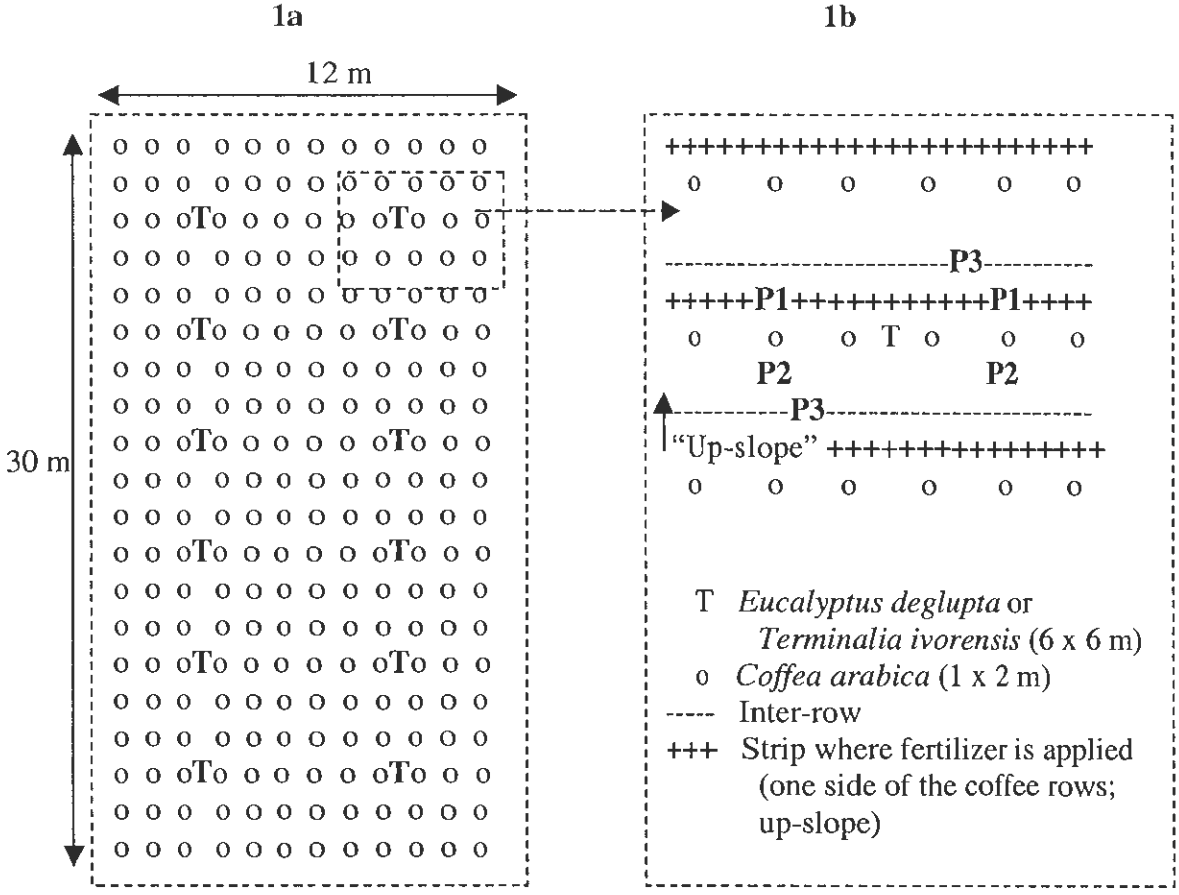
Management practices in three nearby *C. arabica–E. deglupta* associations (planted in 1996, 1997 and 1999), used for the pseudo-chronosequence study, were similar. Coffee plants in the two-year-old association presented *bd*'s around 35 mm and heights around 130 cm. In the 4 and 5-year-old associations, *bd*'s were around 42 and 50 mm, respectively, while plant heights were considered to have reached the maximum height of the cultivar of 200 cm. In the 1996 and 1997 plantations, tree stands were reduced (thinned) to 50% in the year 2000. In March – May 2001, the coffee in the 1996 and 1997 plantations was pruned, leaving every first row untouched, and trimming every second and third row down to 60 and 120 cm height, respectively.

The three differently aged *C. arabica* cv. "Costa Rica 95"–*E. deglupta* plots involved in the pseudo-chronosequence study had similar coffee (1 x 2 m) and tree (6 x 6 m) planting distances.

2.3. Experimental design and sampling scheme

2.3.1. Experimental site

The original experiment (main study) was established as a randomised complete block split-plot design with four replications. Timber shade trees (*E. deglupta* and *T. ivorensis*), with or without supplementary tree fertilisation, and a coffee–*E. poeppigiana* (service shade tree) control formed the main treatments. Localised or uniformly distributed coffee fertilisation were the sub-treatments (split-plots). Localised distribution involved applying fertiliser up-slope about 20 cm from each coffee trunk. Uniform (broadcast) distribution involved homogeneous application of the same fertiliser quantity per hectare over the whole plot surface. This was interrupted in September 2000, after the farm used the topsoil between rows to form ridges along coffee rows. Tree fertilisation in the experiment was performed in a 2 x 2 m square with the tree trunk in the centre, where every quarter of the square received the same amount as directed to each coffee bush, uniformly distributed. The slopes in the sampled plots varied between 4 and 26%.



Root sampling positions (**1b**): P1 = in the fertilisation band, 20 cm above the second coffee bush along the row from the sample tree; P2 = identical to P1, but exactly on the other side and same distance from the coffee bush and hence not in the fertilised band; and P3 = exactly between coffee rows (not in the fertilised band) at the same distance to the sampling tree as P1 and P2.

Figure 1. Root sampling sub-plot [1a] and distribution of sampling positions [1b] in experimental *Coffea arabica*–timber tree associations in Southern Costa Rica.

Fine root measurements were only carried out in locally fertilised coffee sub-plots of three replications (blocks) of the *E. deglupta* or *T. ivorensis* treatments where supplementary tree fertilisation had not been applied. The fourth replication was excluded due to the application by farm workers of decomposed organic matter to the coffee plants. The sub-plots used for the root study (Figure 1) contained 12 timber trees of which three, surrounded by healthy coffee plants, were used for each of the three sampling dates (i.e., three different trees per sampling date). Sampling positions were at 1.6 m from each sample tree, either in the coffee fertilisation band ("fertilised position"), at the opposite side of this coffee line where the fertiliser was not applied ("unfertilised position") or exactly between two coffee rows which also is not fertilised ("inter-row position"). A preliminary fine root study was performed during the 2000 rainy season (June – September; coffee and trees 23 – 28 months old from transplantation) using depth layers of 0 – 10, 10 – 20 and 20 – 40 cm. Three trees (characteristics in Table 2) were sampled per replication (block) with two cores from each position and depth (0 – 10, 10 – 20 and 20 – 40 cm) per tree; i.e., a total of 324 core samples (2 sub-samples per tree x 3 sampling positions x 3 depths x 3 trees x 2 treatments x 3 replications). Subsequently, in the main study (coffee and trees 36 – 45 months old from transplantation), fine root sampling was conducted in associations of recently established *C. arabica* with *E. deglupta* or *T. ivorensis* during the rainy season (July 2001), at the end of the rainy season (November 2001) and during the dry season (February 2002). Three trees were sampled per replication (block) for each sampling date with two cores taken for each position and depth (0 – 10 and 10 – 20) per tree; i.e., a total of 216 core samples for each sampling date (2 sub-samples per tree x 3 sampling positions x 2 depths x 3 trees x 2 treatments x 3 replications).

Table 2. Mean timber tree height (*Ht*), stem diameter at 1.3 m breast height (*DBH*) and crown projection (*CP*) in *Coffea arabica*–shade tree associations in Southern Costa Rica.

Data source	Age[1] (months)	*Ht* (m)	*DBH* (cm)	*CP*[2] (m^2)
Preliminary[3]				
Eucalyptus deglupta	26	7.4 (0.42)[4]	8.7 (0.55)	18.0 (2.20)
Terminalia ivorensis	26	6.9 (0.34)	11.1 (0.35)	20.3 (2.71)
Main trial				
E. deglupta	42	11.9 (0.46)	9.9 (0.29)	36.9 (2.35)
T. ivorensis	42	17.6 (0.58)	9.5 (0.28)	48.1 (2.98)
Pseudo-chronosequence				
E. deglupta 1996	61	13.0 (0.50)	20.8 (1.16)	64.9 (16.17)
E. deglupta 1997	49	11.4 (1.19)	14.9 (0.87)	50.8 (6.00)
E. deglupta 1998[5]	38	9.3 (0.22)	11.0 (0.42)	32.1 (1.81)
E. deglupta 1999	25	6.3 (0.58)	8.9 (0.72)	18.5 (3.62)

[1] Age since out-planting in the field. [2] Mean diameter from within and between coffee lines. [3] Data from the preliminary study and the main trial refer to the same trees at ages 26 and 42 months. [4] Standard errors (n = 9 trees) [5] Data from the main trial.

2.3.2. Pseudo-chronosequence

In these plots, each tree was considered a replication. Three trees surrounded by healthy coffee plants were selected in each plot for each sampling session during (August 2001) and at the end of the rainy season (December 2001) and during the dry season (March 2002). Two cores were taken for each position and depth (0 – 10 and 10 – 20 cm) per tree; i.e., a total of 108 core samples for each sampling date (2 sub-samples per tree x 3 sampling positions x 2 depths x 3 trees x 3 plantation ages). The results from the pseudo-chronosequencial plots were contrasted with the data obtained from the 1998 experiment to obtain a sequence of 2, 3, 4 and 5-year-old associations for *C. arabica–E. deglupta.*

2.4. Measurements

Litter and/or weed roots were carefully removed with a machete before manually introducing a cylindrical auger (8 cm internal diameter) into the soil by hammer blows. Soil cores were transported to the laboratory in a cool-box. Corresponding sub-samples (six for the experiment and two for the pseudo-chronosequence study) were homogenised, stones and other impurities were removed and fine roots were cut to a length $\leq$ 3 cm. From

the original sampling volume, 6.25% was selected for fine root extraction and analysis (Schroth and Kolbe, 1994). Samples were soaked in water for 24 hours, before being washed with tap water to remove soil particles adhering to roots. They were then passed several times through a sequence of 1.0 and 0.5-mm sieves. Roots were collected with forceps in a pan and preserved in a 15% alcohol solution and were refrigerated at 4 – 7 °C, if not analysed immediately.

Under a stereoscope (6 x), living tree fine roots were separated based upon morphological root characteristics such as tissue consistency within the central root cylinder, colour, root flexibility and general root appearance. Fine roots of *C. arabica* were brown-yellowish and presented a smooth branching appearance, while *E. deglupta* fine roots were dark brown with an angular branching appearance. Fine roots of *T. ivorensis* were dark brown to yellowish-green and notably more fragile than the fine roots from the two other species. Total fine root length (root diameter < 2.0 mm) was determined with the WinRHIZO™ (Regent Instrument Inc., Quebec City, Canada) version 3.9a root-scanning software, based on images obtained with a flatbed scanner (HP Scan Jet 6100C/T-colour scanner, Hewlett-Packard Co., USA) with a transparency adapter (HP Transparency Adapter, Hewlett-Packard). Scanning resolution was set at 300 dpi and the threshold level on automatic. No staining was required because of the dark coloration of the tree fine roots. Due to the difficulty of separating living coffee fine roots from organic debris and impurities, these were estimated with Tennant's line intersect method (1975) using a 10 x 15 cm transparent tray, a table model magnifying glass (5x) and a tally counter.

Total fine root length (*R* in cm) of each composite sample was divided by soil sample volume (cm^3) to determine fine root length density (*RLD* in cm cm^{-3}). With the exception of the preliminary study, all tree fine root samples were dried at 65 °C / 48 h. to determine fine root dry weight (*RDW* in mg) in order to calculate tree specific fine root length (*SRL* in cm mg^{-1}) [Eq. 1]:

$$SRL(cm \cdot mg^{-1}) = \frac{R(cm)}{RDW(mg)} \qquad [1]$$

Except for the preliminary study, a soil sample was taken from each of the composite soil core samples (i.e., per depth layer, position, replication, trial/site and sample date) for analysis of pH (H_2O), soil exchangeable acidity, Ca, Mg and K (cmol l^{-1}) and P, Zn, Cu, Mn and Fe (mg l^{-1}). Soil samples totalled 108 for the main and 162 for the pseudo-chronosequence, respectively.

2.5. Analytical methods

Each soil depth was analysed separately. Coffee *RLD*, tree *RLD*, coffee / tree *RLD* ratios, tree *RDW*, tree *SRL* and the ten soil parameters were analysed with the split plot Anova procedure (with dates as the sub-treatment) in SAS release 8 (SAS Institute Inc., Cary, NC, USA, 1999). Where a significant difference by date, position or treatment was detected, Duncan's multiple range test ($p < 0.05$) was used to identify the differences.

3. Results

3.1. Experimental site

In both the preliminary study (age 2 years; Figure 2) and the main study (ages 3 – 4 years; Figure 3) coffee and tree *RLD* tended to be lower ($p < 0.05$) in the inter-row position than in the two positions close to the coffee plants.

In the preliminary study, coffee fine roots were evenly distributed between 0 – 10 and 10 – 20 cm under both tree species while tree *RLD* decreased rapidly below 10 cm (Figure 2). At 20 – 40 cm, *T. ivorensis RLD* was higher than *E. deglupta RLD* ($p < 0.05$). *T. ivorensis RLD* for 10 – 20 cm in the fertilised position was higher than in the unfertilised position. For 20 – 40 cm, *T. ivorensis RLD* in the fertilised position was higher than in the unfertilised and inter-row position ($p < 0.05$). When considering the whole soil profile (0 – 40 cm), 58 – 65% of coffee *RLD*, 80% of *E. deglupta RLD* and 73% of *T. ivorensis RLD* was found in the first 20 cm. *E. deglupta* and *T. ivorensis RLD* for 0 – 10 cm were 55% and 46% of the totals for 0 – 40 cm, respectively. Within any one depth, *RLD* did not differ between treatments.

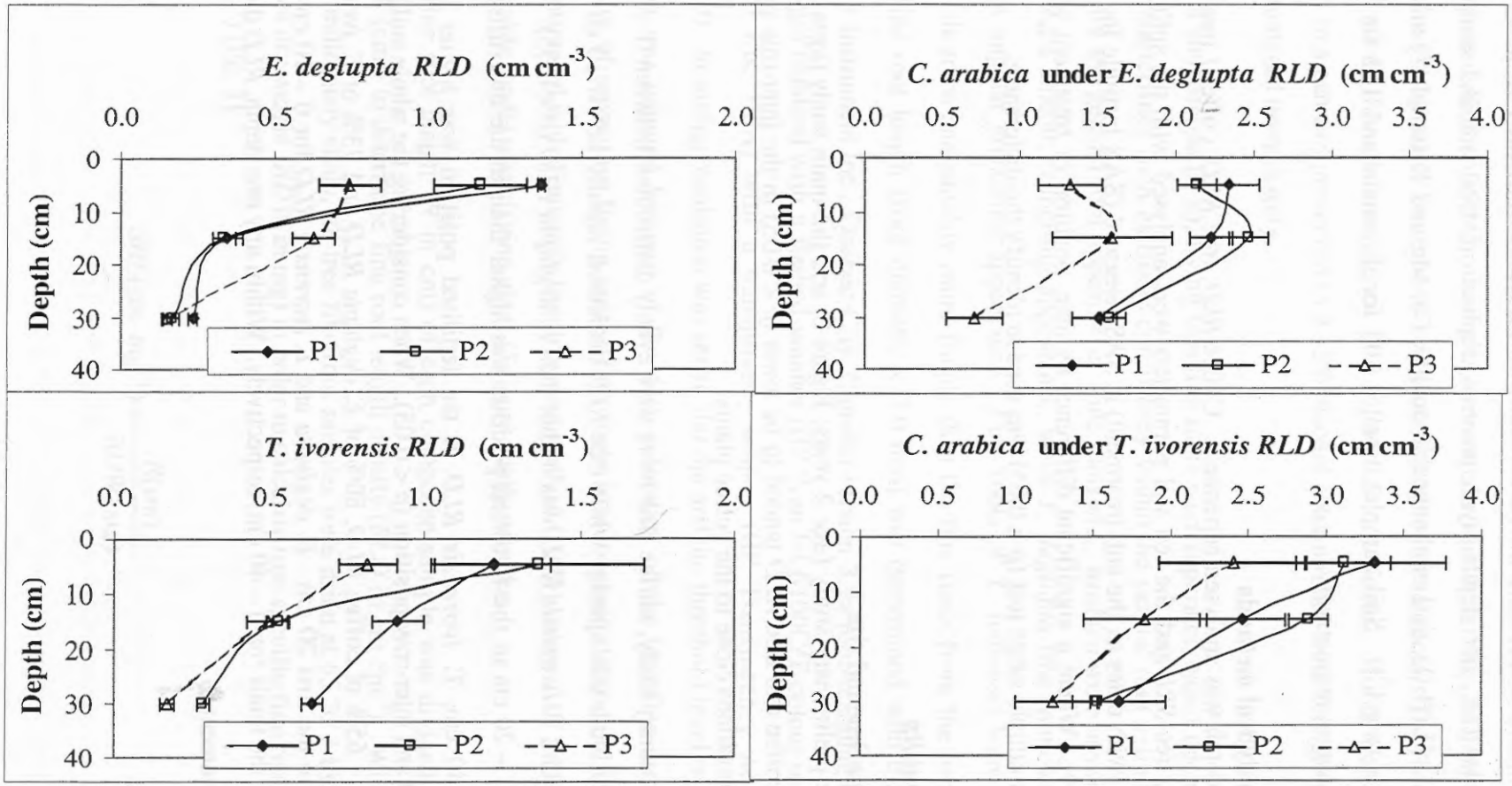


Figure 2. *Coffea arabica* and *Eucalyptus deglupta* or *Terminalia ivorensis* fine root length density (*RLD*; 23 – 28-month-old plants; mean and s.e.; n = 9) in the preliminary study. P1 = close to coffee bush, fertilised band; P2 = close to coffee bush, unfertilised area; P3 = equidistant coffee rows, unfertilised area.

Coffee *RLD* for 0 – 10 cm (Figure 3) was higher during the dry than during the rainy season ($p < 0.05$). Tree *RLD* for 0 – 10 cm in the fertilised position was higher than in the inter-row position ($p = 0.0176$). Tree *RLD* for 10 – 20 cm in the two positions close to the coffee plants were higher than in inter-row position ($p = 0.0036$).

Between seasons, there were no differences between coffee *RLD* in the two systems and no differences between *RLD* of the two tree species (Table 3). Tree *RLD* and sampling dates had significant interactions ($p = 0.0367$ and $p = 0.0032$). In both 0 – 10 and 10 – 20 cm in the main study, *T. ivorensis RDW* in the rainy season was higher than *E. deglupta RDW* (respectively, $p = 0.0007$ and $p = 0.0137$) and tree *RDW* in the two positions close to the coffee plants was higher than in the inter-row position (respectively, $p = 0.0382$ and $p = 0.0045$). On average, *T. ivorensis* fine roots were heavier and thicker than those of *E. deglupta*. Tree *RDW* interacted with sampling dates, respectively $p = 0.0323$ and $p = 0.0006$ for 0 – 10 and 10 – 20 cm. *E. deglupta SRL* for 10 – 20 cm was higher than *T. ivorensis SRL* ($p = 0.002$) and tree *SRL* and sampling dates interacted ($p = 0.0496$) (Table 3).

In the preliminary study, coffee / tree *RLD* ratios (Table 4) did not differ statistically within depth layers. However, the coffee / *E. deglupta RLD* ratio was notably lower for 0 – 10 cm than in the deeper layers. Coffee roots dominated for all positions and depths, i.e., *RLD* ratios always above 1. In the main study, no statistical differences were detected for coffee / tree *RLD* ratios in different positions in the same depth layers. Coffee / tree *RLD* ratios for 10 – 20 cm interacted with sampling dates ($p = 0.0376$). For 0 – 10 cm, on two and four occasions *RLD* ratios were below 1 (i.e., dominance of the tree roots) in the associations with *E. deglupta* and *T. ivorensis*, respectively.

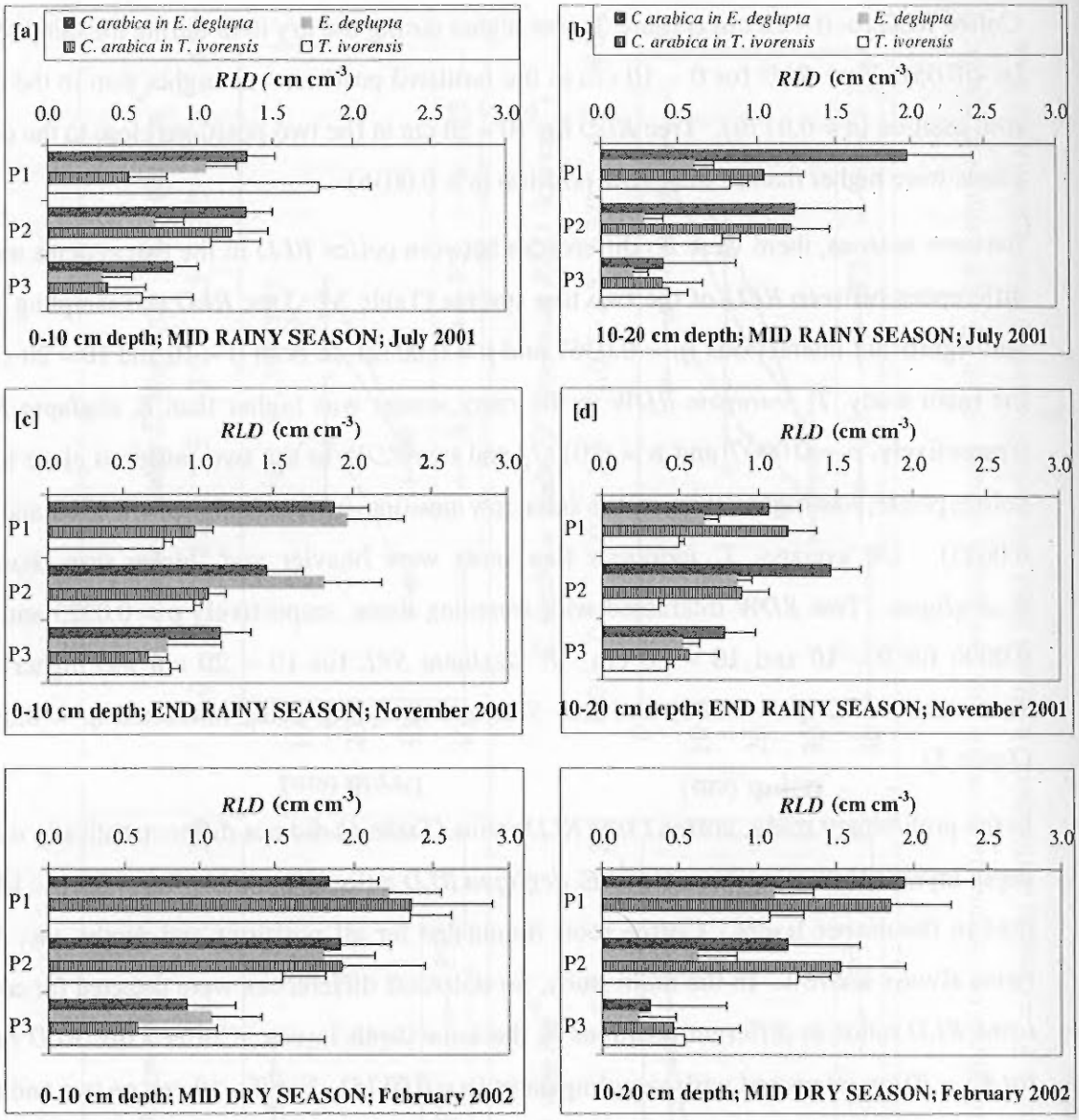


Figure 3. Fine root length density (*RLD*; mean and s.e.; n = 9) in *Coffea arabica* associations with *Eucalyptus deglupta* or *Terminalia ivorensis* (simultaneously established in May 1998) for two depths and three seasons in Southern Costa Rica. P1 = close to coffee bush, fertilised band; P2 = close to coffee bush, unfertilised area; P3 = equidistant coffee rows, unfertilised area.

Table 3. Fine root length density (*RLD*), fine root dry weight (*RDW*) and specific fine root length (*SRL*) in 3 – 4-year-old associations of *Coffea arabica* with *Eucalyptus deglupta* or *Terminalia ivorensis* in Southern Costa Rica.

	Depth	RS[1)]		ERS		DS	
	(cm)	----------	***RLD*** **(cm cm^{-3})**	----------			
C. arabica under *E. deglupta*	0 – 10	1.17	(0.24)[2)]	1.50	(0.33)	1.56	(0.26)
C. arabica under *T. ivorensis*	0 – 10	0.72	(0.16)	0.93	(0.18)	1.62	(0.50)
E. deglupta	0 – 10	0.71	(0.13)	1.52	(0.29)	1.70	(0.22)
T. ivorensis	0 – 10	1.17	(0.35)	0.85	(0.12)	1.81	(0.21)
C. arabica under *E. deglupta*	10 – 20	1.21	(0.28)	1.10	(0.28)	1.15	(0.25)
C. arabica under *T. ivorensis*	10 – 20	0.89	(0.18)	0.88	(0.15)	1.28	(0.24)
E. deglupta	10 – 20	0.37	(0.08)	0.68	(0.08)	0.65	(0.16)
T. ivorensis	10 – 20	0.69	(0.12)	0.43	(0.05)	0.95	(0.13)
		----------	***RDW*** **(mg)**	----------			
E. deglupta	0 – 10	32	(7.6)	75	(18.3)	48	(13.2)
T. ivorensis	0 – 10	100	(26.9)	58	(9.8)	46	(10.0)
E. deglupta	10 – 20	13	(3.4)	40	(8.6)	45	(8.0)
T. ivorensis	10 – 20	72	(13.4)	26	(5.0)	38	(11.0)
		----------	***SRL*** **(cm mg^{-1})**	----------			
E. deglupta	0 – 10	5.63	(1.00)	4.92	(0.64)	3.60	(0.37)
T. ivorensis	0 – 10	2.53	(0.27)	2.97	(0.33)	1.88	(0.39)
E. deglupta	10 – 20	6.01	(1.45)	4.30	(0.70)	3.90	(1.00)
T. ivorensis	10 – 20	2.03	(0.29)	3.73	(0.37)	3.64	(0.91)

[1)] RS = rainy season, ERS = end of rainy season, DS = dry season. [2)] Standard error (n = 9).

Table 4. Mean fine root length density (*RLD*) ratios[1)] in 2 and 3 – 4-year-old associations of *Coffea arabica* with *Eucalyptus deglupta* or *Terminalia ivorensis* in Southern Costa Rica.

	***RLD* ratios at age 2 years for depths (cm)**					
Preliminary study	**0–10**		**10–20**		**20–40**	
C. arabica/E. deglupta						
Fertilised[2)]	1.9	(0.65)[3)]	8.1	(3.04)	6.5	(1.30)
Unfertilised	2.0	(0.56)	7.7	(0.89)	13.6	(6.70)
Inter-row	2.3	(0.94)	3.1	(1.63)	7.2	(5.40)
C. arabica/T. ivorensis						
Fertilised	3.2	(1.10)	3.0	(0.82)	2.5	(0.65)
Unfertilised	3.7	(1.43)	5.6	(0.67)	5.6	(0.89)
Inter-row	3.7	(1.66)	4.8	(2.20)	9.8	(4.90)
	***RLD* ratios at ages 3 to 4 years (0 – 10 cm)**					
Main study	**RS[4)]**		**ERS**		**DS**	
C. arabica/E. deglupta						
Fertilised	1.5	(0.52)	1.1	(0.47)	0.8	(0.14)
Unfertilised	1.7	(0.41)	0.8	(0.09)	1.2	(0.42)
Inter-row	2.2	(0.62)	1.4	(0.92)	1.0	(0.72)
C. arabica/T. ivorensis						
Fertilised	0.6	(0.44)	1.3	(0.50)	1.2	(0.86)
Unfertilised	1.5	(0.49)	1.7	(0.98)	1.3	(0.10)
Inter-row	0.6	(0.05)	0.9	(0.48)	0.4	(0.21)
	***RLD* ratios at ages 3 to 4 years (10 – 20 cm)**					
Main study	**RS**		**ERS**		**DS**	
C. arabica/E. deglupta						
Fertilised	3.7	(1.45)	1.7	(0.54)	2.1	(0.76)
Unfertilised	8.7	(4.92)	1.6	(0.58)	2.2	(0.43)
Inter-row	2.9	(1.44)	2.7	(2.33)	1.4	(0.50)
C. arabica/T. ivorensis						
Fertilised	1.4	(0.30)	2.7	(0.96)	1.8	(0.37)
Unfertilised	1.7	(0.33)	2.4	(0.48)	1.2	(0.07)
Inter-row	0.5	(0.42)	2.1	(1.33)	1.0	(0.43)

[1)] *RLD* ratio = Coffee *RLD* (cm cm^{-3}) divided by tree *RLD*. [2)] "Fertilised" = close to coffee bush, fertilised band; "Unfertilised" = close to coffee bush, unfertilised area; "Inter-row" = equidistant coffee rows, unfertilised area. [3)] Standard error (n = 9). [4)] RS = rainy season, ERS = end of rainy season, DS = dry season.

3.2. Pseudo-chronosequence

Coffee *RLD* for 0 – 10 cm (Figure 4a) was higher ($p = 0.0009$) in the 4 and 5-year-old than in the 2 and 3-year-old associations. In the fertilised zone, coffee *RLD* was higher than in the unfertilised and inter-row positions (0 – 10 cm; $p = 0.0002$). At this depth, sampling positions and dates interacted for coffee *RLD* ($p = 0.0003$). Coffee *RLD* in the fertilised position for 10 – 20 cm was higher than in the unfertilised position, which in turn was higher ($p = 0.0004$) than in the inter-row position.

For 10 – 20 cm, coffee *RLD* was higher ($p < 0.05$) in the 5-year-old than in the 2-year-old association. *E. deglupta RLD* for 0 – 10 cm (Figure 4b) was higher ($p = 0.037$) in the fertilised than in the unfertilised position. Sampling positions and dates interacted for *E. deglupta RLD* ($p = 0.0002$) and *E. deglupta RLD* for 10 – 20 cm at the end of the rainy season was higher ($p = 0.0002$) than during the rainy season and during the dry season.

In 0 – 10 cm, the coffee / *E. deglupta RLD* ratio was higher in the 4-year-old association than in the 2 and 3-year-old associations ($p = 0.044$) and higher in the unfertilised position compared with the inter-row position ($p = 0.026$). Likewise for 10 – 20 cm, the *RLD* ratio was higher in the 4-year-old association than in the 2 and 3-year-old associations ($p = 0.0333$). Furthermore in this depth, sampling positions and dates interacted ($p = 0.0037$) for the *RLD* ratio.

In 0 – 10 cm, tree *RDW* was higher in the 5-year-old association compared with the three other associations ($p = 0.0332$) and higher in the fertilised than in the unfertilised position ($p = 0.0247$). *E. deglupta RDW* at the end of the rainy season was higher than during the rainy and during the dry season ($p = 0.0294$) and the tree *SRL* in the inter-row position was higher than in the unfertilised position ($p < 0.05$). In 10 – 20 cm, tree *RDW* was also higher in the 5-year-old association than in the three other associations ($p = 0.0106$) and higher in the fertilised than in the inter-row position ($p < 0.05$). Tree *RDW* during the dry season was higher than during the rainy season ($p = 0.0214$).

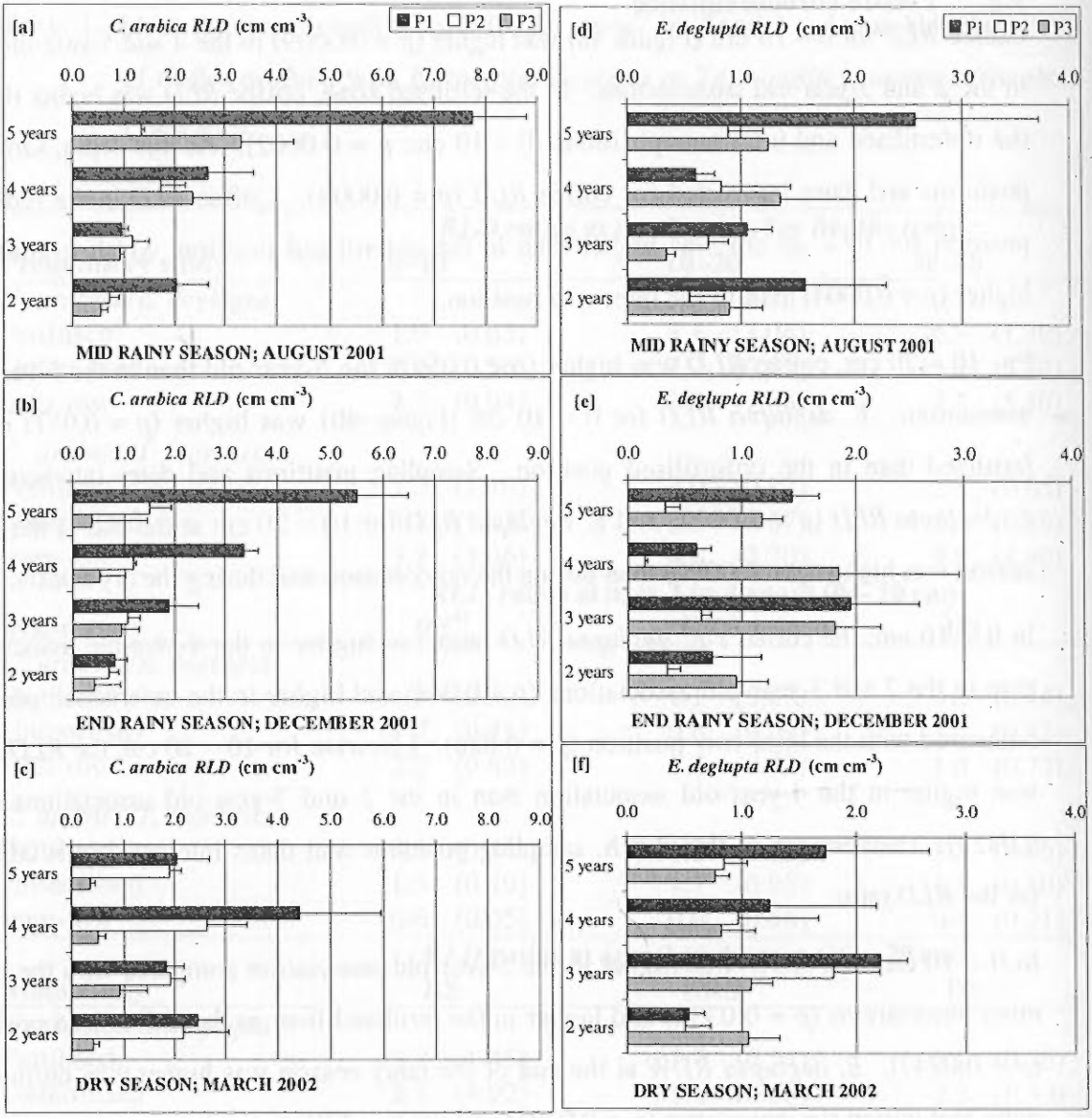


Figure 4a. Fine root length density (*RLD*) (mean and s.e.; n = 9), depth 0 - 10 cm, in four differently aged *Coffea arabica-Eucalyptus deglupta* associations, during three seasons in Southern Costa Rica. P1 = close to coffee bush, fertilised band; P2 = close to coffee bush, unfertilised area; P3 = equidistant coffee rows, unfertilised area.

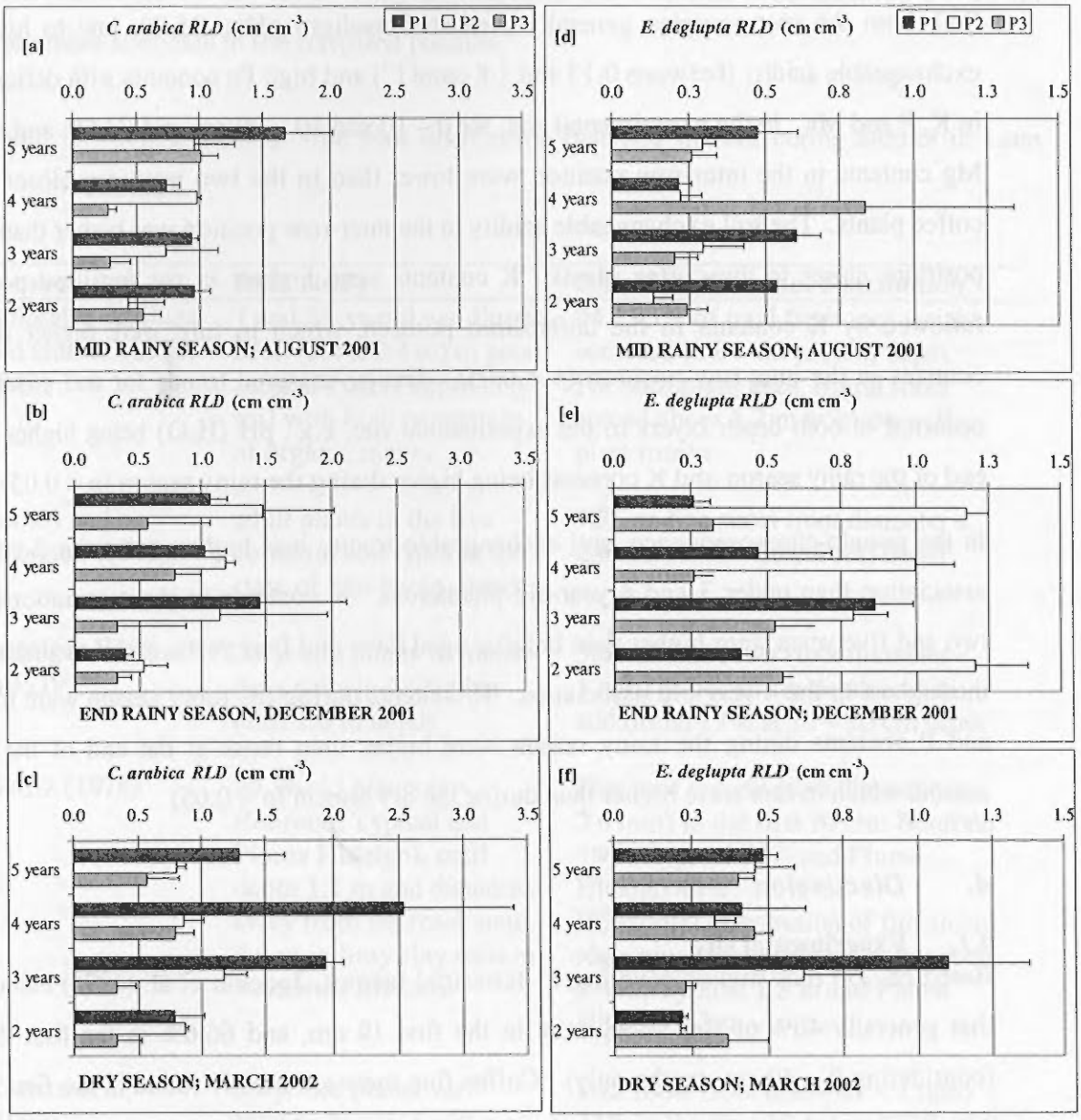


Figure 4b. Fine root length density (*RLD*) (mean and s.e.; n = 9), depth 10 - 20 cm, in four differently aged *Coffea arabica-Eucalyptus deglupta* associations, during three seasons in Southern Costa Rica. P1 = close to coffee bush, fertilised band; P2 = close to coffee bush, unfertilised area; P3 = equidistant coffee rows, unfertilised area.

3.3. Soil nutrient status

Soil from the root samples generally presented medium pH's (H_2O), low to high soil exchangeable acidity (between 0.13 and 1.8 cmol l^{-1}) and high Fe contents with deficiencies in K, P and Mn. In the experimental site, for 0 – 10 and 10 – 20 cm, pH (H_2O), and Ca and Mg contents in the inter-row position were lower than in the two positions closer to the coffee plants. The soil exchangeable acidity in the inter-row position was higher than in the positions closer to the coffee plants. K contents were highest in the fertilised position, followed by K contents in the unfertilised position, which in turn were higher than K contents in the inter-row position ($p < 0.05$). Similar seasonal trends for soil parameters occurred in both depth layers in the experimental site; e.g., pH (H_2O) being higher at the end of the rainy season and K contents being higher during the rainy season ($p < 0.05$).

In the pseudo-chronosequence, soil exchangeable acidity was higher under the 2-year-old association than under 3 and 4-year-old plantations. K contents in the associations aged two and five years were higher than in those aged three and four years, and P contents were the highest in the 4-year-old association. K contents during the rainy season were highest and P contents during the rainy season were higher than those at the end of the rainy season, which in turn were higher than during the dry season ($p < 0.05$)

4. Discussion

4.1. Experimental site

Based on 250 root studies covering 11 terrestrial biomes, Jackson et al. (1996) calculated that generally 40% of fine roots were in the first 10 cm, and 66.6% in the first 20 cm (considering 0 – 40 cm depths only). Coffee fine roots are mostly found in the first 20 to 30 cm of soil depth (Guiscafré-Arrilaga and Gómez, 1940, 1942; Franco and Inforzato, 1946; Suárez de Castro, 1953; Garriz, 1978; and Cuenca et al., 1983; Table 5). Morales and Beer (1998) reported 58% of *E. deglupta* fine roots (root diameter < 2 mm) in depth layer 0 – 10 cm and 21% in the following depth layer 10 – 20 cm considering roots until 60 cm depth in three *C. arabica–E. deglupta* sites in the Costa Rican Central Valley. For depth profile 0 – 40 cm, Schaller et al. (2003) found 59% of coffee and 76% of *E. deglupta RLD* in the first 20 cm, based on root samples taken on three occasions between March and December 1999 in a 4 – 5-year-old coffee–*E. deglupta* association in North-western Costa

Rica (continuously wet site). They also reported that tree fine roots between 0 – 10 cm were more abundant in the fertilised position.

Table 5. *Coffea arabica* fine root distribution obtained in root coring studies in Latin America.

Source	Root study	*C. arabica* fine root distribution
Guiscafré-Arrilaga and Gómez (1940, 1942)	7 and 21-yr-old var. Puerto Rico (2.4 x 2.4 m) in good aerated Puerto Rican clay soil with high percentage of organic matter	94 – 95% of total fresh root weight, occurred in 0 – 30 cm soil depth. For both plant ages, lateral roots spread about 1.2 m from the coffee plant trunks
Franco and Inforzato (1946)	adult plants in the five common soil types in the state of São Paulo, Brazil	70% of fine roots (root diameter < 2.0 mm) in 0 – 30 cm soil depth
Suárez de Castro (1953)	20-yr-old plants in franco-limy soils in Columbia until 1.6 m depth	52% of fine roots (root diameter < 1 mm) at 0 – 10 cm depth and an additional 17% at 10 – 20 cm depth
Garriz (1978)	24-yr-old plants (cv Bourbon, Typical and Pluma Hidalgo), until depth 1.1 m and distances away from the trunk until 2.4 m in limy clay soils in Veracruz, Mexico.	Fine root weight (root diameter < 2.0 mm) in the first 20 cm: Bourbon 58%, Typical 54% and Pluma Hidalgo 44%. Horizontal distribution of functional roots away from the trunk: Bourbon 2.4 m; Typical 1.8 m and Pluma Hidalgo 1.8 m.
Cuenca et al. (1983)	25-yr-old plants var. Mundo Nuevo (< 50 cm depth) in the state of Miranda, Venezuela.	Fine roots (root diameter < 1 mm) 33% in the first 10 cm and 73% in the first 30 cm

Coffee fine root distribution was similar for the different positions in the preliminary study but there were more tree fine roots close to the coffee trunk as compared to the inter-row position (Figure 2). Thus competition between tree and coffee fine roots for nutrients is more likely to occur in the positions close to the coffee trunk, and the root development does appear to be increased in the fertilised position. The same trend was observed in the

main study, and might have been due to an as yet underdeveloped fine root mat of the recently established coffee bushes and the trees, and to lower Ca and Mg concentrations and lower pH (H_2O) in the inter-row position. The farm practice of taking topsoil from the coffee inter-rows to form ridges along coffee rows, shortly after the preliminary sampling (plant age 26 months) and 10 months prior to the sampling in the main study, reduced fine root presence of both species in the inter-rows and probably promoted fine root concentration (of both species) close to the coffee plants, possibly increasing future competition. At both 0 – 10 and 10 – 20 cm depths, nutrient availability in the fertiliser strip (always 20 cm up slope besides the coffee bushes) promoted higher tree and coffee *RLD*. In Nigeria, Falade (1977) also observed promotion of *T. cacao* fine root presence (root diameter < 1.0 mm) in response to N fertilisation at 0.6 and 1.5 m away from the tree trunk.

The 2236 mm rainfall in the study period mainly occurred up to December. In a sap flow study on the same site, Kanten van and Vaast (2003) measured a decline in soil humidity in the first 30 cm depth from 30% in December 2001 to 20% in February and even further to 13% in March 2002; the authors concluded evidence of competition for water between coffee plants and trees, i.e., root competition for water. In the present study, in both depth layers (0 – 10 and 10 – 20 cm), coffee and tree *RLD* was higher during the dry season suggesting that lower soil humidity stimulated fine root growth. If water or nutrients are in short supply within the plant, the root system will get a larger share of the carbohydrate supply and will increase in size relative to the shoot or even in an absolute sense (Van Noordwijk et al., 1996).

In the preliminary study, higher *T. ivorensis RLD* than *E. deglupta RLD* in the 20 – 40 cm depth layer explain lower coffee / tree *RLD* ratios in the treatment with *T. ivorensis*. However, identical root length of different species might correspond to different root activity, inherent to each species, and therefore *RLD* ratios from different species should be interpreted with caution. The combination of lower coffee / tree *RLD* ratios in the 0 – 10 cm soil depth layer (Table 4) and simultaneously higher coffee and tree *RLD* values (Figure 2) indicate higher probability of competition in this soil horizon.

Interaction between sampling dates and treatments for the coffee / tree *RLD* ratio at depth 10 – 20 cm (Table 4) indicates different growth / mortality periods of tree vs. coffee fine roots during the study period. This can be explained by different phenological characteristics of the coffee plant and the two tree species: vegetative and fruit growth of *C. arabica* is faster in the rainy season; *T. ivorensis* drops its leaves during the dry season (January until March) but *E. deglupta* maintains foliage throughout the year even though leaf fall is greater during the dry season. Apart from reacting to seasonal changes and mineral nutrient conservation, fine roots are also affected by the strength of competing sinks for carbon such as flowers and fruits, which differ amongst species (Eissenstat and Yanai, 1997). Nutrient distribution in soil is locally variable (Jackson and Caldwell, 1993), due to topography, vegetation, pedology, climate and site management (Robinson, 1996) and roots of different species will respond differently. Fine root dynamics should be related to other processes such as nutrient cycling, soil microbial activity and overall plantation production (Idol et al., 2000).

Tree *RLD* interaction with sampling dates in both depth layers in the main study (Table 3) indicated that over time, the proportion of coffee to tree fine roots was not consistently higher in the associations with *E. deglupta* or *T. ivorensis*. In depth layer 10 – 20 cm, *E. deglupta* presented lower *RDW* and higher *SRL* and therefore has fine roots with a relatively smaller diameter than *T. ivorensis* (Table 3). *RDW* interacted with the three sampling periods which may also be related to different phenological characteristics for the two tree species. Over the measurement periods, there was interaction for tree *SRL* between treatments and sampling dates indicating no prevalence of tree fine root growth of one species over the other. Assuming constant root density, *SRL* can be considered a good correlate to root diameter (Fitter, 1994) being highest for young root systems and in soils of low fertility (Fitter, 1985; Bakker, 1999).

4.2. Pseudo-chronosequence

Greater coffee superficial (0 – 10 cm) fine root colonisation during the rainy season in the older (four – five year) as compared to the younger (two – three year) associations (Figure 4a) indicates progressive structural root colonisation over time. In the dry season, these differences were not apparent. In the 0 – 10 cm soil horizon, the fertiliser strip had more coffee fine roots; there was no difference between root colonisation in the unfertilised and

the inter-row positions. These findings coincide with observations of Schaller et al. (2003) who studied the same positions in 4 – 5-year-old coffee–*E. deglupta* associations in North-western Costa Rica, in three sampling sessions covering a dry and a wet period.

In the 10 – 20 cm soil horizon, root colonisation in the fertilised and unfertilised position was higher than in the inter-row position. Fine roots principally colonised the upper soil and this might have masked differences between root densities close to and away from the coffee trunks for depth 0 – 10 cm. Suárez de Castro (1953) observed 2.5 times more coffee fine root weight (root diameter < 1.0 mm) in the first 40 cm at distance 15 – 45 cm (104.7 g m^{-2}) than at distance 105 – 135 cm (42.1 g m^{-2}). No differences between *E. deglupta RLD* close to the coffee plants and in the inter-row position suggest complete root colonisation by the trees in the differently aged associations (Figure 4). Nevertheless, in the 0 – 10 cm depth layer, the coffee fertilisation zone had significantly more *E. deglupta* fine roots than the unfertilised zone on the opposite side of the coffee rows.

Higher coffee / tree *RLD* ratios in both depth layers in the 4-year-old association as compared to the 2 and 3-year-old associations indicate relatively more coffee roots in the sampling positions of the older association. Proportionally larger amounts of coffee fine roots in the older association suggests that, at least in the longer term, coffee roots are not displaced by tree roots of this fast-growing timber species. Indeed, it is even possible that the reverse occurs. In depth layer 0 – 10 cm, the *RLD* ratio was higher in the unfertilised as compared to the inter-row position. Therefore, *E. deglupta* fine roots were more abundant in the inter-row position, which is in accordance with findings in two other studies on fine root distribution in coffee–*E. deglupta* associations in Costa Rica; one of Morales and Beer (1998) on 1, 4, 5, 6 and 7-year-old associations and the other of Schaller et al. (2003) on 4 and 5-year-old associations. Increasing tree *RLD*'s further away from the tree with increasing age indicates partitioning of the tree and coffee root systems; a favourable selection criterion for coffee shade trees.

5. Conclusions

In both associations (*C. arabica* with *E. deglupta* or *T. ivorensis*), tree fine roots tended to be more predominant in 0 – 10 cm soil while coffee fine roots were evenly distributed in the topsoil (0 – 20 cm). Growth of fine roots of both coffee and tree species were

stimulated by the fertilisation zone, followed by the zone opposed but close to the plants and were least present in the inter-rows. On average, *T. ivorensis* fine roots were heavier and thicker than those of *E. deglupta* and in the upper, 0 – 10 cm soil depth, *T. ivorensis* appeared to be more competitive than *E. deglupta*. In older *C. arabica–E. deglupta* associations, there is a trend of increased tree fine root length density in the inter-rows. Coffee fine roots appear to be more abundant than tree fine roots and are not likely to be displaced by the tree fine roots. The combined coffee and tree fine root length density might increase with time and result in depletion of water and/or nutrients in the system. Interactions between sampling dates and positions, sampling dates and treatments or treatments and positions, indicate the variability in fine root presence and the necessity for more detailed coring, with more positions, replications per position and sampling dates.

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PAPER III

Water uptake by *Coffea arabica* L. and *Eucalyptus deglupta*, *Terminalia ivorensis* or *Erythrina poeppigiana* in agroforestry systems in Southern Costa Rica.

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Summary

Sap flow was measured in coffee (*Coffea arabica* L.) with Dynagage™ gauges in full sun or under tree shade, during dry (January – March) and wet periods (April – July 2002). Simultaneously, sap flow was evaluated with "Granier" probes in timber trees (*Eucalyptus deglupta* or *Terminalia ivorensis*) or a service tree (*Erythrina poeppigiana*) in 3 – 4-year-old coffee agroforestry systems. Daily coffee water uptake patterns were similar in full sun or under shade but values were lower under timber trees. In the dry period, both coffee and tree transpiration increased with increasing photosynthetic photon flux density (*PPFD* in μmol m^{-2} s^{-1}) and air vapour pressure deficit (*VPD* in kPa) up until a *VPD* threshold level of around 1.5 kPa above which transpiration was restricted. In the wet period, coffee and tree transpiration followed the *PPFD* and *VPD*. In all treatments, coffee transpiration was maximal in April as the result of a vegetative growth spurt that started in March and culminated in April. Minimum and maximum daily water uptake varied between: 0.38 and 1.73 litre day^{-1} m^{-2} for coffee (spacing 1 x 2 m), 47 and 104 litre day^{-1} $tree^{-1}$ for *Eucalyptus deglupta*, 44 and 119 litre day^{-1} $tree^{-1}$ for *T. ivorensis* timber trees (6 x 6 m), and 13 and 90 litre day^{-1} $tree^{-1}$ for *Erythrina poeppigiana* (8 x 8 m). *PPFD* always exceeded the maximum photosynthetic radiation level required by coffee plants, except for two months under high shade level of *T. ivorensis* (81 – 84%). During the dry period, soil moisture content in the first 30 cm was higher ($p < 0.05$) in the coffee–*E. poeppigiana* association than in the coffee–timber tree associations. Water competition in the dry season between trees and coffee was apparent in the associations with timber trees in February and in the association with *E. poeppigiana* in March.

Key words: coffee, fast-growing timber trees, photosynthetic photon flux density, sap flow, water competition

1. Introduction

Coffee (*Coffea arabica* L.) originates from the Ethiopian tropical forests (lat. 6 – 9° N, alt. 1600 – 2800 m a.s.l.) with average annual temperatures of 20 °C, well-distributed annual rainfall (1600 – 2000 mm) and a 3 – 4-months dry season. Originally, the plant has been growing under permanent shade (Maestri and Barros 1977). With the release of highly productive dwarf varieties, coffee in full sun has gradually become the predominant cultivation system during the last 25 years in the favourable areas of producing countries such as Costa Rica (Peters and Samper 2001). In the lower Costa Rican tropical areas (altitude < 800 m a.s.l.), poorly suitable for monoculture, *C. arabica* is grown under shade trees which improves micro-climatic conditions, but decreases coffee production and can compete with the coffee plants for light, nutrients and especially water during the dry period (Cannell 1971, Willey 1975, Beer 1987, Wilson 1999). Coffee floral initiation is fastest during the dry period (low soil water availability) and blossoming and rapid shoot growth are triggered by rains (Cannell 1985), a plant-water relationship called hydro-periodism (Alvim 1977). Often, water is considered the limiting resource in crop or tree physiological processes (Boyer 1982, Kramer 1986). Especially during the period of rapid coffee fruit expansion, water must be freely available to ensure large, high-quality yields (Carr 2001, Vaast et al. 2002). Measurements of sap flow in coffee (in full sun and under shade) and in shade trees allow estimation of transpiration and hence interspecies water-consumption.

Little information is available on sap flow of coffee in full sun (Gutiérrez and Meinzer 1994a, b; Gutiérrez et al. 1994) or under (artificial) shade (Fahl et al. 2000) and none has been found in the literature on coffee–shade tree plantations. In the present study, transpiration rate of the dwarf and highly productive *C. arabica* cv. "Costa Rica 95" was measured with "Dynagage™" sap flow gauges while that of associated shade trees, *Eucalyptus deglupta* Blume., *Terminalia ivorensis* A. Chev. and *Erythrina poeppigiana* (Walp.) O.F. Cook, was evaluated with "Granier" probes in an on-farm agroforestry experiment in Southern Costa Rica. Coffee and tree sap flows were compared in wet and dry periods and correlated with light availability, evapo-transpiration, air temperature, relative air humidity, air vapour pressure deficit and volumetric soil moisture content. For each system, daily water consumption per hectare was estimated.

2. Materials and methods

2.1. Site description

The study was conducted on the commercial Verde Vigor S.A. coffee farm (9°15' N; 83°29' W; alt. 640 m a.s.l.) in Southern Costa Rica. The site has a tropical rainy climate (Amw, Köppen classification), with an annual rainfall of 3516 mm (averaged over 1998 – 2002) and annual mean temperature of 25.7 °C. There is a pronounced dry season from January until March, and a wet season from May until December. Rainfall totalled 1478 mm during the study period (December 2001 until July 2002). Soils were classified as Ustic Palehumult (USDA classification).

2.2. Study site

The study site formed part of a 4 ha on-farm experiment (established in May – July 1998) with coffee cultivar "Costa Rica 95" rows in East-West direction (planted at 1 x 2 m), associated with either *E. deglupta* or *T. ivorensis* (planted at 6 x 6 m) or *E. poeppigiana* (planted at 8 x 8 m) positioned within rows. Average planting densities per hectare were 4723 ± 37 (standard error) for coffee, 250 ± 6 for *E. deglupta* or *T. ivorensis* and 146 ± 6 for *E. poeppigiana*. The experimental design was a completely randomised split-plot with four replications. With or without supplementary tree fertilisation formed the main treatments and uniformly or locally distributed coffee fertilisation the sub-treatments. To avoid loss of electrical signal due to lengthy cables, sap flow was measured in a part of the site where three different associations with uniformly fertilised coffee were adjacent. To simulate a full sun environment, a group of *E. deglupta* trees were removed in November 2001. The study area comprised 256 m^2 (16 x 16 m) for coffee under *E. poeppigiana*, and 144 m^2 (12 x 12 m) for coffee under *E. deglupta* or *T. ivorensis* or in full sun, respectively. Treatments were separated by one border row of the respective tree species and two dataloggers and a micrometeorological station were placed in the centre.

2.3. Species involved

The cultivar Costa Rica 95 was planted on the farm because of its resistance to coffee leaf rust (*Hemileia vastatrix* Berk & Br). Compared with the most common Costa Rican cultivars (Caturra and Catuaí), Costa Rica 95 has lower height and shorter branches, allowing closer planting distances. This cultivar has a higher production and a more precocious harvest but depends on intensive fertilisation to maintain high productivity (Aguilar 1998). Coffee forms its flower buds mainly on branches that are produced during

the previous year. The production cycle from flowering until fruit maturation and harvesting takes between 32 – 42 weeks (Carr 2001). In the present experiment, flowering initiated in the beginning of March and the peak harvest occurred in November 2002.

Eucalyptus deglupta is a fast-growing, evergreen species originating from lowland tropical humid forests in Papua New Guinea. The self-pruning tree has been reported to grow well at altitudes below 1200 m a.s.l. and with annual rainfalls exceeding 1000 mm in Central America. In its natural habit, the mean annual rainfall is between 2500 – 3500 mm (CATIE 1994, Eldridge et al. 1994). Growth rates on suitable sites can be between 25 – 40 m^3 ha^{-1} yr^{-1} during 15 years (Eldridge et al. 1994).

Terminalia ivorensis is a pioneer species of the transitional moist evergreen forest/moist semi-deciduous forest, originally from West Africa, ranging from Guinea to West Cameroon. The tree sheds its leaves during the dry season and is sensitive to water stress. During the experiment, *T. ivorensis* started shedding their leaves moderately at the end of November and heavily at the end of February to fully restore its foliage in mid-April. The fast-growing species can withstand an annual rainfall of less than 1300 mm and a dry season exceeding 4 – 5 months. It grows well at altitudes up to 1200 m a.s.l. and achieves heights of 30 m in 20 – 30 years (Lamb and Ntima 1971, Dupuy and Mille 1993).

Erythrina poeppigiana, a fast-growing tree originating from the Andean foothills from Venezuela to Bolivia, is one of the most predominant Costa Rican coffee shade trees (Neill 1993), present between 150 – 1900 m a.s.l. with average annual rainfall between 1000 – 3000 mm, and tolerating up to 6-month dry seasons. Regular pruning of this nitrogen-fixing tree produces green manure; an interesting low-cost management option for coffee farmers. In the experiment, *E. poeppigiana* was pruned twice a year, resulting in low tree height and trunk bifurcation. The last pruning before sap flow measurement took place in May 2001. Shortly before the rainy season in April, the tree shed its leaves entirely to rapidly recover its foliage within three to four weeks.

2.4. Measurement procedures

Eight coffee plants, 3½ – 4-year-old, were selected (two per association) with diameters at sensor height (35 cm above soil surface) ranging from 20.5 – 27.5 mm and plant heights from 149 – 196 cm. SGB25-ws (operating range of 24 – 32 mm diameter) and SGB19-ws

(18 – 23 mm diameter) stem-flow sensors (Dynamax Inc., Houston, Texas) were used on six and two coffee plants, respectively. For plants with several main (orthotropic) stems, the one bearing the most voluminous crown was selected. Gauges were connected to a centrally positioned Campbell Scientific CR10X datalogger and input multiplexer reading at 15 seconds intervals and storing 15-minute averages in a Campbell Scientific SM192 storage module. The system was powered by a 100 Ampere h^{-1} car battery (connected to a Solarex Solar Panel) and an AVRDC – Adjustable Dual Voltage Regulator – Controlled Power Voltage regulated 3.5 – 4.0 mV output to the gauges.

For each of the coffee plants, leaf area (LA in m^2) was determined for the main orthotropic stem where the gauge was placed. For all left-side leaves on all the branches, measured length and width (L and W in cm) were substituted in Eq. 1 (developed in the trial in September 2001).

$$\text{individual } LA(cm^2) = 0.6245 \times L \times W \qquad (r^2 = 0.98) \qquad [1]$$

If only the right leaf was present, this leaf was measured. Individual LA was duplicated where leaves occurred in pairs, assuming leaf pair symmetry. Total LA (m^2) per plant (the sum of all individual leaf areas) determined in April (transition month to the wet season) varied between 1.1 and 2.2 m^2.

Prior to sensor installation, low branches were cleared, the stem was smoothed with fine sandpaper and dust and grit were removed with a sponge soaked in water and detergent. The dried stem was coated twice with a Teflon easy-release spray, to avoid adherence of the heated strip to the stem, and silicone-based dielectric grease was applied to the heated gauge strip to improve thermal contact. The gauge was placed on the stem, insulated with a lower and upper foam collar o-ring (the latter tapped with plastic-tack sealer), and covered by an aluminium weather and radiation shield, one plastic film, three aluminium foil layers and a thin plastic sheet for protection against radiation and rain.

The sensors operate according to the constant power stem heat balance method (Swanson 1994, Weibel and De Vos 1994, Smith and Allen 1996, Grime and Sinclair 1999, Van Bavel et al. 2000) based on:

$$P_{in} = Q_v + Q_r + Q_{flow} \quad \text{(all in watts)} \qquad [2]$$

where P_{in} = power input of the heater to the stem, Q_r = radial heat conducted through the gauge to the ambient, Q_v = vertical or axial heat conduction through the stem, and Q_{flow} = sap flow heat to be calculated. The automatic power off mode option was activated from 9:00 p.m. to 4:00 a.m., assuming zero sap flow at night hours and eliminating power flow to the heater elements, thus reducing damage to the stem (Grime and Sinclair 1999). Sap flow (F_S), originally measured in g s^{-1}, was calculated on the coffee plant foliar area basis LA (m^2) to give a standardised F_S in ml h^{-1} m^{-2}.

One set of "Granier" probes (consisting of a heated and a reference probe) was installed in each of four trees per species and connected to a second CR10X datalogger and input multiplexer reading every 15 seconds and storing 15 minute intervals in a second SM192 storage module. Each heated probe was connected to a 137 milli Ampere DC (continuous current) potentiometer, receiving its energy from a 12 V / 100 Ampere h^{-1} car battery.

Average difference between simultaneous readings at the two probes was registered by the datalogger. The set of needle probes measures the sapwood heat dissipation capacity, which increases with sap flow and resultant cooling of the heat source. Higher values correspond to higher sap flow velocity. The exact value has to be substituted in Granier's (1987) empiric equation with a dimensional parameter K:

$$K = \frac{dT\,\max - dT}{dT} \qquad [3]$$

where $dTmax$ is the value of dT when there is no sap flow (zero set value) and dT is calculated from the differential voltage measured between the (upper) heated probe and the (lower) reference probe. Sap flow velocity V (m s^{-1}) is related to K:

$$V = 1.19 \times 10^{-4} \times K^{1.231} \qquad [4]$$

and was converted to sap flow rate F_s in litre h^{-1} for the whole tree:

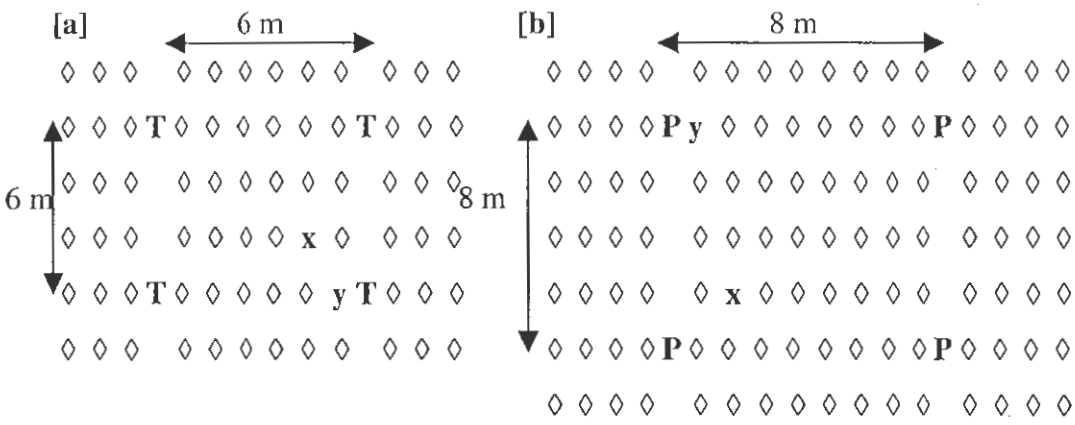
$$F_S = A_S \times V \times 3600(s \cdot h^{-1}) \times 100(cm \cdot m^{-1}) \qquad [5]$$

where A_s = cross sectional area of the conducting sap wood (cm^2).

To expose sapwood, the tree's outer and inner bark and cambium were removed over an area of 16 cm^2 (4 x 4 cm), at 1.30 m for the reference probe and at 1.45 m trunk height, slightly deviated in a vertical line to avoid insertion in the same xylem vessel, for the heated probe. The probes were inserted in 22 mm deep and 2.3 mm wide, electrically drilled holes, always below the first branch bifurcation and positioned in South South-West direction. Probes had to be installed at slightly lower positions in two *E. poeppigiana* trees to insure positioning below the branch bifurcation. The installed probes were protected with a half cylindrical Zinc shield, coated with an aluminium foam sheet from the inside, tied to the tree and covered with a Zinc roof on the top. Water leaks between the roof and tree trunk were avoided with plastic-tack sealer and the whole installation was protected against rain infiltration with a transparent plastic sheet and sealed with tape.

Simultaneous readings were recorded from a Campbell Scientific micro-meteorological station starting from February 2002. The micro-meteorological station consisted of: i) an ARG 100 Tipping Bucket Rain-gauge (*P* registered in 0.2 mm intervals), ii) a 05103-5 Wind-monitor at 2 m height (wind velocity u_2 in m s^{-1}), iii) a HMP45C air temperature (T in °C) and relative air humidity (*RH* in %) probe at 1.8 m height, iv) a SOLEMS PAR-CBE 80 (Palaiseau, France) photosynthetic photon flux density (*PPFD* in µmol m^{-2} s^{-1}) sensor fixed on top of the HMP45C, and v) PAR-CBE 80 *PPFD* sensors, fixed on top of the highest orthotropic stem of each of the eight coffee plants with gauges.

The same eight coffee plants and twelve trees (characterised at the beginning of the experiment (Table 1)) were measured (Figure 1) during 5-day periods per month (December 2001 – July 2002), except one of the coffee plants in full sun which had to be replaced in January. Measuring dates were: 19 – 24 December 2001, 18 – 23 January, 19 – 24 February, 11 – 22 March, 16 – 21 April, 13 – 18 May, 12 – 17 June, and 23 – 28 July 2002, respectively. Sensors were installed at the same position on the coffee stems and new holes were drilled close to the previous ones in the tree trunks, each month. Two trees were measured per treatment in December and January, and four ones for the remaining months. Crown projections (Table 1) were assumed to be circular and calculated with a mean diameter obtained from the projection of the widest branch range within and between coffee lines (*CP* in m^2).



T = *E. deglupta* or *T. ivorensis* (planted at 6 x 6 m) with "Granier" probe

P = *E. poeppigiana* (planted at 8 x 8 m) with "Granier" probe

◊ = *C. arabica* planted at 1 x 2 m

y = *C. arabica* plant with sap flow gauge closer to the tree (0.6 – 0.7 m)

x = *C. arabica* plant with sap flow gauge further away from the tree (2.0 – 2.9 m)

Figure 1 Sap flow plots of *Coffea arabica* associated with *Eucalyptus deglupta* or *Terminalia ivorensis* [1a] or *Erythrina poeppigiana* [1b] in Southern Costa Rica.

Table 1 Tree stem diameter at 1.45 m height (*Diam*), lowest branch height (*CH*), tree height (*H*), crown projection (*CP*) and sap-wood area (A_s) for a sap flow trial (December 2001 – July 2002) in Southern Costa Rica.

Tree[1)]	*Diam* (cm)	*CH* (m)	*H* (m)	*CP*[2)] (m^2)	A_s (cm^2)
Eucalyptus deglupta 1	15.0	4.6	8.3	60.1	85.7
E. deglupta 2	17.8	4.2	9.8	67.9	105.1
E. deglupta 3	10.7	4.6	10.1	24.6	56.0
E. deglupta 4	9.6	4.2	9.0	30.2	48.4
Terminalia ivorensis 1	15.5	3.5	7.4	91.6	84.3
T. ivorensis 2	16.4	4.5	8.0	55.4	90.5
T. ivorensis 3	18.7	4.2	7.8	56.1	106.4
T. ivorensis 4	15.9	4.7	11.1	39.9	87.1
Erythrina poeppigiana 1	12.5	1.8	5.4	30.2	59.4
E. poeppigiana 2	15.3	1.6	5.7	28.7	78.8
E. poeppigiana 3	13.0	1.7	5.5	35.3	62.9
E. poeppigiana 4	15.7	1.4	5.3	30.4	81.6

[1)] Trees 1 and 2 used during the whole study and trees 3 and 4 starting from February 2002.
[2)] At *CP* values higher than 28.3 m^2 *E. deglupta* or *T. ivorensis* trees spaced at 6 x 6 m overlap.

For *E. deglupta* and *T. ivorensis*, conductive cross-sectional sap-wood area (A_S in cm^2) was estimated by cutting a fresh 2 cm high disk of a recently felled tree and emerging the lower part of the disk in a film of a tryphan blue coloured solution. After three hours, the upper part of the disk coloured in blue was identified as A_S. For both tree species, the procedure was repeated with 11 felled trees (one disk per tree) and the *Diam* vs. A_s relation was estimated with a linear regression:

$$E.\ deglupta\ \ A_S(cm^2) = 7.58 \times Diam(cm) \qquad r^2 = 0.77 \qquad [6]$$

$$T.\ ivorensis\ \ A_S(cm^2) = 12.56 \times Diam(cm) \qquad r^2 = 0.81. \qquad [7]$$

For the service tree *E. poeppigiana*, A_S was estimated by cutting one 2 cm high disk from a tree stem at 1.45 m height, repeating the tryphan blue coloured solution procedure. After

A_S characterisation, the cross-sectional area at 1.45 m of another felled tree was measured and A_S was estimated to be on average 81.5% of the total tree stem surface area at 1.45 m.

Soil moisture content (%) was determined with a Moisture-Point MP-917 instrument, Environmental Sensors Inc. E.S.I., Canada, according to the Time Domain Reflectometry (TDR) method, during each sap flow measurement period. Mobile probes (30 cm long) were connected to the MP-917 instrument and inserted in a total of 16 positions, always 20 cm away from the coffee trunks, in each of the four treatments.

Daily reference evapotranspiration (*ETo* in mm) was estimated with the FAO Penman-Monteith equation (Allen et al. 1998) using an adaptation of an Excel spreadsheet developed by the FAO (Food and Agriculture Organisation, United Nations), with inputs u_2, T, and *RH* obtained from the micro-meteorological station. The coffee canopy resistance coefficient and crop height were considered to be 31 s m^{-1} and 170 cm (the mean height of the eight plants in the study), respectively, for all four treatments, without differentiating for systems under different tree shade or in full sun. The number of sun hours (n) was estimated with

$$n = \frac{N \times R_S}{R_a} \qquad [8]$$

$$R_S = k_{R_S} \sqrt{(T_{\max} - T_{\min})} \times R_a \qquad [9]$$

combined into

$$n = N \times k_{R_S} \sqrt{(T_{\max} - T_{\min})} \qquad [10]$$

where N is the maximum possible duration of sunshine or daylight hours (hour), R_s the solar or short-wave radiation (MJ m^{-2} day^{-1}), R_a the extraterrestrial radiation (MJ m^{-2} day^{-1}), k_{Rs} an adjustment coefficient for interior locations where land mass dominates and air masses are not strongly influenced by a large water body (k_{Rs} = 0.16) and ($T_{max} - T_{min}$) the difference between daily maximum and minimum temperature.

Air vapour pressure deficit (*VPD* in kPa) was calculated with the Penman equation:

$$e_a = 0.1 \times \exp(54.88 - 5.03 \times \ln(T + 273.15) - \frac{6791}{T + 273.15}) \quad [11]$$

$$e_d = e_a \times RH \quad [12]$$

$$VPD = e_a - e_d \quad [13]$$

where e_a is the air saturation vapour pressure, e_d the vapour pressure at air temperature T (transformed from degree Celsius into degree Kelvin) and RH the relative air humidity.

2.5. Analytical methods

Data were analysed with SAS release 8 (SAS Institute Inc., Cary, NC, USA, 1999). Coffee F_s in ml h^{-1} m^{-2} of coffee leaf area and tree F_s in litre h^{-1} $tree^{-1}$ was related to *PPFD* and *VPD* in a series of regression analyses for every month from February to July 2002. Mean daily accumulated coffee and tree sap flow *Facc* (in litre day^{-1} m^{-2} and litre day^{-1} $tree^{-1}$, respectively) based on measurements of four full consecutive days were submitted to an analysis of variance (Anova) and a Student-Newman-Keuls (SNK) test for every month from December 2001 to July 2002. Mean daily *PPFD* values from February onwards were grouped into categories 7:00 – 9:00 a.m., 11:00 a.m. – 1:00 p.m. and 3:00 – 5:00 p.m., and submitted to an Anova and a SNK test. Mean daily coffee and tree *Facc* values were used to estimate water consumption per hectare per treatment (in m^3 day^{-1} ha^{-1}) and this estimated consumption submitted to an SNK test.

3. Results and discussion

3.1. Daily coffee water uptake pattern in dry and wet periods

Rainfall totalled 208 mm in the dry period (January – March) and 1305 mm afterwards (Figure 2). Average monthly temperatures varied between 23.2 – 24.8 °C between February and July. The reference evapotranspiration (*ETo*) varied between 4.8 – 5.2 mm day^{-1} (in the dry months and the transition month to the rainy season) and between 4.0 – 4.2 mm day^{-1} in the rainy months afterwards (May – July).

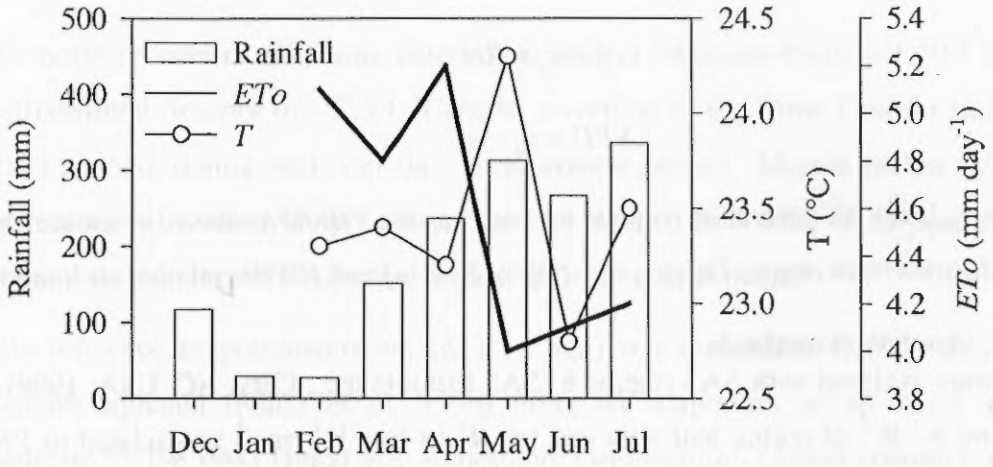


Figure 2. Monthly rainfall, mean air temperature (T) and mean reference Evapotranspiration (*ETo*) in Southern Costa Rica. (*ETo* and T based on 4-day periods per month).

Coffee transpiration was lower in the dry month (February) than in the wet month (June) under *E. deglupta* (Figure 3a), not different in the two contrasting periods under *T. ivorensis* or in full sun (Figure 3b and d) and higher in the dry month than in the wet month under *E. poeppigiana* (Figure 3c). In the dry month, the coffee transpiration for all the treatments (Figures 3) started at 6:45 a.m with the sunrise. The coffee transpiration rate (F_S) reached its peak at 9:15 and 10:15 a.m. under *E. deglupta* and *T. ivorensis* shade, respectively, to remain constant until about 12:30 p.m. and to decrease afterwards. Coffee F_S under *E. poeppigiana* shade or in full sun reached a first and second peak at 9:15 a.m. and 12:30 p.m., respectively, and decreased afterwards. *PPFD* started to increase at 6:30 a.m. (Figure 3), shortly after a sharp increase in air temperature and decrease in *RH* could be observed (Figure 4). Air temperature increased until midday and declined thereafter while *RH* followed the opposite trend.

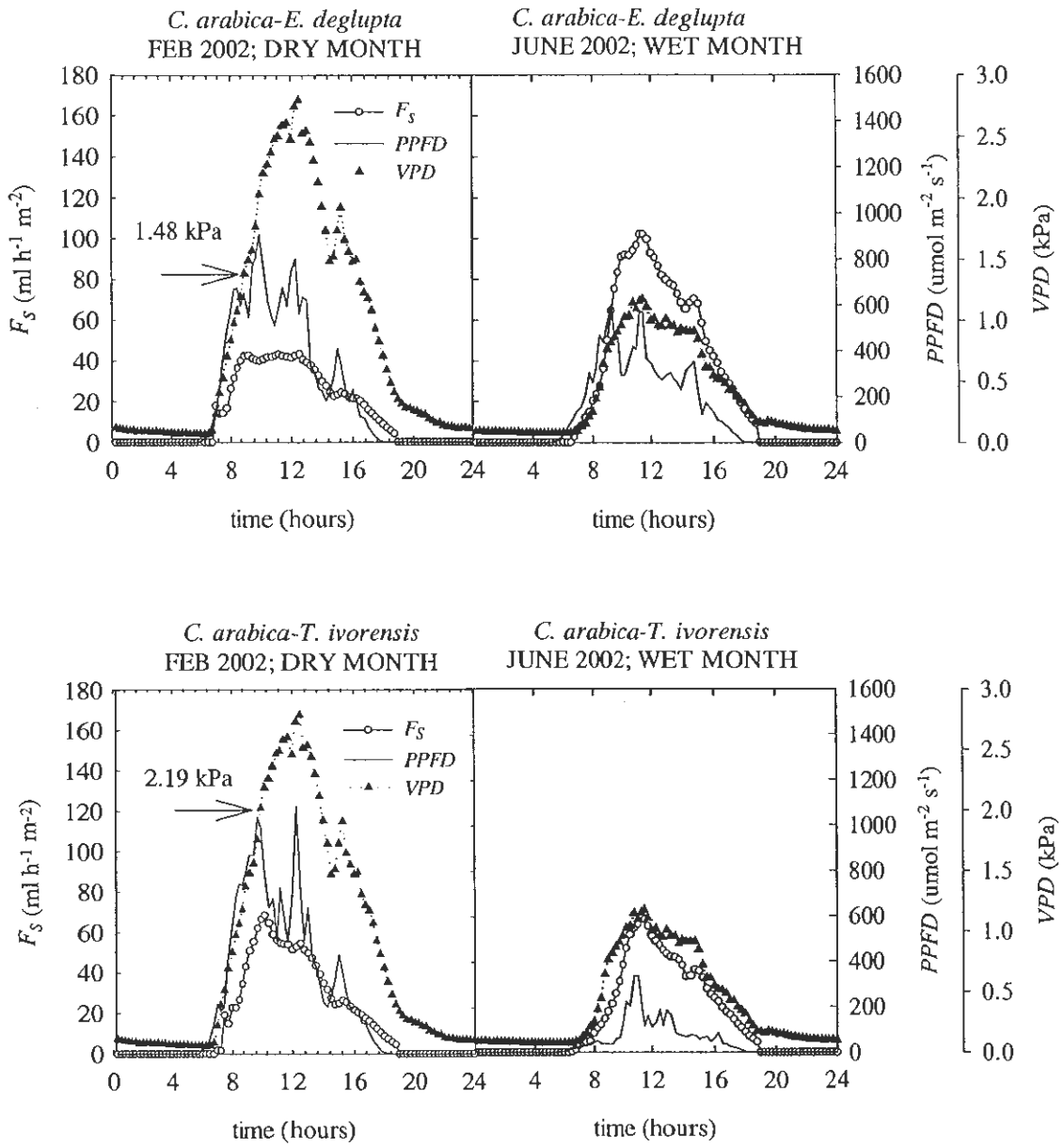


Figure 3a + b. Mean coffee sap flow (F_S) vs. photosynthetic photon flux density (*PPFD*) and air vapour pressure deficit (*VPD*; measured in full sun) based on four consecutive days and two plants under shade of *Eucalyptus deglupta* or *Terminalia ivorensis*for a dry month (February) and wet month (June), in Southern Costa Rica. Values are averages over 15 minute-periods. *VPD* threshold level (when F_S starts to drop in the dry month) indicated with arrow.

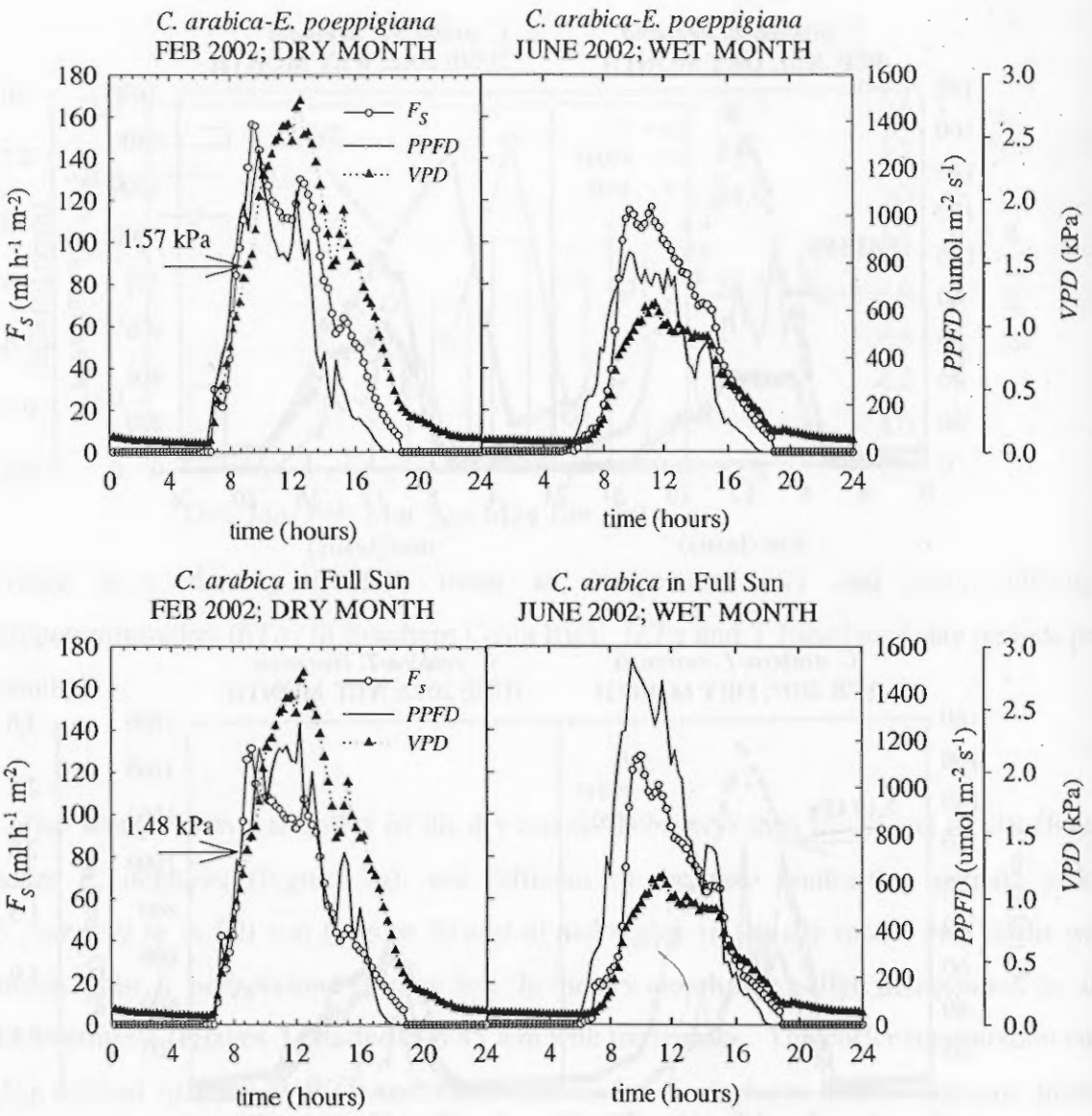


Figure 3c + d. Mean coffee sap flow (F_S) vs. photosynthetic photon flux density (*PPFD*) and air vapour pressure deficit (*VPD*; measured in full sun) based on four consecutive days and two plants under shade of *Erythrina poeppigiana* or in full sun for a dry month (February) and wet month (June), in Southern Costa Rica. Values are averages over 15-minute-periods. *VPD* threshold level (when F_S starts to drop in the dry month) indicated with arrow.

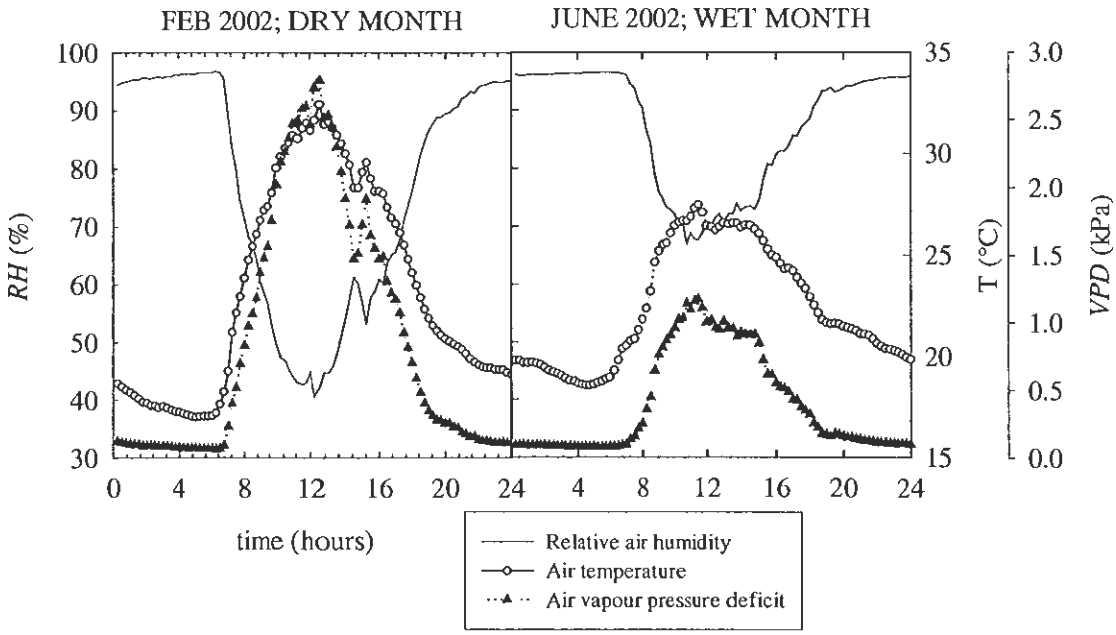


Figure 4. Mean relative air humidity (*RH*), air temperature (T) and air vapour pressure deficit (*VPD*) based on four consecutive days for a dry month (February) and a wet month (June) in Southern Costa Rica. Values are averages over of 15-minute-periods.

PPFD measured on top of the coffee plants was higher in the dry than in the wet period due to higher luminosity and loss of leaves by shade trees during the dry months (Figure 6). Using *PPFD* in full sun from 11:00 a.m. – 1:00 p.m. as a reference (100%); the coffee plants associated with *E. deglupta*, *T. ivorensis* or *E. poeppigiana* received irradiation ranging from 47 – 60; 63 – 69; and 78 – 82%, in the dry months (February and March) and from 41 – 55; 18 – 54; and 69 – 95%, in the wet months (May until July). This resulted in higher coffee F_S in full sun or under *E. poeppigiana* shade.

Lower *RH* values and higher T resulted in higher *VPD* values, which induce stomatal closure (Maestri and Barros 1977, Fanjul et al. 1985, Meinzer 1993, Gutiérrez and Meinzer 1994a, Gutiérrez et al. 1994). In the present experiment, weather data collected in the full sun treatment were used to compute air *VPD* values. These *VPD* values were plotted against coffee F_S for all treatments, although the microenvironment created by the presence

of trees certainly resulted in air temperature, *RH* and hence *VPD* values different from those measured in full sun by the weather station. It can be seen graphically that in all treatments in the dry month, an increase in *VPD* above a threshold level (1.48 kPa for coffee under *E. deglupta* or in full sun, 1.57 kPa for coffee under *E. poeppigiana*, and 2.19 kPa for coffee under *T. ivorensis*) coincided with a drop in coffee F_S, despite increasing *PPFD* and *VPD*. Before reaching the threshold level, coffee transpiration was following the *PPFD* and *VPD* patterns. It should also be pointed out that leaves of the coffee canopy probably do not behave uniformly and the coffee crown can be subdivided in numerous microenvironments subjected to different amounts of light and *VPD* levels, such as emphasized by Dauzat et al. (2001) in a simulation study of coffee transpiration and sap flow applied to a Costa Rican plantation.

Coffee transpiration can decline while *PPFD* and *VPD* are still increasing, as demonstrated by Gutiérrez et al. (1994) measuring maximum stomatal and crown conductance values at 11:00 a.m. on 1 – 5-year-old hedgerow coffee plants in Hawaii (lat. 21°54' S; alt. 98 m a.s.l.). Co-variation between *PPFD*, *VPD* and wind speed made it difficult to determine stomatal response to these variables individually, but after normalization to *PPFD*, these authors demonstrated that stomatal conductance was strongly correlated with *VPD* ($r^2 >$ 0.80).

In the present experiment and during the dry month of February when F_S dropped despite increasing *PPFD* and *VPD*, a regression analysis between F_S vs. *PPFD* and *VPD* resulted in separated equations for the coffee under timber trees (Figure 5a) and the coffee under *E. poeppigiana* or in full sun (Figure 5b).

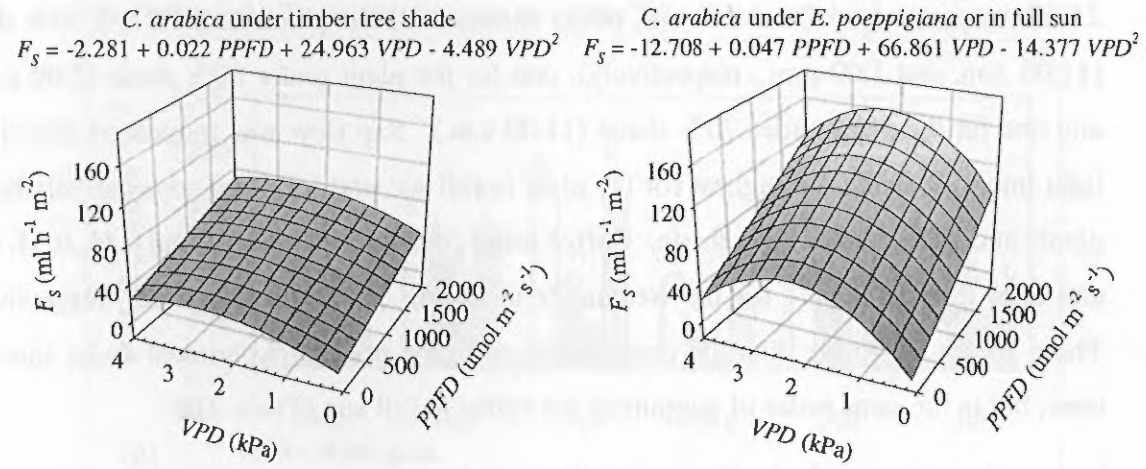


Figure 5. Multiple regressions surface grid for *Coffea arabica* under shade of timber trees (*Eucalyptus deglupta* or *Terminalia ivorensis*) (r^2 = 0.74) or *C. arabica* under *Erythrina poeppigiana* or in full sun (r^2 = 0.71) in a dry month (February) in Southern Costa Rica. (Measurements on two plants per treatment during four consecutive days; photosynthetic photon flux density (*PPFD*) measured on top of each coffee plant; air vapour pressure deficit (*VPD* measured in full sun).

A second, less accentuated coffee F_S peak for the plants in full sun or under *E. poeppigiana* shade at 12:15 p.m. probably had been induced by an increase in *PPFD* during the typical unclouded conditions with maximum temperature, shortly after midday. These observations are in agreement with previous studies. In a study with 11-year-old *C. arabica* var. Caturra under *E. poeppigiana* shade in North-western Costa Rica (9'38° N; 83'88° W; 600 m a.s.l.; 2600 mm annual rainfall), in the beginning of April, Rapidel (1995) observed one coffee sap flow peak occurring around 10:15 a.m. and a second, less accentuated one, at 12:15 p.m. However, this researcher measured a maximal coffee water uptake rate in the range of 0.24 – 0.27 litre h^{-1} m^{-2} of coffee leaf area, well above that of coffee plants under *E. poeppigiana* shade in the present experiment which did not exceed 0.16 litre h^{-1} m^{-2} in the dry month and 0.12 litre h^{-1} m^{-2} in the wet month (Figure 3c). Using Dynagage™ sensors, Fahl et al. (2000) registered different coffee F_s peaks on 3-year-old coffee plants under 70, 50, 30 or 0% artificial shade, in South-eastern Brazil (lat. 22°32' S;

alt. 710 m a.s.l.), in a dry and cold period (minimum and maximum air T of 5 and 25 °C, respectively). Two coffee F_s peaks occurred for the plants under 0 and 30% shade (11:00 a.m. and 1:00 p.m., respectively); one for the plant under 50% shade (2:00 p.m.); and one for the plant under 70% shade (11:00 a.m.). Sap flow was influenced directly by light intensity, being the highest for the plant in full sun and followed consecutively by the plants under 30, 50 and 70% shade. Coffee water consumption was around 0.44, 0.34, 0.54 and 0.94 litre day^{-1} m^{-2}, for the treatments under 70, 50, 30 or 0% shade, respectively. These values are lower than the ones registered in the present experiment under shade of trees, but in the same order of magnitude for coffee in full sun (Table 2).

Low coffee water uptake in the dry month points toward water competition between coffee and *E. deglupta* or *T. ivorensis*. The more flattened coffee F_S curve under *E. deglupta* in dry month might indicate higher water competition from this tree species as compared to *T. ivorensis* (Figure 3a and b). Under *E. poeppigiana* there was no evidence of water competition by the trees in February. However, in the following month, the end of the dry period, coffee F_S in this treatment was considerably lower than the one in full sun (Table 2) probably due to the effect of water competition by the trees.

PPFD values in the three coffee-tree associations were lower in the wet month June (Figure 6). Coffee started to transpire at 6:30 a.m. and reached its peak under shade of the two timber tree species at 11:30 a.m. Under *E. poeppigiana* shade and in full sun, coffee F_s reached its first peak at 10:00 a.m., decreased afterwards, and presented another, less accentuated peak at 11:15 a.m. In all four treatments, coffee transpiration started to decrease moderately from 11:30 a.m. until 2:45 p.m. and more sharply afterwards with decreasing *PPFD* and *VPD* values. In the wet month, *VPD* stayed below the threshold value. In all treatments coffee F_S was not restricted by *VPD* and followed the *PPFD* and *VPD* (and hence air temperature) pattern, responding to the plant evaporative demand.

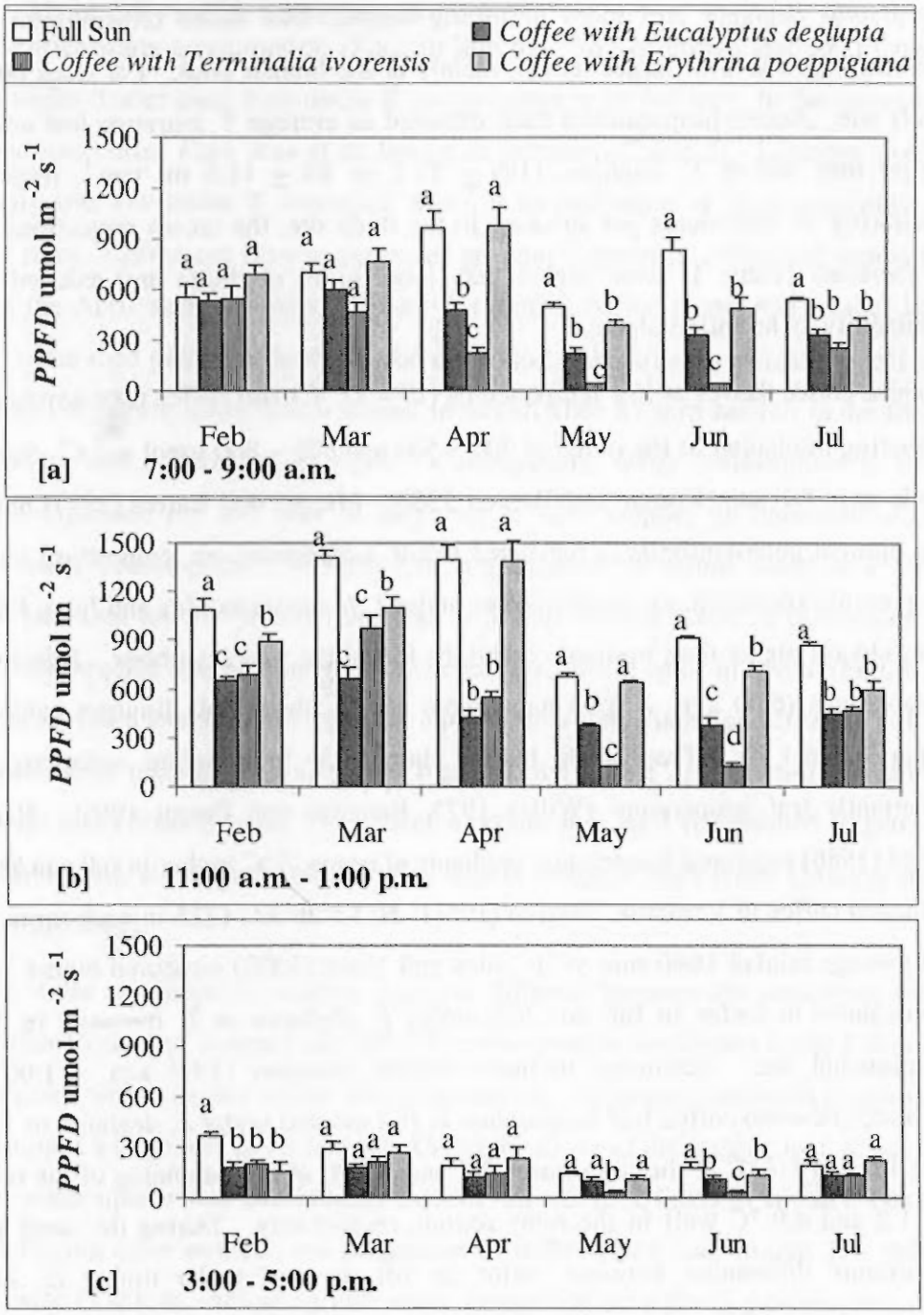


Figure 6. Mean photosynthetic photon flux density (*PPFD*; s.e.) based on two sensors and four consecutive days in Southern Costa Rica. Time periods 7:00 - 9:00 a.m. [6a], 11:00 a.m. - 1:00 p.m. [6b] and 3:00 - 5:00 p.m. [6c]. Different letters within the same month indicate differences (Student-Newman-Keuls test; $p < 0.05$).

Eucalyptus deglupta had more uniformly shaped, less dense crowns than *Terminalia ivorensis* crowns with larger leaves, mainly at the branch ends. For trees bordering the study site, Anzola (unpublished data) obtained an average *T. ivorensis* leaf area 2.9 times bigger than that of *E. deglupta* (189 $\pm$ 22.2 vs. 65 $\pm$ 11.6 m^2 $tree^{-1}$, respectively) by measuring 15 individuals per species. In the study site, the crown projections of the four *T. ivorensis* (Table 1) were higher than those of *E. deglupta* and reduced more light availability to the coffee plants.

Arabica coffee thrives at low temperatures (19 – 22 °C) and coffee photosynthesis requires saturating irradiation in the range of 300 – 500 and 600 – 800 µmol m^{-2} s^{-1}, respectively in shade or in full sun (Kumar and Tieszen 1980). Maestri and Barros (1977) have reported that optimal photosynthesis is registered below a maximum air temperature of 24 °C. In the present experiment, except for coffee under *T. ivorensis* in May and June, *PPFD* values were always higher than optimal conditions for coffee photosynthesis. Average daily air temperatures (6:00 a.m. – 6:00 p.m.) were always above this limiting value of 24 °C (Figure 2 and 4). Tree shade buffers diurnal air temperature variations and more importantly leaf temperature (Willey 1975, Barradas and Fanjul 1986). Barradas and Fanjul (1986) measured temperature gradients of nearly 7 °C higher in full sun as compared to shaded coffee in Veracruz, Mexico (19°31' N; 95°56'W; 1225 m a.s.l. mean T 18.5 °C and average rainfall 1640 mm yr^{-1}). Siles and Vaast (2003) measured higher leaf and air temperatures in coffee in full sun than under *E. deglupta* or *T. ivorensis* in the present experimental site. According to these authors, between 11:00 a.m. – 1:00 p.m., the difference between coffee leaf temperature in full sun and under *E. deglupta* or *T. ivorensis* were 1.0 and 1.7 °C in the dry season, 3.1 and 4.5 °C at the beginning of the rainy season and 1.2 and 4.9 °C well in the rainy season, respectively. During the same period, air temperature differences between coffee in full sun and under timber *E. deglupta* or *T. ivorensis* were 0.8 and 1.4 °C in the dry season, 2.4 and 3.5 °C in the beginning of the rainy season and 0.7 and 3.9 °C well in the rainy season, respectively. These results can explain the higher coffee water uptake in full sun or under *E. poeppigiana* when this tree had completely shed its foliage in the experiment.

3.2. Mean daily coffee water consumption

Daily coffee water consumption (*Facc* in litre day^{-1} m^{-2} of coffee leaf area) tended to be lower under timber trees than under *E. poeppigiana* or in full sun. In the association with *E. deglupta*, coffee *Facc* was at its lowest in February (Table 2). Likewise, coffee F_S in February was low under *T. ivorensis*, which is an indication of water competition by the timber trees. Coffee sap flow is expressed per square meter of coffee leaf area determined during the April measurements. Before this period, coffee plants had smaller leave area since coffee shed part of its leaves in the dry period and started to increase its leaf area with a vegetative growth spurt which started in March after 87 mm rainfall in the first half of this month and culminated in April. Consequently, water consumption in the earlier months expressed per leaf area as measured in April implies an underestimation of the actual water consumption. Nevertheless, a simulation of values based on a 10% lower coffee leaf area for the period December – March did not result in differences. Coffee water consumption was increased by the vegetative growth spurt in March (for the plants in full sun and to a lesser extent the ones under timber tree shade) and in April coffee water use reached its maximum in all of the four systems (Table 2). In April, the rainy season was well established (Figure 2) and soil moisture was well replenished (Figure 7). The vegetative flush at the onset of the rainy season demands high water (Maestri and Barros 1977, Carr 2001).

Coffee water consumption patterns were not different between the timber tree treatments, except for December, January and July when transpiration was lower under *T. ivorensis*, the tree species with a denser shade pattern during the wet season (in the dry season, the tree had dropped a large part of its leaves). Under the shade of the legume tree, *E. poeppigiana*, coffee water uptake was even higher than in full sun ($p < 0.05$) in January, February and July. During these months, the proportion of coffee *Facc* was around 39 – 44% of the association (Table 4), indicating low water competition between *E. poeppigiana* and coffee, and suggesting exploration of deeper soil zones for water by tree roots than by coffee roots.

Table 2 Mean daily accumulated sap flow (*Facc*) based on two coffee plants over four consecutive days of every month (litre day^{-1} m^{-2}) in Southern Costa Rica.

	Coffea arabica with			
Month	*Eucalyptus deglupta*	*Terminalia ivorensis*	*Erythrina poeppigiana*	*C. arabica* in Full Sun
	Facc (litre day^{-1} m^{-2} coffee leaf area)			
December[1)]	0.61 (0.017)bc[2)3)]	0.48 (0.010)c	0.69 (0.038)c	0.73 (0.021)c
January	0.77 (0.022)b	0.56 (0.028)bc	0.97 (0.026)b	0.76 (0.019)c
February	0.38 (0.023)c	0.45 (0.028)c	1.07 (0.079)b	0.86 (0.066)c
March	0.66 (0.057)b	0.67 (0.067)b	0.63 (0.063)c	1.11 (0.124)b
April	1.33 (0.103)a	0.90 (0.086)a	1.73 (0.074)a	1.50 (0.113)a
May	0.61 (0.062)bc	0.44 (0.051)c	0.64 (0.083)c	0.75 (0.066)c
June	0.67 (0.110)b	0.39 (0.068)c	0.75 (0.111)c	0.73 (0.100)c
July	0.62 (0.043)bc	0.39 (0.014)c	1.01 (0.059)b	0.79 (0.036)c

[1)] December 2001 – July 2002. [2)] mean (standard error). [3)] different letters within the same column indicate differences ($p < 0.05$) according to the Student-Newman-Keuls test.

Soil water stress influences coffee leaf water potential, reducing their stomatal aperture and hence, their transpiration rate (Meinzer 1993). However, except for the coffee plants under *E. poeppigiana*, there was no evidence in the present study of lower coffee water consumption in March (Table 2), when volumetric soil moisture content (%) was minimal (Figure 7). Water stress in this period of fruit expansion (Carr 2001) reduces coffee fruit size and hence production (Cannell 1975, Nunes 1976, Vaast et al. 2002) and might result in deficient K and P absorption. K and P were found to be at critically low levels in the experimental site (Kanten van et al. 2003a, b). Coffee photosynthesis and stomatal closure in response to water supply and coffee water status are not fully explained by soil moisture (Meinzer, 1993). Identical soil moisture levels, but different air and leaf temperature as well as *RH* might lead to different coffee leaf water potentials (Kumar and Tieszen 1976).

In the first 30-cm soil depth over the period December 2001 – June 2002, moisture content varied between 13.9 and 35.3, 13.2 and 35.0, 17.2 and 37.1 and 10.9 and 34.0%, in the associations between coffee and *E. deglupta*, *T. ivorensis* or *E. poeppigiana* and coffee in full sun, respectively (Figure 7). Soil moisture content was highest ($p < 0.05$) in the coffee-*E. poeppigiana* association between December 2001 – June 2002. This coincides with

results of Jiménez and Alfaro (1999) who consistently measured higher water contents in 0 – 60 cm soil depths in a coffee–*E. poeppigiana* association and coffee in full sun in comparison to a coffee–*E. deglupta* association in a dry period in the Costa Rican Central Valley (10°N, 84°W; alt. 1020 m a.s.l.; mean T 20 °C). In the present experiment, soil volumetric moisture content decreased to its lowest values in March, the last month of the dry season, and increased subsequently to maximum values for all four treatments in June. Although March, with lowest volumetric soil moisture content should be the critical period for water competition, this proved not to be the case since coffee water uptake increased for the plants in full sun and under timber shade. In the coffee–*E. poeppigiana* association, coffee water uptake lowered which can be attributed to a higher water consumption of the legume tree as explained later (Chap. 3.4).

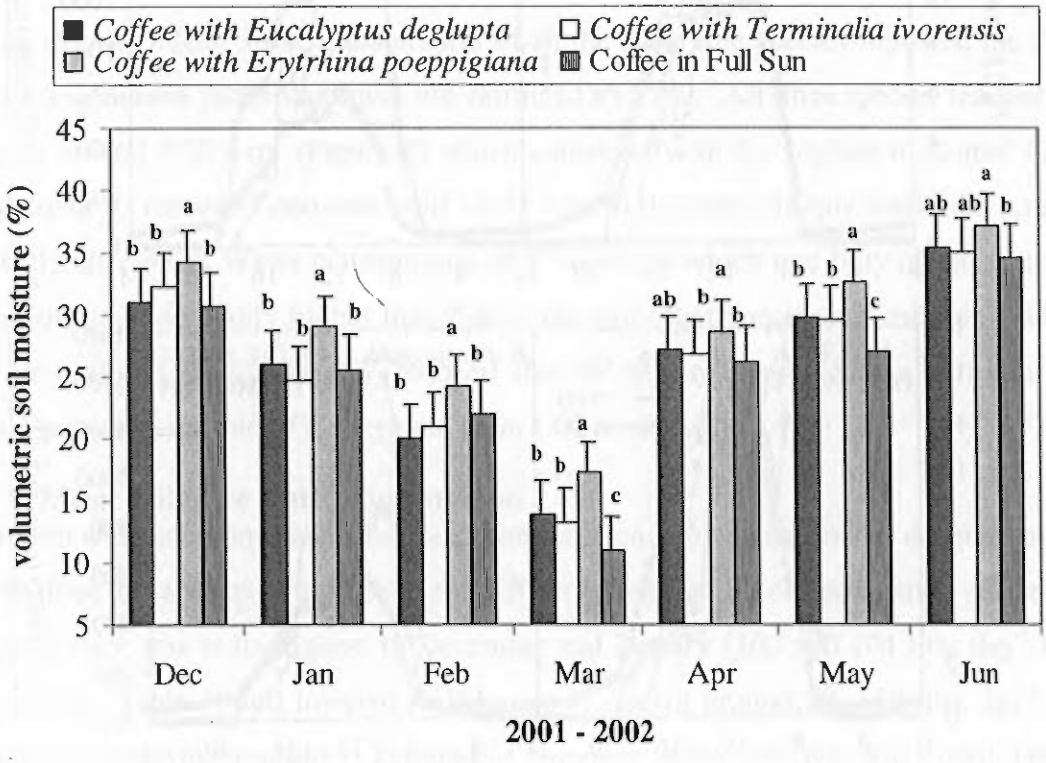


Figure 7. Mean volumetric soil moisture content (s.e.; n = 16) for 0 – 30 cm depth in Southern Costa Rica. Different letters within the same month indicate differences (Lsmean-test ; $p < 0.05$).

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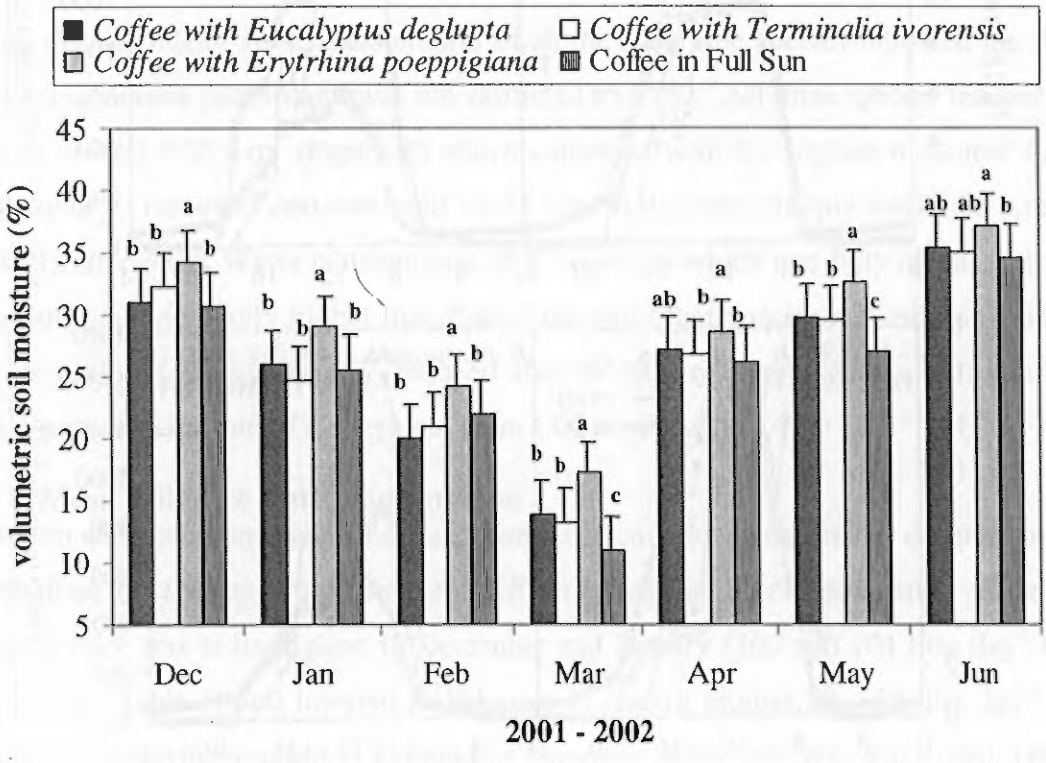

Figure 7. Mean volumetric soil moisture content (s.e.; n = 16) for 0 – 30 cm depth in Southern Costa Rica. Different letters within the same month indicate differences (Lsmean-test ; $p < 0.05$).

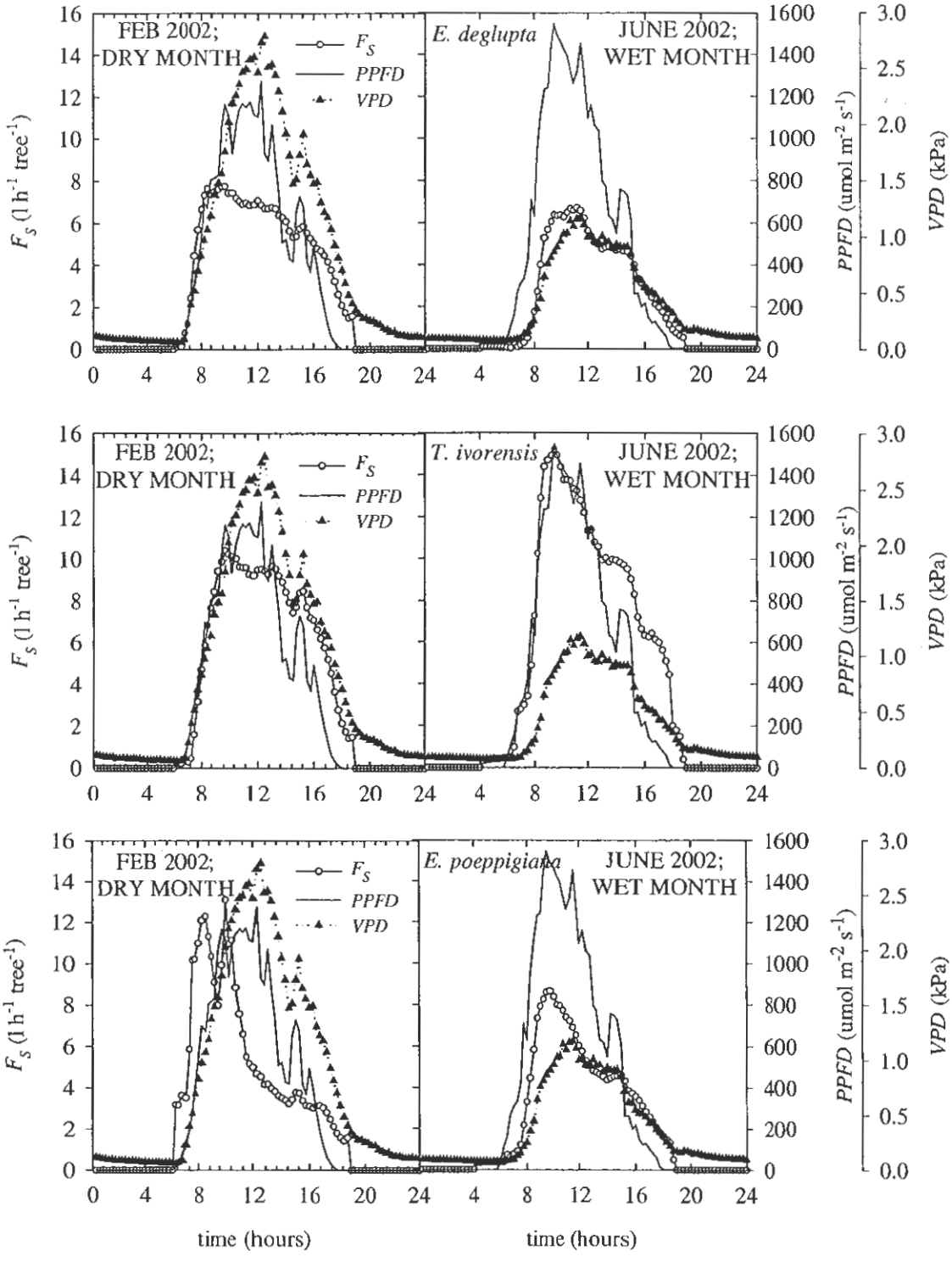

Figure 8. Shade tree sap flow (F_S) based on four trees per species (*Eucalyptus deglupta*, *Terminalia ivorensis* or *Erythrina poeppigiana*) vs. photosynthetic photon flux density (*PPFD*) or air vapour pressure deficit (*VPD*) in full sun, for a dry (February) and a wet month (June) in Southern Costa Rica. Values are averages over 15-minute-periods.

3.3. Mean daily tree water uptake pattern in a dry and a wet month

In the dry month as compared to the wet month, tree transpiration was not different for *E. deglupta*, lower for *T. ivorensis* and higher for *E. poeppigiana* (Figure 8).

In the dry month, February, transpiration was not different among tree species. Trees started to transpire at 6:30 a.m., shortly after the sharp increase in *PPFD* and air temperature (Figure 4 and 8). Both timber tree (*E. deglupta* and *T. ivorensis*) F_S followed the trend of *PPFD* and *VPD* early during the day, but levelled of around 9:45 a.m., at a threshold value of air *VPD* above 1.76 kPa, despite rising *PPFD* and *VPD*. *E. poeppigiana* transpiration was notably high in the first hours of the morning and reached its first peak at 8:30 a.m. and its second at 10:00 a.m. to decline sharply until 11:45 a.m., and gradually afterwards. *E. poeppigiana* transpiration seemed to be restricted by a threshold value of air *VPD* above 2.02 kPa after the second peak at 10:00 a.m.

During the wet month June, transpiration of all the three tree species followed the *PPFD* and air temperature pattern and was not restricted by *VPD*. All three species reached their peak F_S around 9:30 a.m. (Figure 8) which coincided with the highest measured *PPFD*. *E. deglupta* F_S remained constant until 11:45 a.m. to decrease sharply until 1:00 p.m. and gradually afterwards. Water consumption of *T. ivorensis* which had fully re-established its dense foliage was notably higher than that of the two other species and reduced gradually after its peak. *E. poeppigiana* F_S reduced after its peak reading at 9:30 a.m. following a similar pattern as the one of *E. deglupta* from 1:00 p.m. onwards.

3.4. **Mean daily tree water consumption**

Minimum and maximum daily tree water consumption (*Facc*) occurred in different months for the three tree species which presented different phenological characteristics. *Eucalyptus deglupta Facc* was at its highest in December and January (103 and 104 litre day^{-1} $tree^{-1}$, respectively; Table 3) and lowered in February to remain around 50 – 60 litre day^{-1} $tree^{-1}$ during the following months. *Terminalia ivorensis* water use was high until January, lowered to a minimum in March and increased with the wet months to its highest values in June and July when rainfall was abundant with 270 and 335 mm, respectively (Figure 2) and the tree had fully regained its dense foliage. Although not statistically different, *E. poeppigiana* water use tended to be higher in the dry months (70 – 90 litre day^{-1} $tree^{-1}$), especially in March, than in the wet months (60 – 70 litre day^{-1} $tree^{-1}$).

Table 3 Mean daily accumulated sap flow (*Facc*) based on four trees over four consecutive days (litre day^{-1} tree^{-1}) in a trial (2001 – 2002) in Southern Costa Rica.

Month	*Eucalyptus deglupta*	*Terminalia ivorensis*	*Erythrina poeppigiana*
	Facc (litre day^{-1} tree^{-1})		
December[1)]	103 (3.0)a[2)3)]	86 (4.4)a	52 (5.7)a
January[1)]	104 (3.1)a	107 (10.9)a	87 (9.4)a
February	63 (7.9)ab	75 (6.0)a	70 (6.0)a
March	56 (3.6)b	44 (7.8)b	90 (7.3)a
April	62 (4.6)ab	57 (3.2)a	13 (1.7)b
May	49 (6.4)b	69 (3.8)a	64 (7.0)a
June	47 (7.2)b	117 (17.2)a	57 (7.7)a
July	52 (7.6)b	119 (12.8)a	73 (4.3)a

[1)] means of two instead of four trees. [2)] mean (standard error). [3)] different letters within the same column indicate differences ($p < 0.05$) according to the Student-Newman-Keuls test.

The lowest and highest mean *Facc* based on 4-day-period, except for March on a 3-day-period, varied between 47 and 104; 44 and 119; and 13 and 90 litre day^{-1} tree^{-1}, respectively for *Eucalyptus deglupta*, *T. ivorensis*, and *Erythrina poeppigiana* (Table 3). In a calibration test of "Granier" probes, Clearwater et al. (1999) obtained sap flow velocities up to 0.6 mm s^{-1} in 2-year-old *E. deglupta* with stem diameters at breast height (*DBH*) of 6.1 and 6.7 cm, and sap wood depth of 9 and 12 mm, respectively. In the current experiment, sap flow velocities in *E. deglupta* (m s^{-1}; [Eq. 4]) were not greater than 0.3 mm s^{-1} which can be explained by the fact that younger trees within a species, such as those studied by Clearwater et al. (1999), tend to have greater sap flow velocities.

Olbrich (1991) measured sap flow in four 3-year-old and one 16-year-old *E. grandis* trees using the heat pulse velocity and the cut-tree methods in South Africa (lat. 25°03' S; alt. 1100 m a.s.l.; mean T 18.1 °C and average rainfall 1230 mm yr^{-1}). Three-year-old trees with heights between 17.9 – 19.5 m and A_s between 62.7 – 97.1 cm^2 consumed 6 litre h^{-1} on average at their peak at around 12:30 p.m. The 16-year-old tree with 56 m of height and 371.1 cm^2 of A_s consumed about 45 litre h^{-1} at its peak from 11:30 a.m. – 1:30 p.m. The four 3½ – 4-year-old *E. deglupta* in the current experiment, with A_s between 48.4 – 105.1 cm^2, reached an average consumption of 6.7 litre h^{-1} at their peak around 11:15 a.m. in the wet month June (Figure 8).

Kalma et al. (1998) using deuterium-tracing techniques in 5-year-old *E. grandis* planted at 500 trees ha^{-1} in South-eastern Queensland, Australia (lat. 26° S; average rainfall 1340 mm yr^{-1}) obtained daily water consumption values of 13.8 and 12.9 litre day^{-1} for trees with heights of 13.2 and 12.3 m and *DBH* of 12.8 and 12.0 cm, respectively. For another set of seven 5-year-old *E. grandis* varying between 11.9 – 13.5 m height and 10.6 – 13.4 cm *DBH*, the same authors obtained daily water consumption values between 10.0 – 21.6 litre day^{-1} estimated with the heat pulse method. These water consumption values for trees of the same genus, *Eucalyptus*, are substantially lower than those of *E. deglupta* in the present experiment, which varied between 47 and 104 litre day^{-1} (Table 3).

3.5. Water uptake per system

Estimated combined daily water uptake per hectare by both coffee and trees in either one of the three associations was higher than that of coffee plants alone grown in full sun ($p < 0.05$). In full sun, coffee water uptake per hectare was rather constant over most of the months (between 6.0 – 6.5 m^3 day^{-1} ha^{-1}), except at the onset of the rainy season when estimated water uptake per hectare increased from 9.2 (March) to its maximum of 12.4 m^3 day^{-1} ha^{-1} (April).

In the association of coffee with *E. deglupta*, the lowest estimated water uptake per hectare occurred in May and June (17.3 m^3 day^{-1} ha^{-1}) and the highest in January (32.4 m^3 day^{-1} ha^{-1}). The contribution of coffee plants in total water uptake of the association varied between 16 – 41%. Corresponding values for lowest and highest estimated water uptake per hectare and the proportion of coffee water uptake for the coffee-*T. ivorensis* association were 16.6 – 32.9 m^3 day^{-1} ha^{-1} and 10 – 34%, and for the coffee–*E. poeppigiana* association 13.3 – 20.8 m^3 day^{-1} ha^{-1} and 29 – 88% (Table 4).

Table 4 Estimation of mean daily water uptake per hectare (m^3 day^{-1} ha^{-1}) of coffee alone in full sun or coffee and shade trees (based on 4-day periods every month), and the percentage of water used by the coffee plants (*C/S*) in Southern Costa Rica (2001 – 2002).

Month	Coffee in Full Sun[1]	C/S	Coffee and *Eucalyptus deglupta*[2]	C/S	Coffee and *Terminalia ivorensis*[2]	C/S	Coffee and *Erythrina poeppigiana*[3]	C/S
	----------daily water uptake (m^3 day^{-1} ha^{-1})----------							
December	6.1	100%	30.8	16.3%	25.5	15.6%	13.3	42.8%
January	6.3	100%	32.4	19.7%	31.4	14.8%	20.8	38.8%
February	7.1	100%	18.9	16.5%	22.5	16.6%	19.1	46.4%
March	9.2	100%	19.4	27.9%	16.6	33.6%	18.4	28.5%
April	12.4	100%	26.5	41.4%	21.7	34.4%	16.2	88.3%
May	6.2	100%	17.3	29.1%	20.9	17.5%	14.7	36.2%
June	6.0	100%	17.3	32.0%	32.5	9.9%	14.5	42.6%
July	6.5	100%	18.1	28.3%	32.9	9.7%	19.0	43.9%

[1] 4723 ± 37 (mean ± standard error) coffee plants ha^{-1} in full sun or in association. [2] 250 ± 6 *E. deglupta* or *T. ivorensis* trees ha^{-1}. [3] 146 ± 6 *E. poeppigiana* trees ha^{-1}.

Due to the higher weight of the associated tree water consumption than that of coffee in the total consumption per hectare for the three associations, daily water use patterns over the months had strong similarity with the tree water consumption patterns in their respective treatments.

4. Conclusion

Daily coffee water uptake patterns were similar in full sun or under shade. However, values were lower under timber trees (*E. deglupta* or *T. ivorensis*) since the coffee transpiration was mainly determined by the *PPFD* intensity which was lower under the shade of timber trees than under *E. poeppigiana* or in full sun. During the rainy season, coffee transpiration followed the daily patterns of *PPFD* and *VPD*. During the dry season, coffee F_S followed the patterns of *PPFD* and *VPD* in the morning hours until a *VPD* threshold level (between 1.48 and 2.19 kPa) above which transpiration decreased despite increasing *PPFD* and *VPD*. Air temperature was also well above 24 °C (the critical value above which coffee leaf stomatal closure is generally observed) and can be considered a

limiting factor for optimal coffee growth, especially in the dry season when soil water availability was at its lowest. Therefore, monitoring of changes in micro-climate conditions below shade trees, especially *VPD*, as well as coffee water status and stomatal conductance seems worth to be undertaking to further improve our understanding of coffee transpiration depression observed around mid-morning at higher *VPD* values.

Coffee transpiration was higher under regularly pruned *E. poeppigiana* spaced at 8 x 8 m than under the denser spaced timber trees (6 x 6 m). Within the timber tree treatments, coffee water uptake was higher under *E. deglupta* with conical, uniform crowns with open foliage than under *T. ivorensis* with larger crown projection and denser foliage in the rainy months and hence lower light availability for the coffee plants.

Coffee water uptake started to increase in the full sun treatment and to a lesser extent under timber trees in March and was highest in all four treatments in April, due to a vegetative growth spurt which was initiated by early rainfall in the first half of March and culminated in April.

The tree transpiration rate followed the *PPFD* and *VPD* patterns in the morning up until a *VPD* threshold level (between 1.76 and 2.02 kPa) in the dry season, while in the rainy season tree transpiration was driven by *PPFD* and *VPD*. The highest and lowest water uptakes of the three tree species occurred in different months due to very different phonological characteristics. These seasonal phenological differences should be taken into account and the selection of the associated tree species done accordingly.

The estimated water uptake per hectare of the three simultaneously established, 3½ – 4-year-old coffee coffee agroforestry systems was higher than that of coffee plants in full sun. Decreases in coffee and tree transpiration (*Eucalyptus deglupta* and *T. ivorensis*) in February-March despite abundant *PPFD* as well as a decrease in coffee transpiration in March while that of *Erythrina poeppigiana* is increasing, are indicative of probable competition for water between the two associated plants during the critical time of low soil water availability.

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6 RESULTS, DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1. *Timber tree and coffee performance*

6.1.1. Timber tree performance

Terminalia ivorensis crown projection (*CP* in m^2) and *DBH* were higher than those of *E. deglupta* ($p < 0.05$; Paper *I*, Figure 4) but there was no height difference for the measurement period between September 1999 and March 2002. *Terminalia ivorensis* crowns started overlapping at age 29 months, 6 – 9 months before *E. deglupta*, indicating the need of *T. ivorensis* thinning not later than 30 months and *E. deglupta* around 36 months, with avoidance of the dry season (January – March) when the trees are susceptible to water stress. Mean heights and *DBH* obtained for 26-month-old *T. ivorensis* were respectively lower and higher than those reported by Castañeda (1981) who concluded that *T. ivorensis* in Turrialba (North-western Costa Rica) was responding to crop fertilisations in agroforestry systems. Height and *DBH* of 32-month-old *T. ivorensis* in the experiment were, respectively similar and higher than those obtained by Delaunay (1977) for 30-month-old trees in an unfertilised trial in Ivory Coast (Paper *I*, Table 2).

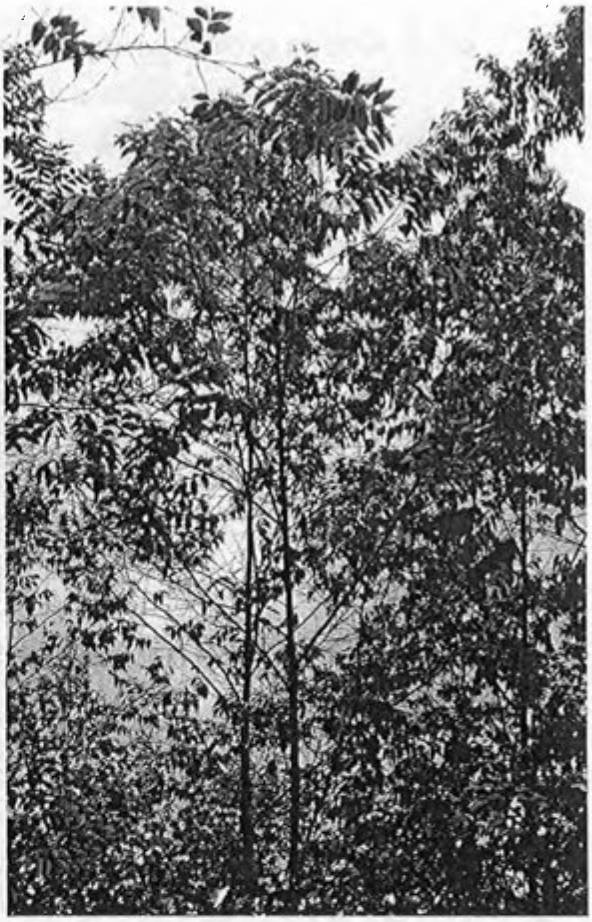
Besides larger crown projections, *T. ivorensis* (Photo 7) had a denser crown than *E. deglupta* (Photo 8) and therefore more shade for the understorey (except for November – March when the tree was gradually shedding its leaves) which was confirmed by photosynthetic photon flux density (*PPFD*) values for the period April – July 2002 (Paper *III*, Figure 6). Higher shade under *T. ivorensis* resulted in a higher proportion of non-productive coffee branches compared with coffee plants below lesser *E. deglupta* shade or in full sun (Aguilar et al. 2001, Angrand et al. 2003). Furthermore, higher fluctuations in shade expected to be occurring when *T. ivorensis* sheds its leaves will increase heat stress on the coffee plants.

According to a 1998 survey of 30 farmers on preferences for 14 coffee shade timber tree species conducted in the same "Pérez Zeledón" region (Tavares et al. 1999), *E. deglupta* was preferred above *T. ivorensis* because the latter requires pruning labour costs for lateral branches in its first years to avoid excessive shading of the coffee crop. In the experiment *T. ivorensis* also required phytosanitary pruning to control the *Nectria* spp. fungal disease.

An analysis over the whole timber tree cycle including timber harvest, however, could change this opinion if *T. ivorensis* turns out to be harvestable at an earlier age than *E. deglupta* and/or provides higher economic revenue to the coffee-timber tree association.

Photo 7. Three-year-old *Coffea arabica–Terminalia ivorensis* association with excessive shade in Southern Costa Rica.
Photo P. Vaast.

[8a]



[8b]

Photo 8. Four-year-old *Coffea arabica–Eucalyptus deglupta* association [8a] with details of the uniform, open foliaged crown [8b], in Southern Costa Rica.
Photos G. Anzola.

6.1.2. Coffee growth and production

Plant height, basal diameter (*bd* in mm) 15 cm above soil surface and coffee yield for the 2001 harvest (*RY*) were higher in the uniformly fertilised coffee plots ($p < 0.05$) than in the locally fertilised ones (Paper *I*, Figure 5). Coffee plant growth (height and *bd*) was consistently higher in the two associations with *E. deglupta* (with and without supplementary tree fertilisation until tree age 27 months) than in the other three treatments and coffee growth in the two *T. ivorensis* associations was also consistently higher than in the *E. poeppigiana* (control) treatment ($p < 0.05$). Better coffee growth under *E. deglupta* can be attributed to a better micro-environment for the coffee plants in terms of temperature and vapour pressure deficit and at the same time a less intense complex of competition factors for water, light and/or soil nutrients.

Neither coffee nor timber tree growth was different in the plots with or without supplementary tree fertilisation. This indicates no effect of more intense interspecies competition when tree fine root systems were expected to expand (and therefore compete) more in the plots which received no additional tree fertilisation on the one hand, and no effect on the coffee plants of the additional fertilisation used for the trees on the other hand.

Coffee growth under *E. poeppigiana* was negatively biased because two blocks were susceptible to soil erosion and several plants were diagnosed with deformed main roots, probably a result of inadequate nursery – transplantation practices. Furthermore, the wider spaced *E. poeppigiana* (8 x 8 m; Photo 9) which was submitted to two pruning events per year had a reduced effect on improvement of the micro-environment for the coffee plants which has certainly been in detriment of coffee growth and production under *E. poeppigiana.*

Photo 9. Four-year-old *Coffea arabica–Erythrina poeppigiana* association with widely spaced (8 x 8 m) trees, submitted to pruning twice a year, in Southern Costa Rica. Photo R. van Kanten

No differences of any practical significance were found with respect to coffee plant distance towards the timber trees (Paper *III*, Table 3). Schaller et al. (2003b) drew the same conclusion for 4 to 5-year-old coffee (variety Catimor 5175)–*E. deglupta* associations in North-western Costa Rica with tree effect on coffee plants at 1.5 and 5.5 m distance. Nutrient concentrations (N, P and K) in coffee leaves were also not different for the two studied distances. A similar development of the coffee at all distances from the nearest tree is a favourable selection criterion for shade trees. Quadratic regressions fitted (r^2 always above 0.90) for coffee height and *bd* curves per type of application of coffee fertilisers (uniformly and locally) and per main treatment (*E. deglupta* or *T. ivorensis* with or without supplementary tree fertilisation).

Predicted coffee yields based on evaluation of eight branches (*PY*) presented a correlation coefficient (r^2) of 0.9540 with *RY* (Paper *I*, Figure 6) and fitted with a quadratic model:

$$RY = 0.00098\ PY^2 + 0.4029\ PY \qquad r^2 = 0.9474\ \ (p < 0.001) \qquad [8]$$

RY and *PY* for the three treatments did not differ significantly when submitted to a t-test, respectively for coffee under *Eucalyptus deglupta* ($p < 0.0922$), *T. ivorensis* ($p < 0.3669$) and *Erythrina poeppigiana* ($p < 0.2537$).

PY was not different for locally fertilised coffee under the two timber tree species without additional fertilisation or under *E. poeppigiana*. Contrary to predictions, actual coffee yield (*RY*) resulted higher under *E. deglupta* ($p < 0.05$) than under the two other tree species.

6.2. Fine root dynamics

6.2.1. Experimental site

Roots were sampled during and at the end of the rainy season and in the dry season (Appendix 1, Figure 1). Tree fine roots sharply decreased below 10 cm horizon, while coffee fine roots were more evenly distributed over 0 – 20 cm (Paper *II*, Figure 2). Coffee fine roots are mostly found in the first 20 to 30 cm of soil depth (Appendix 1, Table 1; Paper *II*, Table 5). In the experimental site, coffee and tree *RLD* tended to be lower in the inter-row position than in the two positions close to the coffee plants. The combination of lower coffee / tree *RLD* ratios for 0 – 10 cm (Paper *II*, Table 4) and simultaneously higher coffee and tree *RLD* values (Paper *II*, Figures 2 and 3) indicates higher probability of competition for nutrients and / or water in this strata. Competition between tree and coffee fine roots for nutrients was more likely to occur in the positions close to the coffee trunk, especially in the fertilised position. This might have been due to an as yet underdeveloped fine root mat of the immature coffee bushes and trees (2 – 4 years old), and to lower Ca and Mg concentrations and lower pH (H_2O) in the inter-row position, such as measured in the main study. The farm practice of taking topsoil from the coffee inter-rows to form ridges along coffee rows, shortly after the preliminary sampling (plant age 26 months) and 10 months prior to the sampling in the main study, reduced fine root presence of both species in the inter-rows and probably promoted fine root concentration (of both species) close to the coffee plants, possibly increasing future competition.

In both depth layers (0 – 10 and 10 – 20 cm) coffee and tree *RLD* was higher during the dry season suggesting that lower soil humidity stimulated fine root growth. Tree *RLD* interaction with sampling dates in both depth layers in the main study (Paper *II*, Table 3)

indicated that neither *E. deglupta* nor *T. ivorensis* fine tree root growth prevailed. Interaction for coffee / tree *RLD* ratios along the seasons at depth 10 – 20 cm (Paper *II*, Table 4) might be explained by different phenological characteristics of the species involved: fine roots are affected by the strength of competing sinks for carbon such as flowers and fruits, which differ amongst species (Eissenstat and Yanai 1997).

6.2.2. Pseudo-chronosequence

Greater coffee fine root colonisation in the older (4 and 5 years) compared with the younger (2 and 3 years) associations (Paper *II*, Figure 4a) indicates increasing *RLD* over time. The fertiliser strip had more coffee fine roots; there was no difference between root colonisation in the unfertilised and the inter-row positions for 0 – 10 cm. These findings coincide with observations of Schaller et al. (2003b) using identical positions in 4 – 5-year-old coffee–*E. deglupta* associations in North-western Costa Rica, in three sampling sessions covering a dry and a wet period.

In depth layer 10 – 20 cm (Paper *II*, Figure 4b), root colonisation in the fertilised and unfertilised position was higher than in the inter-row position. In the 0 – 10 cm depth layer, the coffee fertilisation zone had significantly more *E. deglupta* fine roots than the unfertilised zone on the opposite side of the coffee rows. Similar to findings of Morales and Beer (1998) who studied 1, 4, 5, 6 and 7-year-old *E. deglupta* fine root distribution in coffee associations, and findings of Schaller et al. (2003b), tree *RLD* in the present study did increase further away from the tree with increasing age comparing the 4-year-old association with the 2 and 3-year-old associations. This indicates horizontal partitioning of the tree and coffee root systems; a favourite selection criterion for coffee shade trees.

Higher coffee / tree *RLD* ratios (Appendix 1, Table 2) in both depth layers in the 4-year-old association compared with the 2 and 3-year-old associations indicate relatively more coffee roots in the sampling positions and presumably, relatively less competition from the tree fine roots in the older association. In depth layer 0 – 10 cm the ratio was higher in the unfertilised compared with the inter-row position which can be related to a higher tree root presence in this latter position.

6.3. Plant and soil water status

6.3.1. Soil nutrient and water status

Soil from the root samples (Appendix 1, Tables 3, 4 and 5) generally presented medium pH's (H_2O), low to high soil exchangeable acidity (between 0.13 and 1.8 cmol l^{-1}) and high Fe contents with deficiencies in K, P and Mn, referring to criteria established by Bertsch 1995. Critically low K and P levels might result in deficient coffee fruit formation which could be aggravated if the coffee plants would suffer water stress during fruit formation, such as might have been the case for the coffee under timber trees (*Paper III*) which presented low water uptake in the dry month of February. In the experimental site, for 0 – 10 and 10 – 20 cm, pH (H_2O), and Ca and Mg contents in the inter-rows were lower and soil exchangeable acidity higher than close to the coffee trunks ($p < 0.05$). During the root study in the experimental site, in both depth layers, pH (H_2O) were higher at the end of than during the rainy season ($p < 0.05$). Soil exchangeable acidity was higher in the 2-year-old than in the 3 and 4-year-old plantations ($p < 0.05$) in the pseudo-chronosequence.

Soil moisture content (0 – 30 cm) varied between 10.9 and 37.1 % in the treatments with coffee in full sun or under tree shade (Paper *III*, Figure 7) and was higher in *E. poeppigiana* ($p < 0.05$) than in the three other treatments for December 2001 – June 2002. Jiménez and Alfaro (1999) also measured higher soil moisture contents (0 – 60 cm) in coffee associated with *E. poeppigiana* or in full sun than coffee associated with *E. deglupta* in a dry period in the Costa Rican Central Valley. Higher soil moisture under *E. poeppigiana* as compared to under the timber trees indicates the benefit and may be comparative advantage of this tree species in preserving soil humidity.

6.3.2. Air temperature, air vapour pressure deficit and light environment

Mean daily reference evapotranspiration (*ETo*) varied between 4.8 and 5.2 mm day^{-1} in February and March (dry months) and April (the transition month to the rainy season) and between 4.0 and 4.2 mm day^{-1} in the months afterwards (Paper *III*, Figure 2). Mean air temperatures in the dry and wet months were similar but maximum temperature in the dry months (February and March) was higher and consequently relative air humidity (*RH*) lower. Therefore, air vapour pressure deficit (*VPD* in kPa) calculated with the meteorological parameters measured in the full sun environment and serving as a

basis for comparisons with coffee transpiration, was higher in the dry than in the wet months (Paper *III*, Figures 3 and 6). Light in fall and *VPD* did not solely influence coffee and tree transpiration. Coffee transpiration, for example, was also influenced by physiological plant reactions such as higher plant water demand as consequence of the vegetative growth spurt which started in March, when coffee transpiration increased in full sun and under timber trees, and culminated in April when coffee water use reached its peak in all of the four treatments. In these periods the notable increase in coffee water uptake can be attributed to high water demand for vegetative growth (Maestri and Barros 1977, Carr 2001). Likewise tree transpiration was influenced by the magnitude of the leaf area such as for *E. poeppigiana* in April when the tree with virtually no leaves nearly did not consume water and for *T. ivorensis* when the tree with its dense crown recovered consumed high amounts of water in June and July.

The highest values of *PPFD* (Paper *III*, Figure 3) occurred between 11:00 a.m. – 1:00 p.m. Using *PPFD* in full sun as reference, i.e., 100% irradiation, between 11:00 a.m. – 1:00 p.m., the associations with *E. deglupta*, *T. ivorensis* or *E. poeppigiana* received irradiation in the ranges of 47 – 60; 63 – 69; and 78 – 82%, respectively in the dry, and 41 – 55; 18 – 54; and 69 – 95%, respectively in the wet period (Paper *III*, Figure 6). Average *T. ivorensis* leaf area (*LA*) in the experiment was 2.9 times bigger than average *E. deglupta* *LA* (189 $\pm$ 22.2 vs. 65 $\pm$ 11.6 m^2 $tree^{-1}$; n = 15; Anzola (unpublished data). In the sap flow study, the four *T. ivorensis* trees (paper *III*, Table 1) presented large crown projections which overlapped with the ones of their neighbouring trees, whereas two of the four measured *E. deglupta* trees had their values below and closely above 28.3 m^2 (when crowns of trees spaced at 6 x 6 m start to overlap), respectively. *Terminalia ivorensis* competed more for light with the coffee plants than *E. deglupta*, especially after April when the tree had fully re-established its foliage.

Mean *PPFD* values in the morning hours (paper *III*, Figure 6) were higher than optimal conditions for coffee photosynthesis (300 – 500 and 600 – 800 μmol m^{-2} s^{-1}, respectively in shade or in full sun (Kumar and Tieszen 1980)), except for the coffee plants under *T. ivorensis* with 16 and 19% of the *PPFD* values in full sun in May and June, respectively. Air temperature during the day was always above values of 24 – 25°C which are considered to be the limiting values below which optimal coffee photosynthesis occurs according to

Maestri and Barros (1977) and Mosquiera et al. (1999), respectively. Tree shade buffers diurnal air temperature variations (Barradas and Fanjul 1986) and more importantly leaf temperature (Willey 1975), such as measured in the experiment by Siles and Vaast (2003). Lower air temperature implicating lower *VPD*, lower leaf temperature and less light in fall under timber tree shade, explain lower coffee transpiration under trees as compared to the coffee in full sun or in the *E. poeppigiana* association, especially when this tree had completely shed its foliage in April.

6.3.3. Coffee water consumption

Coffee water consumption presented a different pattern in the dry (February) and wet month (June) (Paper *III*, Figure 3; Appendix 3). In both months coffee transpiration was driven by increasing *PPFD* and *VPD* in the morning hours. The differenee was that coffee transpiration was restricted by values above a *VPD* threshold level in the dry month, while it followed the *PPFD* and *VPD* pattern in the wet month. The magnitude of the *VPD* threshold level, which was based on *VPD* calculated in full sun, must have been less preeise for the tree treatments, especially the timber trees which presented more shade than *E. poeppigiana*. It must also be considered that coffee crowns can be subdivided in a mosaic of different micro-environments which influence the *VPD* at leaf level (Dauzat et al. 2001) which is even differing within the same leaf.

In the experiment, coffee transpiration under *E. poeppigiana* was lower than the one measured by Rapidel (1985) in 11-year-old plants under the same species, and higher than the one measured by Fahl et al. (2000) in 3-year-old coffee plants in full sun and under four different percentages of artificial shade. Coffee water consumption under timber trees presented a similar pattern but was lower under *T. ivorensis* in several months, which might be explained by the earlier mentioned lower light entrance in this system. Coffee water uptake under *E. poeppigiana* was even higher than in full sun ($p < 0.05$) in January, February, and July. In these months, the proportion of coffee *Facc* was around 0.39 – 0.44 (paper *III*, Table 4), indicating low competition for water between *E. poeppigiana* and the coffee plants and suggesting exploration of deeper zones for water by the tree roots than by coffee roots. Water competition was evident in February for the coffee-timber tree associations when coffee water uptake was low, when *PPFD* and *VPD* were high and soil

moisture contents low. The flattened coffee F_S curve under *E. deglupta* in this dry month might indicate higher water competition from this tree species as compared to *T. ivorensis* (Paper *III*; Figure 3a and b). Under *E. poeppigiana* there was no evidence of water competition by the trees in February, but in the following dry month, March, coffee F_S in this treatment was considerably lower than the one in full sun (Paper *III*; Table 2) probably due to the effect of water competition by the trees.

In several cases in the experiment, after the first coffee sap flow (F_S) peak, coffee plants reduced their water uptake as a result of high *VPD* levels but presented another less accentuated peak, probably induced by an increase in *PPFD* during the typical unclouded conditions, shortly after midday, when air temperature reached its peak (Paper *III*, Figure 3). Stomatal closure is certainly responsible for declining coffee water consumption despite rising air temperature in the morning as shown by Siles and Vaast (2003) in the study site. Studying transpiration and stomatal regulation of hedgerow coffee (aged 1 – 5¼ years) in Hawaii (lat. 21°54' S; alt. 98 m a.s.l.), Gutiérrez et al. (1994) measured maximum stomatal and crown conductance values at 11:00 a.m. with a decline thereafter, while *PPFD* and *VPD* were still increasing. The relationship between coffee F_S vs. *PPFD* and *VPD* for the typical dry month in the experiment (Paper *III*, Figure 5) shows the same phenomenon for the plants in the experiment.

Soil water stress influences coffee leaf water potential, reducing the stomatal aperture and hence, transpiration (Wormer 1965, Bierhuizen et al. 1969, Meinzer 1993), which might have occurred in the dry months February and March, when soil moisture (%) was low (Paper *III*, Figure 7). Water stress in this period of fruit expansion (Carr 2001) reduces coffee fruit size and hence production (Cannell 1975, Nunes 1976, Vaast et al. 2002). Apart from soil moisture, factors such as air and leaf temperature, *VPD*, and the ability of the root systems to absorb water, influence upon the coffee leaf water potential (Dagg 1971, Kumar and Tieszen 1976, Meinzer 1993).

6.3.4. Tree water consumption

In the dry month (February) transpiration of the three tree species followed the trend of *PPFD* and *VPD* in the early morning hours to be restricted by values above a *VPD* threshold level (Paper *III*, Figure 4). On the contrary, in the wet month (June) trees

followed the *PPFD* and *VPD* during the whole day. Tree species with similar A_S might reach their maximum F_S at different hours of the day due to differences in water storage capacity, leaf and crown shape and photosynthetic requirements (Meinzer 1993, Meinzer et al. 2001).

Maximum and minimum monthly water consumption occurred in different periods for the tree species (Paper *III*, Table 3) due to different phenological characteristics. There was no information in the literature regarding *T. ivorensis* or *E. poeppigiana* sap flow. Clearwater et al. (1999) obtained sap flow velocities up to 0.6 mm s^{-1} for 2-year-old *E. deglupta* with *DBH* of 6.1 and 6.7 cm, and sap wood depth of 9 and 12 mm, respectively. Sap flow velocities for the 3 to 4-year-old *E. deglupta* (m s^{-1}) in the experiment (Paper *III*, Equation 4) were not greater than 0.3 mm s^{-1} which coincides with the fact that younger trees within a species tend to have greater sap flow velocities. Kalma et al. (1998) working with 5-year-old *E. grandis* planted at 500 trees ha^{-1} in South-Eastern Queensland, Australia (lat. 26° S; average rainfall 1340 mm yr^{-1}) using deuterium-tracing techniques and obtained daily water consumption values of 13.8 and 12.9 litre day^{-1} for two trees, with heights of 13.2 and 12.3 m and *DBH* of 12.8 and 12.0 cm, respectively. For another set of seven 5-year-old *E. grandis* trees varying between 11.9 and 13.5 m height and 10.6 and 13.4 cm *DBH*, the same authors obtained daily water consumption values between 10.0 – 21.6 litre day^{-1} estimated with the heat pulse method. These values are substantially lower than those of *E. deglupta* in the experiment which varied between 47 and 104 litre day^{-1} (Paper *III*, Table 3). However, in the experiment conditions were much wetter and tree densities lower at around 250 trees ha^{-1}.

6.3.5. Water consumption per system

The estimated daily water uptake per hectare (Paper *III*, Table 4) was higher in the coffee–tree combinations than in coffee in full sun ($p < 0.05$). Coffee water uptake in full sun oscillated around 6.0 - 6.5 m^3 day^{-1} ha^{-1}, except for March and April when it reached values of 9.2 and 12.4 m^3 day^{-1} ha^{-1}, respectively. Minimum and maximum mean daily water uptake for the coffee–tree associations varied between 17.3 – 32.4, 16.6 – 32.9 and 13.3 – 20.8 m^3 day^{-1} ha^{-1}, respectively for the associations with *Eucalyptus deglupta*, *T. ivorensis* and *Erythrina poeppigiana*. The percentage of the contribution of coffee plants in water

uptake under *Eucalyptus deglupta*, *T. ivorensis* and *Erythrina poeppigiana* varied between 16 – 44, 10 – 34 and 29 – 88%, respectively. There was a notable drop in proportion of the coffee plants in water uptake of the coffee–*T. ivorensis* combination that was reduced to about 10% in June and July, also due to higher tree water uptake (Paper *III*, Table 3). The total consumption per hectare, especially in the two associations with timber trees was mainly determined by the tree water consumption. This resulted in a strong decrease of the contribution of coffee water uptake in the total water consumption per hectare under *T. ivorensis* when tree transpiration increased in June and July.

6.4. Conclusions

Terminalia ivorensis crown projection and *DBH* were higher than those of *E. deglupta* (aged 1 – 4 years) but there was no height difference. The timber species may have benefited from the coffee fertilisation but there was no evidence that they responded to supplementary tree fertilisation. Early height and *DBH* growth was lower for *E. deglupta* and equal if not greater for *T. ivorensis* compared with other studies. Coffee plant height and *bd* was higher in the uniformly than in the locally fertilised plots, highest under *Eucalyptus deglupta* and lowest under *Erythrina poeppigiana*. There were no effects of proximity of timber shade trees on coffee growth. Estimated coffee berry yield, based on an evaluation of eight branches per plant, matched the actual harvested berry yield (r^2 = 0.9474; $p < 0.001$) but at least two years of data are needed to calibrate coffee berry yield predictions. Actually harvested coffee under *Eucalyptus deglupta* was higher than under *T. ivorensis* or *Erythrina poeppigiana*. Coffee plants performed best under *E. deglupta* shade and were restricted under *T. ivorensis* which require extra labour for lateral branch pruning in their first two to three years of establishment and present larger fluctuations in shade levels since the tree drops its leaves during the end of the rainy season and the dry season. Low coffee plant performance under *E. poeppigiana* might have been due to insufficient shade of the tree, which was wider spaced, pruned twice a year and shed its leaves during one month at the end of the dry season.

Tree fine roots tended to prevail in 0 – 10 cm soil while coffee fine roots were generally distributed in the 20 cm topsoil. Coffee and tree fine roots were most present in the fertilisation zone and least present in the inter-rows. Coffee and tree fine roots were more

abundant during the dry season when soil moisture was low. On average, *T. ivorensis* fine roots were heavier and thicker than those of *E. deglupta* and in the upper 10 cm soil depth *T. ivorensis* appeared to be more competitive than *E. deglupta*. In older *C. arabica–E. deglupta* associations tree *RLD* tended to increase in the inter-rows. Coffee fine roots appeared to be more abundant than tree fine roots and were not likely to be displaced by the tree fine roots. Contrary to expectations, coffee fine roots seemed to be displacing tree fine roots. Combined coffee and tree *RLD* might increase over time and result in elevated nutrient competition in the system, especially if farm management will reduce the fertiliser application in view of continuing low world market coffee prices.

Coffee water uptake was similar in full sun or under tree shade, although with lower amplitudes under timber trees. Both coffee and tree water uptake followed *PPFD* and *VPD* in the early morning hours in the dry season, before being restricted after exceeding a *VPD* threshold level (roughly above 1.5 kPa). In the wet season both coffee and tree transpiration were determined by the *PPFD* and *VPD* pattern. *PPFD* values above coffee crowns in full sun or under *E. poeppigiana* were higher than the ones under timber trees and values always exceeded the saturating level needed by coffee plants to photosynthesise optimally, except when shade provided by *T. ivorensis* was above 80% in the rainy season (May and June). Air temperature, well above the critical 24 – 25 °C (when stomatal closure of coffee leaves is generally observed), can be considered a limiting factor for optimal coffee transpiration. Minimum and maximum daily tree water consumption occurred in different months for the three tree species since they presented different phenological characteristics. Water uptake of 3½ to 4-year-old coffee-shade tree systems was higher than that of evenly old coffee in full sun during eight months of observation. Soil moisture content (0 – 30 cm depth) was higher in the coffee–*E. poeppigiana* association.

Coffee water uptake under *E. deglupta* was higher than under *T. ivorensis*, a tree with larger crown projection and dense foliage in the rainy season. This, together with higher coffee plant growth and production under *E. deglupta*, more uniform and less dense shade than *T. ivorensis* during the year, hardly no necessity for tree pruning for shade regulation or phytosanity, lower coffee / *E. deglupta RLD* ratios in the top soil (0 – 10 cm) and lower

E. deglupta water consumption point to this species as the less competitive one with coffee and therefore a more promising coffee shade timber tree than *T. ivorensis*.

6.5. Recommendations

Research should be continued in the complex interactions between coffee plants and shade trees in terms of light environment, *VPD*, and the availability of water and nutrients to better understand the effects on coffee growth, bean quantity and quality, as well as the tree growth and timber production. This, in order to determine more accurately, which of the two coffee–timber tree associations is more promising and what are the recommended cultural practices. Other fast-growing timber species can be incorporated in the research given the fact that timber shade trees are an attractive alternative for coffee farmers in the Pérez Zeledón region in the light of continuing low coffee prices without better prospects in the near future which have negatively influenced the regional economy.

In on-farm research, coordination between researchers and farm management should be focussing continuously on streamlining farm management practices with the research methodology and research activities with farm production. As a result of the experiment the farm management adopted uniformly coffee fertilisation and improved tree management practices.

Despite the obvious necessity, timber trees were not thinned. Given the relatively new experience for farmers of coffee cultivation under fast-growing timber trees, more emphasis should be given to make farm managers become acquainted with the pruning, thinning and stand density principles. Emphasis should be given on formation pruning for both species and additionally phytosanitary pruning and shade regulation of *T. ivorensis*. In the experiment a 50% selective thinning could be recommended for 30-month-old *T. ivorensis* and 36-month-old *E. deglupta*, finally reducing harvestable stands to about 70 – 100 trees ha^{-1}.

Regularly pruned *E. poeppigiana* should be spaced at 6 x 6 m instead of 8 x 8 m to increase the shade intensity for the coffee plants and to create a micro-environment with less light in fall and lower *VPD*. *Terminalia ivorensis* with its fast-growth and attractive timber might be an interesting economic option for association with coffee (provided that the timber

market develops) but aforementioned pruning activities (formation, shade regulation and disease control) need to be closely monitored.

The fine root studies require additional quantitative information on nutrient presence and soil moisture as well as more coring positions, replications and sampling frequency, to obtain a detailed picture of fine root presence over time. This is directly related to the processing capacity of the core samples; root washing and especially the availability of labourers trained in fine root separation.

Measurements must be intensified on sap flow (in coffee stems, coffee branches, tree trunks, several positions within the same tree trunk, and tree branches), *PPFD* and *VPD* at plant level, stomatal conductance, plant water status, leaf and air temperature of the micro-environment, and soil moisture, in order to establish closer relationships between transpiration and the complex of micro-environmental factors. Tree sap flow can be related to leaf area calculated with models developed by the CASCA project for the tree species at the site in a study on analysis and modelling of light interception by coffee shade trees. More intensive measurements are directly related to the availability of more equipment as well as the processing capacity of dataloggers and multiplexers. Given the large quantity of cables and the necessity of close protection of the equipment, an on-station trial might be preferred above an on-farm trial, especially because activities like coffee harvest executed by eventual labourers will coincide with the year-on measurements.

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Appendix 1

Root study

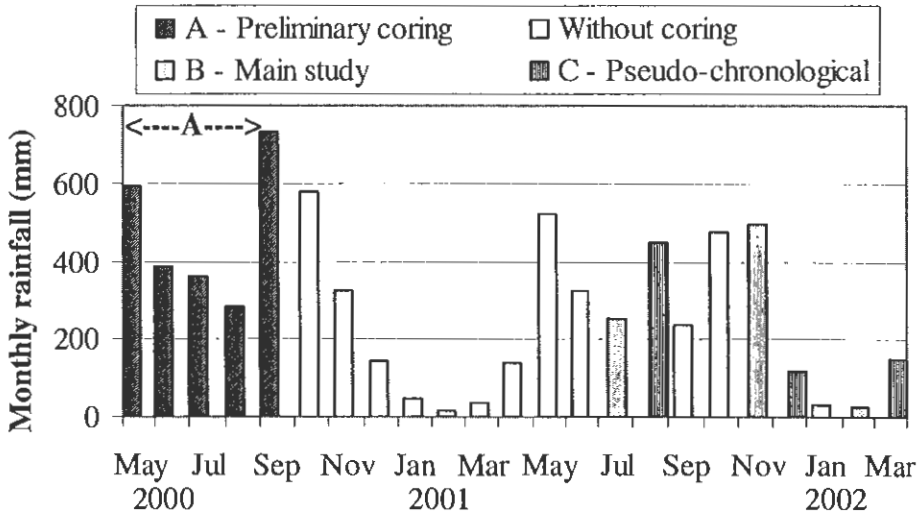


Figure 1 Monthly rainfall during root sampling periods in associations of *Coffea arabica* with *Eucalyptus deglupta* or *Terminalia ivorensis* in Southern Costa Rica.

Table 1. Fine root length (%) distributed over a 0 – 40 cm profile in two-year-old *Coffea arabica*–shade tree associations in Southern Costa Rica.

Depth (cm)	*C. arabica* fine roots in association with		Tree fine roots	
	Eucalyptus deglupta	*Terminalia ivorensis*	*E. deglupta*	*T. ivorensis*
	----------(%)----------		----------(%)----------	
0 – 10	27	34	55	46
10 – 20	31	31	25	27
20 – 40	42	35	20	27

Table 2. *Coffea arabica* and *Eucalyptus deglupta* fine root length density (*RLD*) ratios for different seasons in Southern Costa Rica.

Position	Year	Depth (cm)	RS[1)]	ERS	DS
			RLD ratio		
Fertilised[2)]	1996	0 – 10	4.0 (1.3)[3)]	4.0 (0.9)	1.7 (0.6)
	1997	0 – 10	4.6 (0.9)	6.1 (1.2)	12.6 (6.1)
	1998	0 – 10	1.0 (0.3)	1.1 (0.5)	0.8 (0.1)
	1999	0 – 10	1.5 (0.2)	1.5 (0.4)	4.9 (1.3)
Fertilised	1996	10 – 20	3.6 (0.5)	4.3 (0.4)	2.6 (0.5)
	1997	10 – 20	3.7 (1.0)	4.2 (2.0)	10.9 (5.3)
	1998	10 – 20	1.6 (0.3)	1.6 (0.6)	2.1 (0.8)
	1999	10 – 20	2.9 (2.0)	1.0 (0.2)	3.5 (0.8)
Unfertilised	1996	0 – 10	2.3 (1.1)	7.8 (4.4)	2.4 (0.5)
	1997	0 – 10	6.2 (2.9)	8.5 (1.9)	8.3 (4.3)
	1998	0 – 10	1.7 (0.4)	1.7 (0.5)	1.2 (0.4)
	1999	0 – 10	5.6 (4.9)	2.2 (0.6)	5.5 (2.4)
Unfertilised	1996	10 – 20	3.7 (1.6)	1.2 (0.4)	1.9 (0.4)
	1997	10 – 20	5.8 (2.3)	1.2 (0.1)	3.2 (1.4)
	1998	10 – 20	3.6 (1.5)	1.4 (0.9)	2.2 (0.4)
	1999	10 – 20	3.5 (1.6)	0.5 (0.2)	4.1 (0.2)
Inter-row	1996	0 – 10	4.6 (2.1)	3.0 (0.8)	0.5 (0.1)
	1997	0 – 10	2.3 (0.5)	4.1 (2.3)	1.0 (0.5)
	1998	0 – 10	2.7 (0.4)	0.8 (0.1)	1.0 (0.7)
	1999	0 – 10	0.6 (0.1)	1.3 (0.6)	0.4 (0.1)
Inter-row	1996	10 – 20	4.5 (1.0)	5.3 (1.8)	1.3 (0.4)
	1997	10 – 20	0.5 (0.1)	3.6 (1.8)	1.7 (0.2)
	1998	10 – 20	2.1 (1.6)	2.7 (2.3)	1.4 (0.5)
	1999	10 – 20	2.5 (0.9)	0.9 (0.2)	0.8 (0.3)

[1)] RS = rainy season; ERS = end rainy season; DS = dry season. [2)] "Fertilised" = close to coffee bush, fertilised band; "Unfertilised" = close to coffee bush, unfertilised area; "Inter-row" = equidistant coffee rows, unfertilised area. [3)] Mean (standard error) n = 9.

Table 3. Soil processing procedures.

Component	Procedure
pH (H_2O)	Extracted from 10 g of soil (air dried and sieved at 2 mm) diluted with 25 ml distilled water. Readings on a "Hanna" pH-meter calibrated at pH 7.0 and 4.0.
Exchangeable Acidity	Extracted with 1M KCl, diluted with distilled water to a soil solution ratio of 1:1 and valorised with 0.01 N NaOH.
Ca and Mg	Extracted with 1M KCl with "Hunter" equipment. Readings on a "Shimadzu AA680" spectrophotometer.
K, Zn, Cu, Mn and Fe	Extracted with the Olson modified method by "Hunter" equipment. Readings on a "Shimadzu AA680" spectrophotometer using "Perkin Elmer" certified patterns.
P	Extracted with the Olson modified method and measured with a colorimeter by the ammonium molybdate method with readings at 660 nm (Spectronic 21).

Source: Icafé Chemical Laboratory – Pérez Zeledón, Costa Rica.

Table 4. Mean soil nutrient parameters (s.e., n = 9) in cores of three root sampling sessions in *Coffea arabica*–timber-tree associations, simultaneously established in May 1998, in Southern Costa Rica.

Root sampling	**July 01**		**November 01**		**February 02**	
Depth layers (cm)	**0-10**	**10-20**	**0-10**	**10-20**	**0-10**	**10-20**
***C. arabica–Eucalyptus deglupta* association**						
pH (H_2O)	5.7	5.3	6.3	5.6	6.1	5.5
	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
Exchangeable Acidity cmol litre^{-1}	0.19	0.29	0.11	0.34	0.12	0.32
	(0.08)	(0.05)	(0.02)	(0.08)	(0.02)	(0.06)
K cmol litre^{-1}	0.23	0.16	0.17	0.10	0.15	0.11
	(0.04)	(0.03)	(0.02)	(0.01)	(0.02)	(0.01)
P mg litre^{-1}	6.67	7.11	5.11	9.78	3.11	4.00
	(1.00)	(1.72)	(0.86)	(1.75)	(0.48)	(0.75)
Mn mg litre^{-1}	0.60	0.78	1.56	1.56	1.04	0.88
	(0.11)	(0.12)	(0.44)	(0.44)	(0.13)	(0.09)
Fe mg litre^{-1}	265	342	374	745	430	348
	(30)	(54)	(60)	(103)	(214)	(41)
***C. arabica–Terminalia ivorensis* association**						
pH (H_2O)	5.7	5.0	6.4	5.4	6.1	5.4
	(0.1)	(0.1)	(0.2)	(0.0)	(0.1)	(0.1)
Exchangeable Acidity cmol litre^{-1}	0.17	0.51	0.13	0.20	0.14	0.48
	(0.05)	(0.08)	(0.03)	(0.05)	(0.04)	(0.10)
K cmol litre^{-1}	0.21	0.16	0.11	0.08	0.10	0.08
	(0.05)	(0.04)	(0.01)	(0.02)	(0.01)	(0.02)
P mg litre^{-1}	4.22	5.00	3.56	7.78	5.58	4.33
	(0.81)	(0.88)	(0.29)	(1.87)	(1.08)	(0.50)
Mn mg litre^{-1}	0.64	0.67	0.66	1.02	1.17	1.34
	(0.11)	(0.08)	(0.14)	(0.15)	(0.09)	(0.19)
Fe mg litre^{-1}	213	358	286	577	256	440
	(43)	(46)	(58)	(113)	(40)	(76)

Table 5. Mean soil nutrient parameters (s.e., n = 9) in cores of three root sampling sessions for 2, 3, 4 and 5-year-old *Coffea arabica–Eucalyptus deglupta* plots in Southern Costa Rica.

	August 2001		December 2001		March 2002	
Depth layer (in cm)	**0 – 10**	**10 – 20**	**0 – 10**	**10 – 20**	**0 – 10**	**10 – 20**
pH (H_2O) 5-yr-old	6.0	4.8	6.5	5.4	5.5	5.2
	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)
pH (H_2O) 4-yr-old	6.1	5.2	5.9	5.3	6.0	5.7
	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)
pH (H_2O) 3-yr-old	5.7	5.3	6.3	5.6	6.14	5.5
	(0.2)	(0.2)	(0.1)	(0.1)	(0.1)	(0.1)
pH (H_2O) 2-yr-old	5.2	4.8	5.6	5.2	5.7	5.9
	(0.3)	(0.2)	(0.2)	(0.1)	(0.2)	(0.2)
Exchangeable acidity 5-yr-old	0.12	0.90	0.09	0.68	0.79	1.37
(in cmol litre^{-1})	(0.02)	(0.12)	(0.01)	(0.11)	(0.21)	(0.22)
Exchangeable acidity 4-yr-old	0.14	0.44	0.38	0.51	0.22	0.48
	(0.02)	(0.10)	(0.10)	(0.13)	(0.09)	(0.10)
Exchangeable acidity 3-yr-old	0.19	0.29	0.11	0.34	0.12	0.32
	(0.08)	(0.05)	(0.02)	(0.08)	(0.02)	(0.06)
Exchangeable acidity 2-yr-old	0.99	1.81	0.54	1.64	0.49	0.33
	(0.38)	(0.46)	(0.19)	(0.24)	(0.12)	(0.10)
K 5-yr-old	0.42	0.22	0.30	0.17	0.28	0.16
(in cmol litre^{-1})	(0.03)	(0.03)	(0.04)	(0.02)	(0.03)	(0.02)
K 4-yr-old	0.23	0.15	0.14	0.07	0.15	0.14
	(0.02)	(0.02)	(0.02)	(0.01)	(0.02)	(0.03)
K 3-yr-old	0.23	0.16	0.17	0.10	0.15	0.11
	(0.04)	(0.03)	(0.02)	(0.01)	(0.02)	(0.01)
K 2-yr-old	0.40	0.19	0.36	0.20	0.16	0.21
	(0.07)	(0.03)	(0.08)	(0.03)	(0.03)	(0.04)
P 5-yr-old	4.56	5.11	1.67	2.89	4.22	5.89
(in mg litre^{-1})	(0.73)	(0.72)	(0.24)	(0.81)	(0.52)	(0.61)
P 4-yr-old	8.67	11.67	6.99	6.89	5.22	6.67
	(1.31)	(2.15)	(1.12)	(0.81)	(0.66)	(1.31)
P 3-yr-old	6.67	7.11	5.11	9.78	3.11	4.00
	(1.00)	(1.72)	(0.86)	(1.75)	(0.48)	(0.75)
P 2-yr-old	6.89	5.33	4.67	3.11	3.90	3.89
	(1.32)	(0.94)	(0.94)	(0.70)	(1.19)	(0.48)

Appendix 2

Spreadsheet input and formulae for the Penman-Monteith reference evapotranspiration (ETo in mm day^{-1}) calculations

Excel version Office 2000. Source. Adapted from the FAO (Food and Agriculture Organisation, United Nations).

Table 1. Input for the Penman-Monteith spreadsheet (Cells in increasing row order; from row 21 onwards, for each day, information is entered in a different column).

Cell	Input
D3	Location name
D4	Latitude coordinates
D5	Altitude (m)
F13	Height of the Anemometer (cm)
G13	Height of the Thermometer (cm)
H13	Crop height (cm)
B21	Date
B23	Maximum temperature
B24	Minimum temperature
B25	Average relative humidity
B27	Average wind velocity (km day^{-1})
B52	Julian day

Table 2. Formulea for the Penman-Monteith spreadsheet (Cells in increasing row order; from row 21 onwards, for each day, information is entered in a different column).

Cell	Formula
E4	=(D4-TRUNC(D4))*5/3+TRUNC(D4)
F4	=E4*PI()/(180)
E13	=LN(($F13-0.667*H13)/(0.123*$H13))*LN(($G13-0.667*$H13)/(0.0123*$H13))/0.41^2
E15	=200/(0.24*H15)
F15	=200/(1.5*LN(H15)-1.4)
B19	=0.622*3.486*86400/E13/1.01
C19	=E$15/E13
D19	=F$15/E13
B26	=B39/B36*100
B28	=B60*(0.16*SQRT(B23-B24))
B30	=B76
B32	=(B23+B24)/2
B33	=B28/B60
B34	=B27/86.4
B36	=0.6108*EXP((17.27*B23)/(B23+237.3))
B37	=0.6108*EXP((17.27*B24)/(B24+237.3))
B38	=(B36+B37)/2
B39	=B25/(50/B37+50/B36)
B40	=B39/B36/2+B39/B37/2

Cell	Formula
B41	=2049*B36/(B23+237.3)^2+2049*B37/(B24+237.3)^2
B42	=101.3*((293-0.0065*$D$5)/293)^5.253
B43	=2.501-(0.002361*(B32))
B44	=0.0016286*B42/B43
B45	=$E$15
B46	=$E$13/B34
B47	=B44*(1+B45/B46)
B48	=B41/(B41+B47)
B49	=B44/(B41+B47)
B50	=(B49)*($B$19)/(B32+273)*B34*(B38-B39)
B53	=SIN(2*PI()/365*B52-1.39)*0.4093
B54	=SIN(B53)*SIN($F$4)
B55	=COS(B53)*COS($F$4)
B56	=ACOS(-TAN(B53)*TAN($F$4))
B57	=(1+0.033*COS((2*PI()/365)*B52))
B58	=37.586*B57*(B56*B54+SIN(B56)*B55)
B59	=24/PI()*B56
B60	=(1-$E$8)*B58*($E7+$G7*B33)
B62	=($G9+$E9*B33)
B63	=0.00000000245*((B23+273.16)^4+(B24+273.16)^4)
B64	=($E$10+$G$10*SQRT(B39))
B65	=0.00000000245*($E$10+$G$10*SQRT(B39))*(((B23+273)^4)+((B24+273)^4))

Cell	Formula
B66	=0.00000000245*($E10+$G10*SQRT(B39))*($G9+$E9*B33)*(((B23+273.16)^4)+((B24+273.16)^4))
B68	=B60-B66
B69	=0.14*(B32-H32)
B70	=B68-B69
B71	=B48*B68/B43
B72	=B48*B70/B43
B74	=B71+B50
B75	=(B74-B76)/B74
B76	=B72+B50

	A	B	C	D	E	F	G	H
1	PENMAN-MONTEITH CALCULATIONS							
2								
3	Give :	Location name :		Verde Vigor				
4		Latitude :		9.16	9.27	0.16	rad	
5		Altitude :		640	m.			
6								
7	Parameters :	Short Wave Rad		a =	0.25	b =	0.50	
8		Albedo		alpha =	0.23			
9		Long Wave Rad.		a =	0.90	b =	0.10	
10				al =	0.34	bl =	-0.139	
11								
12		Instrument height				wind	temp	Crop height
13		AerDyn Resistance		ra * U =	30	200	190	170
14					Crop	Coffee		
15		Canopy resistance		rc =	5	32		170
16								
17			Crop	Coffee				
18		AeroT Cff	Gamma*Cff	Gamma*Cff				
19		6092	0.16	1.04				
20								
21		18feb	19feb	20feb	21feb	22feb	23feb	24feb
22								
23	Tmax	32	34	33	34	33	30	33
24	Tmin	18	15	16	15	16	20	19
25	RHmean	78	73	73	69	79	86	79
26	RHmin	46	37	37	33	43	61	46
27	Wind (km/d)	7	16	17	17	13	13	20
28	Sunhours	7.16	8.06	7.95	8.30	7.66	5.95	7.25
29								
30	ET fao	4.15	5.13	5.18	5.40	4.71	3.94	5.05
31								

	A	B	C	D	E	F	G	H
32	Avg Temp	25.05	24.57	24.45	24.69	24.69	24.57	25.97
33	n/N	61%	69%	68%	71%	65%	51%	62%
34	Wind (m/s)	0.08	0.19	0.20	0.20	0.16	0.15	0.23
35								
36	Ea(Tmax)	4.84	5.25	5.14	5.44	5.02	4.14	5.14
37	Ea(Tmin)	2.03	1.75	1.76	1.70	1.86	2.28	2.14
38	Ea(Tx)-Ea(Tn)	3.44	3.50	3.45	3.57	3.44	3.21	3.64
39	Edew	2.24	1.93	1.92	1.80	2.15	2.53	2.38
40	RH(max-min)	78%	73%	73%	69%	79%	86%	79%
41	Dlt(ETx-ETn)	0.20	0.20	0.20	0.21	0.20	0.19	0.21
42	P-atm.	94.0	94.0	94.0	94.0	94.0	94.0	94.0
43	lambda	2.44	2.44	2.44	2.44	2.44	2.44	2.44
44	gamma	0.06	0.06	0.06	0.06	0.06	0.06	0.06
45	rc	5	5	5	5	5	5	5
46	ra	363	164	152	153	195	200	132
47	gamma*	0.06	0.06	0.06	0.06	0.06	0.06	0.07
48	dl/dl+gm*	0.76	0.76	0.76	0.76	0.76	0.75	0.76
49	gm/dl+gm*	0.24	0.23	0.24	0.23	0.24	0.25	0.23
50	Aeroterm	0.49	1.40	1.49	1.67	0.98	0.53	1.35
51								
52	dayno	49	50	51	52	53	54	55
53	soldeclin	-0.213	-0.207	-0.201	-0.194	-0.194	-0.187	-0.181
54	xx	-0.034	-0.033	-0.032	-0.031	-0.031	-0.030	-0.029
55	yy	0.965	0.966	0.967	0.968	0.969	0.970	0.971
56	omega	1.54	1.54	1.54	1.54	1.54	1.54	1.54
57	dr	1.02	1.02	1.02	1.02	1.02	1.02	1.02
58	Ra	35.03	35.12	35.20	35.29	35.29	35.38	35.46
59	N	11.73	11.74	11.75	11.75	11.76	11.76	11.77
60	Rns	15.0	16.0	16.0	16.4	15.6	13.7	15.2
61								
62	f(n/N)	0.65	0.72	0.71	0.74	0.69	0.56	0.65

	A	B	C	D	E	F	G	H
63	sigma(Tx_Tn)	38.89	38.72	38.65	38.81	38.74	38.57	39.37
64	emissivity	0.13	0.15	0.15	0.15	0.14	0.12	0.13
65	Rbo	5.11	5.68	5.68	5.94	5.26	4.58	4.94
66	LWR	3.33	4.09	4.04	4.38	3.62	2.55	3.24
67								
68	Rn (Rns-R1)	11.65	11.95	11.91	12.01	12.03	11.15	12.00
69	G	-0.13	-0.07	-0.02	0.03	0.00	-0.02	0.20
70	Rn-G	11.78	12.02	11.93	11.97	12.03	11.17	11.81
71	Rad Term	3.62	3.71	3.69	3.74	3.73	3.41	3.76
72	Rad Term(-G)	3.66	3.73	3.69	3.73	3.73	3.42	3.70
73								
74	ETcomb	4.11	5.11	5.17	5.41	4.71	3.94	5.11
75		-1.0%	-0.4%	-0.1%	0.2%	0.0%	-0.1%	1.2%
76	ET (-G)	4.15	5.13	5.18	5.40	4.71	3.94	5.05
77								

Appendix 3

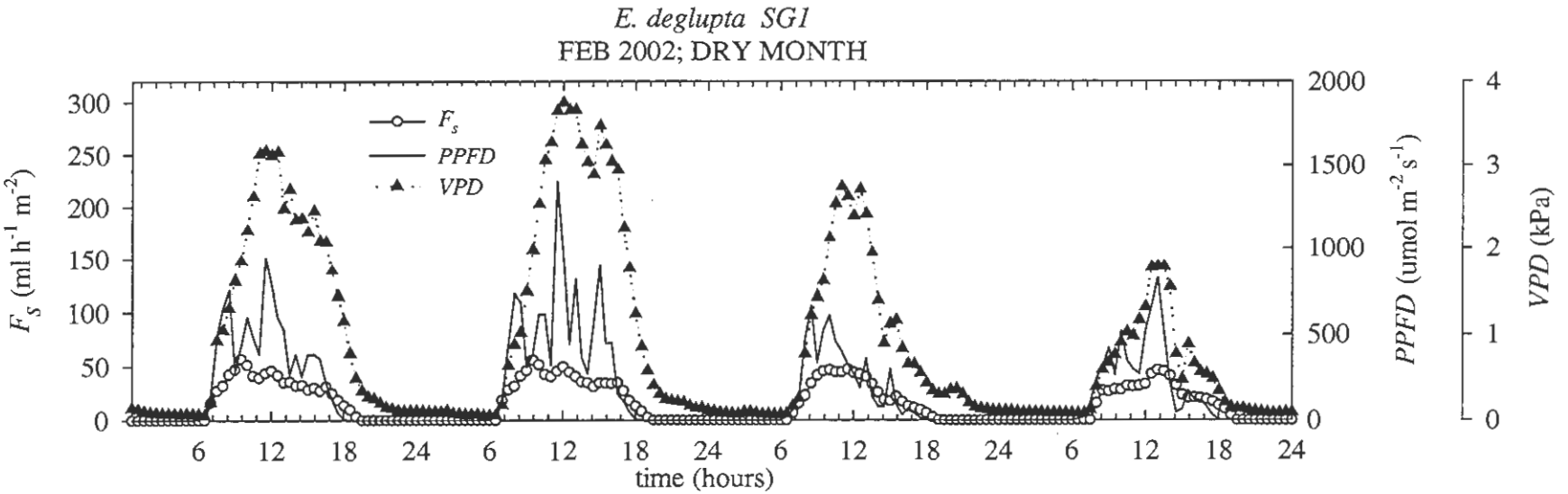
Coffee sap flow (F_S in ml h^{-1} m^{-2}) vs. photosynthetic photon flux density (PPFD in µmol m^{-2} s^{-1}) and air vapour pressure deficit (VPD in kPa; measured in full sun) per individual coffee plant, per month.

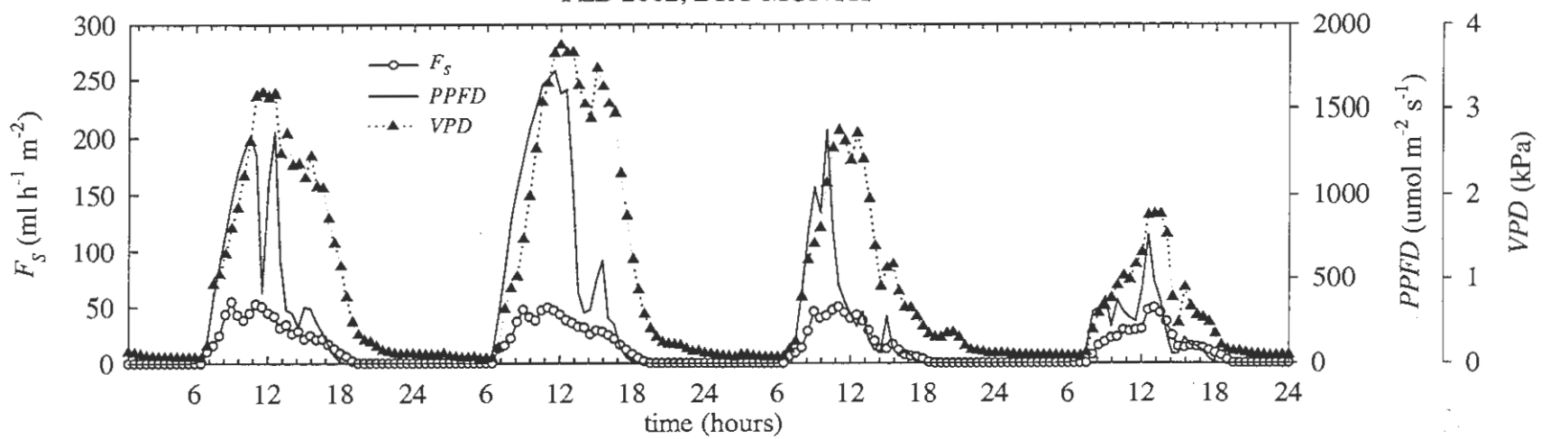
Measurements presented for a period of four consecutive days for eight plants (Table 1), i.e., two plants per treatment (averages for 30-minute-periods).

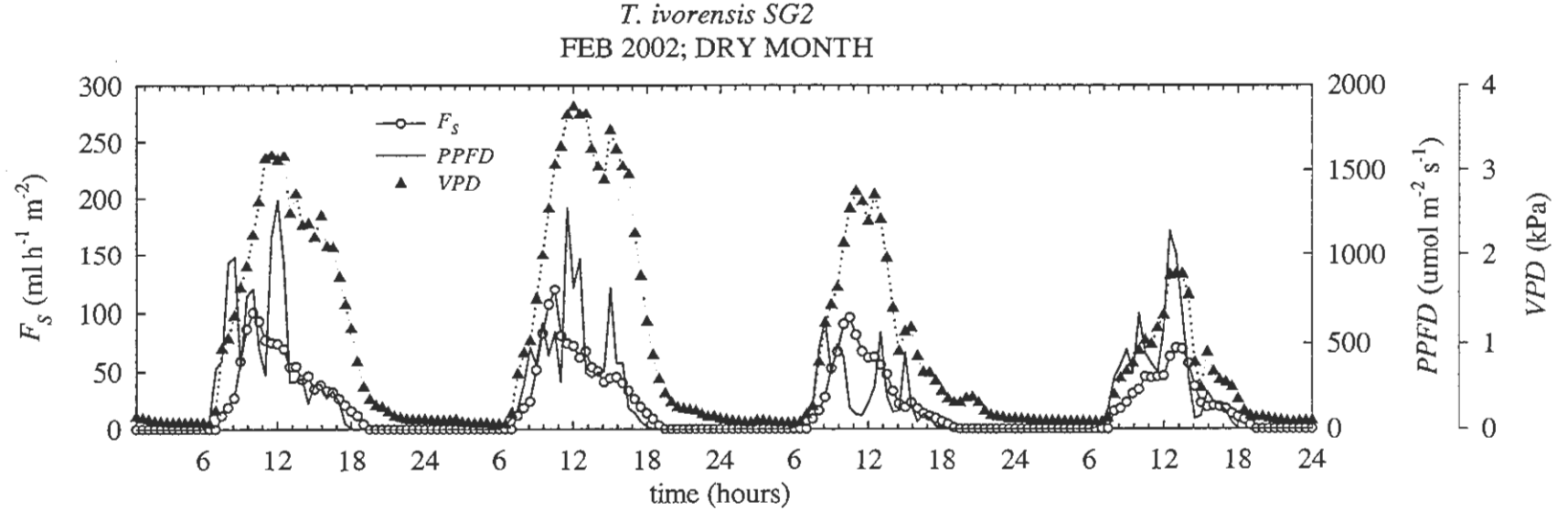
Table 1. Specification for coffee plants in a sap flow study in Southern Costa Rica.

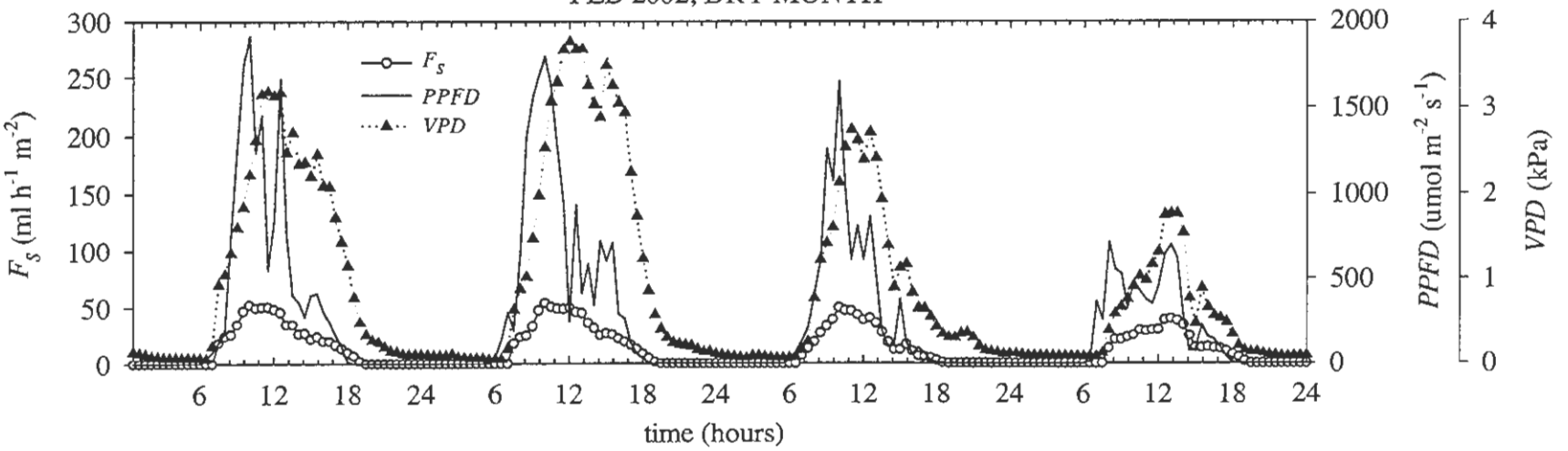
Plant	Location
SG1	0.5 m from the *Eucalyptus deglupta* tree
SG7	2.7 m from the *E. deglupta* tree
SG2	0.5 m from the *Terminalia ivorensis* tree
SG8	2.9 m from the *T. ivorensis* tree
SG4	2.0 m from the *Erythrina poeppigiana* tree
SG5	0.5 m from the *E. poeppigiana* tree
SG3	Full sun
SG6	Full sun

Note: For the month of June, F_S scaling (0 – 300 ml h^{-1} m^{-2}) was expanded to 0 – 600 and 0 – 400 ml h^{-1} m^{-2} for the coffee plants under *E. poeppigiana* or in full sun, respectively.

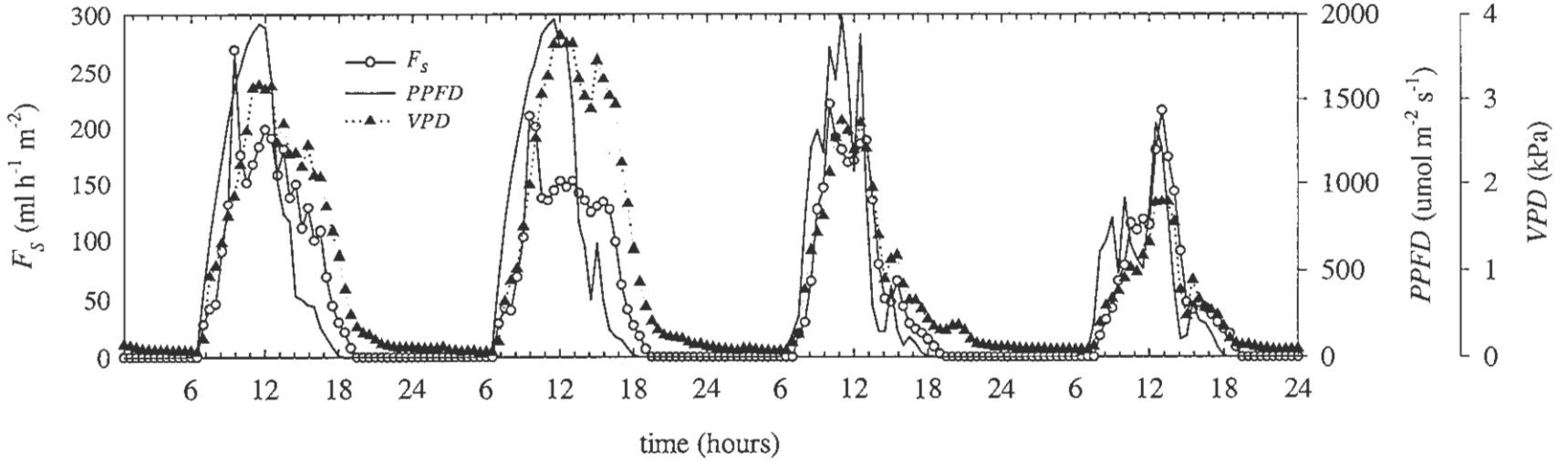

E. deglupta SG1
FEB 2002; DRY MONTH
F_s
PPFD
VPD
F_s (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)


E. deglupta SG7
FEB 2002; DRY MONTH
F_s
PPFD
VPD
F_s (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)

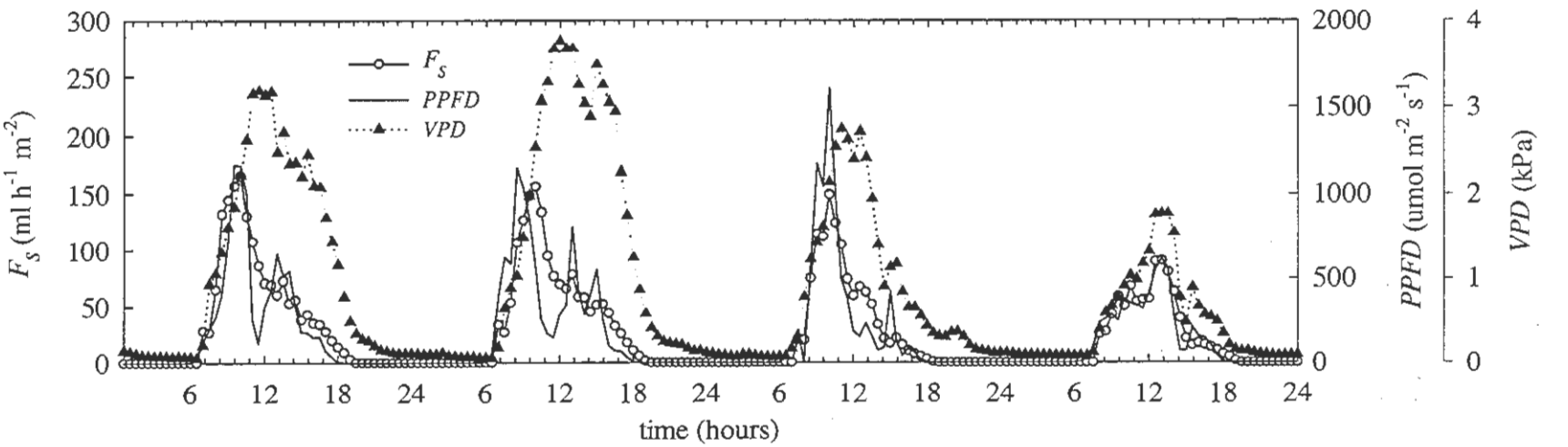

T. ivorensis SG2
FEB 2002; DRY MONTH
F_S
PPFD
VPD
F_S (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)

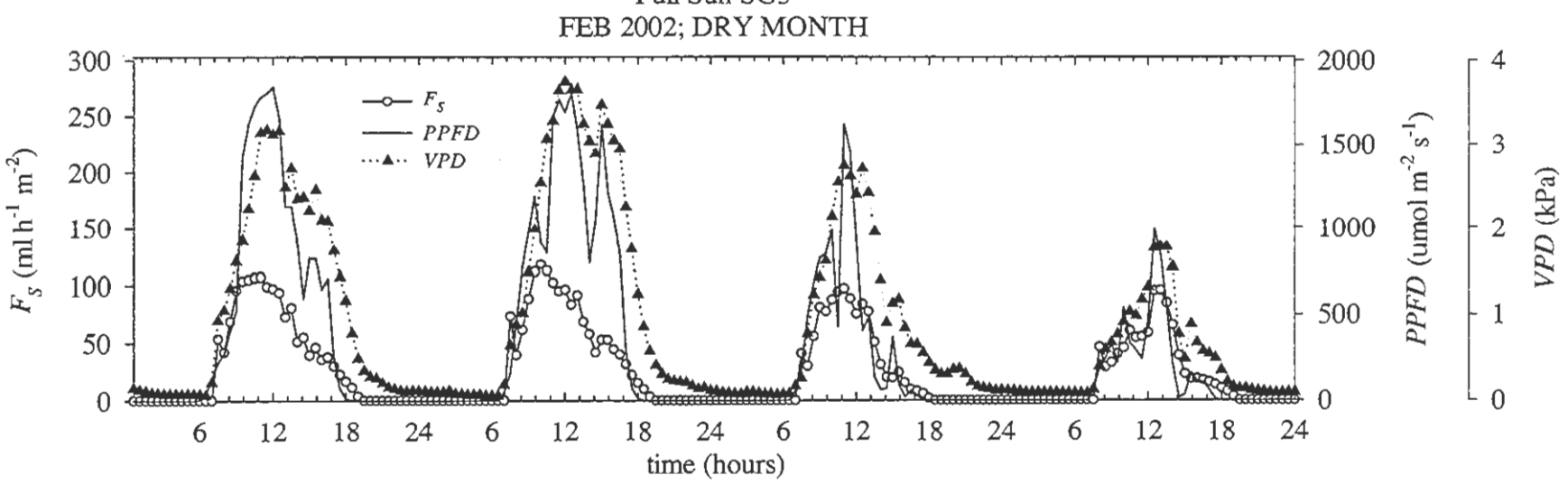

T. ivorensis SG8
FEB 2002; DRY MONTH
F_S
PPFD
VPD
F_S (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)

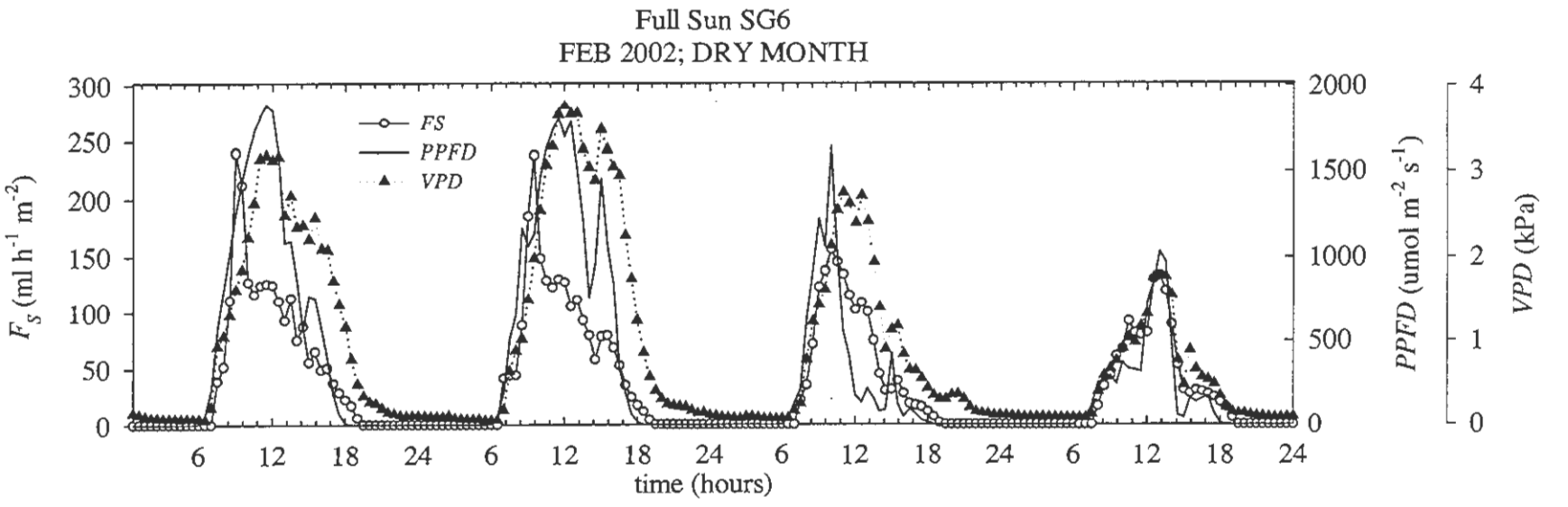
E. poeppigiana SG4
FEB 2002; DRY MONTH

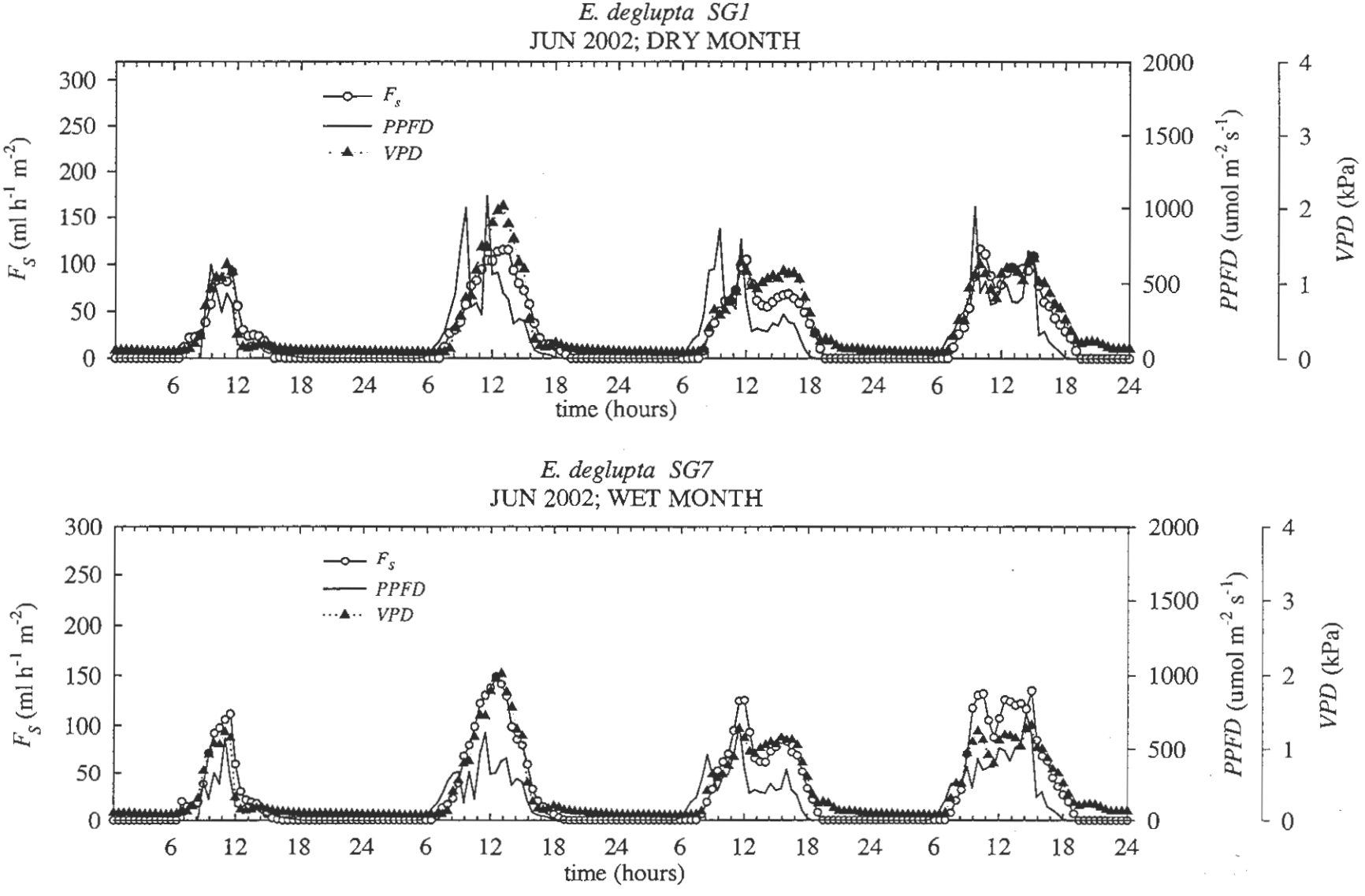


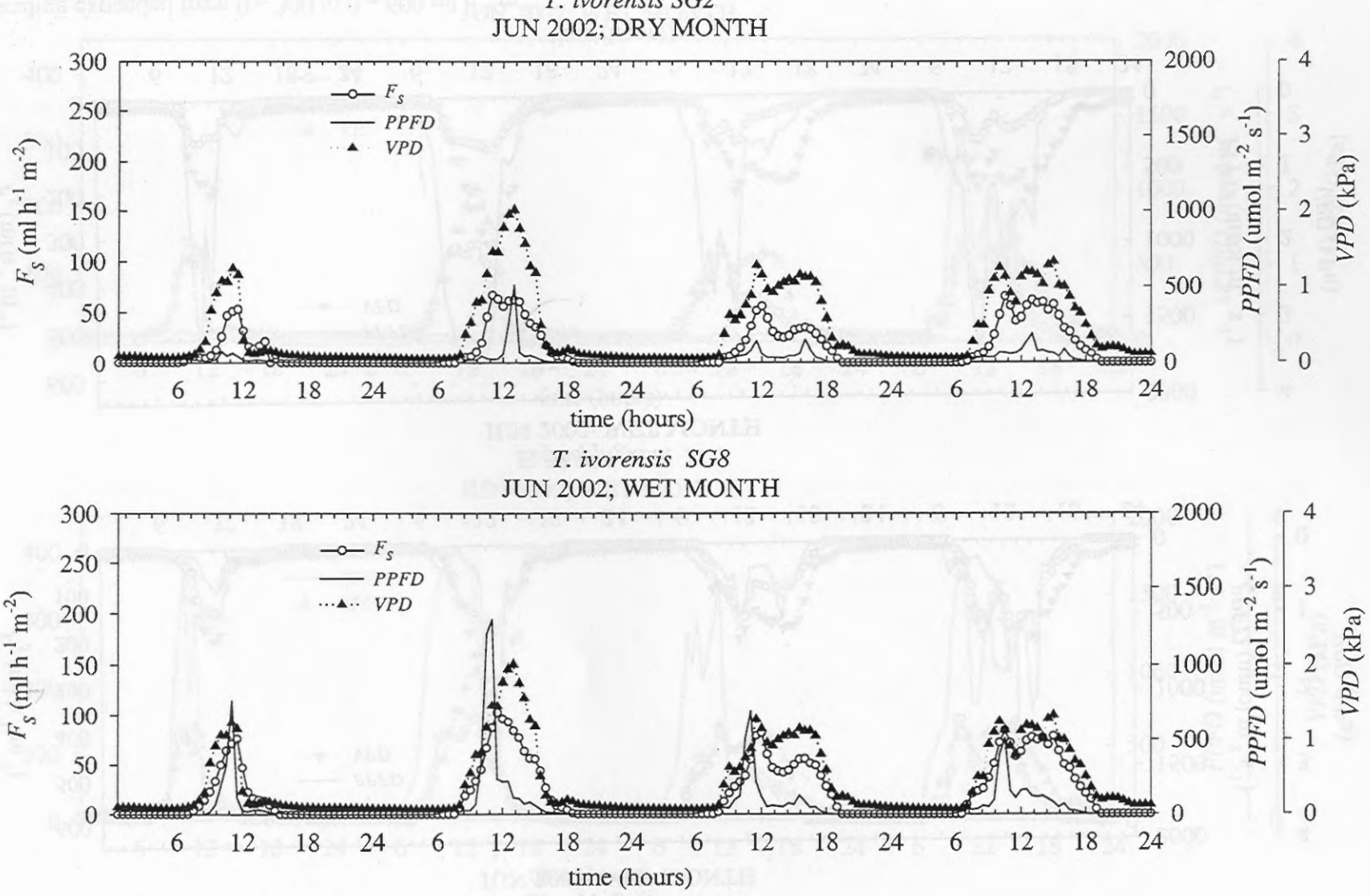
E. poeppigiana SG5
FEB 2002; DRY MONTH

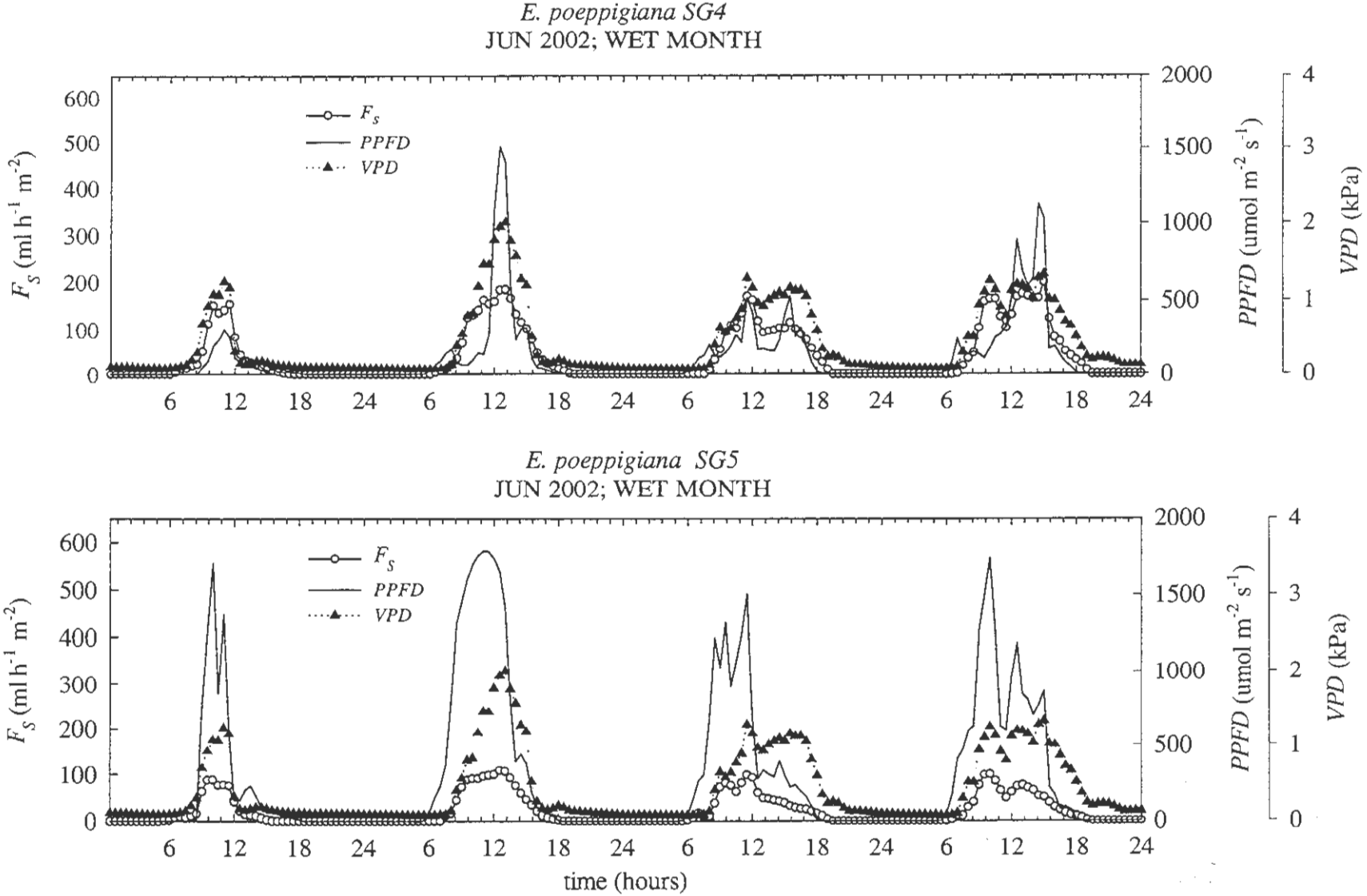



Full Sun SG3
FEB 2002; DRY MONTH
F_S
PPFD
VPD
F_S (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)

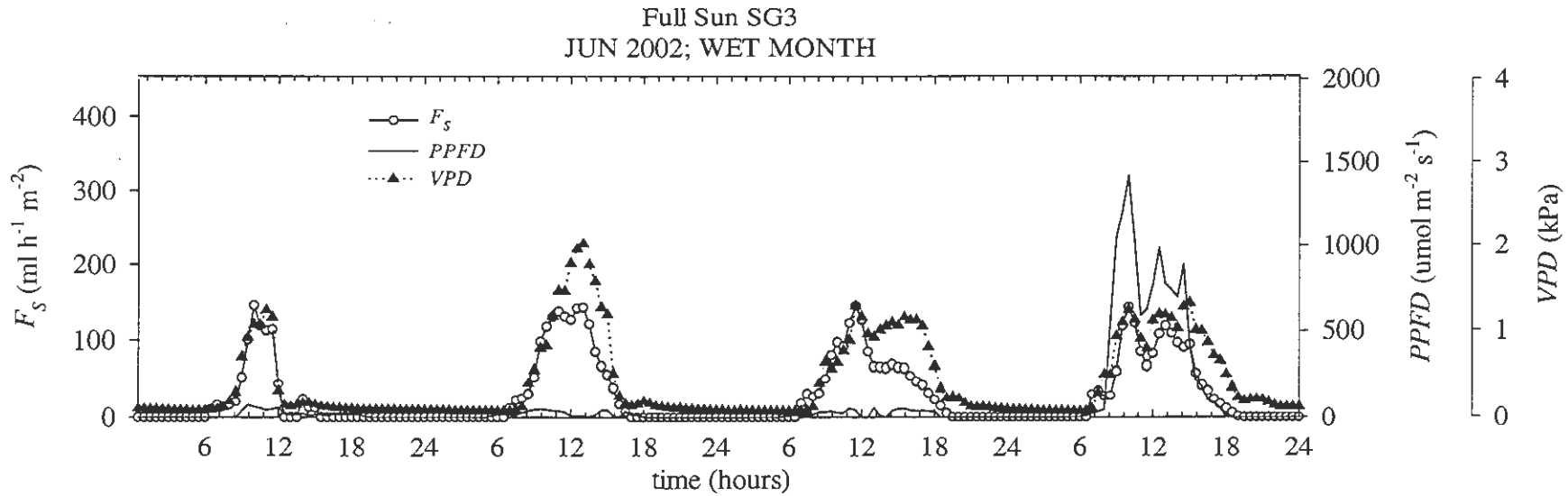

Full Sun SG6
FEB 2002; DRY MONTH
FS
PPFD
VPD
F_S (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)

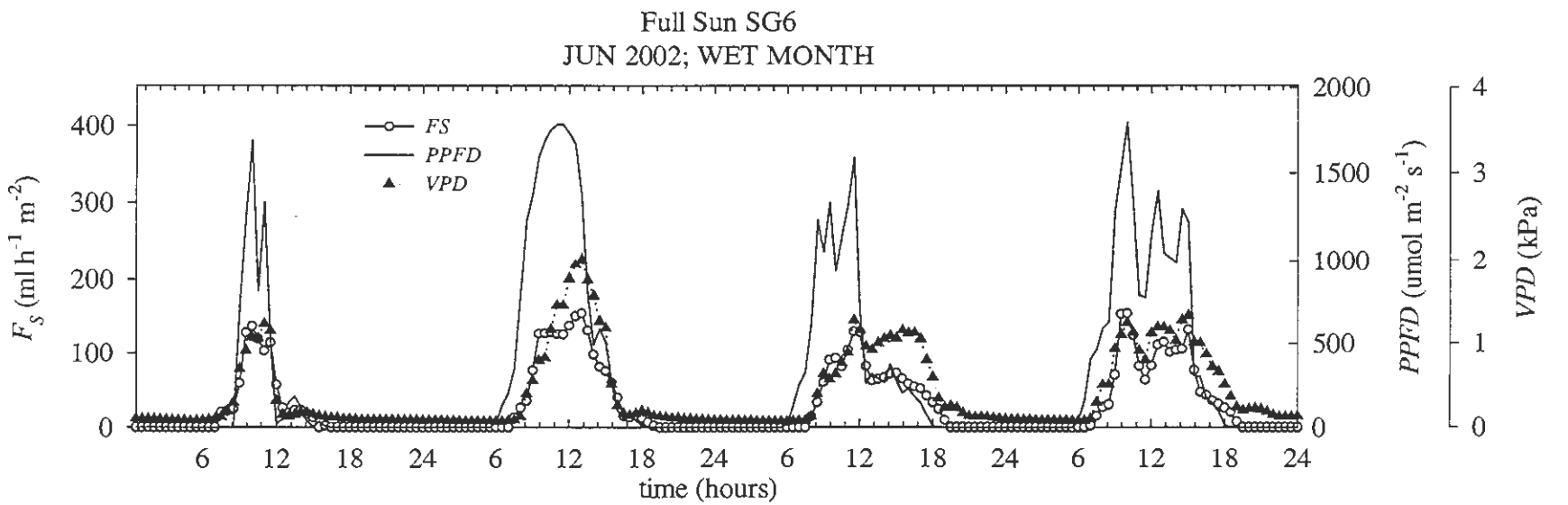

E. deglupta SG1
JUN 2002; DRY MONTH
F_s
PPFD
VPD
F_S (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)
E. deglupta SG7
JUN 2002; WET MONTH
F_s
PPFD
VPD
F_S (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)


T. ivorensis SG2
JUN 2002; DRY MONTH
F_S
PPFD
VPD
F_S (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)
T. ivorensis SG8
JUN 2002; WET MONTH
F_S
PPFD
VPD
F_S (ml h^{-1} m^{-2})
PPFD (umol m^{-2} s^{-1})
VPD (kPa)
time (hours)



Note: F_S scaling expanded from 0 – 300 to 0 – 600 ml h^{-1} m^{-2}.





Note: F_S scaling expanded from 0 – 300 to 0 – 400 ml h^{-1} m^{-2}.