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**Impact of Shade Trees on Soil Fertility and
Coffee Production in Coffee-Agroforestry
Systems in Southern Yunnan Province**

By

Clément René Matthieu RIGAL

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摘要

自 20 世纪 90 年代以来，云南高产的单一栽培咖啡(*Coffea Arabica* L.)迅速扩张。截至 2016 年，咖啡农场面积超过 115000 公顷，占中国咖啡种植面积的 95% 以上。然而，众所周知，密集单一栽培咖啡系统对土壤肥力有负面影响，并使农民面临高风险，特别是由于国际市场上咖啡价格剧烈迅速且剧烈的波动，以及极端气候事件影响而产生的金融风险。为了让咖啡行业应对这些挑战，普洱和西双版纳的地方政府于 2012 年启动了从单一栽培系统向咖啡农林复合系统的大规模转型计划，并向其管辖范围内的所有咖啡农免费发放遮荫树苗。这些遮荫树具有提供多种生态系统服务的潜力，且咖啡是适应遮荫的物种，从而有助于咖啡的可持续生产，同时保持高产量。

长期以来，在传统的咖啡生产国，人们一直在研究遮荫树的影响。然而，这些研究大多是在成熟的咖啡-农林复合系统中进行的，但关于从单一栽培到成熟农林复合系统过渡时期的信息很少。此外，这种知识缺口还与缺乏云南咖啡农场使用的特定遮荫树种及其对当地种植条件的影响的文献有关。为了促进普洱、西双版纳两地从单一栽培模式向咖啡农林复合经营模式的成功转型，本研究以云南南部集约经营的咖啡农场为研究对象，重点研究了幼树和常用遮荫树种对土壤肥力和咖啡产量的影响。

第一章主要介绍研究课题，第二章主要介绍研究领域。然后，在第一项研究(第三章)中，我在普洱和西双版纳两州的咖啡农场进行了 29 个遮荫树试验点。这些研究地点的树木清单显示出农场(平均每个农场有 15 个物种)和景观水平(估计总共有 162 个树种)的多样性水平都很高，从而突显了农林复合系统有助于生物多样性保护的潜力。根据这些树木目录，我确定了 30 种遮荫树种，它们是咖啡农场中最常见的树种。使用基于排名系统(Bradley-Terry 方法)的参与式方法，我采访了 143 名咖啡农，并记录了他们关于这些常见遮荫树种所提供的生态系统服务和危害的民族植物学知识。我发现当地政府推广的九种树种 - *Alstonia scholaris* (灯台叶)，*Bischofia javanica* (茄苳)，*Cerasus cerasoides* (樱花)，*Cinnamomum camphora* (番樟)，*Delonix regia* (凤凰木)，*Dimocarpus longan* (龙眼)，*Litchi chinensis* (荔枝)，*Macadamia integrifolia* (澳洲坚果) 和 *Mangifera indica* (芒果) - 因其被认同的经济潜力和防止咖啡树受到环境危害的保护能力而受到高度青睐。我还发现了一些没有被推广的物种，比如菠萝蜜和柿子树，它们在咖啡农场提供与当地有关的生态系统服务上很有潜力。这些结果促进了在线工具(www.shadetreeadvice.org)的升级，该工具通过扩展服务生成推荐遮荫树种的列表，这些遮荫树种是根据云南南部特

定的当地生态环境和农民个人的需求定制的。最后，本研究指出了在遮荫树对土壤肥力、咖啡产量、咖啡质量以及病虫害控制的影响方面，咖啡农户的知识缺口。

在第二项和第三项研究(第四章和第五章),我在普洱州六顺乡建立一个现场试验,评估三个常见遮荫树种的影响:*B. javanica* (茄苳)、*C. camphora* (番樟)和*Jacaranda mimosifolia* (蓝花楹),主要针对树种对土壤肥力,咖啡产量,还有咖啡质量三个方面,时间是仅在引入集约管理的单一咖啡农场 4 年后。对于土壤肥力(第四章),主要检测了表层(0-20cm)土壤化学参数(总 N,有效 P,可交换钾,钙,镁,有机质、pH 值),土壤生物群落(线虫和微生物群落)和土壤酶活性(β -葡萄糖苷酶, N-乙酰氨基葡萄糖苷酶和酸性磷酸酶),以及遮荫树和咖啡树的根系和土壤水分剖面,深度 1.2 米。我论证了所有三种遮荫树种都有助于提高土壤肥力。特别地,我测量了更高的土壤化学肥力(更高的 pH、OM、N、P 和 Ca 浓度);全年类似或更高的土壤酶活性(所有三种测得的酶);全年真菌群落更丰富;在旱季,遮荫树下的微生物群落比开阔地区丰富。土壤水分剖面显示,每年的降雨足以为咖啡树和遮荫树提供足够的水资源。另一方面,根侧轮廓显示,0- 20cm 土层的蓝花楹与咖啡树之间的根系竞争非常激烈,20 cm 以下的番樟和咖啡树之间的根系竞争非常激烈。总的来说,第四章证明了在集中管理的咖啡农场中,遮荫树迅速有助于保持和/或恢复土壤肥力和缓冲土壤生物活动的季节性变化。

在第五章中,我评估了这些遮荫树对地上咖啡产量和咖啡质量的影响。为此,2016 年 11 月我估算了 309 棵咖啡树的产量,正是在收获的前一个月。在 2017 年,我记录了三个选定遮荫树种的树冠下,以及开放条件下一年的微气候数据(气温和湿度,30 分钟/次)。同时跟踪了 90 棵咖啡树的发展周期,这些咖啡树有的位于树荫下,有的位于树荫檐的边缘,有的则位于开放条件下。具体来说,我在一个生长期,记录了第一朵花到收获的单一本枝条上花蕾、花、咖啡针尖/果实和败育果数量。在 2017-2018 年冬季,我收获了这 90 棵咖啡树,测量了产量,并对咖啡样品进行了物理和有机质量评估。这项研究显示,年轻的遮荫树形成的微气候可增加咖啡在遮荫下的产量。夏季相比开放区域显示出气压不足(-0.5 - -0.9 kPa)和最高温度较低(3 到 6° C),在冬季相比开放区则显示出更高的最低温度(+ 0.5 + 1° C)。这对 2017 年 12 月开放区温度降到 0° C 的极端温度形成了保护。座果率随遮荫强度降低;然而,在豆类灌浆和成熟阶段,果实产量有所下降。因此,在连续两年的光照条件下,在开阔区域和阴凉条件下,咖啡产量相似(2016 年为 2.8 公斤/棵,2017 年为 4.5 公斤/棵)。只有 *C. camphora* (番樟)下方的咖啡树的产量明显低于其他咖啡树(2016 年为 2.8 公斤/棵,2017 年为 4.5 公斤/棵)。最后,树荫对咖啡品质没有明显影响。总体而言,第五章表明,树冠较低的遮荫树 *B. javanica* (茄苳)

和 *J. mimosifolia* (兰花楸) 在树冠下提供了良好的微气候, 对咖啡产量和品质没有负面影响。另一方面, 树冠浓密的遮荫树—*C. camphora*(番樟)—确实能够保护咖啡树免受气候灾害的影响, 但代价是咖啡的产量降低。这突出了对遮荫树的适应性管理实践的需求, 例如: 与咖啡生产周期同步的修剪管理。

此项研究表明, 经过精心挑选和管理的遮荫树在进入云南南部集中管理的咖啡农场仅仅四年之后就提供了大量的生态系统服务。它们特别有助于生物多样性的保护、保护和/或恢复土壤肥力和保护咖啡树免受气候灾害。此外, 充足的树冠密度和遮荫水平, 农民可以在遮荫下保持较高的咖啡产量, 再加上类似开放地区的咖啡质量。因此, 由地方政府发起的普洱和西双版纳地区从单一栽培向咖啡农用复合林业系统的转变, 将给咖啡农带来短期和长期的利益, 促进景观健康, 以及云南南部咖啡行业的可持续发展。

关键词: 农林系统, 阿拉伯咖啡, 咖啡质量, 生态系统服务, 民族植物学知识, 土壤肥力, 咖啡产量

ABSTRACT

Highly productive monoculture coffee (*Coffea Arabica* L.) farms have rapidly expanded in Yunnan Province since the 1990s. As of 2016, coffee farms covered more than 115000 ha, producing over 95% of all coffee grown in China. However, intensive monoculture coffee systems are known to have negative impacts on soil fertility and to expose farmers to high risks, notably financial risks stemming from rapid and strong variations in coffee prices on the international market as well as vulnerability to extreme climatic events. In an effort to prepare the coffee sector to face these challenges, the local governments of Pu'er and Xishuangbanna Prefectures initiated a large-scale transition program from monoculture systems to coffee-agroforestry systems in 2012; distributing free shade tree seedlings to all coffee farmers in their jurisdictions. These shade trees have the potential to provide multiple ecosystem services and thus contribute to more sustainable coffee production, while maintaining high yield, since coffee is a shade adapted species.

The impacts of shade trees has been long studied in traditional coffee-producing countries. However, most of these studies were carried out in mature coffee-agroforestry systems, while there is a paucity of information on the transition period from monoculture to mature agroforestry systems. Furthermore, this knowledge gap is coupled with a lack of documentation on the specific shade tree species used in Yunnan coffee farms and their impacts in local growing conditions. To contribute to the successful transition from monoculture to coffee-agroforestry systems in Pu'er and Xishuangbanna Prefectures, the present research focuses on assessing the impacts of young and commonly used shade trees on soil fertility and coffee production in intensively managed coffee farms of southern Yunnan.

Chapter I introduces the research topic and Chapter II describes the study area. Then, in the first study (Chapter III), I carried out 29 shade tree inventories in coffee farms in Pu'er and Xishuangbanna Prefectures. These inventories revealed an unexpectedly high level of diversity at both farm (average of 15 species per farm) and landscape levels (estimated 162 tree species overall), and thus highlighted the potential for agroforestry systems to contribute to biodiversity conservation. Based on these tree inventories, I then identified the 30 shade tree species most commonly found on coffee farms. Using a participatory approach based on a ranking system (the Bradley-Terry method), I interviewed 143 coffee farmers and documented their ethnobotanical knowledge regarding the ecosystem services and disservices provided by these common shade tree species. I found that the nine tree species promoted by local governments – *Alstonia scholaris*, *Bischofia javanica*, *Cerasus cerasoides*, *Cinnamomum camphora*, *Delonix regia*, *Dimocarpus longan*, *Litchi chinensis*, *Macadamia integrifolia* and *Mangifera indica* – were

highly favored for their perceived economic potential and the protection that they provided to coffee trees against environmental hazards. I also identified non-promoted species, such as *Artocarpus heterophyllus* and *Diospyros kaki*, with high potential to provide locally relevant ecosystem services in coffee farms. These results led to the upgrade of an online tool (www.shadetreeadvice.org) which allows extension services generating lists of recommended shade tree species tailored to the specific local ecological context of southern Yunnan and to individual farmers' needs. Lastly, this study pointed out knowledge gaps from coffee farmers regarding the impacts of shade trees on soil fertility, coffee yield, coffee quality and pests and diseases control.

In the second and third studies (Chapters IV and V), I set up a field experiment in Liushun Township, located in Pu'er Prefecture, to assess the impacts of three commonly found shade tree species – *B. javanica*, *C. camphora* and *Jacaranda mimosifolia* – on soil fertility, coffee yield, and coffee quality only four years after their introduction into intensively managed monoculture coffee farms under near-optimal growing conditions. For soil fertility (Chapter IV), I examined soil chemical parameters (total N, available P, exchangeable K, Ca and Mg, organic matter, pH), soil biological communities (nematodes and microbial communities) and soil enzyme activities (β -glucosidase, N-acetyl-glucosaminidase and acid phosphatase) in the top (0-20 cm) soil layer, as well as root systems of shade trees and coffee trees and soil water profiles to a depth of 1.2m. I demonstrated that all three shade tree species contributed to improving soil fertility. In particular, I measured higher soil chemical fertility (higher pH, OM, N, P and Ca concentrations); similar or higher soil enzyme activities throughout the year (all three measured enzymes); more abundant fungi communities throughout the year; and more abundant microbial communities during the dry season below shade trees than in open areas. Soil water profiles highlighted that annual rainfalls were sufficient to provide enough water resources for both coffee trees and shade trees. On the other hand, root profiles pointed out fierce root competition between *B. javanica* and coffee trees in the 0-20 cm soil layer and between *C. camphora* and coffee trees below 20 cm depth. Overall, Chapter IV evidenced that shade trees rapidly contributed to preserving and/or restoring soil fertility and buffering seasonal variability in soil biological activity in intensively managed coffee farms.

In Chapter V, I assessed the above-ground impacts of these same shade trees on coffee yield and coffee quality. To do so, I estimated the yield of 309 coffee trees from their fruit load in November 2016, one month before harvest. In 2017, I recorded micro-climate data (air temperature and humidity every 30 minutes) for one year below the canopies of the three selected shade tree species and in open conditions. I simultaneously followed the coffee development cycle of 90 coffee trees located either below shade tree canopies, at the edge of shade tree canopies or

in open conditions. Specifically, I recorded the number of flower buds, flowers, coffee pinheads/cherries and aborted fruits on a sample of branches during one growing period, from first flowers to harvest. In the winter of 2017-2018, I harvested these 90 coffee trees, measured yields and carried out physical and organoleptic quality assessments on coffee samples. This study showed that young shade trees created micro-climates favorable to coffee production below their canopies, with lower vapor pressure deficit (-0.5 to -0.9 kPa) and lower maximum temperatures (-3 to -6°C) than in open areas in the summer days, and higher minimum temperatures (+0.5 to +1°C) than in open areas in the winter days. This protection from extreme temperatures was particularly important when temperatures hit 0°C in open areas in December 2017. Fruit set decreased with shade intensity; however fruit drop also decreased during the bean filling and maturation stages. As a result, coffee yields were similar in open areas and in shaded conditions over two consecutive years (2.8kg.tree⁻¹ in 2016 and 4.5kg.tree⁻¹ in 2017). Only coffee trees below *C. camphora* had significantly lower yield than other coffee trees (2.4kg.tree⁻¹ in 2016 and 2.8kg.tree⁻¹ in 2017). Lastly, shade trees had no visible impact on coffee quality. Overall, Chapter V showed that shade trees with low canopies - *B. javanica* and *J. mimosifolia* - provided a favorable micro-climate under their canopies, with no negative impacts on coffee yield and quality. On the other hand, shade trees with dense canopies - *C. camphora* – did provide protection from climatic hazards but at the expense of coffee yield. This highlighted the needs for adapted management practices of shade trees, such as pruning practices timed with the coffee production cycle.

This PhD thesis demonstrates that carefully selected and managed shade trees provided substantial ecosystem services only four years after their introduction into intensively managed coffee farms in southern Yunnan. In particular, they contributed to biodiversity conservation, preservation and/or restoration of soil fertility and protection of coffee trees from climatic hazards. Furthermore, with adequate tree canopy density and shade level, farmers can maintain high coffee yield under shade, combined with cup quality similar to the one in open areas. Therefore, the conversion from monoculture to coffee-agroforestry systems in Pu'er and Xishuangbanna Prefectures, initiated by local governments, should bring both short-term and long-term benefits to coffee farmers, support landscape health and contribute to the sustainability of the coffee agriculture sector in southern Yunnan.

Keywords: Agroforestry system, *Coffea arabica*, Coffee quality, Coffee yield, Ecosystem service, Ethnobotanical knowledge, Soil fertility

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ACRONYMS AND ABBREVIATIONS

- ACP – Acid Phosphatase
ANOVA - Analysis of variance
AMF – Arbuscular Mycorrhiza Fungi
BG – β -glucosidase
CAS – Chinese Academy of Sciences
DAF – Days After Flowering
DD – Growing Degree Days
ED – Ecosystem Disservice
ES – Ecosystem Service
ET – Potential Evapotranspiration
FAO - Food and Agriculture Organization (of the United Nations)
Gram+ – Gram-positive bacteria
Gram- – Gram-negative bacteria
ICRAF - World Agroforestry Centre
KIB - Kunming Institute of Botany
LAI – Leaf Area Index
LEK – Local Ecological Knowledge
NAG – N-acetyl-glucosaminidase
PLFA – Phospholipid Fatty Acid
RDA – Redundancy Analysis
SOM – Soil Organic Matter
VPD – Vapor Pressure Deficit

CHAPTER 1 - General Introduction

1.1. Coffee growing in Yunnan Province

Coffee often ranks as the first commodity in the international agricultural trade market (DaMatta 2004). Most of the production is shared between Arabica coffee (*Coffea arabica*) and Robusta coffee (*Coffea canephora* var. *Robusta*), the former accounting for 55% of the world production while the latter accounts for the remaining 45% (FAO). It is estimated that 25 million households rely on coffee production to sustain their livelihoods, underlying its importance in the global rural economy (Pendergrast 1999). In China, coffee consumption and production have been growing at double digit rates since the mid-90s and, according to the International Coffee Organization (ICO), this trend shows no sign of slowing down.

Over 95% of the coffee grown in China is sourced from Yunnan Province (Zhang et al. 2014), a region traditionally devoted to tea cultivation. Its mild climate and mountainous landscape offers near optimal growing conditions for Arabica coffee. Indeed, Arabica coffee performs best in mountainous areas with annual average temperatures ranging from 18 to 22 °C (Descroix and Snoeck 2008; Zullo et al. 2011) and acid soils with pH values ranging from 5.0 to 6.0 (Descroix and Snoeck 2008; Vaast et al. 1998). Arabica coffee requires 1200 to 2000mm of annual precipitation as well as a marked dry season coinciding with a cool season and lasting 2 to 4 months, which plays an important role in stimulating flowering (DaMatta and Ramalho 2006; Descroix and Snoeck 2008). Members from the Jingpo cross border ethnic minority group and French missionaries first took advantage of these suitable growing conditions and introduced Arabica coffee in Yunnan Province at the end of the 19th century, thereby contributing to some of the oldest coffee plantations in the area, such as those found in Baoshan and Dali (Chen 2017).

These coffee estates remained confined to a few thousand hectares during most of the 20th century (Chen 2017; FAO). The introduction of the Catimor cultivar, a hybrid resistant to coffee leaf-rust disease (*Hemileia vastatrix*) contributed to the expansion of coffee farms in the 1980s (Zhang et al. 2014). Indeed, *H. vastatrix* is one of the main coffee diseases worldwide, causing up to 20 to 25% losses in harvest during bad years (McCook 2006). This fungal disease is also found in Yunnan Province. For this reason, around 90% of coffee cultivars cultivated in Yunnan are now derived from Catimor (Zhang et al. 2014); this cultivar is resistant to *H. vastatrix*, and it produces high yield with a cup quality suitable to commodity coffee. It was introduced along with intensive farming practices similar to those promoted in Central America in the 1970s, relying on dense monoculture plantations (around 5000 trees.ha⁻¹) and sustained with high mineral fertilizer inputs (Haggar et al. 2011; McCook 2006). Unfortunately, new races of *H. vastatrix*

have recently been identified in China and detected in cultivated Catimor cultivar samples, highlighting a susceptibility of Catimor to these new rust races (Zhang et al. 2014).

The second factor explaining the boost in coffee production in Yunnan Province is the arrival of major agro industries in the 1980s and 1990s, following the economic reforms and the opening of Chinese economy (Jia et al. 2017). These companies offered an outlet for a commodity otherwise seldom consumed within the domestic market at the time. Following that, coffee estates underwent a rapid areal growth in locations traditionally dominated by tea production. Coffee areas reached 17200 ha in 2005 and 117000 ha in 2016 (+20% annually) according to government statistics (Yunnan Statistical Yearbook 2017). This rapid expansion has secured China a seat within the top 15 coffee growing countries (FAO). As a comparison, Chinese coffee production in 2014 exceeded that of Costa Rica and Kenya, two well-established coffee producing countries (FAO). This rapid growth is best illustrated in Pu'er Prefecture, where the local government recorded 42000 ha of coffee farms in 2012 (Pu'er Statistical Yearbook 2012). The second largest coffee production center is located in Dehong and Baoshan Prefectures, with over 25000 ha recorded in 2012 (Dehong and Baoshan Statistical Yearbooks 2012).

1.2. The challenges to coffee growing in Yunnan Province

The rapid expansion of coffee farming areas under intensive management practices has successfully established Yunnan Province as an important coffee growing center. With yield over 3 t.ha⁻¹.yr⁻¹ recorded in Baoshan and Dehong Prefectures (Liu et al. 2018; Zhang et al. 2014), coffee yield in Yunnan is indeed among the highest worldwide (Siles et al. 2010; Vaast et al. 2006). The coffee growing sector nonetheless faces several challenges that threaten its sustainability. First, despite the emergence of a select few specialty coffee producers (Sun and Thurston 2013), Yunnan coffee remains characterized by low to medium quality beans sold as commodity coffee. Due to global and recurrent oversupplies of coffee, commodity coffee often fetches low prices (Pendergrast 1999). In spring 2018, Arabica coffee sold for approximately 1.2 USD.lb⁻¹ on the commodity market, barely enabling smallholder farmers to cover their yearly production costs. Furthermore, the commodity market is prone to high price volatility – fetching as high as 3.0USD.lb⁻¹ in April 2011, and as low as 1.1USD.lb⁻¹ in October 2013 – and hence exposes coffee farmers to high financial vulnerability (Gemech and Struthers 2007).

In addition, due to high mineral fertilizer inputs, often exceeding 200 kg.N.ha⁻¹.yr⁻¹ as frequently observed in smallholder farms in China (Ju et al. 2016), and low return of organic matter, intensively managed monoculture coffee farms are confronted to a continuous decline in soil fertility (Cannavo et al. 2013). As documented by Zhao et al. (2018a) in a chronosequence of

coffee farms in Hainan Province, soils in intensively managed coffee farms suffer from erosion, acidification, depletion of their organic carbon content, and a reduction of their microbial activity. This decline in soil fertility in turn leads to a rising need for external inputs to replace the loss of soil regulated ecosystem services (Sandhu et al. 2010) and delay an otherwise inevitable decline in coffee yield.

Lastly, coffee species are known to be highly sensitive to climate change (Bunn et al. 2015; Craparo et al. 2015), and smallholder farmers particularly vulnerable to its consequences (Baca et al. 2014; Harvey et al. 2014; Morton 2007). In Yunnan Province, annual rainfalls have already declined since 2000, while droughts have increased in frequency (Qiu 2010; Zomer et al. 2015). This observation is of particular importance considering that drought is the main environmental factor hindering coffee yield in most coffee growing areas (Laderach et al. 2011). The effects of droughts are especially pronounced when they occur during the coffee bean filling stage, with losses reaching up to 80% in extremely dry years (DaMatta et al. 2018). Furthermore, the changes in climate can already be observed through studying the average annual temperature, which has increased by 1.6C in the last 50 years (Wong et al. 2010) and is projected to further increase by 1.6 to 4.8C by 2050 (Zomer et al. 2015). As shown in previous studies, an increase in temperature should result in a reduction in coffee growth (DaMatta et al. 2018); more frequent photoinhibition periods (Batista et al. 2012; Chaves et al. 2007); faster ripening of coffee cherries (Pezzopane et al. 2008); and an overall decline in coffee quality (Tolessa et al. 2017). On top of these expected negative impacts on coffee yield and coffee quality, climate change will also increase the frequency of extreme temperature events (Adachi et al. 2013) and might favor pest outbreaks (Kutywayo et al. 2013).

1.3. The promotion of agroforestry practices to answer these challenges

In many countries, coffee is traditionally grown under agroforestry systems, whereby perennial trees are integrated into coffee fields. The World Agroforestry Center (ICRAF) defines agroforestry (AFS) as “a sustainable land management system which increases the overall yield of the land, combines the production of crops (including tree crops) and forest plants and/or animals simultaneously or sequentially, on the same unit of land, and applies management practices that are compatible with the cultural practices of the local population” (King and Chandler 1978). These more complex ecological systems are especially well-suited for coffee cultivation since coffee originated in the shaded high tropical forests of Ethiopia (Zullo et al. 2011). Their management requirements are also more complex than in the case of monoculture coffee systems. Nonetheless, these systems provide multiple socio-economic benefits and environmentally positive impacts, referred to as ecosystem services (ES) (Cerdán et al. 2012).

Amongst others, agroforestry systems can simultaneously provide resources to local stakeholders such as food, fodder, or fuelwood (Neupane and Thapa 2001; Rao et al. 2007; Rice 2008). They are especially well-suited for smallholder farmers thanks to their high potential in decreasing vulnerability towards market fluctuations (Hagggar et al. 2011). Agroforestry practices can additionally benefit Yunnan coffee farmers as an efficient mitigation strategy against the white stem borer (*X. quadripes*), which is the main pest in the area (Waller et al. 2007).

Shade trees are also known to sustain higher soil fertility than conventional monoculture systems (Barrios 2007). Deep rooted shade trees can access deep soil layers and recycle water and nutrients otherwise inaccessible to coffee plants (Lehmann 2003; Padovan et al. 2015; Tully et al. 2012). AFS advantages water infiltration over runoff (Cannavo et al. 2011) and reduces soil erosion (Barrios et al. 2012; Blanco Sepúlveda and Aguilar Carrillo 2015). Litter input from shade trees contributes to soil nutrient and organic matter (Payán et al. 2009; Tully and Lawrence 2012). Combined with trees below-ground activity, litter also contributes to larger and richer soil communities (Bagyaraj et al. 2015; Muleta et al. 2008) and increases nutrient use efficiency (Cannavo et al. 2013; Nygren et al. 2012). Nonetheless, these benefits are subject to the choice and management of relevant shade tree species, to ensure that they promote beneficial ecosystem services while circumscribing above-ground and below ground competition (Beer et al. 1998; Hagggar et al. 2011).

Furthermore, *C. arabica* lacks efficient mechanisms to regulate its fruit set in open conditions (Cannell 1985). Shade helps to balance fruit production and vegetative growth, attenuating the common phenomenon of biannual patterns in yield, when high crops are followed by a recovery period with low yield (Beer et al. 1998; DaMatta 2004), thereby reducing farmers' economic vulnerability. Shade, like altitude, also slows down the ripening of coffee beans and better synchronizes it with the ripening of coffee pulp, thereby improving the physical, chemical, and organoleptic qualities of coffee beans (Vaast et al. 2006). The increase in coffee quality can help farmers reaching specialty coffee standards. This can in turn lead to higher incomes and can lower their vulnerability to quick market fluctuations for commodity coffee. As a general rule, these benefits increase as growing conditions become less favorable to coffee agriculture (Beer et al. 1998; Rahn et al. 2018). On the other hand, shade trees can be detrimental to coffee yield and quality under optimal conditions (Siles et al. 2010). Similarly, highly competitive and poorly managed shade trees can reduce coffee yield and quality (Steiman et al. 2011; Vaast et al. 2008).

Furthermore, agroforestry systems are more efficient than monocultures in sequestering carbon dioxide and thus in tackling climate change (Ramachandran Nair et al. 2009). In addition, they are especially well-suited for smallholder farmers, thanks to their high potential in decreasing

vulnerability to extreme climatic events (Charles et al. 2013; Lin et al. 2008). Shade tree canopies buffer extreme temperatures and can reduce leaf damages from heat waves and cold spells (Lin 2007; Vaast et al. 2016). Shade trees also increase relative air humidity during daytime, decrease vapor pressure deficit and, given that below-ground competition for water is not too fierce, relieve hydric stress and improve the water status of coffee trees located under their canopies (Cannavo et al. 2011; van Kanten and Vaast 2006). This can in turn increase coffee stomatal conductance and light use efficiency of this shade-adapted species (Batista et al. 2012; Franck and Vaast 2009).

In light of all these assets, agroforestry is receiving more and more attention from researchers and policy makers, and is getting wildly promoted amongst smallholder farmers (Garrity et al. 2010). In Pu'er and Xishuangbanna Prefectures in particular, local governments have adopted agroforestry as a strategy to answer the many challenges faced by the coffee sector, in particular the decrease in soil fertility and low coffee prices. In 2012, after a similar campaign for promoting the use of shade trees in tea estates, the government began to encourage the large-scale production of “ecologically-friendly coffee” by distributing free shade tree seedlings to coffee farmers. The distribution of a set of both indigenous and exotic shade tree species, among which were included a few trees of economic importance such as the Macadamia nut tree (*Macadamia integrifolia*), illustrates the trade-off between biodiversity conservation and economic objectives. There has been a large-scale transition from monoculture coffee to shaded coffee cultivation in both Pu'er and the neighbouring prefecture of Xishuangbanna following this campaign.

1.4. Research Gaps

Preliminary investigations revealed that most coffee-agroforestry systems in Pu'er and Xishuangbanna Prefectures relied on young shade trees. These young trees were planted in the past five years following promotion activities by local governments. However, due to the recent expansion of coffee farms, and the more recent expansion of shaded coffee, no comprehensive description of these farming systems could be found in scientific literature except for studies focusing on cultivar selection (Bai et al. 2014; Zhang et al. 2014; Zhang et al. 2011) and irrigation (Liu et al. 2018). Liu et al. (2017) calls for further research on coffee farming practices in Yunnan Province, based on experiences retrieved from other traditional coffee producing countries. Contributing to research on coffee-agroforestry in Yunnan Province therefore requires a description of the existing farming practices and inventories of shade trees currently found in coffee estates.

Coffee-agroforestry systems have long been studied worldwide in traditional coffee-producing countries (Tscharntke et al. 2011). However, despite the general consensus regarding the beneficial impacts of trees among agricultural systems, more research is needed in order to understand agroforestry systems to an extent that would permit the development of comprehensive models (Avelino et al. 2004; Luedeling et al. 2014). In particular, the global impact of shade on coffee ecophysiology, coffee production and coffee quality is now well understood (DaMatta 2004; Rahn et al. 2018), but research is still needed to untangle the impacts of specific shade tree species in specific growing conditions and under specific management practices. For instance, it is now broadly accepted that shade increases coffee quality, as does altitude, by delaying the ripening process of the berries, and that coffee quality decreases with fruit load (Avelino et al. 2005; Vaast et al. 2006). Shade trees are also known to improve coffee growing conditions, especially in sub-optimal environments, with negligible negative impacts on coffee yield within a shade coverage range between 0 and 20-30% (DaMatta 2004). Nonetheless, the impacts of shade trees on coffee vary between coffee farms in optimal conditions (Siles et al. 2010; Vaast et al. 2006) and those in sub-optimal conditions (Vaast et al. 2008; van Kanten and Vaast 2006); alongside elevation gradients (Avelino et al. 2005; Bertrand et al. 2006); and in organic versus intensively managed farms (Hagggar et al. 2011; Tully et al. 2013). In addition, ecosystem services and disservices from agroforestry systems vary with the shade intensity provided by shade tree canopy (Beer et al. 1998; Charbonnier et al. 2013; Jonsson et al. 2014; Klein et al. 2003), shade tree species and shade tree species mixes (Bagyaraj et al. 2015; Boreux et al. 2013; Nesper et al. 2017; Romero-Alvarado et al. 2002). Research is hence needed to understand the specific impacts of a set of shade tree species in intensively managed coffee systems in Yunnan Province, in order to design locally adapted coffee-agroforestry systems. This is particularly the case in Yunnan Province, where agroforestry systems have recently spread and where shade trees are still young, since most research to date has been carried out in mature systems where the impacts of shade trees are most visible (Babbar and Zak 1994; Munroe et al. 2015; Tully and Lawrence 2011).

1.5. Research question and hypotheses

The overall research question of this PhD thesis is the following: what are the impacts of young shade trees on soil fertility, coffee yield and coffee quality in emerging coffee-agroforestry systems in Southern Yunnan Province? Answering this question will contribute to the development of sustainable coffee farming practices in Yunnan Province. In order to answer that overall question, this PhD thesis will fulfill the specific objectives mentioned below. Each objective is formulated alongside its main hypothesis.

Obj 1. Describing the existing coffee-agroforestry systems in southern Yunnan.

H1 Coffee farming systems contain low shade tree biodiversity compared to forested areas, due to their recent conversion from coffee monocultures.

Obj 2. Assessing the potential of shade trees to benefit soil fertility in coffee farms.

H1 There is already a positive impact of young shade trees on soil fertility, especially on soil communities and soil enzyme activities;

Obj 3. Assessing the impact of shade trees on coffee production.

H1 Young shade trees hinder coffee yield but increase coffee quality.

1.6. Thesis structure

This thesis contains six chapters including the current one.

Chapter 1 describes the overall background of the present research, the research gaps, the objectives and hypotheses of the thesis.

Chapter 2 describes the study sites.

Chapter 3 focuses on the description of existing coffee-agroforestry systems and on the ethnobotanical knowledge of coffee farmers regarding the provision of ecosystem services by shade trees.

Chapter 4 focuses on the impact of young shade trees on soil fertility.

Chapter 5 focuses on the impact of young shade trees on coffee yield and coffee quality.

Finally, chapter 6 discusses the overall findings of the previous chapters and provides recommendations for locally adapted coffee agroforestry systems.

CHAPTER 2 - Study Site

2.1. Study site 1: Pu'er and Xishuangbanna Prefectures

Fieldwork for the description of coffee farming systems and the assessment of local ecological knowledge of coffee farmers was conducted in Pu'er and Xishuangbanna Prefectures (22.80N - 100.97E / 22.00N - 100.78E), of Southern Yunnan, China. These prefectures are located between the Southeast Asian Peninsular and continental Asia (Cao and Zhang 1997). The climate is sub-tropical, with an annual average temperature of 19°C (Figure 2-2). Annual rainfall reaches 1400 mm, of which nearly 80% occurs during the rainy season from May to September (Figure 2-2). Mountains dominate the region, with elevations ranging from 340 to 3160 meters as it rises from mainland Southeast Asia to the Eastern Himalayas (Zomer et al. 2014). Most soils fall under Acrisols and Ferralsols types (FAO - Harmonized World Soil Database v1.2). Areas below 800 m elevation support tropical seasonal rain forests, tropical montane rain forests are found between 800 m and 1200 m high, and tropical montane evergreen broad-leaved forests are found at higher elevations (Cao and Zhang 1997; Song et al. 2016b). This succession of ecosystems along the elevation gradient harbors an exceptionally high biodiversity (Cao and Zhang 1997; Zhang and Cao 1995).

The landscape was traditionally cultivated with swidden-fallow practices (Xu et al. 2009). From 1965 onward, changes in land-use rights and market economy led to the conversion of swidden-fallow fields and secondary forests to perennial cash crops, such as tea and rubber plantations (Xu et al. 2009). In the early 1990's, economic liberalization and the establishment of international buyers in Yunnan Province provided market opportunities for coffee production. Government-owned model farms began cultivating this new cash crop and distributing coffee seedlings to neighbouring farmers. Coffee farms spread between 900 and 1300 m elevation, where climate is most suitable for coffee growing. They replaced perennial fields and patches of secondary tropical montane rain forest. By the early 2000's, farms were privatized and coffee farming kept expanding, driven by smallholder farmers and large commercial companies. Smallholder farmers typically manage 0.5 to 1.5 ha of coffee plantations. Coffee represents their main source of revenues in the farm. Most of them possess small post-harvest treatment stations for wet processing, a necessary condition to comply with the certification schemes required by large agri-businesses in recent years. From spring to fall, when coffee does not require heavy labour inputs, they complement their incomes with temporary jobs outside of the farm such as construction jobs, especially important in periods of low coffee prices. Coffee companies own long-term leases for lands ranging from ten to several hundred ha. Workers typically live on farm in villages built by companies and manage plots of 0.8 to 1.2 ha. By 2012, Pu'er and

Xishuangbanna Prefecture had 95,000 ha under coffee cultivation (Pu'er Statistical Yearbook 2012), making them the main regional centres for coffee production in Yunnan according to governmental statistics (Figure 2-1).

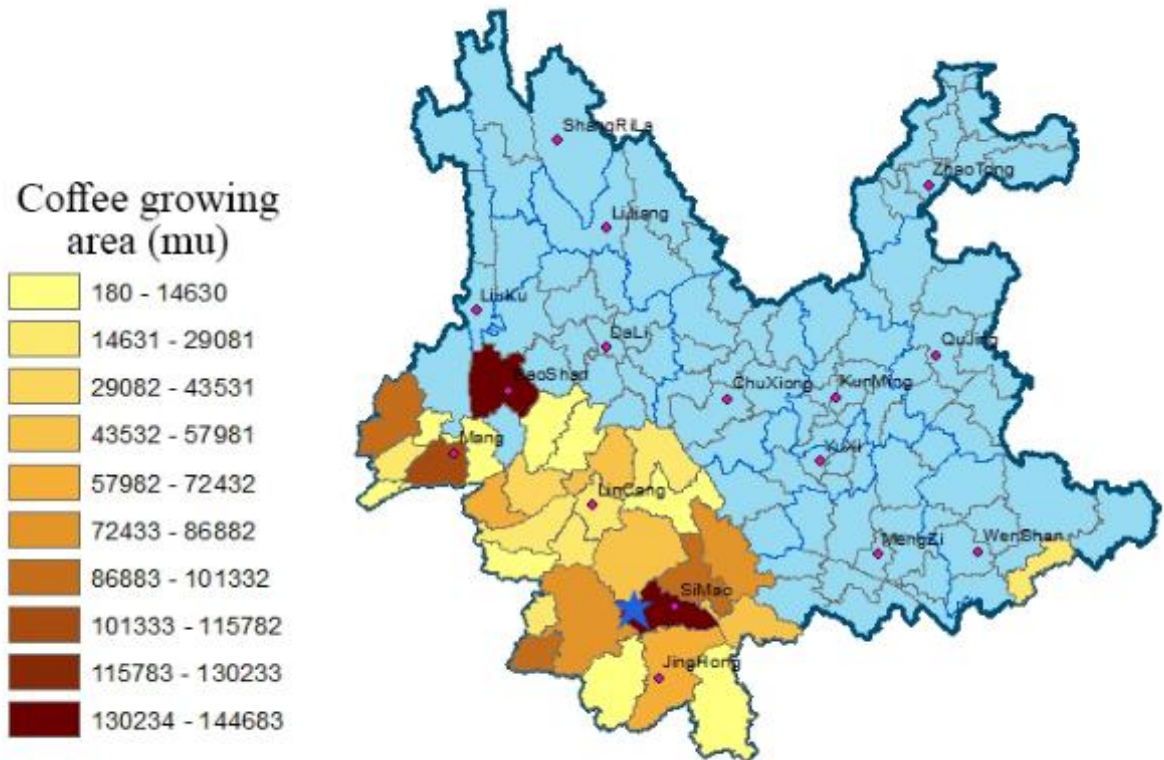


Figure 2-1: Coffee growing areas by county in Yunnan Province in 2012 (retrieved from 2013 statistical yearbooks). Liushun Township is represented by the blue star.

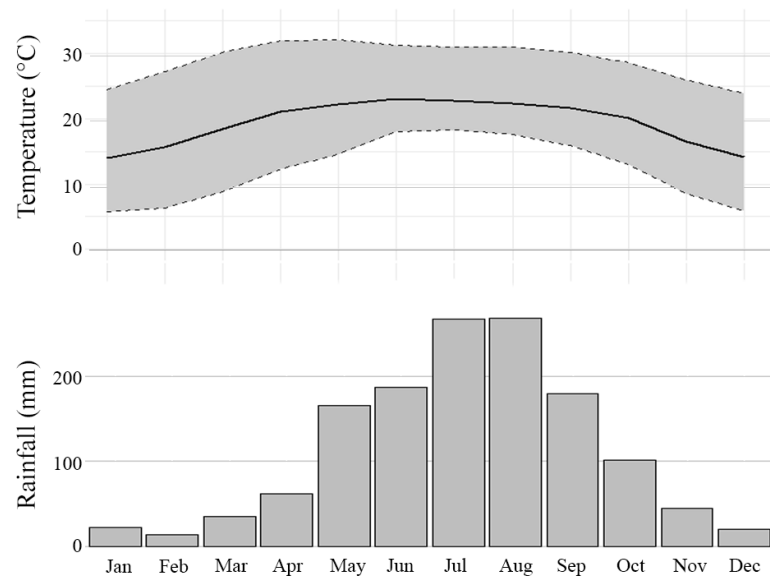


Figure 2-2: Average monthly temperatures and rainfall in Pu'er Prefecture, from 2002 to 2011

Until 2012, all plantations (bar some demonstration farms) had been established within the past 30 years. They relied on intensive management practices, with high planting densities of unshaded Catimor coffee (often 5000 plants ha⁻¹) and high inputs of mineral fertilizer (often exceeding 200 kg N ha⁻¹ yr⁻¹). Farmlands were terraced, which reduced land erosion, increased water infiltration and eased manual management practices. Fungicides were seldom used, due to the leaf rust resistance of Catimor and to the absence of other major diseases. The white stem borer, *Xylotrechus quadripes*, is present, but cannot be effectively controlled by chemical inputs (Venkatesha and Dinesh 2012; Waller et al. 2007). Preliminary interviews with governmental sources indicated that local authorities began free distribution of 1-year old and 2-year old shade tree seedlings in 2012, at a density of 60 to 120 trees.ha⁻¹. This led farmers to converting their full sun coffee to shaded coffee systems.

2.2. Study site 2: Liushun Township

Studies focusing on the impact of young shade trees on soil fertility, micro-climate, coffee yield and coffee quality were conducted in Liushun Township (N22.611 / E100.669), on a mountainside representative of the coffee landscape found in Pu'er Prefecture; high density Catimor cultivars (1 m * 2 m i.e. 5000 plants ha⁻¹) planted on terraced lands, with one row of coffee trees per terrace. 1337 mm of rainfall were recorded between March 2017 and March 2018, with a dry season extending until the end of June 2017. The soils are Acrisol (FAO - Harmonized World Soil Database v1.2) with a top layer characterized by light clay texture. The mountainside was first converted to a coffee farm by a private company in 1997-1998. In the early 2000's, the land was divided into plots of 0.5 to 2 ha and redistributed to local farmers. In 2013, the local government distributed and planted 2-year old shade tree seedlings within coffee rows, at a density of 56 trees.ha⁻¹ (12 m * 15 m), as part of a large-scale campaign to convert monoculture coffee farms into AFS. On the selected mountainside, the majority of planted trees belonged to *Alstonia scholaris*, *Bischofia javanica*, *Cinnamomum camphora*, *Jacaranda mimosifolia* and *Macadamia integrifolia*. They were planted within coffee rows at a density of 56 trees.ha⁻¹ (12 m * 15 m).

The experimental design for these experiments was set up in a single mountainside, in 7 coffee plots managed by 5 smallholder farmer families. Elevation ranged from 1000 to 1050 meters above sea level and orientation varied between East and North. Lately, with low coffee prices, farmers only applied fertilizers twice a year; first application in June at the beginning of the rainy season and a second one in August or September before the ripening stage of coffee cherries. Fertilizers are spread right below coffee trees. Nitrogen inputs often exceeded 300 kg ha⁻¹ year⁻¹. Weeding was carried out both manually and with herbicides. The major pest is trunk

borer *Xylotrechus quadripes* and the two major diseases are fungal diseases, namely *Hemileia vastatrix* and *Colletotrichum coffeanum*. Due to the resistance of Catimor cultivars to *H. vastatrix*, the relatively low incidence of *C. coffeanum* and the difficulty to control *X. quadripes* population with insecticides (Venkatesha and Dinesh 2012; Waller et al. 2007), farmers seldom use chemical pesticides. Coffee harvest occurs during the dry season, from November to February.

CHAPTER 3 - Tree inventories and ethnobotanical surveys in coffee-agroforestry systems

3.1. Introduction

Scientific data regarding the impacts of shade trees in coffee farms in Yunnan Province is lacking to select a list of relevant shade tree species to promote locally (Liu et al. 2017). In this context, local experts should be identified (Davis and Wagner 2003; Mathez-Stiefel et al. 2012) and their ethnobotanical knowledge should be used to identify suitable tree species, to complement existing scientific data and to guide future research (Cámara-Leret et al. 2014; Gram et al. 2017; Liebig et al. 2016). In particular, studies investigating Local Ecological Knowledge (LEK) have confirmed that this ethnobotanical knowledge is highly reliable and advocated for its greater integration into policy recommendations and conservation programs (Coe et al. 2014; Cook et al. 2014; Malley et al. 2009). Furthermore, the comparison of farmers' possession of LEK according to gender, ethnicity and farming practices can help refining our understanding of factors underpinning this ethnobotanical knowledge and improving policy recommendations (Ayantunde et al. 2008; Cerdán et al. 2012; Yuan et al. 2014). In the present study, it can be expected that farmers with mature coffee-agroforestry systems have a rich experience and can put the list of tree species promoted by local authorities into perspective. Farmers from ethnicities traditionally settled in mountainous areas might be better acquainted with indigenous tree species from tropical montane forests, and therefore better able to point out indigenous species suitable for coffee-agroforestry systems (Brandt et al. 2013). Additionally the comparison of LEK according to gender could reveal discrepancies in perceptions reflecting the division of responsibilities at the farm level (Egunyu and Reed 2015). Therefore, with a concerted effort to involve farmers, an ethnobotanical approach has recently been developed to explore coffee farmers' LEK regarding shade tree species and which Ecosystem Services (ES) and Ecosystem Disservices (ED) they can provide in coffee farms (Gram et al. 2017; Lamond et al. 2016; van der Wolf et al. 2016).

In this chapter, I first document coffee-agroforestry systems and their shade tree biodiversity at the farm and landscape levels, in view of the recent establishment of coffee as a commodity crop and the even more recent large-scale conversion from coffee monoculture towards shaded systems. Then, with ethnobotanical surveys based on van der Wolf et al. (2016), I document farmers' LEK regarding shade tree species and their provision of ES and ED in coffee landscapes, including on ES and ED related to soil fertility and coffee production. I hypothesize that the species promoted by the government are perceived favorably by farmers, especially by those most experienced in coffee-agroforestry practices. Second, I expect to find differences in

farmers' LEK according to gender. Lastly, I hypothesize that coffee farmers from mountain ethnicities would rank indigenous tree species higher than would farmers from lowland ethnicities.

3.2. Materials and methods

3.2.1. Data collection

Fieldwork was conducted in Pu'er and Xishuangbanna Prefectures in 2016. A detail description of the study site is given in Chapter 2.1. In April 2016, inventories of shade tree species were conducted in 29 coffee farms (S1 Appendix). All the trees in coffee plantations with a diameter at breast height ≥ 5 cm were systematically identified to the lowest taxonomic level possible. Abundance was estimated through rapid appraisal (visual assessment) combined with farmers' saying. These farms were selected to include plantations representative of both young (≤ 15 year) and more mature trees (> 15 year) and both light shaded ($\leq 20\%$) and medium shaded ($> 20\%$) coffee agroforestry farms. Our sample also included 3 demonstration farms with high levels of tree diversity. All these farms were located along a latitudinal gradient (North 22.00 to North 23.26) in order to encompass the diversity of shade tree species likely to be found in the study area. Tree identification cards depicting tree characteristics along with their local names, were created for tree species that scored higher than 1% in a rank-abundance analysis and were seen in more than 20% of the coffee farms.

Between May and August 2016, coffee farmers were interviewed to document their local knowledge about shade tree species and their impacts on locally important ES & ED, following the methodology of van der Wolf et al. (2016). 122 farmers were selected from the list of 4C-certified suppliers working with Nestlé Company. Furthermore, additional farms that I identified during our visits or referred to us by local authorities, which were not 4C-certified but nonetheless supported diverse and mature agroforestry systems, were also included in the sample. This way, 21 additional farmers with rich experience in agroforestry systems were added to the sample (Davis and Wagner 2003). In total, 143 coffee farmers whose agroforestry systems had been established four or more years ago were interviewed. It was made clear to farmers that the results of this independent research would not impact their support either by the government or Nestlé. Farmers with mature shade trees (> 15 year), medium shaded systems ($> 20\%$) and high tree species richness (> 15) were expected to have richer first-hand agroforestry experience and were therefore included in priority in the sample to increase the quality of the LEK results as proposed by Davis and Wagner (2003). I tried to have a gender-balanced sample of respondents, and to interview both farmers of ethnic minority groups traditionally inhabiting mountainous areas

(Bulang, Hani, Lahu, Wa, Yi, and Zang) and Han and Dai farmers, who traditionally inhabit valleys (Wu et al. 2001). Each farmer was asked to list the shade tree species present in their farm, aided by the tree identification cards. Any additional tree species that were named during this process were cross-checked with the results from previous inventories and given a new tree identification card. In total, 44 cards were produced. Interviewees were then asked to select up to 10 tree species present in their farms, with which they were the most familiar. Using the tree identification cards, tree species selected by interviewees were ranked for their performances for each of the ten locally most important ES & ED, plus one additional rank for overall personal preference. Ties were allowed in the ranking. During this exercise, farmers were asked to comment on and explain their choices. This allowed checking how reliable their rankings were and further understanding the conceptions underlying LEK on shade trees.

Locally important ES & ED were identified in a step-wise manner. A list of 28 ES & ED was derived from the literature. Through discussions with coffee workers and managers during coffee-farm inventories, I reduced this list to 24 locally relevant ES & ED. A final list was established after the completion of 30 interviews and rankings, with each respondent selecting what they considered to be the ten most relevant ES & ED. At the end of the initial set of 30 interviews, a final list was produced of the ten most frequently mentioned ES & ED.

During the interviews, socio-economic information about the respondents was collected, including gender, ethnicity, original hometown and year of arrival in the village if respondents were not local. I also gathered comprehensive background information about their coffee farms and management practices.

3.2.2. Data analysis

Shade tree species inventories were analysed using the Vegan and Biodiversity R packages in R3.3.1 (Kindt and Coe 2005). The species accumulation curve was plotted with its confidence interval and the total richness of shade tree species was extrapolated using a first-order Jackknife formula (Kindt and Coe 2005). Rankings by respondents on their perceptions of the shade tree species performances were analysed using the BradleyTerry2 package in R2.2.11 (Turner and Firth 2012). Rankings were converted into pairwise comparisons to be fitted to the Bradley-Terry model. A separate analysis was conducted for each ES or ED. To take into account the small sample size, the model was fitted with a bias-reduced maximum likelihood. Species that were ranked less than 10 times by coffee farmers were excluded from the analysis, to ensure enough comparisons between tree species to yield statistically significant results (Lamond et al. 2016). Consequently, 28 tree species were included in the analysis. A score α_i and quasi-standard

error were calculated for each species i and each ES & ED. These scores reflect the likelihood that species i would perform better than species j for the considered attribute based on equation (1). These are comparative, rather than absolute values. For ease of comparison, scores were normalized between 0 and 1 before being uploaded to an online tool (<http://www.shadetreeadvice.org>) (van der Wolf et al. 2016). The quasi-standard errors give an indication of how many times a species was selected and an indication of consistency in the respondents' rankings. High quasi-standard errors indicate low LEK regarding a given species. Scores were compared pairwise using a Wald test. Results were then presented and validated through focus group discussions with coffee farmers and extension agents.

Equation (1):

$$P(\text{Species } i \text{ performs better than Species } j) = \frac{\alpha_i}{\alpha_i + \alpha_j}$$

where α_i is the score of species i

3.2.3. Exploration of local knowledge

The Bradley-Terry method has previously been used to analyze rankings of tree species (Gram et al. 2017; Lamond et al. 2016). When comparing the perceptions of respondents from distinct groups, for instance based on gender or elevation, these studies conducted separate analysis for each group and compared the resulting scores. The present study is the first to incorporate predictor variables into applications of the Bradley-Terry method to LEK. This allows comparing perceptions of respondents from distinct groups through a single analysis, thus maintaining the initial sample size. Specifically, it allows analysis of interactions between a tree species characteristic and a socio-economic attribute of respondents' rankings. This analysis is used to answer the question: do farmers with this attribute rank tree species with this characteristic differently than do other farmers? Tree species were classified as being promoted or not by the local authorities and as indigenous species versus exotic ones. Respondents were assigned three qualitative attributes: 1) gender (M / F), 2) agroforestry system (low shade / medium shade) and 3) traditional location of ethnic groups (mountains / lowlands). The shade tree species richness on their farms was included as a quantitative attribute.

Interactions between respondent attributes and tree species attributes were incorporated into separate analyses to test the following three models:

- Model A: Farmers with high tree species richness and medium shaded systems (respondent attributes) rank promoted species (tree species attributes) more highly than farmers with low species richness and low shaded systems.

- Model B: Gender affects the rankings of promoted species.
- Model C: Farmers from mountain ethnicities give higher ranks to indigenous species than farmers from lowland ethnicities.

3.2.4. Suitability of government-promoted tree species

The regional impact of government promotion of shade tree species, through the distribution of free seedlings, was quantified by comparing scores of promoted species versus non-promoted species using a Student's T test for each ES or ED. Then, scenarios were simulated for three hypothetical coffee farmers, all located in the study area, but facing contrasting local constraints and hence adopting different strategies (Figure 3-4). These were: 1) a farmer whose land is located at high altitude and has a need for additional frost-protection by shade trees, 2) a farmer who is enhancing soil fertility through the addition of shade trees to reduce fertilizer inputs, and 3) a farmer whose goals are to cut input costs (fertilizers) and enhance income diversification with shade trees. Based on the results from the Bradley-Terry analysis and on the tree selection tool developed by van der Wolf et al. (2016), scores were attributed to 28 tree species for each scenario. In each scenario, species with the highest scores are those perceived to have the highest performance for the selected set of ecosystem services, and so would be the species recommended to farmers in comparable circumstances.

3.3. Results

3.3.1. Shade tree species inventories

During initial inventories in coffee farms, 162 shade tree species were encountered, of which two could not be identified, five were identified up to genus level and the other 155 were identified to species level. Across the 29 inventoried coffee farms, the Shannon index ranged from 0.00 to 3.42, with a mean value of 2.22. The effective number of species, calculated as the exponential of Shannon entropy (Jost 2007), ranged from 0 to 30.57 species, with a mean value of 9.21 species. The Simpson index varied from 0.00 to 0.96, with a mean value of 0.79. Further details are provided in S2 Appendix. First-order Jackknife formula was used to extrapolate the total richness of shade tree species in the study area. This led to an estimated value of 218 tree species (Figure 3-1), according to which 74 % of all shade tree species were encountered during our inventories. When two non-representative demonstration farms which each exhibited a high and non-representative level of tree species diversity were removed from the analysis, the extrapolated number was reduced to only 162 tree species.

Only 17 tree species accounted for more than half (51 %) of all the trees inventoried (Figure 3-2). 84 species were only encountered in one or two coffee farms. The nine government-promoted species (Table 3-1) represented 27 % of all the trees inventoried. The two most abundant non-promoted species were *Mangifera indica* and *Schima wallichii*. The latter is an early successional species that has spread through natural regeneration.

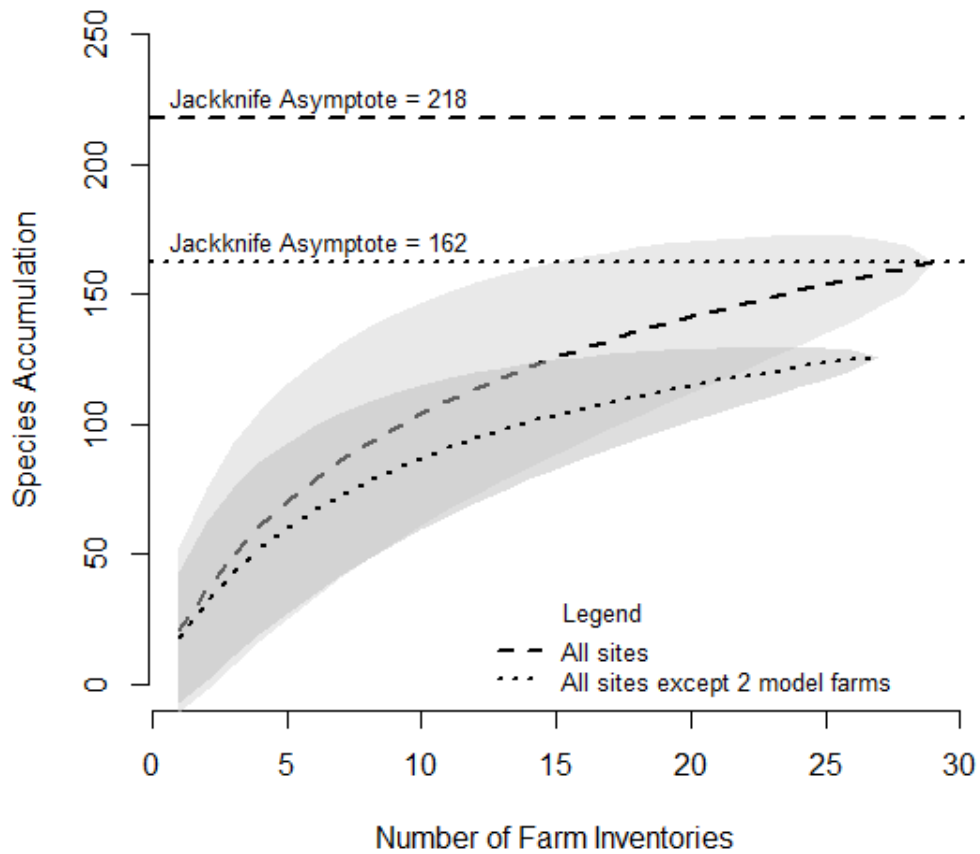


Figure 3-1: Species accumulation curves and 1st order Jackknife asymptotes with (dashed line) and without (dotted line) data from 2 demonstration farms. Grey areas represent the 95% confidence intervals.

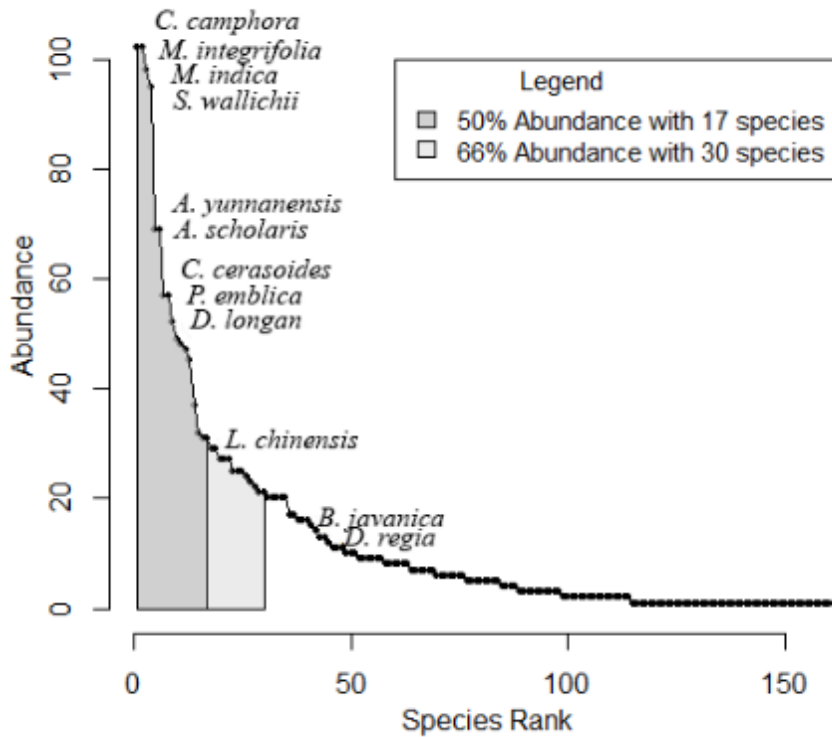


Figure 3-2: Rank-abundance curve from coffee farm inventories. The 9 most abundant species and the promoted species are represented on the curve.

3.3.2. Main characteristics of tree species

A total of 42 tree species were selected and ranked by respondents. 28 of these species were ranked more than 10 times for each attribute and therefore included in the ranking analysis. Amongst these, 20 species were endemic to the study area. Nine species have been actively promoted by the local authorities through distribution of free seedlings, amongst which five are fruit tree species and four are species valued as ornamental trees for urban landscaping

Table 3-1: List of the 28 shade tree species ranked by coffee farmers and ecosystem services reported by farmers

Latin Name	Chinese Name	Promotion Status	Indigenous (I) / Exotic (E)	Ecosystem Services
<i>Albizia kalkora</i>	山合欢		I	N-fixation
<i>Alstonia scholaris</i>	灯台树	Promoted	I	Urban landscaping, Medicine
<i>Aporosa villosa</i>	毛银柴		I	Fruit
<i>Aporosa yunnanensis</i>	滇银柴		I	Fruit
<i>Artocarpus heterophyllus</i>	菠萝蜜		E	Fruit
<i>Betula alnoides</i>	西南桦		I	Timber
<i>Bischofia javanica</i>	重阳木	Promoted	E	Urban landscaping, timber
<i>Castanopsis calathiformis</i>	枹丝锥		I	Firewood
<i>Cerasus cerasoides</i>	云南樱桃	Promoted	I	Fruit, Ornamental
<i>Cinnamomum camphora</i>	香樟	Promoted	I	Urban landscaping, Medicine
<i>Delonix regia</i>	凤凰木	Promoted	E	Urban landscaping, Ornamental
<i>Dimocarpus longan</i>	龙眼	Promoted	I	Fruit
<i>Diospyros kaki var. silvestris</i>	野柿		I	Fruit
<i>Eurya groffii</i>	岗柃		I	Shade
<i>Ficus hispida</i>	对叶榕		I	Shade
<i>Leucaena leucocephala</i>	银合欢		E	N-fixation
<i>Litchi chinensis</i>	荔枝	Promoted	I	Fruit
<i>Litsea sp.</i>	木姜子		I	Shade, Fruit
<i>Macadamia integrifolia</i>	澳洲坚果	Promoted	E	Fruit
<i>Mallotus tetracoccus</i>	四籽野桐		I	Shade
<i>Mangifera indica</i>	芒果	Promoted	I	Fruit
<i>Melia azedarach</i>	苦楝		I	Seeds
<i>Michelia baillonii</i>	合果木		I	Timber
<i>Phyllanthus emblica</i>	余甘子		I	Shade, Fruit
<i>Psidium guajava</i>	番石榴		E	Fruit
<i>Schima wallichii</i>	西南木荷		I	Timber
<i>Syzygium szemaoense</i>	思茅蒲桃		I	Shade, Fruit
<i>Toona ciliata</i>	红椿		I	Timber

3.3.3. Main characteristics of interviewees

143 coffee farmers were interviewed, of whom 124 responded by ranking shade tree species against ecosystem services and disservices. 19 respondents who could not rank tree species were excluded from analysis. Of the 124 respondents who did rank tree species, 42 were women (34 %) and 82 were men (66 %); 60 were smallholder farmers (48 %), 42 were agricultural workers (34 %) and 22 were coffee farm managers (18 %). 48 respondents belonged to mountain ethnicities (39 %) and 76 to lowland ethnicities (61 %). 103 respondents were autochthons (born in the study area) (83%) and were 21 allochthons (17%). The area of coffee farms ranged from 0.3 to 180 ha, with an average of 10 ha and a median value of 2 ha. 65 respondents (52 %) worked in coffee-agroforestry farms that were classified as low-shaded and 59 respondents (48 %) worked in agroforestry farms that were classified as medium-shaded. Respondents listed 4 to 32 species of shade trees per farm, reporting an average of 15 species per coffee farm.

3.3.4. Tree species rankings and pairwise comparisons

After the initial 30 interviews, the following ten ES & ED were assessed as the most locally important: 1) protection of coffee trees against high temperatures (ES), 2) soil moisture enhancement (ES), 3) protection of coffee trees against cold temperatures (ES), 4) suppression of weeds (ES), 5) negative impact of shade trees on average coffee yield (ED), 6) control of the white stem borer (WSB) (ES), 7) protection from soil erosion (ES), 8) root competition between shade trees and coffee trees (ED), 9) soil nutrient cycling enhancement from leaf litter and N-fixation (ES) and 10) additional economic benefits from the shade trees (ES) (Figure 3-3). After conducting the Bradley-Terry analysis on the 124 rankings, pairwise comparisons of species' scores showed that tree species were easiest to rank for economic benefits, weed control and protection from high temperatures (81 %, 76 % and 75 % of all pairs were significantly distinct ($p \leq 0.05$)). Trees were hardest to rank for their impact on coffee yield, root competition and enhancement of nutrient cycling (59 %, 62 % and 66 % of all pairs were distinct). No respondents were able to rank tree species for ability to control WSB, so this ES was excluded from the analysis. Although coffee quality did not make it into the top ten ES and ED, it is interesting to note that no farmer was able to rank tree species against this important ES during the 30 first interviews. In their views, rainfalls during harvest seasons was the single most influential parameter impacting coffee quality.

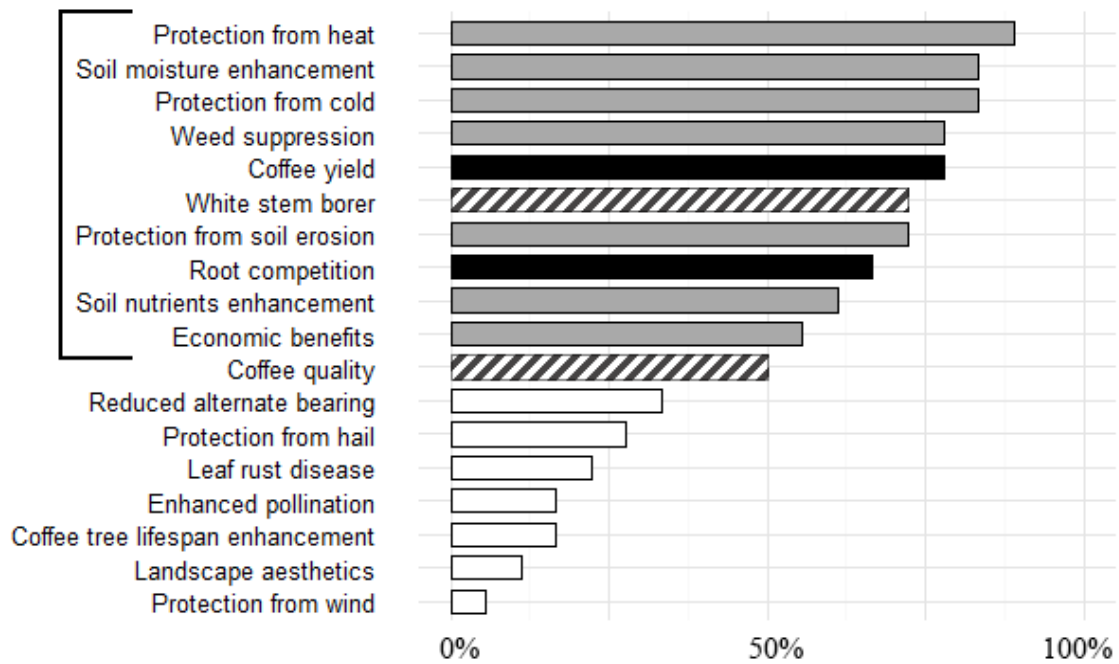


Figure 3-3: Locally relevant ecosystem services and disservices (ES & ED) after the 30 first interviews. Boxes represent the percentage of respondents for which each ES or ED was locally relevant. Grey boxes show the ES and black boxes show the ED selected for further ranking of shade tree species. The 2 striped boxes indicate ES that respondents thought were locally relevant, but for which they were unable to rank tree species.

3.3.5. Promoted tree species

Promoted species were perceived to perform significantly better than non-promoted species for all attributes except one ES (nutrient cycling enhancement), and two ED, (reduction in coffee yield and root competition (Table 3-2). Seven of the nine promoted species were ranked in the top eight of species favoured by coffee farmers (Figure 3-4). *Artocarpus heterophyllus* was the only highly favoured non-promoted species. *Cerasus cerasoides* (ranked 13th) and *Delonix regia* (ranked 16th) were the only two promoted shade tree species that were ranked lower than some non-promoted species.

3.3.6. Coffee farming practices and ranking

Overall, farmers gave similar rankings to trees regardless of the tree species richness and degree of shade in their farms (Table 3-3 – Model A). However, respondents whose farms supported higher tree species richness perceived lower root competition between promoted species and coffee plants ($p \leq 0.05$). Respondents whose agroforestry systems had more shade thought that promoted species were beneficial to soil moisture ($p \leq 0.05$), but had a negative impact on coffee yield ($p \leq 0.05$). Promoted species scored high in the list of preferred species for

all respondent groups. Farmers with lower species richness and lower shade intensity on their farms had an even stronger preference for promoted species ($p \leq 0.01$).

3.3.7. Gender, ethnicity and tree species preferences

Women were more likely than men to perceive non-promoted species as more beneficial to nutrient cycling enhancement ($p \leq 0.1$). Men were more likely to perceive promoted trees to bring higher economic income ($p \leq 0.1$) and showed a significant preference for these species ($p \leq 0.05$) (Table 3-3 – Model B). Men showed higher overall preferences than women for *C. camphora* and *C. cerasoides* while women ranked *Litchi chinensis* and *Leucaena leucocephala* higher than men did (Figure 3-5).

Autochthon farmers from mountain ethnicities expected greater economic benefits from indigenous species than did farmers from lowland ethnicities (Table 3-3 – Model C). Farmers from mountain ethnicities gave high rankings for economic benefits to the indigenous species *Alstonia scholaris*, *Toona ciliata*, *Diospyros kaki*, *Michelia baillonii*, *Betula alnoides* and *S. wallichii* (Figure 3-6). However, they thought that indigenous species had higher negative impacts on coffee yield through below ground interactions.

3.3.8. Tailored list of recommended species

Promoted species outranked most of the non-promoted species for economic gain via cutting fertilizer cost and boosting incomes through diversification (Figure 3-4 Scenario 4). However, in this scenario, the non-promoted *A. heterophyllus* and *D. kaki* were advised species while the promoted *C. cerasoides* and *D. regia* were among least recommended species. Although many respondents reckoned that timber from *M. baillonii* is in high demand, it was only ranked 25th out of 28.

Among the short-list of 28 trees, tree species that gave the best financial returns were also the best in protecting coffee trees from frost (Figure 3-4). Strikingly, the top nine trees for frost-protection were also the nine overall most-preferred trees. These included seven trees promoted by the local authorities, plus *A. heterophyllus* and *L. leucocephala*. As explained by farmers, six of these promoted trees were evergreen species with dense canopies, which are likely to tolerate cold temperatures and buffer coffee plants underneath from cold spells.

Tree species promoted by local authorities were not necessarily the best choice for nutrient cycling, limiting root competition or sustaining coffee yield. For this set of ES and ED,

only five promoted species were among the ten most recommended trees (Figure 3-4). The other five non-promoted species included indigenous species with low economic benefits but perceived as enhancing soil fertility, mostly through leaf litter, such as *Melia azedarach*, *Ficus hispida* and *S. wallichii*, and *L. leucocephala*, identified as a Nitrogen-fixing tree by farmers in Nestlé's demonstration farm.

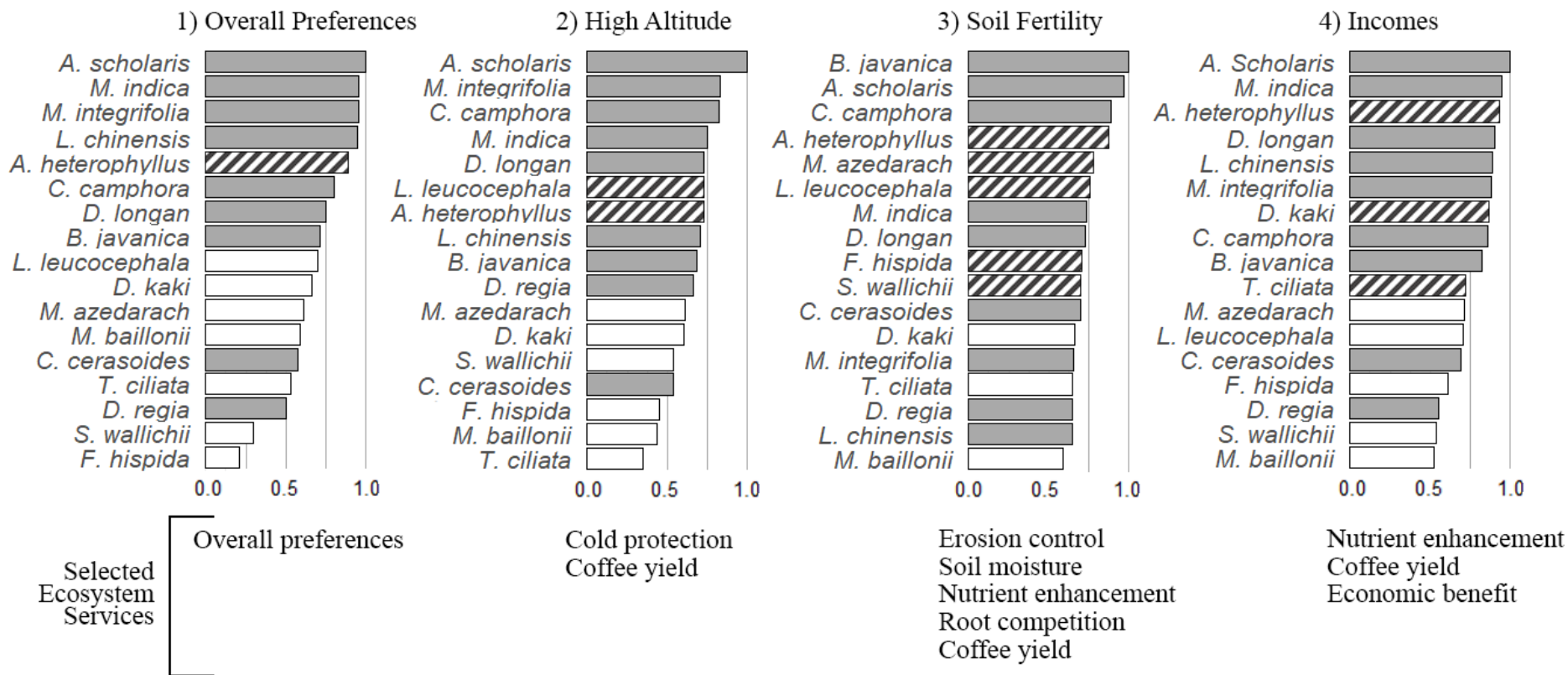


Figure 3-4: Tool outputs displaying scores for 17 shade tree species out of 28 according to four scenarios: 1) overall preference, 2) a high altitude farm exposed to frost risks, 3) a farm with limited or no input of chemical fertilizers, and 4) a farm where trees are primarily planted and managed for income diversification. Grey boxes indicate promoted species; striped boxes indicate non-promoted species that score highly in a specific scenario.

Table 3-2: Mean scores of promoted versus non-promoted shade tree species for individual ES & ED and overall preference according to the Bradley Terry analysis. Student T-test results highlight significant differences between groups for each ES & ED. Statistical significance is indicated by '****' < 0.001 / '**' < 0.01 / '*' < 0.05 / '.' < 0.1 / 'NS' Non Significant.

Species	Heat Protection	Cold Protection	Erosion Control	Soil Moisture	Nutrient Enhancement	Root Competition	Coffee Yield	Weed Control	Economic Benefit	Overall Preferences
Promoted	0.74	0.71	0.66	0.63	0.63	0.53	0.73	0.67	0.66	0.80
Not Promoted	0.48	0.38	0.39	0.46	0.51	0.53	0.62	0.44	0.33	0.42
Significance	**	****	*	.	NS	NS	NS	*	**	***

Table 3-3: Interactions between coffee farmer attributes and their rankings of promoted and indigenous shade tree species by ecosystem services and disservices. Only significant results are shown. Statistical significance is indicated by '****' < 0.001 / '**' < 0.01 / '*' < 0.05 / '.' < 0.1. (†) refers to quantitative variables.

	Heat Protection	Cold Protection	Erosion Control	Soil Moisture	Nutrient Enhancement	Root Competition	Coffee Yield	Weed Control	Economic Benefit	Overall Preferences
Model A										
Promoted Spp. × Spp Richness (†)						0.01 *				-0.01 **
Promoted Spp. × Medium-Shade AFS				0.09 *			-0.13 *			-0.12 **
Model B										
Promoted Spp. × Gender [M]	-0.07 *				0.10 .			0.11 **	0.06 .	0.11 *
Model C										
Indigenous Spp. × Mountain Ethnicity					-0.13 *	-0.14 *	-0.19 **		0.12 ***	

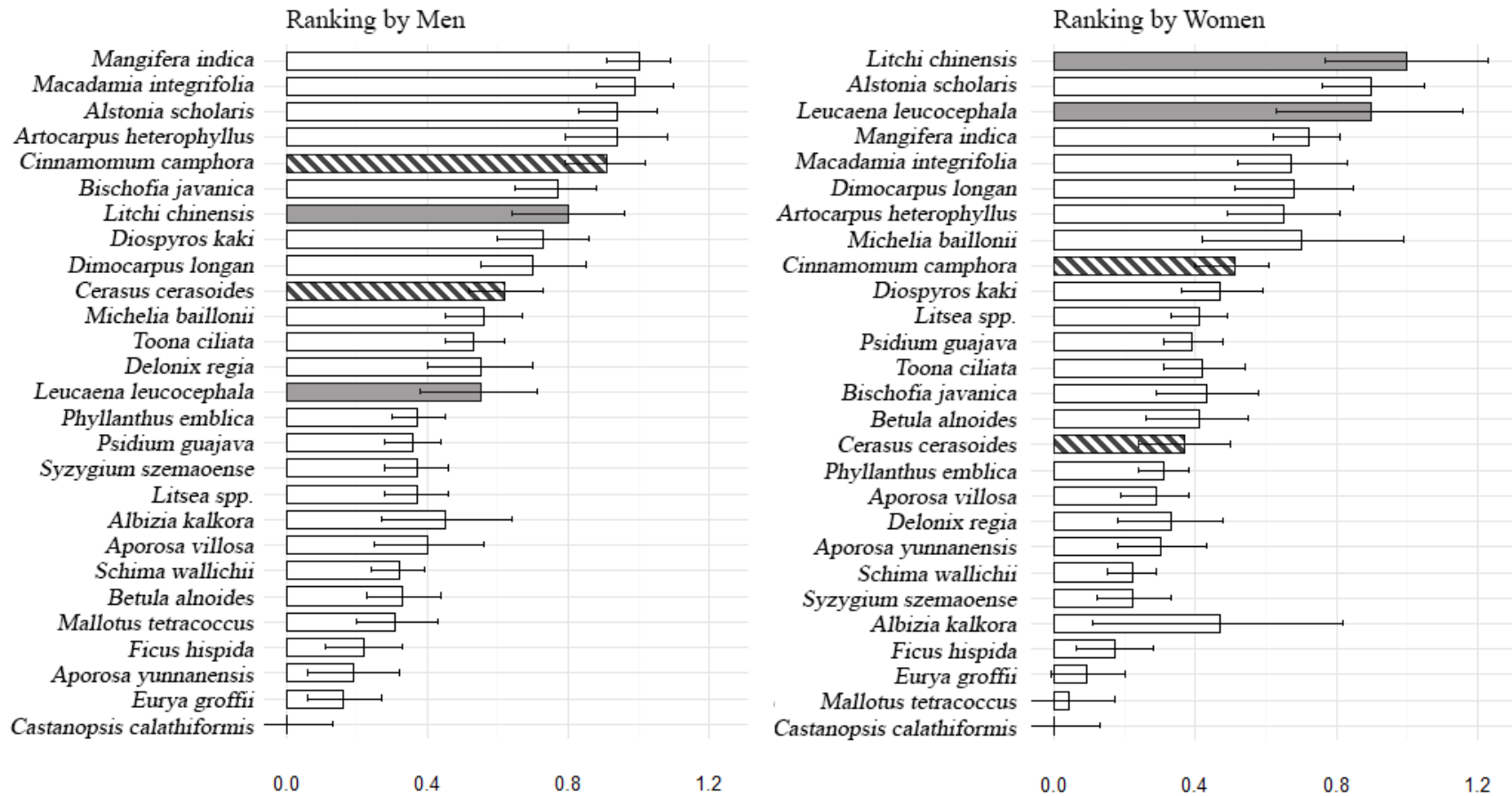


Figure 3-5: Scores and 95% confidence intervals for overall preferences of shade tree species broken down by gender. Grey areas indicate species ranked more highly by female respondents; striped boxes indicate those ranked more highly by male respondents.

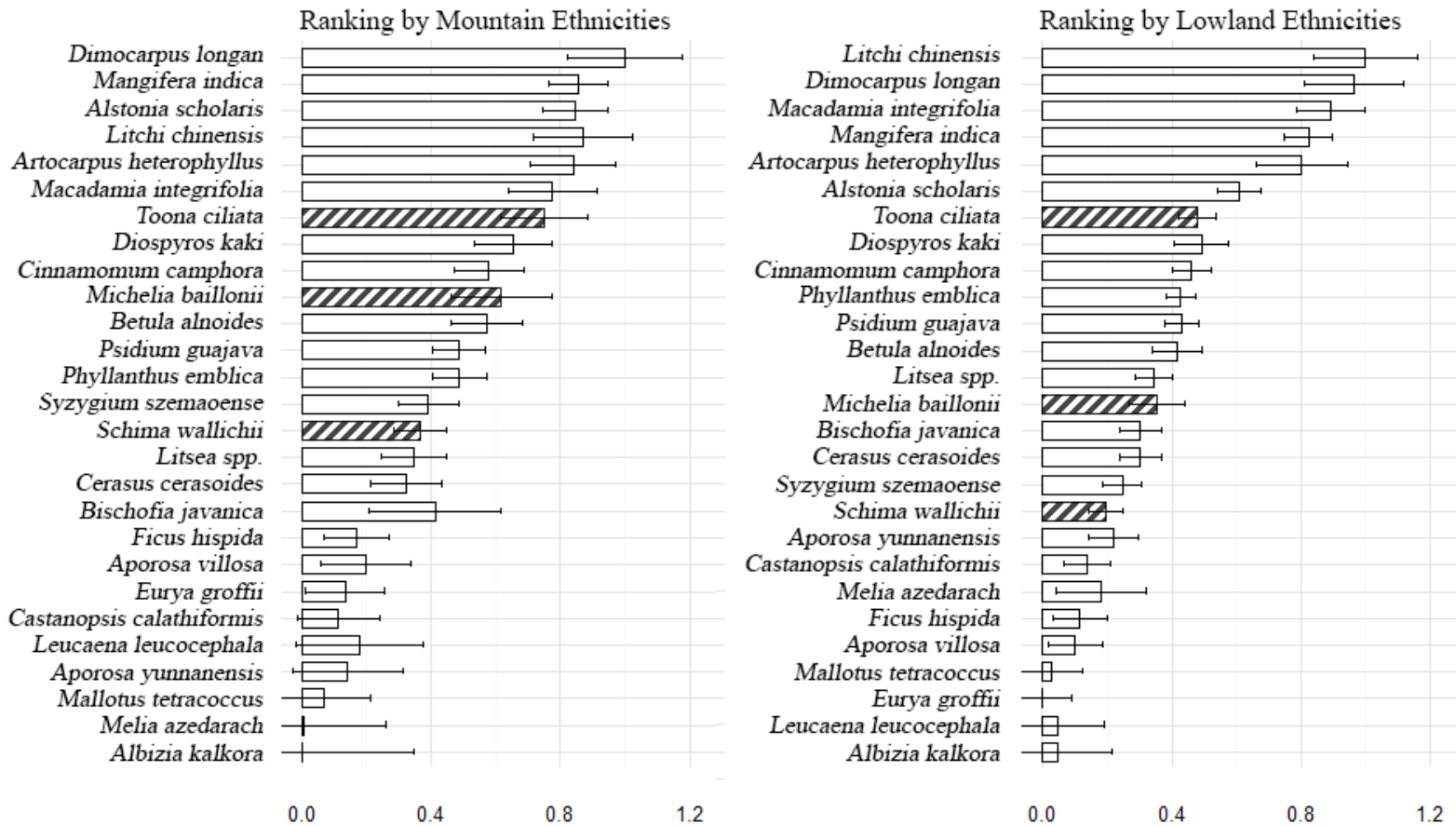


Figure 3-6: Scores and 95% confidence intervals for economic benefits from shade tree species broken down by groups of ethnicities. Grey boxes indicate timber species for which respondents from mountain ethnicities perceived more economic potential than respondents from lowland ethnicities did.

3.4. Discussion

3.4.1. Tree diversity, richness and density on coffee farms

I expected to find low tree species diversity in coffee farms, due to the recent expansion of coffee areas and current adoption of coffee agroforestry practices in Yunnan Province. In fact, our tree species inventories showed that the study area supports an estimated 162 tree species. This unexpectedly high tree species diversity is likely to reflect the biodiversity of previous ecosystems in the study area. Coffee farms spread in areas used for swidden-fallow practices until the mid-20th century (Xu et al. 2009), or previously dominated by secondary to mature tropical montane rain forests (Zhu et al. 2005; Zhu et al. 2004). Song et al. (2016b) recorded 156 tree species between 800 and 1400m elevation and Cao and Zhang (1997) noted that rank-abundant curves were characterized by long tails, indicating that the tree species diversity of tropical montane forests mostly depended on rare species. The dominance of *S. wallichii* and *Castanopsis* species (Song et al. 2016b; Zhu et al. 2005) , also common in our tree inventories, further indicate similarities between shade trees found in coffee farms and the forest ecosystems they replaced. Lastly, diversity indices from these forest studies were also similar to those derived from our tree inventories.

Diversity indices from the present study can be compared to those derived from tree inventories conducted in similar intensive coffee systems, located between 800 and 1,250 m elevation in Costa Rica (Häger et al. 2015). That study recorded only 104 shade tree species in conventional farms. On the other hand, there were 19 species on average per farm in Costa Rica compared to 15 species per farm in our study area.

Tree species were unevenly distributed across our study area, with 52% of species occurring in only one or two farms. Dawson et al. (2013) emphasized that the prospects of conservation for low density species in the agricultural landscape are poor because these species are particularly vulnerable to being wiped out by the decision-making process of a few farmers. Low densities can also restrict pollination and reproduction. If maintenance of high coffee yield requires the thinning of shade trees, the least appreciated tree species will be the first to be felled (Pinard et al. 2014). This is likely to reduce biodiversity by increasing the proportion of economically profitable non-native species (Albertin and Nair 2004).

3.4.2. Gaps in ethnobotanical knowledge of shade trees

Agroforestry practices in coffee systems have only recently been promoted and adopted on a wide-scale across Yunnan. Still, ethnobotanical knowledge on shade tree species and their impacts on ecosystem services in coffee farms is well-developed. 87% of respondents could rank tree species for at least one issue. Some level of LEK was present across all socio-economic groups, although the degree of LEK varied with agroforestry systems, gender and ethnicities.

Although coffee farmers know local tree species and their phenology, they still have limited experience of the impact of mature shade trees on coffee yield. They gave high ranks to several fruit tree species such as *M. integrifolia*, *L. chinensis* and *Dimocarpus longan*, which have dense canopies and hence have high potential to compete for light with coffee plants. Because most shade trees are young, such negative impacts may not yet have become apparent (Beer et al. 1998; DaMatta 2004), or farmers could be more concerned about other economic factors. Farmers with more first-hand experience in agroforestry systems did nonetheless perceive higher negative impacts of promoted species on coffee yield, than did farmers with seemingly less experience. Farmers varied widely in their assessment of root competition and nutrient cycling. This would be expected because such complex below-ground factors are the most difficult to assess (Graefe et al. 2017; Lamond et al. 2016; Smith Dumont et al. 2014). They also lacked knowledge regarding the white stem borer and coffee quality. As farmers gain greater experience in cultivating coffee, their LEK is likely to be progressively enriched (Soto-Pinto et al. 2007).

3.4.3. Relevance of promoted tree species

Local stakeholders perceived the tree species promoted by the local authorities to provide the best protection against weather hazards and bring the greatest economic benefits. It appears that shade tree species were preferentially promoted when they have dense canopies and high economic returns, despite their negative impact on coffee yield. Apart from *D. regia*, which has only aesthetic value, all promoted species were perceived to have positive economic returns. Income can be derived from fruit production or selling saplings to the emerging market for tree landscaping in nearby fast-growing cities. Five year-old saplings are uprooted and sold for re-planting alongside the new roads and sidewalks of China's rapidly expanding cities. Our respondents reported that *A. scholaris* is the "urban tree" in highest demand, followed by *C. camphora* and *B. javanica*. Income diversification is a prime motive for the selection of shade tree species by coffee farmers. Therefore,

it is not surprising that farmers prefer those promoted species that produce fruit or saleable saplings. The non-promoted fruit trees, *A. heterophyllus* and *D. kaki*, were thus also highly ranked.

Farmers appeared to be most interested in gaining short-term economic benefits. They did not favor valuable indigenous timber species (*M. baillonii* and *T. ciliata*) that require long-term investment. Regional policies that emphasize forest protection and hence prohibit felling trees (Xu et al. 2006) currently discourage growing timber crops. Although there are specific conditions under which permits are granted for timber harvest, these are seldom delivered, leaving farmers doubtful of their ability to harvest timber, a concern frequently mentioned during interviews. Such problems have been reported in Kodagu, India, where policies for the protection of indigenous species in coffee estates counter-intuitively lead to decreased planting of species that will be difficult to harvest and the replacement of indigenous trees with exotic shade trees (Garcia et al. 2010; Nath et al. 2016). There is a need for incentive programs that support the use of indigenous timber trees and promote their planting and/or natural regeneration.

Governmental promotion of some tree species can also succeed in shaping the preferences of farmers. In Mexico, Valencia et al. (2015) showed that there had been little scientific foundation for the promotion of *Inga oerstediana* in coffee agroforestry systems by NGOs and government agencies 30 years ago. Nonetheless, farmers still highly prefer this species. In the present study, because farmers are new to coffee-growing and agroforestry practices, promotion and dissemination of shade trees is especially likely to shape their perceptions and actions. Indeed, farmers with seemingly low experience in agroforestry systems ranked promoted species higher than farmers with rich first-hand experience in overall preference rankings. This further support the interpretation of a collective bias driven by promotion activities from local authorities. It is therefore important to keep in mind the limits of ethnobotanical approaches. Perceptions of trees can be biased or reflect partial views about provision of ES/ED by particular tree species (van der Wolf et al. 2016). Wherever possible, studies on LEK should thus be complemented and validated with on-farm studies of the actual interactions between shade trees and coffee trees.

3.4.4. Gender, ethnicity and tree species ranking

Impact of gender on tree preferences was noticeable, with men having a stronger preference for promoted species (Egunyu and Reed 2015). Women were the most likely to include N-fixing tree species in their list of favoured shade trees. No explanation could be found to substantiate

either findings. Surprising gender differences in LEK have been found elsewhere; Ayantunde et al. (2008) pointed out that women, who were responsible for cooking, could identify fewer firewood species than men. In our study, men and women had similar responsibilities in coffee farms; all participated in agricultural activities such as fertilizing, weeding, harvesting and processing crops. Further investigation of how gender is affecting LEK will require complementary tools (e.g. ATK tool), to relate rankings with socio-economic attributes (Lamond et al. 2016; Su et al. 2017).

I had expected that farmers from ethnicities traditionally settled in mountainous areas might exhibit preferences for some indigenous tree species commonly found at these altitudes that would not be valued in other areas (Brandt et al. 2013). Indeed, indigenous timber trees were ranked higher by these farmers. Coffee farmers from mountain ethnicities thereby exhibited a ‘hybrid type of knowledge’ (Gómez-Baggethun et al. 2013), combining their traditional knowledge with both first-hand experience and outside sources, in our case promotion activities from the local authorities.

3.4.5. Tailored list of recommended species

I produced three separate lists of tree species that I recommend for three different farmer priorities (Figure 3-4). Our lists were very similar to that of the government, when considering strategies to diversify income sources (our third scenario), and to lower the frost risk in high-altitude farms while maintaining high coffee yield (our first scenario). The government’s list of promoted species thus appears to be well suited to coffee farmers whose priorities are primarily related to either economic benefits or protection from climatic hazards. Based on farmers’ overall preferences, and these two simulated scenarios, I recommend future promotion of *A. heterophyllus* and *L. leucocephala*.

Simulations based on soil fertility enhancement (our second scenario) would lead to the recommendation of additional species such as *M. azedarach*, *L. leucocephala*, *F. hispida* and *S. wallichii*. The promoted shade tree species boost profits at the expense of below-ground ecosystem services. On the other hand, the suggested additional species do not bring high economic benefits but are perceived to favor soil fertility. Therefore, there is no single solution for a top list of the best tree species for the entire study area. The list of shade-tree species promoted by the local authorities is a useful starting point, but it cannot address the need for complex agricultural strategies or trade-offs between economics and key ecosystem services. Rather, recommendations

should be area-specific and farmer specific. The lists generated in the present study can be used as a starting point. Individual farmers should then modify them to take into account their individual LEK, their local conditions and their economic strategies.

3.5. Conclusion

This study on newly emerging coffee farming systems in Pu'er and Xishuangbanna Prefectures revealed an unexpectedly high level of diversity amongst shade tree species, at both farm and landscape levels. At the landscape level, tree species richness in coffee farms was similar to that documented in tropical montane forests in southern Yunnan. This indicates that tree species diversity has persisted despite the spread of intensive coffee monoculture and the governmental promotion of a limited number of species. These governmentally-promoted tree species were valued by coffee farmers for their perceived high economic returns and protection against environmental hazards. Favorable perceptions of promoted trees also probably reflected a collective bias driven by promotion activities by governmental extension services. However, as trees grow, there will be increased competition between some shade trees and coffee trees for light, water and nutrients. Combining the existing LEK with further research on the actual interactions between mature shade trees and coffee trees is needed in order to refine locally adapted advice on shade tree management practices, including thinning and pruning.

Currently, there appears to be a hybrid ethnobotanical knowledge that mostly relies on traditional knowledge of tree species combined with fresh experience from newly-implemented coffee-agroforestry practices. Farmers of traditional ethnic groups from mountain areas or with richer first-hand experience in coffee-agroforestry practices differed from other farms in their perceptions of shade trees and their impacts on ES and ED; they preferred some indigenous and non-governmentally-promoted species. LEK still needs to be enriched by developing experience with mature shade trees. Furthermore, this study identifies knowledge gaps regarding the impact of shade trees on coffee yield, coffee quality, soil fertility and control of the white stem borer. These gaps should orientate future research works to complement the existing LEK.

This ethnobotanical approach results in the upgrading of an online tool (www.shadetreeadvice.org) which complements the top-down engineered program of the government, by allowing farmers and extension services producing lists of tree species tailored to the farmers' needs and the local ecological contexts of Yunnan Province. Further research will

improve this decision support tool on tree selection and contribute to sustainable coffee management benefiting farmers' livelihood and landscape health in Yunnan Province.

3.6. Supporting information

3.6.1. Methodological steps

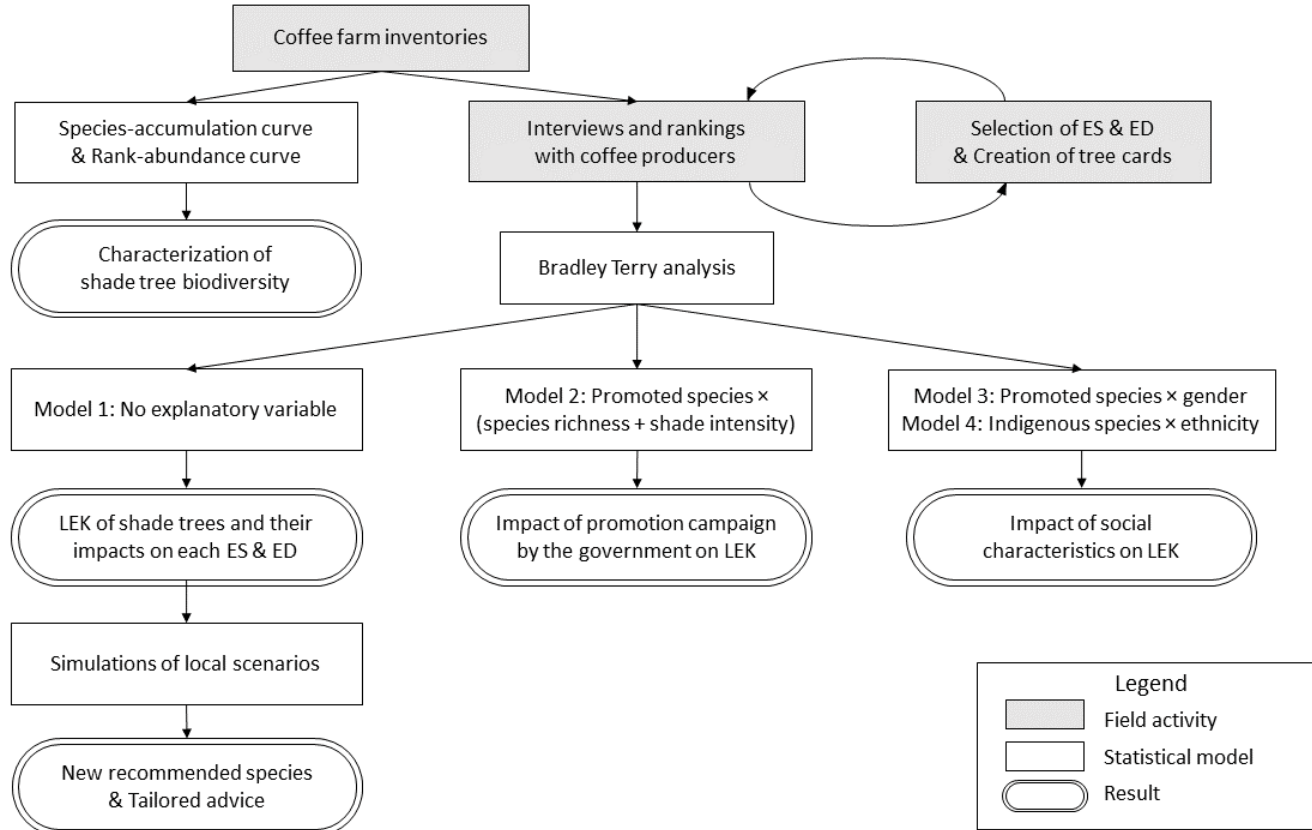


Figure 3-7: Methodological steps for inventorying shade trees in coffee farms and documenting the associated ethnobotanical knowledge

3.6.2. Additional information on shade tree inventories in coffee farms

Diversity indices are detailed for the 3 model farms in Table 3-4. It can be seen that shade tree species in model farm 3 are slightly more diverse than in the 2 other model farms. Higher diversity could result from the larger area under coffee farming. However, these species were found not only in model farm 3 but also in other coffee farms, while many shade tree species found in model farms 1 and 2 were only encountered in these 2 farms.

There is a positive relationship between coffee farm area and tree species richness, as found from the respondent database (Figure 3-8). Tree density was not estimated. Nonetheless, it is likely to be higher than 180 trees/ha, which would represent the density resulting from the average number of tree seedlings distributed by the government, plus trees originating from natural regeneration, as high levels of seedling survival were observed.

Table 3-4: Biodiversity indices for three model farms

Model Farm	Area (ha)	Shannon	Simpson	Effective number
Farm 1 (Nestlé)	16	3.35	0.95	28.50
Farm 2 (Nandaohe)	14	3.07	0.90	21.54
Farm 3 (Aini - Starbucks)	30	3.42	0.96	30.57

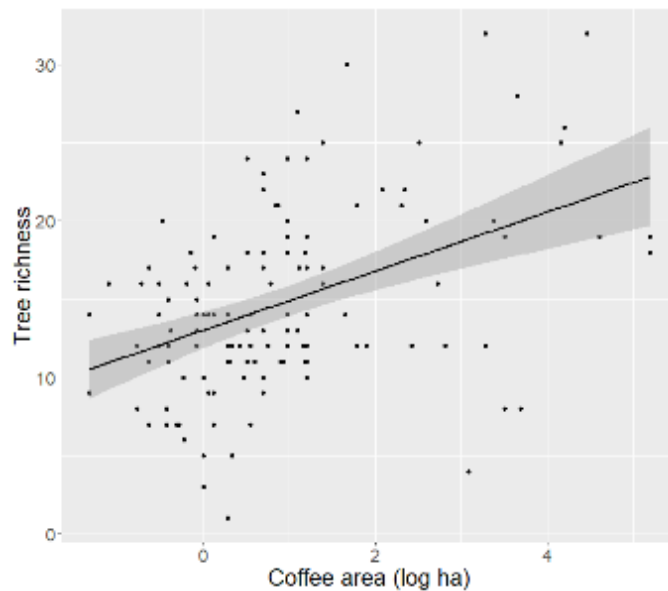


Figure 3-8: Relationship between shade tree richness and coffee farm area based on the database of respondents ($R^2 = 0.19$, p -value $< 10^{-6}$)

CHAPTER 4 - Impact of shade trees on soil fertility

4.1. Introduction

Soil fertility is commonly defined as “the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health” (Bünemann et al. 2018). In recent years, the development of cheap, reliable and reproducible techniques to quantify soil microbial communities (Willers et al. 2015) and soil enzyme activities (Adetunji et al. 2017) has made it increasingly feasible to include these fundamental aspects of soil dynamic performances alongside soil physical characteristics, chemical composition, macrofauna and microfauna communities (Barrios 2007). Indeed, soil communities and nutrient cycling rates can rapidly be altered by management practices (Feng et al. 2003; Treseder 2008; Ugarte et al. 2013) and therefore efficiently complement the monitoring of slow-changing soil physico-chemical parameters. They offer a more detailed picture of seasonal fluctuations (Finney et al. 2017) and fine-scale spatial differences within farms (Scharroba et al. 2016). Additionally, they evidence the link between management practices, soil community composition and provision of a set of ecosystem services, which include nutrient cycling (Adetunji et al. 2017) and control of soil-borne pathogens (Djigal et al. 2012).

The study of nematode communities offers one such indicator of soil fertility. Indeed, due to their central role in soil food web (Neher 2010; Scharroba et al. 2016), nematodes have been widely used as indicators of soil health (Djigal et al. 2012). Soil nematodes comprise individuals from five trophic groups: phytophages, bacterivores, fungivores, omnivores and predators. As such, they are key actors of soil ecosystem services and disservices, such as decomposition and mineralization of nutrients (Djigal et al. 2012; Neher 2010), overgrazing, or control of plant-feeding nematodes (Ferris 2010). Soil nematodes quickly respond to disturbances and environmental changes (Bongers and Ferris 1999). For instance, Song et al. (2017) showed their sensitivity to soil temperature changes while in a previous study, Song et al. (2016a) illustrated the impact of N and water addition on nematode abundance and richness broken down by trophic groups. Soil nematodes are also sensitive to pH (Song et al. 2016a), bottom-up (resource availability) and top-down (predation) pressures (Djigal et al. 2012), seasonality and management practices (Scharroba et al. 2016).

Additionally, soil microbial communities are increasingly encompassed in the study of soil fertility (Lehman et al. 2015). They provide services amongst which soil formation, nutrient cycling through enzymatic actions and control of pathogens (Buyer et al. 2017). Through a feedback loop, microbial communities are in turn linked to plant communities which provide micro habitats and energy resources through litter (Singh et al. 2016) and root exudates (Schweinsberg-Mickan et al. 2012). Coffee being a perennial crop, it is believed to harbor numerous beneficial species in its rhizosphere (Mulaw et al. 2010). These include for instance auxin-producer Gram-positive bacteria, which in turn stimulate nutrient uptake by plants and root growth (Tsavkelova et al. 2006). Fungi are equally central to nutrient cycles and nutrient uptake by plants (Barrios et al. 2012). They play an active role in C cycle and C transfer as well as in improved diffusion of nutrients otherwise limited to plants such as P, Zn and Cu (Balakrishna et al. 2017). Being both inside and outside the roots, and occurring in about 80% of plant species including coffee (Vaast and Zasoski 1992), Arbuscular Mycorrhizal (AM) fungi are essential in the plant-soil interface (Bagyaraj et al. 2015). Furthermore, they sometimes form tripartite alliances with Gram-positive bacteria which strengthen the mycorrhizal symbiosis (Francis et al. 2010).

As stated above, the study of soil enzymes is also increasingly associated with soil fertility assessment. For instance, β -glucosidase, which catalyzes the hydrolysis of maltose and cellobiose (C cycle), is the most common enzyme used as indicator of soil quality (Gil-Sotres et al. 2005). This reaction takes place in the last stage of plant debris degradation to produce glucose, used as an energy source for soil microorganisms (Adetunji et al. 2017). Its activity is impacted by soil pH and soil moisture content (Adetunji et al. 2017). Furthermore, acid phosphatase is the main enzyme that intensify the solubilization of phosphate in soil with pH values ranging from 4 to 6 (Adetunji et al. 2017). These enzymes are key to agricultural systems since most P in soil is organically bound and therefore inaccessible to plants, and are thus good indicators of phosphorus availability to plants (Nannipieri et al. 2012). N-Acetyl- β -D-glucosaminidase degrades chitin, a major structural component of cell walls amongst insects and fungi, which are important pools of C and N (Parham and Deng 2000). Its importance in C and N cycles has thus long been recognized, all the more since it has an optimum pH value of 5.5 while many other soil enzymes involved in N cycle function better in alkaline soils (Parham and Deng 2000).

The development of more comprehensive soil fertility indicators has confirmed that coffee-AFS sustain higher soil fertility than conventional monoculture systems (Bagyaraj et al. 2015; Barrios et al. 2012; Muleta et al. 2008). These benefits of slow-growing shade trees on soil fertility

become more visible as systems age (Vallejo et al. 2010) and under low-input management practices (Tully and Lawrence 2011). Researchers have thus mostly focused their work on long-term trends, and few studies have investigated the short-term impacts of shade trees on soil fertility rapidly after conversion of conventional agriculture systems into intensively managed AFS (Hergoualc'h et al. 2012; Youkhana and Idol 2015). With the availability of cheap and highly reliable techniques to measure soil fertility parameters, I believe that potential short-term soil benefits are more detectable. In the present study, I therefore examine soil chemical parameters, soil communities and enzyme activities, as well as root systems and soil water profiles, to assess the impact of young shade trees on soil fertility, only four years after conversion from intensively managed monoculture Arabica coffee into intensively managed AFS in Pu'er Prefecture, located in southwest China. Our first working hypothesis was that fine scale spatial and temporal variability patterns would be detectable, with higher soil fertility within coffee rows than in the inter-rows and higher activity during the rainy season than the dry season. Second, I expected that soil communities and enzyme activities would already show significant positive impacts from the introduction of shade trees, but that soil chemistry would not have yet been significantly impacted.

4.2. Materials and Methods

4.2.1. Experimental design

Fieldwork was conducted in Liushun Township, in Pu'er Prefecture, from March 2017 to March 2018. A detailed description of the study site and of the coffee farming system is given in Chapter 2.2. Three tree species planted by the local government and commonly found on the mountainside were selected for the experiment: *Bischofia javanica*, *Cinnamomum camphora* and *Jacaranda mimosifolia*. These species were planted within coffee rows, with alternate tree species within a shade tree row. *Bischofia javanica* is a deciduous broadleaved tree species native to the study area. It is commonly found in areas with a distinct dry season, on deep loose soils and occasionally on limestone soils. In the study area, it reached 5 m high on average, 11 cm DBH and 10m² of ground canopy projection. It shed its leaves from December 2016 to March 2017 and from February 2018 to March 2018. *Cinnamomum camphora* is an evergreen broadleaved tree species with a dense canopy. This tree species has been widely cultivated in Southeastern China since ancient times and used for camphor production (Kameyama and Nakajima 2018). It is a light demanding tree that grows well on fertile well drained soils. In the study area, it reached 5 m high on average, 10 cm DBH and 6 m² of canopy projection. *Jacaranda mimosifolia* is a deciduous tree native to South America, often used as an ornamental tree in urban areas and gardens due to the

light shade it provides and the spectacular sight of its flowers in full bloom. It grows best in highland areas with a mean temperature around 20°C and on well drained sandy loams. In the study area, it reached 7 m high on average, 11 cm DBH and 16 m² of canopy projection. It shed its leaves concomitantly to *B. javanica*.

Six replicates were selected for each tree species after an inventory of all trees present on the mountainside, a characterization of coffee trees located below and around their canopies and a set of preliminary soil chemical analysis. The selection was based on shade tree sizes, shapes, locations, coffee trees size and vigor and results from soil analysis, so as to reduce intra-species variability and secure a set of coffee trees and growing conditions as homogeneous as possible. Each shade tree was at least 10 meters away from the next closest shade tree. 4 locations were designated around each shade tree; 1) within the coffee row and below the shade tree canopy; 2) in inter-row and below the shade tree canopy; 3) within the coffee row and outside of the shade tree canopy; 4) in inter-row and outside of the shade tree canopy. Samples taken in inter-rows were located 20 to 30 cm away from the edge of the coffee canopy. Samples taken outside of the shade tree canopy were located at least 2m away from the edge of the shade tree.

Soils samples were collected from the top 20 cm using a stainless steel auger, after removal of the litter horizon. Visible stones and roots were removed. Each location was sampled 3 times. Soils sampled either in December 2017 or 2018 were air dried and sent for chemical analysis. Soils sampled in June-July 2017 and January 2018 were stored at 4°C until tested for a set of biological activity indicators including nematode abundance, microbial communities and soil enzyme activities.

4.2.2. Soil chemical properties

Soil chemistry was determined on air-dried samples. Soil pH was measured in 1:2.5 soil-water suspension. Soil organic matter (SOM) was measured following the Walkley-Black method (Nelson and Sommers 1982). Soil total nitrogen concentration was determined using the semi-micro Kjeldahl method (Bremner and Mulvaney 1982). Available P was determined with Olsen extraction (Olsen and Sommers 1982). Exchangeable Potassium, Calcium and Magnesium were measured with titration after extraction with ammonium acetate (Ciesielski et al. 1997).

4.2.3. Soil communities

Soil community indicators were measured in both the rainy and the dry seasons, except for earthworm abundance which was only measured during the rainy season (Fonte et al. 2010). Soil microbial communities were characterized using phospholipid fatty acid (PLFA) method. PLFA analysis was performed on 10 g field-moist sub-samples using the procedure of (Bossio and Scow 1998). Selected PLFAs were used as molecular markers based on previous research (Feng et al. 2003; Frostegård and Bååth 1996; Mathew et al. 2012). These included Gram-positive (Gram+) bacteria (i15:0, a15:0, i16:0, i17:0, a17:0), Gram-negative (Gram-) bacteria (cy17:0, cy19:0, 18:1 ω 7c), non-specified bacteria (14:0, 15:0, 16:0, 17:0, 18:0), arbuscular mycorrhiza fungi (AMF) (16:1 ω 5c) and non-AMF fungi (18:1 ω 9c). Absolute amounts were expressed in nmol.g⁻¹ dry soil based on the 19:0 internal standard (Zelles 1999). Bacterial sums were calculated using the Gram+, Gram- and non-specified bacteria markers. The fungi to bacteria ratios were calculated by dividing 18:1 ω 9c by the bacterial sums. Total microbial community was estimated using the sum of all PLFA markers.

Free living nematodes were extracted using Baermann's funnel method on 100 g sub-samples immersed in water for 48 h (Van Bezooijen 2006). Nematodes were counted using a microscope. Nematode abundance was expressed as individuals per 100 g of equivalent dry soil. Earthworms were collected by hand from pits (25 * 25 * 30 cm) excavated in August 2017 (Fonte et al. 2010). The 30 cm deep horizons were inspected for burrows of deeper dwelling earthworms. However, due to low mean earthworm occurrence after digging the first 10 pits (average of 0.9 earthworm per pit), this measurement was discontinued.

4.2.4. Soil enzyme activities

Activities of three soil enzymes, β -glucosidase (BG) involved in C cycling, N-acetylglucosaminidase (NAG) involved in C and N cycling, and acid phosphatase (ACP) involved in P cycling, were assayed in both the rainy and the dry seasons, following a method adapted from (Tabatabai 1994). All chemical reagents were bought from Suzhou Comin Biotechnology Company, with modified protocols for reducing sample sizes and solutions while maintaining the original soil to solutions ratios. Briefly, air-dried soil samples were ground and sieved through a 0.6 mm mesh. BG activity was assayed using duplicate 0.02 g samples, one incubated for 1h at 37°C with tuolene and p-nitrophenyl- β -D-glucopyranoside used as substrate, and one control to which substrate was only added to after the incubation. Upon termination of the incubation, soil

solutions were filtered and analyzed colorimetrically at 400 nm. The absorbance value from the control sample was subtracted from that of the test sample to assay the release of p-nitrophenol. Each soil sample was tested twice following this method and results were averaged. NAG activity was assayed using a similar protocol, incubated with p-nitrophenyl-N-acetyl-b-D-glucosaminidine used as substrate. ACP activity was assayed using 0.1g samples incubated with p-nitrophenyl phosphate used as substrate. All enzyme activities were expressed in μmol of p-nitrophenol released.g⁻¹ of soil.day⁻¹.

4.2.5. Litter

Litter was captured in 0.25 m² (50 cm * 50 cm) meshed baskets and collected every six weeks from May 2017 to April 2018. Twenty four litter traps were installed on the mountainside; 75% of the traps under the canopy of *B. javanica*, *C. camphora* and *J. mimosifolia* and the remaining 25% in open areas, half of which below coffee rows and half in inter-rows. Trapped litter was dried at 80°C for 48 h in an oven and manually sorted in coffee leaf, shade tree leaf, woody and miscellaneous fractions before being weighed. Annual litter inputs from coffee and shade trees were extrapolated to the farm level using tree densities and areas of canopy projection to the ground.

In February 2018, three samples made of 4th developed pairs of leaves were taken from coffee trees. nine samples were collected from shade trees. Samples were dried, ground and analyzed for chemical composition. Total N, P, K, Ca and Mg were determined using an atomic absorption spectrophotometer after tissue wet extraction with sulphuric and perchloric acid. Iron concentration was assessed using the wet ash method. Lignin was determined through the acid detergent lignin measurement method.

4.2.6. Data analysis

Soil chemical, biological and biochemical parameters were analyzed separately in R.3.4.4. Outliers were identified as beyond two times the inter-quartile range from the first or third quartile and excluded from analysis. Shapiro's test was used to test for normality. Levene's test was used to test for homogeneity of variances. Whenever necessary, data were log-transformed to meet these two assumptions. Analysis of variance was used to detect significant effects of season, shade, location within coffee rows compared to inter-rows, and all the interactions between these factors. Terraces were used as a random effect in the ANOVA, in order to take into account variability in management practices among the five smallholder farmers. In a first analysis, the three selected

shade tree species were considered as three treatment levels and open coffee a fourth level. In a second analysis, the three shade tree species were pooled to increase sample size and reflect the general impact of shade trees as compared to open areas. Throughout the article, values are expressed as means \pm standard error.

When significant effects were detected, they were investigated through Student t-tests on pairwise differences between treatment samples and control samples. Specifically, when investigating the seasonal impact, values from samples taken during the dry season were subtracted from values from the corresponding samples taken during the rainy season. When studying the impact of coffee trees and fertilizer inputs within coffee rows on soil fertility, values from samples in inter-rows were subtracted from values from the corresponding samples within coffee rows. When studying the impact of shade trees, values from samples taken below shade tree canopies were subtracted from values from the corresponding samples taken in open areas.

Redundancy analysis (RDA) was performed to assess the linear relationships between soil communities and a set of explanatory variables encompassing soil water content, soil chemical composition and indicators of litter input (dry mass, N:lignin ratio). Most discriminating variables were selected through a forward procedure and tested for significance (1000 permutations) using the vegan package in R3.4.4 (Oksanen et al. 2018). Similarly, RDA was performed to assess the relationships between soil enzyme activities and a set of explanatory variables encompassing soil water content, soil chemical composition and soil communities.

4.3. Results

4.3.1. Litter

Planted at a density of 56 trees.ha⁻¹, 5 years old *B. javanica* would provide an estimated amount of 450 (\pm 90) kg dry leaf.ha⁻¹.yr⁻¹. At the same density, *C. camphora* would provide an estimated amount of 100 (\pm 20) kg.ha⁻¹.yr⁻¹ and *J. mimosifolia* in the range of 140 (\pm 10) kg.ha⁻¹.yr⁻¹. In comparison, planted at a density of 5000 trees.ha⁻¹, coffee trees in AFS would provide an estimated amount of 4170 (\pm 203) kg.ha⁻¹.yr⁻¹ and monoculture coffee in the range of 4281 (\pm 421) kg.ha⁻¹.yr⁻¹. Woody and miscellaneous fractions provided an estimated average of 1890 (\pm 292) kg dry matter.ha⁻¹.yr⁻¹ in all 4 coffee systems, most of which being aborted coffee cherries. *Bischofia javanica* leaf litter thus represented less than 10% of total leaf litter in shaded coffee farms. This amount fell below 3% in the case of *C. camphora* and *J. mimosifolia*. However, this overall low

contribution of shade tree leaf litter hid important spatial differences. Within coffee rows and under their canopies, *B. javanica*, *C. camphora* and *J. mimosifolia* leaf litter respectively represented 68%, 49% and 23% of the total leaf litter falling in that location. In the corresponding inter-rows, these percentages increased to 93%, 71% and 55%. Spatial variability was also evidenced with an estimated amount of 553 (± 78) kg.m⁻².yr⁻¹ of coffee leaf litter falling within coffee rows in open areas, compared with an estimated amount of 334 (± 19) kg.m⁻².yr⁻¹ in the inter-rows.

Based on coffee leaf and shade tree leaf analysis (Table 4-1), leaf litter could return 99 to 107 kg.N.ha.yr⁻¹, 5 to 6 kg.P.ha.yr⁻¹ and 67 to 73 kg.K.ha.yr⁻¹ (Figure 4-1). Nutrient return was consistently higher in *B. javanica*-coffee AFS than in the 3 other systems, in accordance with the additional input of leaf litter from this shade tree species, although differences are not statistically significant due to high variability in coffee leaf litter amounts.

4.3.2. Seasonal impact on soil fertility

Soil water content was 1.5 to 2.8% higher during the rainy season than the dry season, in all sample locations. Free living nematodes, total PLFA, bacterial communities, fungi and AMF were all significantly more abundant during the rainy season than during the dry season, both within coffee rows and in inter-rows, and in shaded and open areas (Table 4-3). Only fungi communities in shaded inter-rows were not statistically more abundant during the rainy season (2.4 ± 0.2 nmol.g⁻¹) than during the dry season (1.9 ± 0.2 nmol.g⁻¹). Fungi to bacteria ratios remained similar in the dry and the rainy seasons. Gram+ to Gram- bacteria ratios also remained similar, except under shaded coffee rows where this ratio decreased in the dry season (-0.46 ± 0.13). ACP activity rates were higher in the rainy season under coffee rows (66 ± 3 μ mol.g⁻¹.d⁻¹) than in the dry season (45 ± 6 μ mol.g⁻¹.d⁻¹), but did not show seasonal variations in inter-rows (Table 4-4). Although not expected, C and N cycling rates were slower during the rainy season than during the dry season, as indicated by lower NAG and BG activities (rainy season: 26 to 37 μ mol.g⁻¹.d⁻¹; versus dry season: 38 to 71 μ mol.g⁻¹.d⁻¹).

Table 4-1: Leaf chemical composition of shade trees (BJ: *B. javanica*; CC: *C. camphora*; JM: *J. mimosifolia*) and coffee trees (mean \pm standard error, replicates = 3)

	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (mg/kg)	Lignin (%)
BJ	2.54 (± 0.51)	0.13 (± 0.02)	1.63 (± 0.65)	1.21 (± 0.55)	0.28 (± 0.14)	79.10 (± 8.46)	16.22 (± 4.80)
CC	2.50 (± 0.24)	0.12 (± 0.02)	0.71 (± 0.19)	3.59 (± 0.30)	0.20 (± 0.05)	91.55 (± 28.27)	8.44 (± 0.64)
JM	2.32 (± 0.34)	0.10 (± 0.02)	0.60 (± 0.07)	1.46 (± 0.10)	0.19 (± 0.06)	117.05 (± 11.29)	8.60 (± 1.68)
Coffee	2.30 (± 0.21)	0.13 (± 0.02)	1.59 (± 0.27)	2.08 (± 0.21)	0.43 (± 0.07)	121.29 (± 11.43)	3.98 (± 0.71)

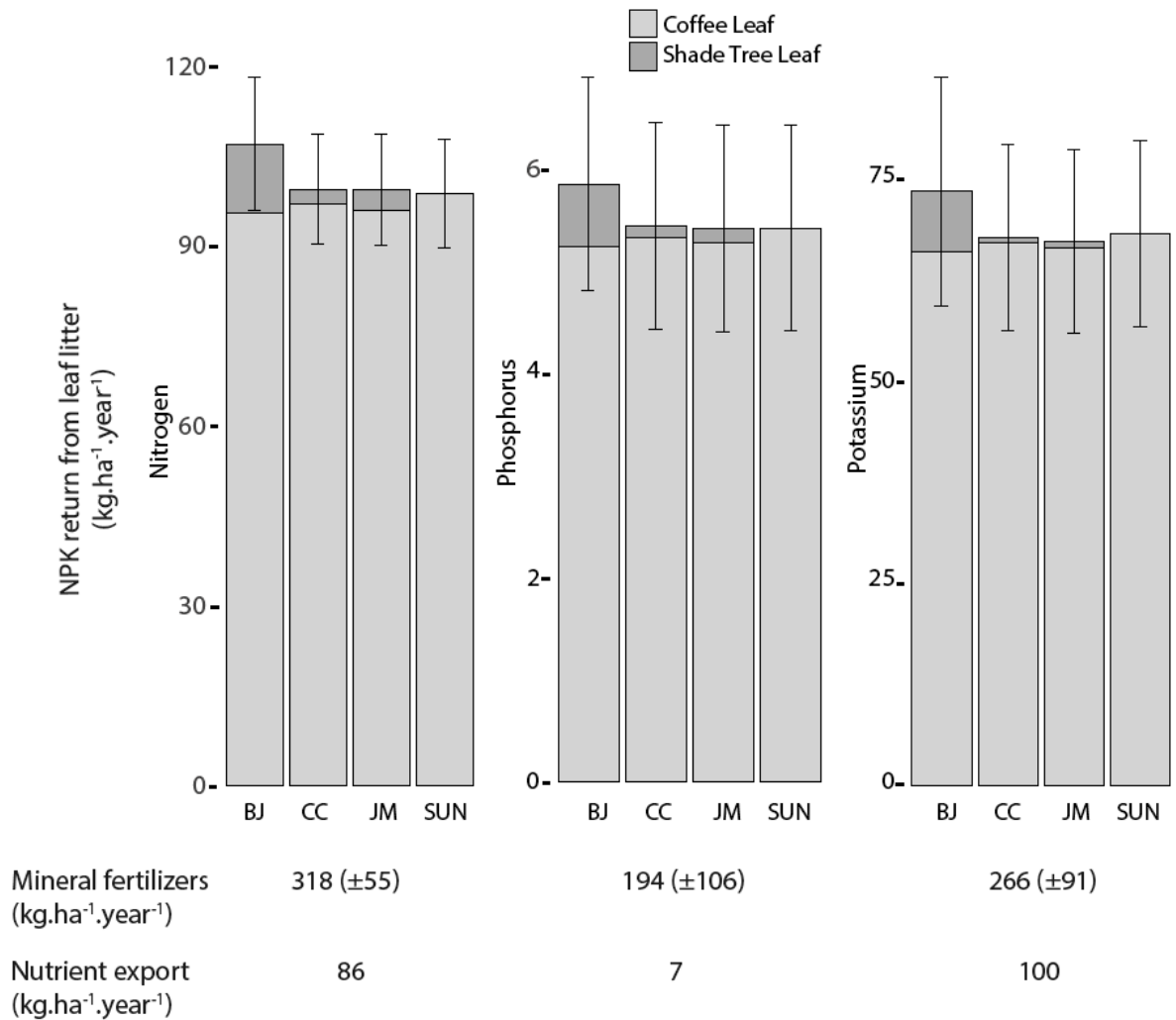


Figure 4-1: Annual NPK return from leaf litter extrapolated for 3 coffee agroforestry systems (BJ: *B. javanica*; CC: *C. camphora* and JM: *J. mimosifolia*) and monoculture (SUN) in comparison to average annual mineral fertilizer inputs and nutrient export through harvested coffee cherries. Error bars represent standard errors (replicates = 3).

Table 4-2: Soil chemistry as affected by position with respect to coffee row or inter-row under shade of trees (3 species pooled) or sun (monoculture) (Mean \pm Standard Error, replicates = 18)

Row	Shade	pH (water 2.5:1)	SOM (g/kg)	N (g/kg)	P (mg/kg)	K (cmol /kg)	Ca (cmol /kg)	Mg (cmol /kg)
Coffee row	Pooled Trees	4.9 (\pm 0.1)	28.4 (\pm 1.1)	1.6 (\pm 0.0)	110 (\pm 20)	0.61 (\pm 0.09)	3.43 (\pm 0.33)	0.49 (\pm 0.06)
Coffee row	Sun	4.5 (\pm 0.1)	25.8 (\pm 1.2)	1.3 (\pm 0.1)	36 (\pm 10)	0.48 (\pm 0.05)	2.36 (\pm 0.43)	0.45 (\pm 0.06)
Inter-row	Pooled Trees	4.5 (\pm 0.1)	24.2 (\pm 1.2)	1.6 (\pm 0.1)	34 (\pm 7)	0.68 (\pm 0.07)	1.30 (\pm 0.25)	0.32 (\pm 0.04)
Inter-row	Sun	4.6 (\pm 0.1)	22.0 (\pm 0.9)	1.4 (\pm 0.0)	27 (\pm 8)	0.61 (\pm 0.06)	1.00 (\pm 0.12)	0.33 (\pm 0.04)
p-values								
Row		0.03 *	<0.001 ***	0.87	0.001 **	0.26	<0.001 ***	0.007 **
Shade		0.32	0.02*	0.003**	0.03*	0.36	0.02 *	0.58
Row * Shade		0.002 **	0.82	0.33	0.03*	0.46	0.19	0.66

Table 4-3: Soil communities as affected by position with respect to coffee row or inter-row under shade of trees (3 species pooled) or sun (monoculture)

Season	Row	Shade	Nematodes ln(ind.100g ⁻¹)	All PLFA nmol.g ⁻¹	Bacteria nmol.g ⁻¹	Gram+:Gram- ratio	Fungi nmol.g ⁻¹	AMF nmol.g ⁻¹	Fungi:Bacteria ratio
Rainy	Coffee row	Pooled Trees	5.3 (\pm 0.1)	53.4 (\pm 3.6)	38.3 (\pm 2.5)	3.0 (\pm 0.1)	3.5 (\pm 0.3)	1.4 (\pm 0.2)	0.091 (\pm 0.003)
Rainy	Coffee row	Sun	5.0 (\pm 0.1)	49.1 (\pm 4.4)	35.4 (\pm 3.1)	2.9 (\pm 0.1)	3.0 (\pm 0.3)	1.3 (\pm 0.2)	0.085 (\pm 0.004)
Rainy	Inter-row	Pooled Trees	4.7 (\pm 0.1)	41.1 (\pm 1.9)	30.2 (\pm 1.4)	3.1 (\pm 0.1)	2.4 (\pm 0.2)	0.9 (\pm 0.1)	0.074 (\pm 0.004)
Rainy	Inter-row	Sun	4.3 (\pm 0.1)	46.8 (\pm 6.4)	34.5 (\pm 4.6)	3.0 (\pm 0.2)	1.8 (\pm 0.2)	1.0 (\pm 0.1)	0.062 (\pm 0.004)
Dry	Coffee row	Pooled Trees	2.8 (\pm 0.3)	34.5 (\pm 2.6)	26.0 (\pm 2.0)	2.6 (\pm 0.1)	2.5 (\pm 0.3)	0.8 (\pm 0.1)	0.091 (\pm 0.004)
Dry	Coffee row	Sun	3.0 (\pm 0.3)	21.1 (\pm 1.9)	16.0 (\pm 1.4)	2.7 (\pm 0.1)	1.4 (\pm 0.2)	0.5 (\pm 0.0)	0.088 (\pm 0.004)
Dry	Inter-row	Pooled Trees	2.4 (\pm 0.3)	29.3 (\pm 2.1)	22.5 (\pm 1.7)	2.8 (\pm 0.1)	1.9 (\pm 0.2)	0.5 (\pm 0.0)	0.083 (\pm 0.005)
Dry	Inter-row	Sun	2.8 (\pm 0.3)	21.9 (\pm 1.9)	16.6 (\pm 1.4)	3.0 (\pm 0.1)	1.2 (\pm 0.1)	0.5 (\pm 0.1)	0.074 (\pm 0.005)
p-values									
Season			<0.001 ***	<0.001 ***	<0.001 ***	0.001 **	<0.001 ***	<0.001 ***	0.4 *
Row			0.002 **	0.01 *	0.04 *	0.06 .	<0.001 ***	<0.001 ***	<0.001 ***
Shade			0.98	0.11	0.06 .	0.36	<0.001 ***	0.43	0.004 **
Season : Row			0.12	0.28	0.34	0.43	0.04 *	0.13	0.09 .
Season : Shade			0.02 *	0.02 *	0.01*	0.12	0.25	0.20	0.63
Row : Shade			0.91	0.11	0.12	0.55	0.74	0.16	0.33
Season : Row : Shade			0.59	0.66	0.60	0.95	0.33	0.54	0.99

Table 4-4: Soil enzymatic activities as affected by position with respect to coffee row or inter-row under shade of trees (3 species pooled) or sun (monoculture) and according to rainy and dry seasons (Mean \pm Standard Error, replicates = 18)

Season	Row	Shade	NAG $\mu\text{mol.g}^{-1}.\text{d}^{-1}$	BG $\mu\text{mol.g}^{-1}.\text{d}^{-1}$	ACP $\mu\text{mol.g}^{-1}.\text{d}^{-1}$
Rainy	Coffee row	Pooled Trees	32.4 (± 2.0)	37.3 (± 2.8)	65.8 (± 3.1)
Rainy	Coffee row	Sun	32.2 (± 1.5)	35.5 (± 3.1)	66.6 (± 3.5)
Rainy	Inter-row	Pooled Trees	27.5 (± 1.5)	36.7 (± 1.9)	52.6 (± 3.4)
Rainy	Inter-row	Sun	26.0 (± 1.5)	35.7 (± 3.4)	44.4 (± 3.6)
Dry	Coffee row	Pooled Trees	42.1 (± 2.2)	65.6 (± 5.5)	46.0 (± 2.5)
Dry	Coffee row	Sun	37.6 (± 3.5)	62.7 (± 7.9)	44.3 (± 6.4)
Dry	Inter-row	Pooled Trees	42.1 (± 2.4)	70.5 (± 7.7)	49.0 (± 5.2)
Dry	Inter-row	Sun	43.6 (± 3.1)	69.5 (± 7.8)	35.2 (± 3.1)
p-values					
Season			<0.001 ***	<0.001 ***	<0.001 ***
Row			0.17	0.64	<0.001 ***
Shade			0.13	0.09 .	0.05 *
Season : Row			0.002 **	0.22	0.007 **
Season : Shade			0.58	0.96	0.49
Row : Shade			0.50	0.74	0.07 .
Season : Row : Shade			0.21	0.96	0.77

Table 4-5: Coffee yield (kg.tree^{-1}) under shade trees and in open conditions for 2 consecutive years (mean \pm standard error). Letters represent Wilcoxon significant groups within a year.

	<i>B. javanica</i>	<i>C. camphora</i>	<i>J. mimosifolia</i>	Open coffee
2016-2017	2880 (± 240) ab	2210 (± 120) b	2510 (± 140) ab	2810 (± 120) a
2017-2018	4250 (± 300) a	2730 (± 450) b	5240 (± 1010) a	4260 (± 540) ab

4.3.3. Impact of coffee rows on soil fertility

SOM, exchangeable Ca and exchangeable Mg were significantly higher within coffee rows than in inter-rows, irrespective of the presence of shade trees (Table 4-2). Under the combined effect of shade trees and coffee rows, soils also had significantly higher pH and available P than in inter-rows. There was no significant effect of coffee rows on total N and exchangeable K. Soil bulk density was similar in all sample locations, averaging $1.63 \pm 0.10 \text{ g.cm}^{-3}$.

Most significant effects of coffee rows on soil biology and biochemistry were detected during the rainy season (Table 4-3 & Table 4-4). These included significantly more abundant free-living nematodes within coffee rows than in inter-rows. Similarly, fungi and AMF were more abundant and fungi:bacteria ratios were significantly higher under coffee rows than in inter-rows, in both shaded and unshaded areas. Soils under coffee rows also had increased C, N and P cycling rates compared to inter-rows, shown by significantly greater NAG ($+5.6 \pm 2.1 \mu\text{mol.kg}^{-1}.\text{h}^{-1}$ in shaded area and $+6.2 \pm 1.8 \mu\text{mol.kg}^{-1}.\text{h}^{-1}$ in open area) and ACP activities ($+13.2 \pm 4.3 \mu\text{mol.kg}^{-1}.\text{h}^{-1}$ in shaded area and $+22.3 \pm 5.1 \mu\text{mol.kg}^{-1}.\text{h}^{-1}$ in open area). There was no marked effect on BG activities. Bacterial communities ($+9.4 \pm 3.1 \text{ nmol.g}^{-1}$) and total microbial communities ($+14.1 \pm 4.2 \text{ nmol.g}^{-1}$) were more abundant under the combined effect of shade trees and coffee rows. No effect of coffee rows on soil bacterial communities was detected in open areas.

During the dry season, there was no marked difference in soil water content, abundance of free-living nematodes, bacterial communities, total microbial communities and P cycling rates between coffee rows and inter-rows. Fungi and AMF communities were more abundant within shaded coffee rows compared to shaded locations in inter-rows ($+0.6 \pm 0.3$ and $+0.38 \pm 0.08 \text{ nmol.g}^{-1}$). There was no significant effect of coffee rows on NAG and BG activities under shade trees, but NAG and BG activities were lower in coffee rows than in inter-rows in unshaded locations ($-7.2 \pm 3.0 \mu\text{mol.kg}^{-1}.\text{h}^{-1}$ for NAG and $-9.9 \pm 4.3 \mu\text{mol.kg}^{-1}.\text{h}^{-1}$ for BG).

4.3.4. Impact of shade trees on soil fertility

As few significant differences between shade tree species were detected in the analysis (Table 4-6 to Table 4-8), the rest of the article focuses on shade tree effects with shade tree species pooled. Most significant effects of shade trees on soil chemistry were detected within coffee rows (Table 4-2). These included higher pH ($+0.50 \pm 0.14$), SOM ($+3.0 \pm 1.2 \text{ g.kg}^{-1}$), total N ($+0.36 \pm 0.08 \text{ g.kg}^{-1}$), available P ($+79 \pm 23 \text{ mg.kg}^{-1}$) and exchangeable Ca ($+0.90 \pm 0.44 \text{ cmol kg}^{-1}$) under shaded

coffee than under open coffee. There was no marked effect on exchangeable K and Mg. In inter-rows, shade trees only had a significant impact on soil pH which was lower than in open areas (-0.30 ± 0.11).

During the rainy season, free living nematodes were more abundant under shade trees than in open areas, both within coffee rows ($+1.6 \pm 1.1$ ind.100g⁻¹) and in inter-rows ($+1.5 \pm 1.1$ ind.100g⁻¹) (Table 4-3). There was no significant impact of shade trees on soil microbial communities, except on the fungi:bacteria ratio that was higher in inter-rows in shaded areas than in inter-rows in open areas ($+0.011 \pm 0.005$). Shade trees had a positive impact on C and N cycling rates, as indicated by a higher BG activity under coffee ($+5.2 \pm 1.8$ $\mu\text{mol.kg}^{-1}.\text{h}^{-1}$) and a higher NAG activity in inter-rows ($+2.9 \pm 1.4$ $\mu\text{mol.kg}^{-1}.\text{h}^{-1}$) (Table 4-4). Shade trees had no marked effect on ACP activity.

Most significant effects of shade trees on soil biology were detected during the dry season (Table 4-3). These included more abundant bacterial communities, fungi and total microbial communities in shaded areas than in open areas, both within coffee rows and in inter-rows. Bacterial communities showed similar compositions in shaded and in open areas, as indicated by similar Gram+ to Gram- ratios. Within coffee rows, AMF were more abundant in shaded areas than in open areas ($+0.36 \pm 0.08$ nmol.g⁻¹). In inter-rows, fungi:bacteria ratios were higher in shaded areas than in open areas ($+0.014 \pm 0.006$). Shade trees had no marked effect on enzyme activities (Table 4-4), except on ACP activity higher in shaded inter-rows than in open inter-rows ($+17.3 \pm 5.1$ $\mu\text{mol.kg}^{-1}.\text{h}^{-1}$). There was no marked effect of shade trees on soil water and abundance of free living nematodes.

4.3.5. Redundancy Analysis

Soil communities' composition was best explained by soil water, exchangeable Mg and the dry weight of litter input (Figure 4-2). Fungi:bacteria ratio was positively correlated with litter input and exchangeable Mg. Gram+:Gram- ratio was negatively correlated with litter input and exchangeable Mg. Nematode abundance was best correlated with soil water. In both the rainy and the dry season, AMF, fungi and soil water were discriminating variables selected in the RDA models that best explained soil enzyme activities (Figure 4-3). ACP cycling rate was positively correlated with AMF and fungi communities. NAG and BG were positively correlated with soil water content.

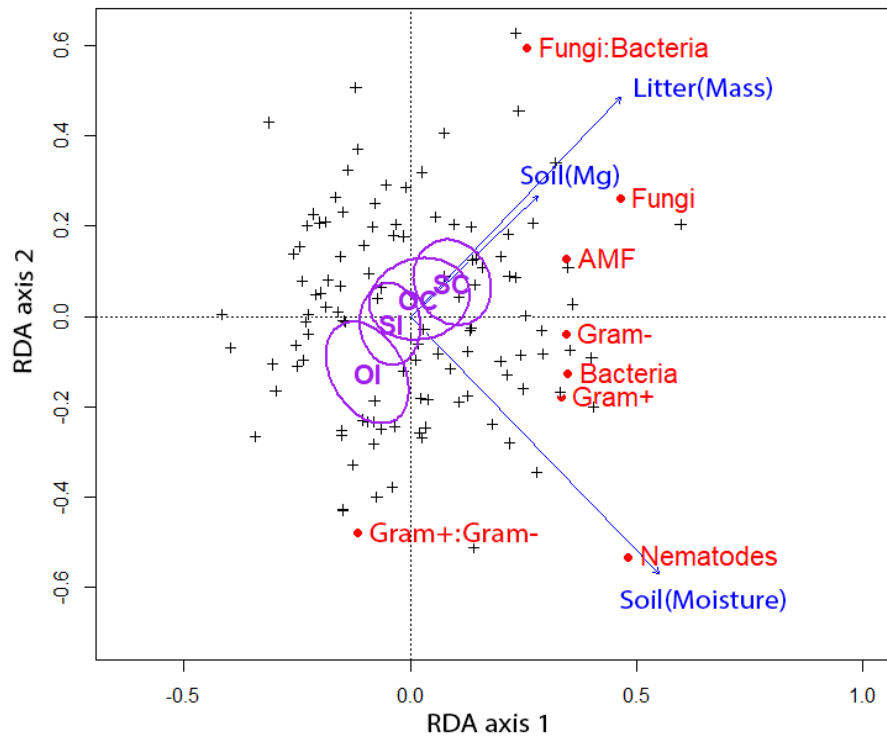


Figure 4-2: Redundancy analysis (RDA) of soil communities (dots) constrained by soil chemical properties and litter input indicators (arrows). Discriminating explanatory variables were selected with a forward procedure. Axes 1 and 2 represent 10.4% and 2.0% of the total variation. Crosses represent soil samples. Ellipses represent 95% confidence interval of the mean samples for Shaded Coffee (SC), Open Coffee (OC), Shaded Inter-row (SI) and Open Inter-row (OI)

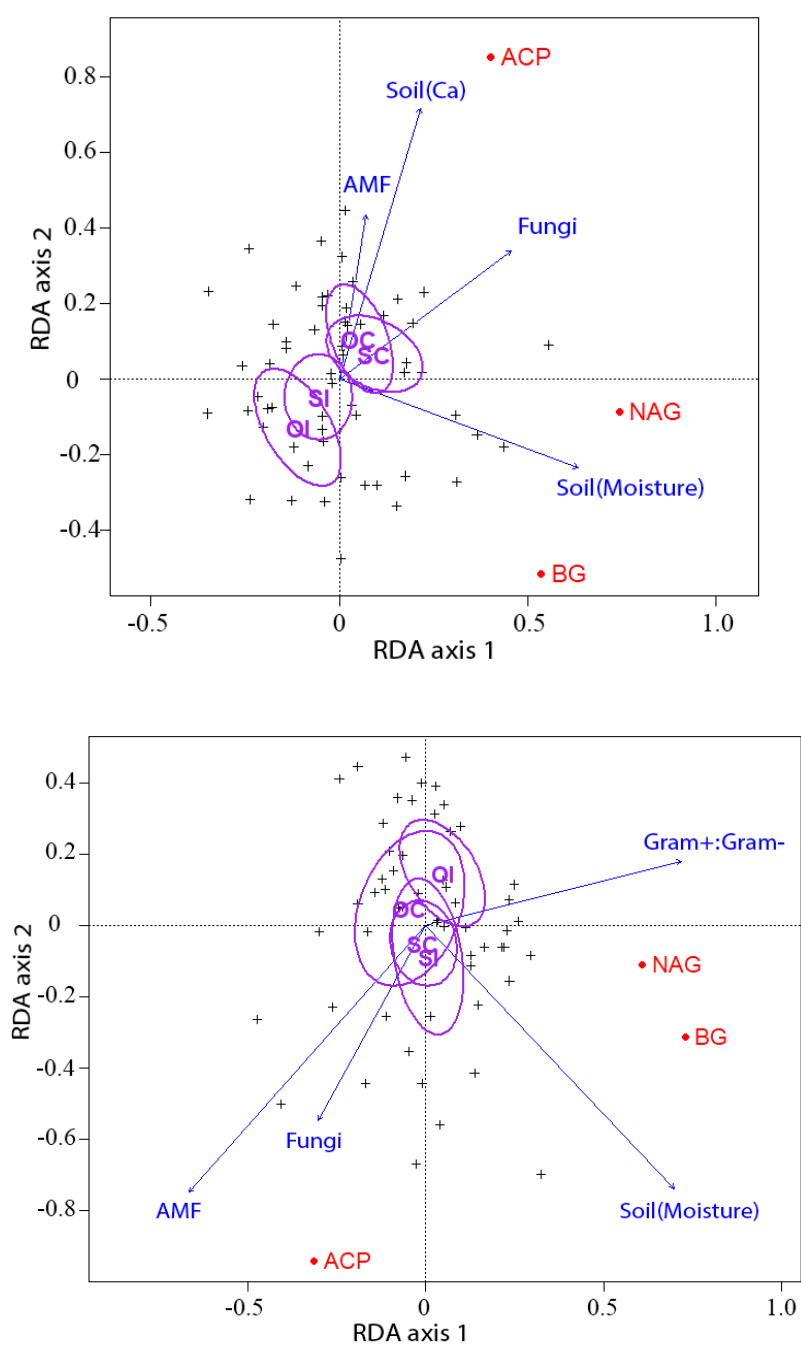


Figure 4-3: Redundancy analysis (RDA) of soil enzyme activities (dots) constrained by soil chemical properties and soil communities (arrows). Discriminating explanatory variables were selected with a forward procedure. In the rainy season (top), axes 1 and 2 represent 25.8 and 14.5% of the total variation. In the dry season (bottom), axes 1 and 2 represent 36.3 and 7.2% of the total variation. Crosses represent soil samples. Ellipses represent 95% confidence interval of the mean samples for Shaded Coffee (SC), Open Coffee (OC), Shaded Inter-row (SI) and Open Inter-row (OI).

4.4. Discussion

4.4.1. Soil chemistry

Chemical fertilization is the most common management practice to influence soil fertility. It is used to compensate for potential soil deficiencies in nutrients and replace depletions caused by plant growth, export of crops and lixiviation (Tully and Lawrence 2011). The studied mountainside exhibits high nutrient concentrations (Table 4-2), which indicate high mineral fertilizers inputs, frequent in smallholder farming systems in China (Ju et al. 2016). In a chronosequence of intensively managed monoculture coffee farms in Hainan Province, China, Zhao et al. (2018a) evidenced the long-term decrease in soil fertility through the combined loss of SOM and increase in soil acidity. In the present study, with current SOM values between 22.0 and 28.4 g.kg⁻¹ and soil pH values between 4.5 and 4.9, SOM is already low and acidity high, although not unusual (Banks et al. 2011; Lopez-Rodriguez et al. 2015). These values are already significantly lower than those found in natural forests ecosystems and indicate soil degradation (Zhao et al. 2018b). A further decrease in SOM and pH would nonetheless hinder coffee growth and be detrimental to coffee production (Snoeck and Lambot 2008; Zhao et al. 2018a). Furthermore, a number of studies have highlighted the low recovery rate of mineral fertilizers in high input systems, resulting in economic losses and downstream pollutions. For instance, in Costa Rica, due to high water drainage, coffee farms receiving 250 kg.N.ha⁻¹.year⁻¹ lost 33-55% of it through NO₃- leaching alone (Cannavo et al. 2013). On the other hand, it is common practice in coffee farms worldwide to use coffee pulp, a by-product of post-harvest processing, as compost. In the study area, farmers solely relied on chemical fertilizer. A change in their management practices, to include these readily available organic fertilizers, would contribute to increasing soil chemical fertility.

4.4.2. Seasonal impact on soil fertility

As expected, soil biological activity was significantly higher during the rainy season than the dry season. The density of all measured soil communities increased. These findings are in agreement with previous studies highlighting the rapid seasonal response of soil communities to changes in soil water content and justifying their use as sensitive soil fertility indicators (Buscardo et al. 2018; Feng et al. 2003; Finney et al. 2017; Prescott and Grayston 2013). Seasonal changes in soil communities are also often linked to an increase in root growth and exudates during the rainy months, increasing the available carbon for microorganisms in the root rhizosphere (Feng et al. 2003; Geisseler and Scow 2014; Kong et al. 2011). In the present study, density of soil communities

below the three shade tree species were not significantly different (Table 4-7). In addition, there was no evidence of changes in soil community compositions, as indicated by steady fungi:bacteria and Gram+:Gram- ratios. These results might reflect high levels of disturbances and low microbial diversity in intensively managed landscapes (Bowles et al. 2014).

Nutrient cycling also underwent significant seasonal variations. The increase in ACP activity during the rainy season was best explained by the increase in fungi communities (Figure 4-3). This result is in line with other studies linking P-cycling rates to fungi communities and soil water content (Adetunji et al. 2017). It could also be associated with N and P fertilizer inputs (Adetunji et al. 2017; Geisseler and Scow 2014; Olander and Vitousek 2000; Zhang et al. 2016). On the other hand, the lower NAG and BG activities during the rainy season than during the dry season was unexpected. In the majority of existing studies, higher C and N cycling rates follow an increase in soil water content (Adetunji et al. 2017), N fertilization (Geisseler and Scow 2014; Jian et al. 2016; Mbutia et al. 2015; Zhang et al. 2016) and an increase in C availability from sources such as root exudates (Bowles et al. 2014; Prescott and Grayston 2013; Zhao et al. 2016). I suspect this result to be the consequence of an atypical 50mm rainfall event that took place 8 days before sample collection in January. The re-wetting of dry soils could explain a short-lived C and N mineralization pulse, with NAG and BG activities higher than those measured in the rainy season (Borken and Matzner 2009; Mikha et al. 2005). Overall, higher soil biological activity and P-cycling rate during the rainy season confirm our first hypothesis of seasonal variations in soil fertility, albeit with uncertainties regarding seasonal effects on C and N mineralization rates

4.4.3. Impact of coffee rows on soil fertility

Soils under coffee rows exhibited significantly higher chemical, biological and biochemical fertility than soils in inter-rows (Table 4-2 to Table 4-4). Coffee leaf litter was 66% more abundant below coffee trees than in inter-rows, which partly explained this result. In addition, higher soil fertility below coffee trees highlights 20 years of high mineral fertilizer inputs placed below coffee trees. Higher concentrations of available P, exchangeable Ca and exchangeable Mg presumably reflected excessive fertilization practices (Zhao et al. 2018a; Zhao et al. 2016). Considering N and K fertilizer inputs well in excess of crop demands (Figure 4-1) (Tully and Lawrence 2011), we also expected total N and exchangeable K concentrations higher in coffee rows than in inter-rows. However, we did not detect significant differences with N and K soil concentration. On top of the direct effect of fertilizer inputs on soil chemistry, long-term

fertilization also resulted in increasing root turnover, root exudate and crop residues, which all contribute to SOM and soil chemical fertility (Defrenet et al. 2016; Geisseler and Scow 2014) and support the growth of soil communities (Finney et al. 2017; Geisseler and Scow 2014; Mbutia et al. 2015). This was specifically evidenced in coffee farms, with Defrenet et al. (2016) recording 125% higher coffee fine root biomass and 140% higher fine root net primary productivity in the 0-30cm soil layer within coffee rows than in inter-rows. This increase in coffee below-ground activity supports the present results of more abundant free-living nematodes, bacteria and fungi in coffee rows than in inter-rows (Table 4-3). Fertilization and organic matter input are also known to contribute to higher NAG activity (Bowles et al. 2014; Mbutia et al. 2015; Zhang et al. 2016) and ACP activity (Adetunji et al. 2017), especially when fertilizers are applied on soils with low SOM (Adetunji et al. 2017). In addition, high dependency of coffee plants to vesicular arbuscular mycorrhizal fungi (Andrade et al. 2009; De Beenhouwer et al. 2015; Vaast et al. 1997) could explain that AMF communities were more abundant in coffee rows than in inter-rows, in turn supporting ACP activity (Adetunji et al. 2017). Non-AMF fungi were also more abundant in coffee rows than in inter-rows. According to the redundancy analysis, litter weight explained this difference better than litter quality did. This predominant effect of amount over quality has been seen, especially in farming systems where N is not as limiting a factor (Huang et al. 2013), although it cannot be generalized (Brennan and Acosta-Martinez 2017; Prescott and Grayston 2013). Nonetheless, fungi:bacteria ratios in coffee rows remained low and highlighted a state of high soil disturbance, especially due to intensive mineral fertilization practices (Bowles et al. 2014; Brennan and Acosta-Martinez 2017).

Higher soil fertility in coffee rows than in inter-rows was best visible during the rainy season. Most biological differences evened out during the dry season, reflecting an overall decrease in plant and soil activity. Only NAG and BG activities were higher in unshaded inter-rows than below open coffee trees in the dry season. I suspect this to result from the atypical 50 mm rainfall event leading to an increased C and N mineralization pulse in unshaded inter-rows (Borken and Matzner 2009; Mikha et al. 2005). In contrast, I suspect that shade trees and coffee trees intercepted part of the rainfall (Cannavo et al. 2011; van Kanten and Vaast 2006). This interpretation is further evidenced by the correlation between soil water content and NAG and BG activities in the redundancy analysis for winter enzyme activities (Figure 4-3).

4.4.4. Impact of shade trees on soil fertility

Despite the marked effect of 20 years of intensive fertilization practices and abundant coffee leaf litter on soil fertility, I still observed a richer soil chemical fertility under shade trees than in open areas, only four years after the conversion from monoculture to agroforestry. pH, SOM, total N, available P and exchangeable Ca concentrations were all higher under shaded coffee than under open coffee. The positive impact of shade trees on chemical fertility in coffee farms has been widely evidenced in mature AFS and can be explained by shade trees' below-ground activity and litterfall (Hairiah et al. 2006; Huang et al. 2018; Lopez-Rodriguez et al. 2015; Notaro et al. 2014; Payán et al. 2009; Tully and Lawrence 2012). In our study, shade tree leaf litter did contribute 23 to 68% of all leaf litter biomass under shaded coffee.

In addition, throughout the year and in all sample locations, soil communities and soil enzyme activities were always similar or higher under shade trees than in corresponding open areas. This demonstrates that shade trees also had a positive impact on soil biological and biochemical fertility. This positive impact was most visible during the dry season, when microbial communities were all significantly more abundant under shade trees than in open areas (Table 4-3). In the present study, leaf litter biomass best explained the higher abundance of fungi communities under shade trees while bacterial communities were best correlated with soil water content (Figure 4-2). These results are in line with many studies showing that shade trees support higher and more diverse microbial communities than monoculture systems (Bagyaraj et al. 2015; Bainard et al. 2011; Bainard et al. 2013; Barrios et al. 2012; Mortimer et al. 2015). Our study also highlights the buffering effect of shade trees on seasonal variability of soil communities.

Impacts of trees on soil fertility are usually not detected so rapidly (Souza et al. 2012; Vallejo et al. 2010). For example, 6 to 9 years after the introduction of shade trees in an intensively managed monoculture coffee farm, (Hergoualc'h et al. 2012) did not notice any change in SOC. In Kenyan highlands, soils under 20 to 30 years of agroforestry practices tended to exhibit higher soil chemical and biological fertility, but differences with monoculture systems were not statistically significant (Lagerlöf et al. 2014). Therefore, the detection of clear positive impacts of young shade trees on soil fertility in an intensively managed system is one of the main results of this study (Schaller et al. 2003). These positive impacts are all the more important considering the long-term trend of soil chemical and biological degradation under intensive monoculture coffee (Zhao et al. 2018a). The present study hence highlights the fact that shade trees can not only be part of long-

term solutions to produce more sustainable coffee, but can also have some immediate contributions to preservation and/or restoration of soil fertility. A reduction in mineral fertilizer inputs should complement this agro-ecological intensification and further contribute to preservation and/or restoration of soil fertility (Tschardt et al. 2011). Indeed, as shade trees grow, their root systems will increasingly reduce nutrient leakage (Cannavo et al. 2013; Tully et al. 2012) and their leaf litter will be an increasingly important component of nutrient cycling in coffee AFS (Tully and Lawrence 2011). I also expect that differences in impacts of shade tree species on soil fertility, which were not apparent in this study, will become more distinguishable as trees grow (Bagyaraj et al. 2015; Tumwebaze et al. 2012). According to the local ecological knowledge of coffee farmers in southern Yunnan documented in Chapter IV, *B. javanica* should eventually outperform other shade tree species for preservation and/or restoration of soil fertility. According to that same chapter, *Artocarpus heterophyllus*, *Melia azedarach* and the N-fixing *Leucaena leucocephala* would also highly benefit soil fertility.

4.5. Conclusion

This study demonstrated a clear positive and rapid impact of shade trees on soil fertility in the 0-20 cm soil layer, only four years after their introduction into previously monoculture coffee farms. This improvement in soil fertility translated in higher soil chemical fertility below shaded coffee trees than below open coffee, more abundant fungi communities all year long and a buffering effect during the dry season on all soil microbial communities under shade tree canopies compared to open areas. These results are particularly important in light of the long-term soil degradation documented in intensively-managed monoculture coffee farms. They indicate that agroforestry practices can not only be part of long-term solutions for more sustainable coffee systems, but that shade trees can also quickly contribute to preserving and/or restoring soil fertility.

The introduction of shade trees in coffee systems should then be complemented with changes in management practices, notably through a reduction of the currently excessive fertilizer inputs. This would result in a comprehensive agro-ecological intensification supported by the provision of ecosystem services by shade trees, whether these are improvement in superficial soil chemical and biological fertility, reduced nutrient leakage in deep soil layers or enhanced nutrient cycles through abundant leaf litter. Altogether, this agro-ecological intensification would contribute to the production of more sustainable coffee in southern Yunnan.

4.6. Supporting information

4.6.1. Soil water profiles

Soil water content was measured twice towards the end of the dry season, in March 2017 and April 2018, and once after the peak of the rainy season, in September 2017. Soil was sampled with an auger from 0 to 120 cm depths at 20 cm intervals. Soil samples were weighed in the field then dried in an oven at 105°C for 48 h. A total of 36 soil water profiles were derived from the measurements; 9 under each of the 3 selected shade tree species and 9 in full sun. One of the terraces had a sandy 60-80 cm soil horizon that contrasted with the rest of the study site. Soil water content measurements were therefore stopped at 60 cm depth for this terrace.

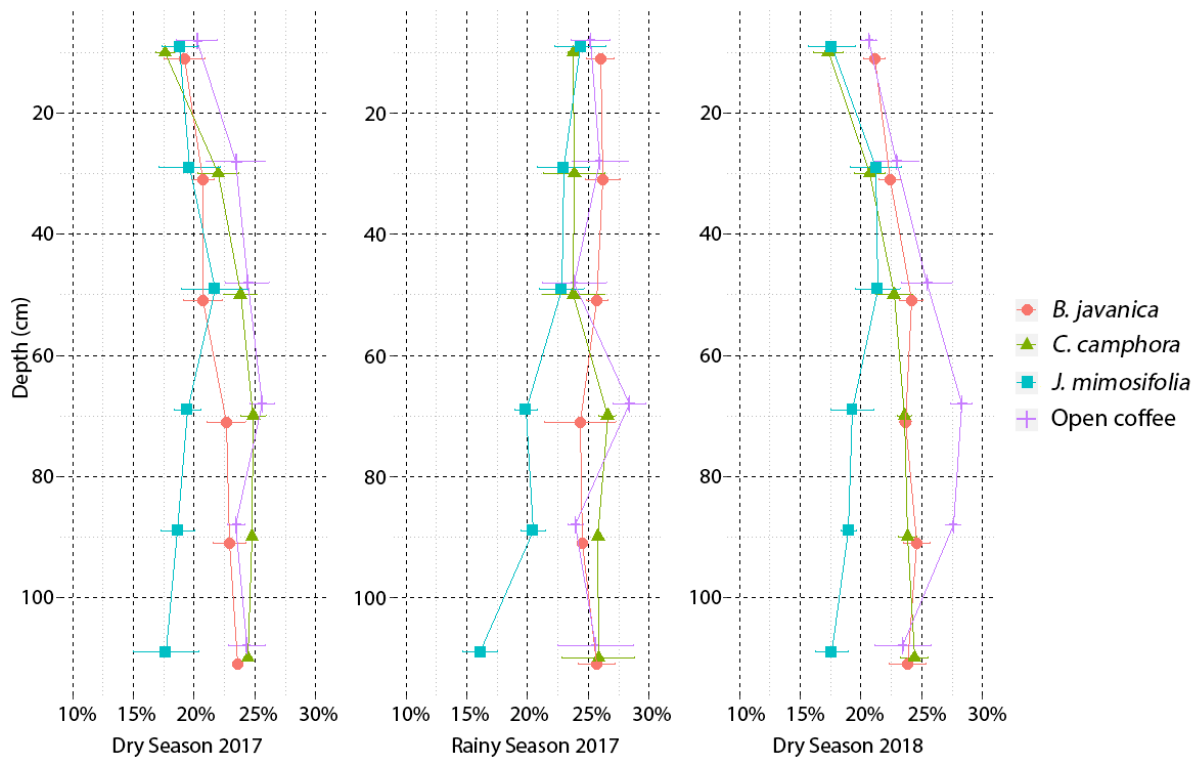


Figure 4-4: Soil water profiles dug under each of the 3 selected shade tree species and in open areas (replicates = 3)

Soil gravimetric water content ranged from 17 to 28% (Figure 4-4). Soils under *C. camphora*, *J. mimosifolia* and in open conditions followed a similar fluctuation pattern. Water recharge during the rainy season was most noticeable in the upper 40 cm; the top 20 cm soil water content increased by 5 to 7%, and the 20-40 cm depth water content increased by 2 to 5%. Below 40 cm, water content was stable, with seasonal fluctuations below 2%. Water recharge between

March and September 2017 was higher under *B. Javanica*, with 5 to 7% water content increase in the 0-60 cm soil horizon. There was no noticeable seasonal fluctuation below 60 cm depth.

Soil water content measured in January 2018 at the 0-20 cm soil depth showed intermediate values between those of the rainy and the dry seasons, averaging 23%. Seasonal fluctuations ranged from 1.5% in inter-rows to 2.8% under coffee rows. Shade trees had no significant impact on soil water content in the top 20 cm horizon.

Arabica coffee grows best in areas with 1400 to 2000 mm of annual rainfall, 1 to 3 dry months necessary to trigger flowering and a rainy season concomitant to fruit development (Carr 2001; Descroix and Snoeck 2008). These conditions were met in the present study and explain the absence of hydric stress found in the present study. Indeed, soil water profiles (Figure 4-4) show that coffee trees and shade trees mostly used water from the 0-40 cm soil layer. All root systems extended deeper than 1m deep so coffee trees and shade trees also have access to deeper water pools in the event of severe droughts. Shade trees had no significant effect on soil water content. These results are in line with studies highlighting a complementary use of water resources by coffee trees and shade trees under sufficient precipitations in Costa Rica (Cannavo et al. 2011; Lin 2010; van Kanten and Vaast 2006). In contrast, coffee yield in Baoshan Prefecture, Yunnan Province, was dependent to irrigation practices due to a severe lack of rainfall with only 755 mm.yr⁻¹ (Liu et al. 2018).

4.6.2. Root system distribution

Vertical root distribution of coffee trees and shade trees was recorded using the root impact counting method (van Noordwijk et al. 2000). 4 trenches were dug parallel to the terraces, 1 for each shade tree species planted within a coffee row and 1 for full sun coffee. Trenches were 2 m wide and 1.2 m deep, located about 30 cm from the coffee and shade tree stems. Root intersections with the vertical plane were recorded using a 10 cm * 10 cm grid. Roots were categorized into 2 diameter classes: fine roots (≤ 2 mm) and coarse roots (> 2 mm). Roots from coffee trees and shade trees were distinguished based on color and odor. Trenches were extended to about 15 cm from coffee stems to observe a second profile wall following the same methodology (van Noordwijk et al. 2000). Vertical root distributions were converted as percentages of total root impacts per tree.

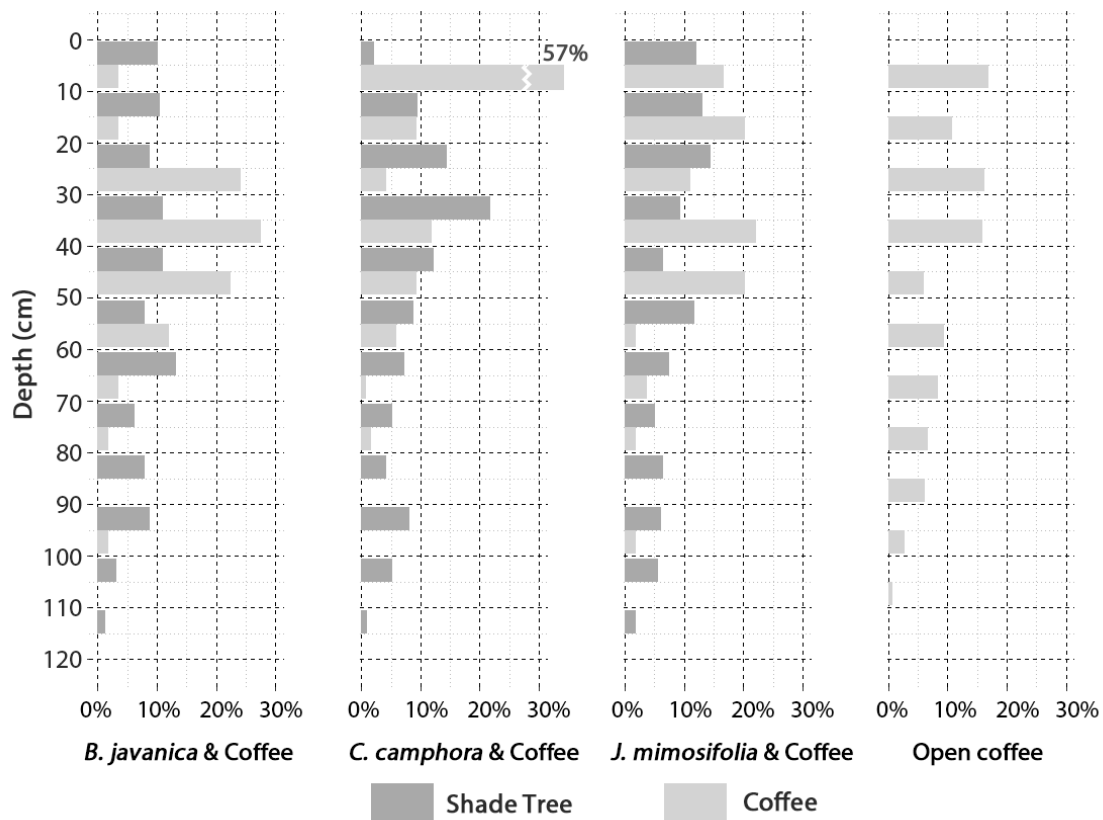


Figure 4-5: Root distribution of coffee trees and shade trees in three coffee-agroforestry systems (*B. javanica*, *C. camphora* and *J. mimosifolia*) and in coffee-monoculture (open coffee). Root counts are expressed in percentages

All shade tree root systems reached 120 cm depth (Figure 4-5), with approximately 70% of fine roots (≤ 2 mm) and 30% coarse roots (> 2 mm). In contrast, coffee roots were not recorded below 110 cm depth and exhibited proportionally more fine roots, with a 85:15 fine to coarse roots ratio. *Jacaranda mimosifolia* and *B. Javanica* roots were homogeneously distributed from 0 to 60 cm depth, with approximately 10% of root impacts per 10 cm layer, and a decreasing root concentration in deeper soil layers. In contrast, *C. camphora* had a very low root density in the top 10 cm horizon and half of its roots concentrated between 20 and 50 cm depths.

Open coffee trees had 60% of their roots located in the top 40 cm soil layer, and a decreasing root density in deeper soil layers, down to 110 cm depth. Vertical root distribution was most similar to open coffee one in the case of coffee trees shaded by *J. mimosifolia*, but significantly altered for coffee trees shaded by *B. javanica* and *C. camphora*. In the first case, 86% of roots were concentrated in the 20 to 60 cm soil layer, with less than 7% in the top 20 cm layer. On the contrary

under *C. camphora*, 57% of coffee roots were located in the top 10 cm soil layer and only 25% in the 10 to 40 cm layer.

With 75% of roots located in the 0-60 cm soil layer (Figure 4-5), coffee root systems in open conditions were similar to those documented in Costa Rica and Nicaragua (Defrenet et al. 2016; Padovan et al. 2015; Siles et al. 2010). Extensive colonization of the fertile 0-60 cm soil layer enabled a good access of coffee plants to nutrient and water resources. In comparison, the root systems of shade trees and shaded coffee trees illustrated three distinct scenarios (Figure 4-5). The low level of disturbance of coffee roots below *J. mimosifolia* illustrated complementarity between this shade tree species and coffee trees. *Bischofia javanica* exhibited a root profile similar to that of *J. mimosifolia* but was significantly more competitive in the 0-20 cm soil layer, where it nearly excluded coffee roots. Still, the absence of noticeable water stress as well as high coffee yield under *B. javanica* indicate that coffee roots could take up sufficient water and nutrient resources in the 20-60 cm soil layer. Lastly, *C. camphora* exhibited the most competitive root system of all shade tree species. It confined more than half of coffee roots into the top 0-10 cm soil layer. This could be especially detrimental to coffee trees in case of an extended dry season (Cannavo et al. 2011; Padovan et al. 2015). Already, coffee yield was lower below *C. camphora* than below other shade tree species or in open conditions.

4.6.3. Results of soil fertility analysis by tree species

Table 4-6: Soil chemistry as affected by position with respect to coffee row or inter-row under shade trees (*B. javanica*, *C. camphora*, *J. mimosifolia*) or sun (monoculture) (Mean \pm Standard Error, replicates = 6)

Row	Shade	pH (water 2.5:1)	SOM (g/kg)	N (g/kg)	P (mg/kg)	K (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)
Coffee row	<i>B. javanica</i>	5.1 (\pm 0.1)	26.2 (\pm 1.9)	1.5 (\pm 0.1)	52 (\pm 11)	0.35 (\pm 0.03)	3.02 (\pm 0.62)	0.30 (\pm 0.02)
Coffee row	<i>C. camphora</i>	4.9 (\pm 0.3)	29.8 (\pm 1.0)	1.7 (\pm 0.0)	115 (\pm 31)	0.59 (\pm 0.08)	3.27 (\pm 0.43)	0.55 (\pm 0.13)
Coffee row	<i>J. mimosifolia</i>	4.7 (\pm 0.1)	29.4 (\pm 2.8)	1.7 (\pm 0.1)	173 (\pm 43)	0.93 (\pm 0.20)	4.07 (\pm 0.64)	0.60 (\pm 0.11)
Coffee row	Pooled Trees	4.9 (\pm 0.1)	28.4 (\pm 1.1)	1.6 (\pm 0.0)	110 (\pm 20)	0.61 (\pm 0.08)	3.43 (\pm 0.33)	0.49 (\pm 0.06)
Coffee row	Sun	4.5 (\pm 0.1)	25.8 (\pm 1.2)	1.3 (\pm 0.1)	36 (\pm 10)	0.47 (\pm 0.05)	2.36 (\pm 0.43)	0.45 (\pm 0.06)
Inter-row	<i>B. javanica</i>	4.6 (\pm 0.1)	21.2 (\pm 0.8)	1.3 (\pm 0.1)	20 (\pm 12)	0.41 (\pm 0.02)	0.68 (\pm 0.07)	0.27 (\pm 0.03)
Inter-row	<i>C. camphora</i>	4.3 (\pm 0.0)	25.5 (\pm 1.3)	1.7 (\pm 0.1)	45 (\pm 11)	0.63 (\pm 0.05)	1.03 (\pm 0.12)	0.23 (\pm 0.03)
Inter-row	<i>J. mimosifolia</i>	4.6 (\pm 0.2)	26.7 (\pm 3.0)	1.6 (\pm 0.2)	35 (\pm 13)	0.92 (\pm 0.09)	2.24 (\pm 0.62)	0.48 (\pm 0.11)
Inter-row	Pooled Trees	4.5 (\pm 0.1)	24.2 (\pm 1.2)	1.6 (\pm 0.1)	34 (\pm 7)	0.67 (\pm 0.06)	1.30 (\pm 0.25)	0.32 (\pm 0.04)
Inter-row	Sun	4.6 (\pm 0.1)	22.0 (\pm 0.9)	1.4 (\pm 0.0)	27 (\pm 8)	0.60 (\pm 0.06)	1.00 (\pm 0.12)	0.33 (\pm 0.04)

Table 4-7: Soil communities as affected by position with respect to coffee row or inter-row under shade trees (*B. javanica*, *C. camphora*, *J. mimosifolia*) or sun (monoculture) (Mean \pm Standard Error, replicates = 6)

Season	Row	Shade	Nematodes log(ind.100g ⁻¹)	All PLFA nmol.g ⁻¹	Bacteria nmol.g ⁻¹	Gram+:Gram- ratio	Fungi nmol.g ⁻¹	AMF nmol.g ⁻¹	Fungi:Bacteria ratio
Rainy	Coffee row	<i>B. javanica</i>	5.5 (\pm 0.2)	52.0 (\pm 6.5)	37.0 (\pm 4.5)	2.9 (\pm 0.3)	3.4 (\pm 0.4)	1.4 (\pm 0.3)	0.091 (\pm 0.004)
Rainy	Coffee row	<i>C. camphora</i>	5.2 (\pm 0.0)	53.8 (\pm 2.5)	39.0 (\pm 1.9)	3.1 (\pm 0.1)	3.5 (\pm 0.3)	1.2 (\pm 0.2)	0.091 (\pm 0.007)
Rainy	Coffee row	<i>J. mimosifolia</i>	5.3 (\pm 0.1)	54.7 (\pm 10.1)	39.2 (\pm 6.9)	3.1 (\pm 0.3)	3.5 (\pm 0.7)	1.8 (\pm 0.5)	0.091 (\pm 0.001)
Rainy	Coffee row	Pooled Trees	5.3 (\pm 0.1)	53.4 (\pm 3.6)	38.3 (\pm 2.5)	3.0 (\pm 0.1)	3.5 (\pm 0.3)	1.4 (\pm 0.2)	0.091 (\pm 0.003)
Rainy	Coffee row	Sun	5.0 (\pm 0.1)	49.1 (\pm 4.4)	35.4 (\pm 3.1)	2.9 (\pm 0.1)	3.0 (\pm 0.3)	1.3 (\pm 0.2)	0.085 (\pm 0.004)
Rainy	Inter-row	<i>B. javanica</i>	4.6 (\pm 0.1)	44.4 (\pm 2.8)	32.9 (\pm 1.9)	2.8 (\pm 0.2)	2.7 (\pm 0.4)	1.0 (\pm 0.1)	0.080 (\pm 0.008)
Rainy	Inter-row	<i>C. camphora</i>	4.7 (\pm 0.1)	38.4 (\pm 3.7)	28.3 (\pm 2.6)	3.3 (\pm 0.1)	2.3 (\pm 0.5)	0.9 (\pm 0.0)	0.070 (\pm 0.005)
Rainy	Inter-row	<i>J. mimosifolia</i>	4.9 (\pm 0.2)	39.3 (\pm 3.5)	28.6 (\pm 2.5)	3.1 (\pm 0.0)	2.3 (\pm 0.1)	0.8 (\pm 0.1)	0.072 (\pm 0.005)
Rainy	Inter-row	Pooled Trees	4.7 (\pm 0.1)	41.1 (\pm 1.9)	30.2 (\pm 1.4)	3.1 (\pm 0.1)	2.4 (\pm 0.2)	0.9 (\pm 0.1)	0.074 (\pm 0.004)
Rainy	Inter-row	Sun	4.3 (\pm 0.1)	46.8 (\pm 6.4)	34.5 (\pm 4.6)	3.0 (\pm 0.2)	1.8 (\pm 0.2)	1.0 (\pm 0.1)	0.062 (\pm 0.004)
Dry	Coffee row	<i>B. javanica</i>	3.8 (\pm 0.2)	39.4 (\pm 3.8)	29.5 (\pm 3.0)	2.6 (\pm 0.1)	3.2 (\pm 0.5)	0.9 (\pm 0.1)	0.096 (\pm 0.003)
Dry	Coffee row	<i>C. camphora</i>	2.2 (\pm 0.5)	31.1 (\pm 5.6)	23.1 (\pm 4.2)	2.7 (\pm 0.1)	2.1 (\pm 0.3)	0.9 (\pm 0.1)	0.093 (\pm 0.005)
Dry	Coffee row	<i>J. mimosifolia</i>	2.4 (\pm 0.3)	32.9 (\pm 3.6)	25.3 (\pm 2.5)	2.4 (\pm 0.2)	2.2 (\pm 0.4)	0.8 (\pm 0.1)	0.084 (\pm 0.010)
Dry	Coffee row	Pooled Trees	2.8 (\pm 0.3)	34.5 (\pm 2.6)	26.0 (\pm 2.0)	2.6 (\pm 0.1)	2.5 (\pm 0.3)	0.8 (\pm 0.1)	0.091 (\pm 0.004)
Dry	Coffee row	Sun	3.0 (\pm 0.3)	21.1 (\pm 1.9)	16.0 (\pm 1.4)	2.7 (\pm 0.1)	1.4 (\pm 0.2)	0.5 (\pm 0.0)	0.088 (\pm 0.004)
Dry	Inter-row	<i>B. javanica</i>	2.2 (\pm 0.8)	34.0 (\pm 2.6)	28.2 (\pm 1.0)	2.6 (\pm 0.0)	2.1 (\pm 0.4)	0.6 (\pm 0.1)	0.077 (\pm 0.010)
Dry	Inter-row	<i>C. camphora</i>	2.1 (\pm 0.4)	23.5 (\pm 2.6)	17.5 (\pm 1.9)	3.2 (\pm 0.2)	1.6 (\pm 0.2)	0.4 (\pm 0.0)	0.091 (\pm 0.010)
Dry	Inter-row	<i>J. mimosifolia</i>	2.9 (\pm 0.3)	31.6 (\pm 4.2)	24.0 (\pm 3.1)	2.3 (\pm 0.1)	2.0 (\pm 0.4)	0.5 (\pm 0.1)	0.080 (\pm 0.006)
Dry	Inter-row	Pooled Trees	2.4 (\pm 0.3)	29.3 (\pm 2.1)	22.5 (\pm 1.7)	2.8 (\pm 0.1)	1.9 (\pm 0.2)	0.5 (\pm 0.0)	0.083 (\pm 0.005)
Dry	Inter-row	Sun	2.8 (\pm 0.3)	21.9 (\pm 1.9)	16.6 (\pm 1.4)	3.0 (\pm 0.1)	1.2 (\pm 0.1)	0.5 (\pm 0.1)	0.074 (\pm 0.005)

Table 4-8: Soil enzymatic activities as affected by position with respect to coffee row or inter-row under shade trees (*B. javanica*, *C. camphora*, *J. mimosifolia*) or sun (monoculture) and according to rainy and dry seasons (Mean \pm Standard Error, replicates = 6)

Season	Row	Shade	NAG $\mu\text{mol.g}^{-1}.\text{d}^{-1}$	BG $\mu\text{mol.g}^{-1}.\text{d}^{-1}$	ACP $\mu\text{mol.g}^{-1}.\text{d}^{-1}$
Rainy	Coffee row	<i>B. javanica</i>	32.8 (± 4.7)	32.5 (± 1.9)	65.1 (± 6.4)
Rainy	Coffee row	<i>C. camphora</i>	35.7 (± 2.4)	44.6 (± 6.1)	60.8 (± 4.2)
Rainy	Coffee row	<i>J. mimosifolia</i>	28.0 (± 2.0)	33.3 (± 3.0)	72.6 (± 4.8)
Rainy	Coffee row	Pooled Trees	32.4 (± 2.0)	37.3 (± 2.8)	65.8 (± 3.1)
Rainy	Coffee row	Sun	32.2 (± 1.5)	35.5 (± 3.1)	66.6 (± 3.5)
Rainy	Inter-row	<i>B. javanica</i>	28.2 (± 0.7)	36.9 (± 3.0)	40.2 (± 2.0)
Rainy	Inter-row	<i>C. camphora</i>	31.2 (± 2.1)	43.5 (± 1.5)	59.8 (± 4.9)
Rainy	Inter-row	<i>J. mimosifolia</i>	22.2 (± 3.0)	29.7 (± 2.4)	59.0 (± 6.8)
Rainy	Inter-row	Pooled Trees	27.5 (± 1.5)	36.7 (± 1.9)	52.6 (± 3.4)
Rainy	Inter-row	Sun	26.0 (± 1.5)	35.7 (± 3.4)	44.4 (± 3.6)
Dry	Coffee row	<i>B. javanica</i>	42.4 (± 4.2)	66.2 (± 6.2)	43.2 (± 1.0)
Dry	Coffee row	<i>C. camphora</i>	46.9 (± 3.3)	77.1 (± 11.3)	41.5 (± 2.6)
Dry	Coffee row	<i>J. mimosifolia</i>	35.8 (± 3.0)	51.1 (± 8.0)	53.3 (± 6.1)
Dry	Coffee row	Pooled Trees	42.1 (± 2.2)	65.6 (± 5.5)	46.0 (± 2.5)
Dry	Coffee row	Sun	37.6 (± 3.5)	62.7 (± 7.9)	44.3 (± 6.4)
Dry	Inter-row	<i>B. javanica</i>	40.5 (± 0.7)	78.6 (± 3.4)	63.7 (± 7.3)
Dry	Inter-row	<i>C. camphora</i>	44.4 (± 4.9)	87.6 (± 13.9)	31.8 (± 4.0)
Dry	Inter-row	<i>J. mimosifolia</i>	40.7 (± 4.5)	43.6 (± 6.0)	51.6 (± 8.9)
Dry	Inter-row	Pooled Trees	42.1 (± 2.4)	70.5 (± 7.7)	49.0 (± 5.2)
Dry	Inter-row	Sun	43.6 (± 3.1)	69.5 (± 7.8)	35.2 (± 3.1)

CHAPTER 5 - Impact of shade trees on coffee yield and quality

5.1. Introduction

Coffea arabica is a shade-adapted species that originated in the high tropical forests of Ethiopia (Batista et al. 2012). Its saturation irradiance threshold for photosynthesis is low, between 300 and 600 $\mu\text{mol photon.m}^{-2}.\text{s}^{-1}$ (Franck and Vaast 2009), compared to a photosynthetic active radiation regularly above 2000 $\mu\text{mol photon.m}^{-2}.\text{s}^{-1}$ in open conditions around middays (Chaves et al. 2007). Furthermore, coffee leaves in open conditions regularly experience photoinhibition around midday and in the afternoon from temperatures above 30°C and vapor pressure deficit (VPD) above 1.5kPa (Franck and Vaast 2009). In these conditions, shade trees can create a favorable above-ground environment below their canopies, lowering temperatures and VPD (Chaves et al. 2007; DaMatta et al. 2018) while maintaining a photosynthetic active radiation above saturation irradiance if their canopies is not too dense (Charbonnier et al. 2013; Siles et al. 2010). In addition, coffee trees lack efficient mechanisms to regulate fruit set. In open conditions, large flowering events and high fruit sets result in high competition between fruits for water resources during the expansion stage (Cannell 1974), and high competition for nutrients and carbohydrates during the bean filling stage and the maturation stage. Lack of resources in turn leads coffee trees to shed numerous fruits during the coffee cherry development cycle (Bote and Jan 2016). It also contributes to smaller and lighter coffee cherries at harvest, compared to cherries from shaded conditions. Furthermore, fruits act as priority sinks for carbohydrates and nutrients (Bote and Jan 2016). High fruit sets therefore hinder vegetative growth (Cannell 1971), lower the amount of newly produced fruiting nodes and flowers per node and hence hinder yield in the following year (Cannell 1985). This in turn leads to the well-documented biannual pattern in coffee production, when high yield alternate with low yield. All these reasons partly explains why coffee yield in shaded conditions can be similar to or higher than coffee yield in open conditions (Bote and Jan 2016; Vaast et al. 2008). Shade trees are also known to impact coffee quality. In sub-optimal conditions, shade and elevation similarly delay coffee ripening (Geromel et al. 2008; Vaast et al. 2006), allowing for a better filling of the beans and higher physical, chemical and organoleptic attributes (Bertrand et al. 2006; Bote and Vos 2017; Tolessa et al. 2017). However, shade can also become detrimental in optimal conditions or under high elevations (Bosselmann et al. 2009; Rahn et al. 2018).

In this chapter, I studied the impacts of young shade trees providing a gradient of shade intensity on micro-climate, coffee development cycle, coffee yield and coffee quality. Overall, I researched whether or not young shade trees provided ecosystem services similar to those provided by mature shade trees, albeit at a smaller scale. More specifically, our first hypothesis was that young shade trees delayed coffee

phenophases, from flowering to cherry ripeness. Second, I expected young shade trees to decrease coffee flower set as well as fruit losses throughout the coffee cherry development cycle. Third, I hypothesized that young shade trees would hinder coffee yield but increase coffee quality.

5.2. Materials and methods

5.2.1. Experimental design

This chapter relies on the same experimental set up as that used in chapter 4. The study site is described in details in Chapter 2.2. Fieldwork was conducted from November 2016 to March 2018. The same six replicates of *B. javanica*, *C. camphora* and *J. mimosifolia* were used in this experiment, for a total of 18 shade trees. Between four and eight coffee trees were selected around each shade tree, for a total of 90 coffee trees. They were categorized as follow: 40 fully located below shade tree canopies (C1 = shaded coffee); 24 located below the edge of shade tree canopies or being the first or second coffee trees encountered outside of shade tree canopies (C2 = buffer coffee); and 26 located further away from shade tree canopies (C3 = open coffee).

5.2.2. Shade characterization

Leaf area index (LAI) was used as a proxy for shade intensity throughout the 2017-2018 fruit development cycle. To estimate LAI, three replicates were selected for each shade tree species. Their leaves were periodically counted (*B. javanica* and *J. mimosifolia*) or extrapolated from a sub-sample of branches (*C. camphora*) from February 2017 to March 2018. At each occurrence, 15 representative leaves were harvested, scanned, and their areas measured using the image analysis software ImageJ 1.50i. LAI was obtained by multiplying the number of leaves by their mean area, and dividing this number by the area of canopy projected to the ground. LAI was then averaged within shade tree species.

5.2.3. Micro-climate characterization

Air temperature and relative humidity were recorded every 30 minutes by four data loggers (ibuttons DS1923-F5#). The data loggers were mounted both below shade tree canopies (C1) and in open conditions (C3). In both cases (C1 and C3), data loggers were placed directly above coffee trees and protected from direct sunlight. Following a cold spell in December, damages on coffee leaves were evaluated through a visual assessment, ranking coffee trees from 0 (no visible damage) to 5 (all new leaves were damaged and/or aborted). Temperature data was combined with the dates of blossom peak and harvest

peak to calculate growing degree days (DD) of coffee cherries for each coffee tree, using a base temperature of 10°C (Pezzopane et al. 2012; Rahn et al. 2018). Furthermore, monthly maximum temperatures (T_{\max}) were calculated as the average of maximum daily temperatures for each month. Monthly minimum temperatures (T_{\min}) and monthly average temperatures (T_{avg}) were calculated in the same way. Monthly wind speed and sunshine hours were retrieved from the weather station in Pu'er city airport, through LocClim 1.10 software. Monthly vapor pressure deficit (VPD) and monthly potential evapotranspiration of coffee trees (ET_0 in open areas, ET_c in shaded areas) were estimated according to Allen et al. (1998). In shaded areas, ET_c was calculated for the coffee trees themselves, excluding the evapotranspiration of the shade trees in their direct vicinity.

5.2.4. Fruit development cycle

Coffee cherry development was studied throughout the growing season 2017-2018, from first flowers to final harvest, on each of the 90 selected coffee trees. To do so, the two stems with most productive branches were selected from each coffee tree before the first flowering event. Three to five productive branches were then selected on each of these stems: three branches if fewer than 20 productive branches were recorded, four branches if fewer than 25 productive branches were recorded, and five branches otherwise. These branches were selected following an ascending spiraling pattern in order to be representative of all heights and orientations. They were carefully tagged and used for all subsequent follow-up activities.

The number of flower buds, flowers, fruits (from pinheads to ripe cherries), and aborted fruits were periodically counted on each tagged branch. Counting activities were carried out in March (twice), April, and May to encompass all the main flowering events. Because both flowering events in March were modest, they were aggregated and analyzed together. Blossom peak was defined as the weighted average date of flowering, with weights corresponding to the percentage of blossom at each counting event. Two more counting activities occurred in June and September to follow-up fruit shedding during swelling and filling stages. A last counting was carried out in November 2017, one month before the start of harvest. Green coffee cherries on branches suffering from die-back and *C. coffeanum* were considered unable to reach a ripeness degree suitable for harvest, and were considered aborted in November. Data from May served as the reference point to correct indistinguishable flower buds from previous counting activities and aborted fruits in subsequent counting. Data was multiplied by the number of productive branches to extrapolate results to the coffee tree.

5.2.5. Coffee yield

In the studied area, coffee harvest occurs during the dry season, from November to February, with a peak in December and January. Yields were recorded over 2 consecutive harvests - in 2016-2017 and 2017-2018 - to encompass the well-documented biannual cycle of coffee production (DaMatta 2004). In November 2016, coffee yield was estimated from fruit load two weeks prior to harvest. A sample of 309 coffee trees was selected and categorized as C1 (44%), C2 (35%), and C3 (21%). The number of productive branches was recorded and coffee cherries counted on 20% of them. Fruit load was then extrapolated to coffee trees.

In year two (2017-2018), fruit loads from the 90 monitored coffee trees were derived from counting activities that occurred in November 2017. Fully ripe coffee cherries (exhibiting dark red pericarps) were then harvested in three harvests, from mid-December to mid-February, and weighed in the field. When a coffee tree was at peak ripeness, with more than 40% of its cherries being ripe, then all cherries were harvested at once. Days after flowering (DAF) was estimated based on blossom peak and harvest peak. After cherries were weighed in the field, the weight of green cherries was multiplied by a 1.22 factor to account for the lower density of the yet-to-ripen cherries. This 1.22 factor was derived from field measurements in February 2018. A linear relationship between fruit loads and measured yields was then established through regression analysis for the 2017-2018 crop. This equation was then used to estimate yields for the 2016-2017 crop.

5.2.6. Coffee quality

At harvest peak, samples of fully ripe coffee cherries were set aside and used to assess coffee quality through physical and organoleptic attributes. First, the average weight of the coffee cherries was determined in the field from a subsample of 100 cherries. Due to small sample size from individual coffee trees, samples from coffee trees located in the same category (C1 to C3) and under the same shade tree replicate were aggregated for subsequent quality assessment. Samples were then wet-processed on the day they were harvested. Specifically, samples were depulped with a small mechanical drum pulper, kept separated in fine mesh bags and put to fermentation in a bucket of water until mucilage could easily detach from the endocarp (12 to 18 hr). Samples were then washed manually, left to dry in the sun until humidity content reached around 11%, and then stored appropriately. In April, parchment was hulled, green beans were weighed and tested for density, and the percentage of beans over sieve size 16 (16/64 in) was measured.

After beans with visual defects were manually removed, 52 samples of 100 g green beans were roasted to a light-medium roast. The following day, a panel of 11 professional cuppers assessed beverage quality after a round of calibration using a standard wet-processed Yunnan coffee. Cupping took place in 5 rounds of 9 samples and 1 round of 6 samples, using the Sustainable Coffee Institute cupping form. Three 200 mL infusions were prepared with 11 g of coffee per cup. In addition, two cups of the standard coffee used for calibration were added at each end of the cupping tables. Cuppers evaluated the following organoleptic attributes on a scale from 6 to 10 with 0.25 increments: fragrance, aroma, flavor, acidity, body, sweetness, and pleasant aftertaste. Three additional attributes were used to evaluate defects - fresh crop, off-flavor, and uniformity - and were each rated 10 points in the absence of noticeable defect. Samples with too light (coffee crust self-breaks) or too dark (oil on the beans and smoky flavor) a roast were noted and discarded. Results from 1 cupper were found inconsistent with results from the 10 others and thus excluded from analysis. Scores of individual attributes were averaged among cuppers and summed up to get a total score out of 100 points.

5.2.7. Data analysis

Parameters related to fruit development, coffee yield, and coffee quality were analyzed separately through analysis of variance (ANOVA). Data normality was tested with Shapiro's test, and homogeneity of variances with Levene's test. Data was log-transformed to meet these assumptions whenever necessary. Terraces were considered as a random effect in the ANOVA model, to account for small-scale variability in soil fertility and fertilizer inputs. Significant groups were separated with Wilcoxon's test. All results were expressed as mean \pm standard error.

A redundancy analysis (RDA) was performed to explain organoleptic quality parameters from a matrix of explanatory variables that included shade tree species, coffee category, coffee yield, percentage of aborted fruits, DD, ET_c/ET_0 , month of harvest peak, and physical quality indicators. The most discriminating variables were selected through a forward procedure and tested for significance with 1000 permutations, using the vegan package in R3.4.4 (Oksanen et al. 2018).

5.3. Results

5.3.1. Shade and micro-climate

LAI of *C. camphora* was steady throughout the year, averaging 6.3 ± 0.6 (Figure 5-1). LAI of *B. javanica* and *J. mimosifolia* increased with the development of new leaves in the spring, averaging 2.1 ± 0.6

and 0.7 ± 0.2 in April 2017, respectively. Their LAI peaked around September, reaching 3.1 ± 0.3 and 2.4 ± 0.1 , respectively, then decreasing when the trees shed their leaves in February 2018. Throughout the year, canopies of *C. camphora* were denser than those of *B. javanica*, which in turn were denser than those of *J. mimosifolia*.

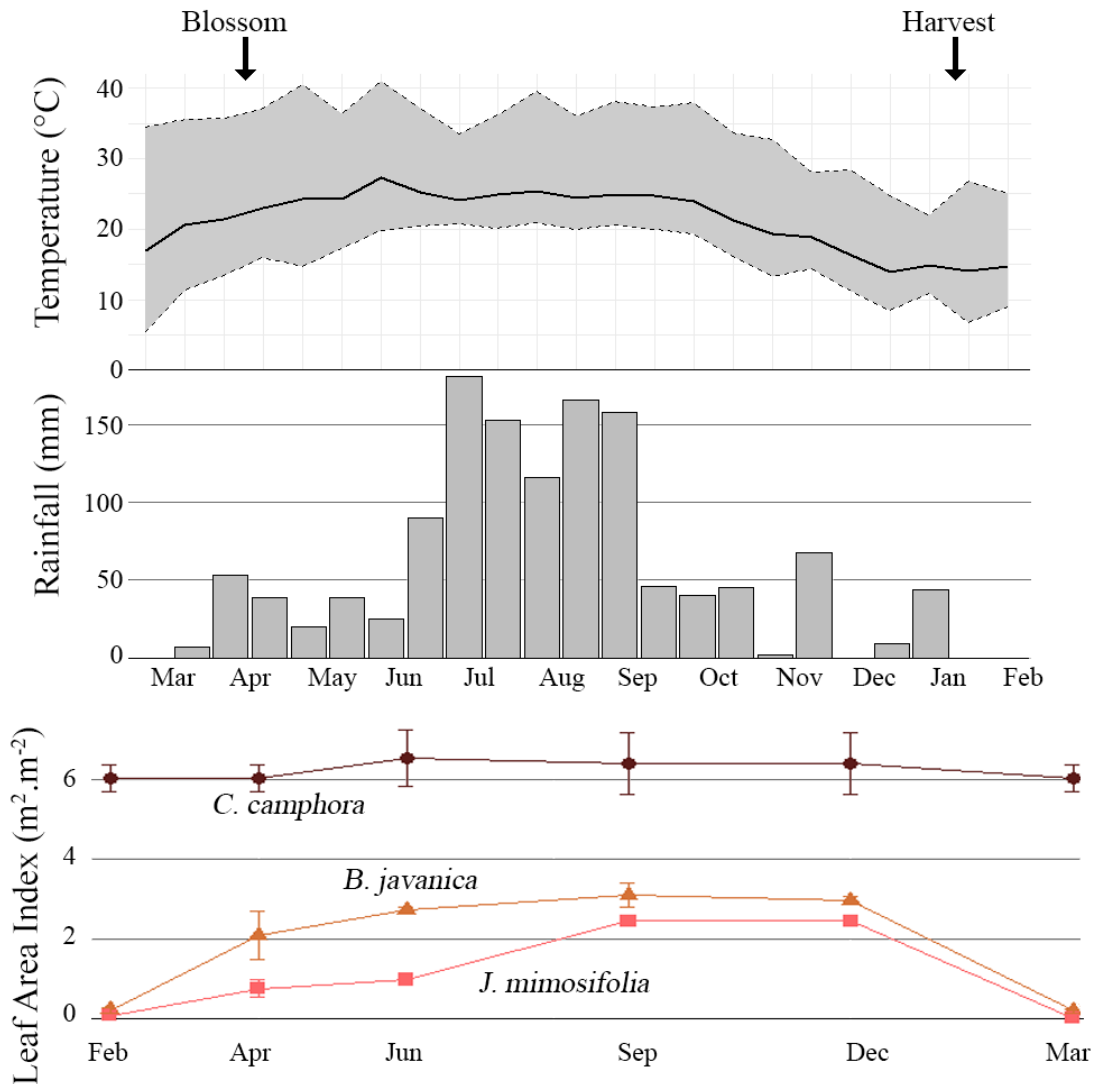


Figure 5-1: Climatic data in 2017 in open areas averaged over half-month periods. Minimum, maximum and average temperatures (top) and rainfall (middle). Leaf area index of the 3 selected shade tree species (bottom) (mean \pm se, n=3)

Yearly average temperatures were similar in open conditions and under *J. mimosifolia*, averaging 21.2°C (Figure 5-1). In comparison, yearly average temperatures below *B. javanica* and *C. camphora* averaged 20.8 and 20.1°C , respectively. In August, the hottest month of the rainy season during 2017, T_{avg}

reached 24.9°C in open conditions, whereas T_{avg} under shade ranged from 23.1 to 24.3°C. In January, the coldest month of the dry season during 2017-2018, T_{avg} reached 14.5°C in open conditions. The same month, T_{avg} reached 15.3°C under *J. mimosifolia*, 14.7°C under *B. javanica*, and 14.0°C under *C. camphora*.

T_{max} was always higher in open conditions than under shade trees, except in December 2017 and January 2018. In June, at the end of the dry period, T_{max} peaked at 39.1°C in open conditions. During the same month, T_{max} reached 36.0°C under *J. mimosifolia*, 33.4°C under *B. javanica*, and 32.9°C under *C. camphora*. In August, T_{max} reached 37.8°C in open conditions, 31.4°C under *J. mimosifolia* and *B. javanica*, and 29.1°C under *C. camphora*.

T_{min} was similar throughout the year in open conditions and under *C. camphora*, and was on average 0.5°C lower than T_{min} under *B. javanica* and *J. mimosifolia*. In December, T_{min} reached 9.8°C in open conditions, compared to 9.9°C under *C. camphora*, 10.3°C under *B. javanica*, and 10.6°C under *J. mimosifolia*. During the sole frost event of the recorded growing period (the night of December 20th to 21st), temperatures recorded in open conditions reached 0°C twice (at roughly 6am and 8am); however, the temperatures under shade trees was always 0.5 to 1°C higher (Figure 5-2). The buffering effect from shade trees was confirmed in February through a visual assessment showing a clear and significant trend of increasing damage with decreasing shade ($p < 10^{-5}$). On the scale of damages ranging from 0 to 5, C1 coffee trees averaged 0.88 ± 0.17 , C2 coffee trees averaged 1.74 ± 0.34 , and C3 coffee trees averaged 2.91 ± 0.37 .

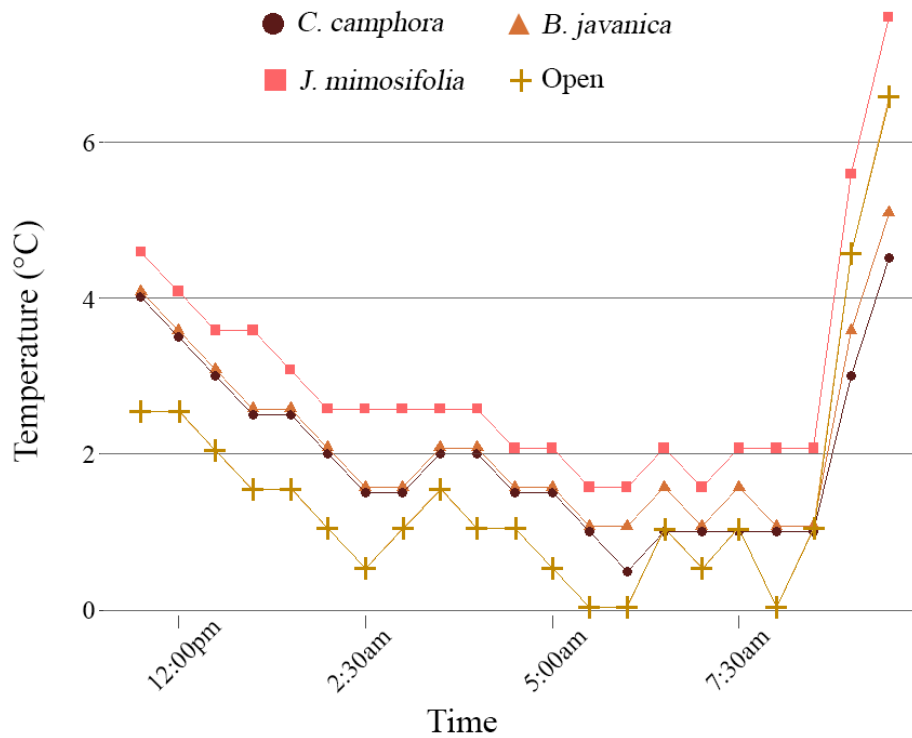


Figure 5-2: Temperatures recorded under shade trees and in open areas during the cold spell, December 21st 2017

Shade trees also significantly impacted VPD. Yearly VPD averaged 1.6 kPa in open conditions, as compared with 1.0 kPa under *C. camphora*, 1.2 kPa under *B. javanica*, and 1.3 kPa under *J. mimosifolia*. During the 2nd half of the dry season, from March to June, VPD was on average 0.5 kPa higher in open conditions than under shade. The difference between open and shaded conditions further increased to an average of +0.9 kPa during the rainy season (August to October), before leveling off in winter (December to February).

5.3.2. Fruit growing period

Coffee trees at the edge of *B. javanica*, and those in open conditions, were the first to bloom, with average blossom peaks between April 13th and April 15th (± 2 days). Coffee trees below *C. camphora* were the last to bloom, doing so on April 25th on average (± 2 days). All other coffee trees bloomed on average between April 18th and April 21st. Furthermore, shade delayed the average date of harvest peak. Coffee trees in open conditions (C3) reached harvest peak around January 13th (± 6 days); those at the edge of shade trees (C2) reached harvest peak around January 27th (± 5 days); and coffee trees below shade trees (C1) reached harvest peak around January 31st (± 4 days). Overall, there was a trend of increasing DAF with shade

intensity, but it was not significant; C3 coffee trees were harvested 273 days (± 6), C2 coffee trees 282 days (± 4), and C1 coffee trees 285 days (± 4) after blossom peak.

The number of DD decreased with shade intensity (Figure 5-3). It took 3380 to 3470 DD for coffee fruits to reach ripeness in open conditions under *J. mimosifolia*.; 3200 ± 40 DD under *B. javanica*, an amount 5% lower than in open conditions; and 2990 ± 40 DD under *C. camphora*, an amount 12% lower than in open conditions. Similarly, ET_c and ET_0 decreased with shade intensity (Figure 5-3). ET_c and ET_0 between blossom peak and harvest peak reached 880 ± 10 mm both in open conditions and under *J. mimosifolia*. In comparison, ET_c ranged from 790 to 800 ± 20 mm under *B. javanica* and *C. camphora*, an amount 10% lower than in open conditions.

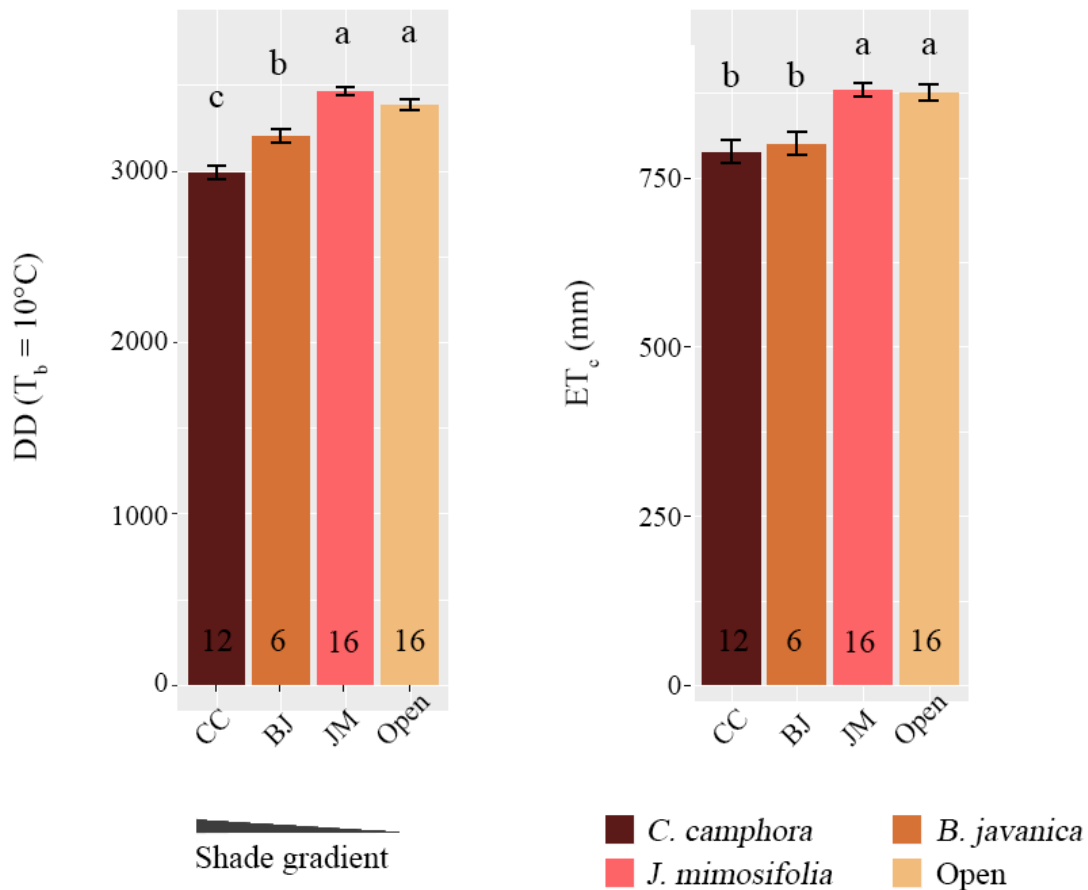


Figure 5-3: Growing degree days (DD, left) and potential evapotranspiration of coffee trees from blossom peak to harvest peak (ET_c , right) in 3 coffee agroforestry systems (BJ: *B. javanica*; CC: *C. camphora* and JM: *J. mimosifolia*) and in coffee monoculture (Open) (mean \pm se, letters indicate significant Wilcoxon groups and numbers indicate replicates)

5.3.3. Fruit development cycle

Results describing the coffee cherry development cycle are presented in absolute values (Figure 5-4) and percentages (Figure 5-5). The amount of flower buds per coffee tree recorded in March 2017 (the beginning of the growing season) showed a marked correlation with shade intensity. Coffee trees below *C. camphora* had the least flower buds (7900 ± 1790), while coffee trees in open conditions had the most numerous flower buds (14860 ± 1580). Coffee trees under intermediary shade intensities, either located below *B. javanica* or *J. mimosifolia*, or at the edge of shade trees, exhibited intermediary amounts of flower buds (9020 to 13820).

Two small blooming events took place in March, followed by two larger blooming events in April and May (Figure 5-5). The cumulative percentage of flowers which bloomed in March and April was a function of shade intensity. Coffee trees below *C. camphora* exhibited the lowest percentage of flowers that bloomed within these 2 months ($35 \pm 7\%$). Coffee trees which showed the largest bloom in this period of time were those located at the edge of *B. javanica* ($74 \pm 4\%$), followed by those located in open conditions ($64 \pm 2\%$). Coffee trees under intermediary shade intensities exhibited intermediate percentages (46 to 60%). For all coffee trees, the majority of flowers had bloomed by the end of April. The only exception was coffee trees below *C. camphora*, which had a higher percentage of flowers blooming during the May flowering event ($50 \pm 5\%$) than the cumulative percentage from March and April ($35 \pm 7\%$). It should be noted that the temporal pattern of early versus late flowering was already visible by the end of March, with the lowest percentage of blooming flowers on coffee trees under *C. camphora* (2%), and the largest number of open flowers on coffee trees at either the edge of *B. javanica* or in open conditions (8 to 12%). Lastly, 3 to 13% of flower buds had not bloomed by the end of May and were counted as aborted from June onward.

In June, fruits were either in the pinhead stage or entering the expansion stage, and 14 to 20% of all flower buds were counted as aborted (Figure 5-5). Coffee trees under *B. javanica* and in open conditions counted comparatively more aborted fruits than coffee trees under *C. camphora*, but differences were relatively small with a maximum of 6% difference between shade intensities. Fruit loads in June still reflected flower sets (Figure 5-4), with the least fruits found under *C. camphora* (6560 ± 1340), and the most fruits found on coffee trees in open conditions (11730 ± 1260).

Coffee trees all shed a large percentage of their fruit during the summer. In early September, only $43 \pm 4\%$ of flower sets remained on trees as coffee cherries, irrespective of shade intensity (Figure 5-5). Coffee trees continued shedding fruit between September and November, when cherries entered the filling

and ripening stages. During this time, relative losses were markedly higher with decreasing shade. Coffee trees below shade trees (C1) shed $7 \pm 1\%$, coffee trees at the edge of shade trees (C2) shed $10 \pm 1\%$, and coffee trees in open conditions (C3) shed $17 \pm 2\%$ of their cherries. As a result, fruit loads were all similar at the beginning of the harvest (2910 to 4290), despite higher fruit sets in open conditions and under light shade intensity (Figure 5-4). Only coffee trees below *C. camphora* had significantly fewer cherries (2,422 \pm 412).

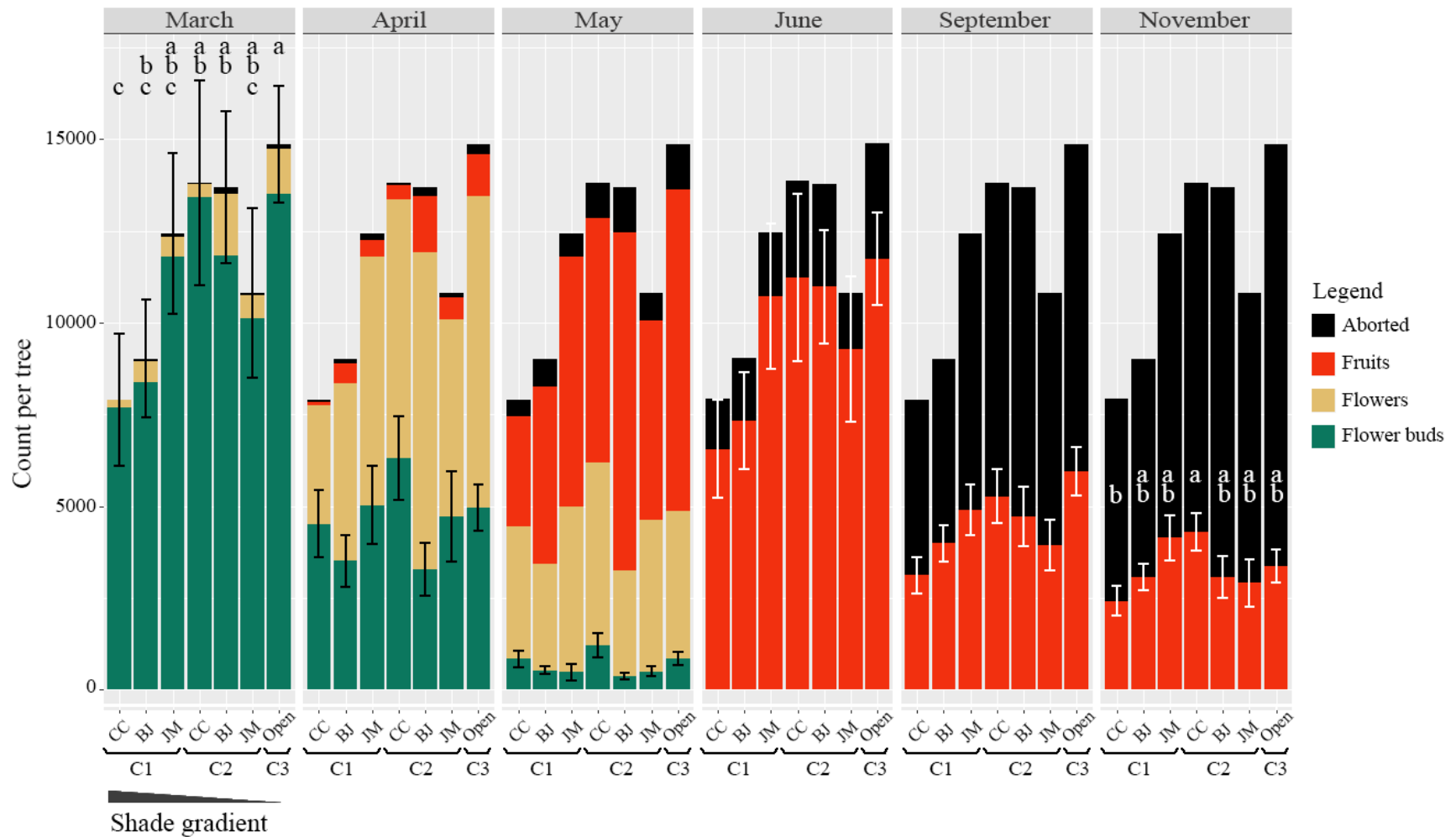


Figure 5-4: Coffee cherry development cycle in 2017 in three coffee-agroforestry systems (*B. javanica*, *C. camphora* and *J. mimosifolia*), at different distance from shade trees (C1: below shade tree canopy, C2: at the edge of shade tree canopy, C3: open coffee) (mean \pm se, letters indicate significant groups)

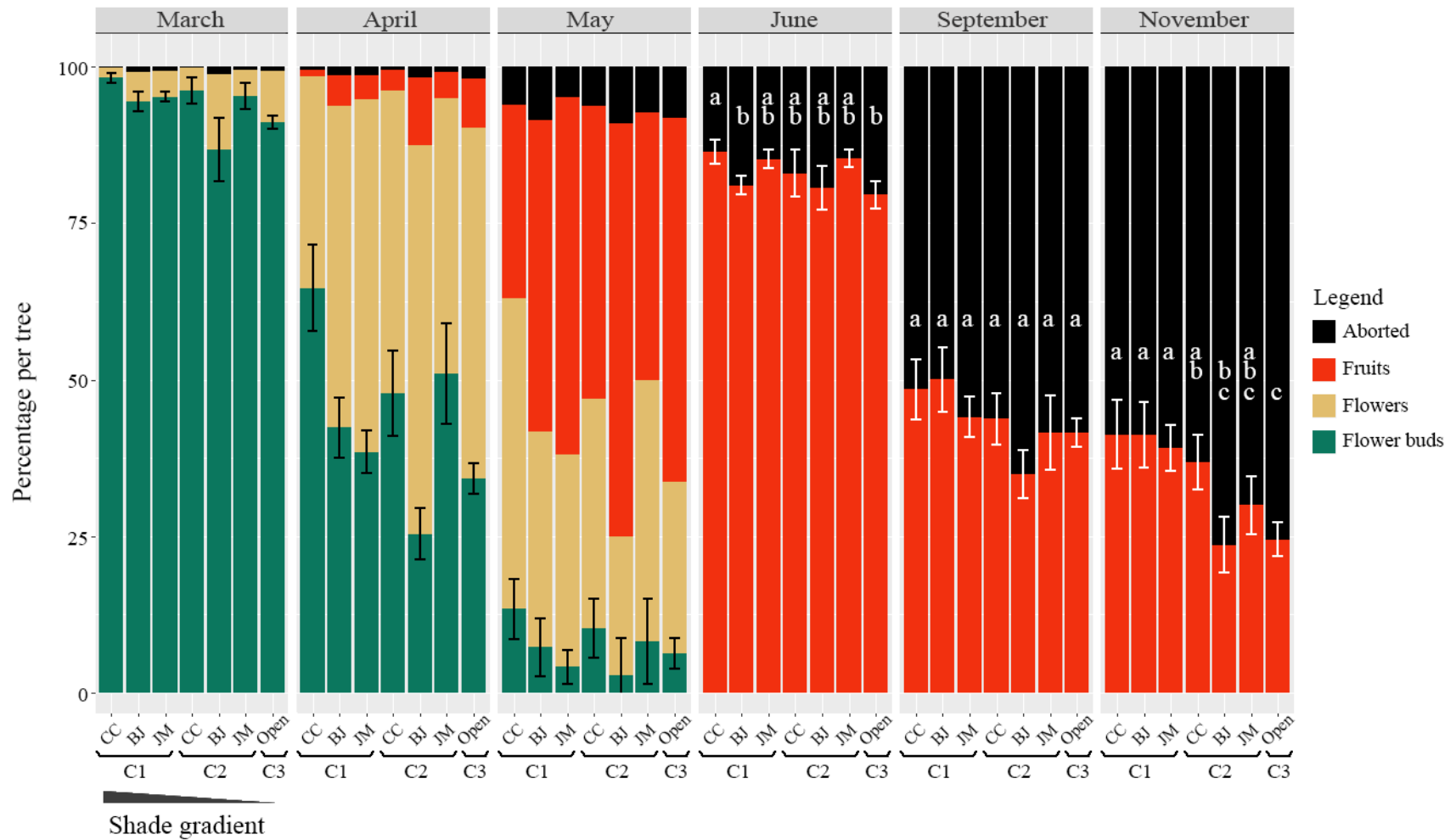


Figure 5-5: Coffee cherry development cycle shown in percentages in 2017 in three coffee-agroforestry systems (*B. javanica*, *C. camphora* and *J. mimosifolia*), at different distance from shade trees (C1: below shade tree canopy, C2: at the edge of shade tree canopy, C3: open coffee) (mean \pm se, letters indicate significant groups)

5.3.4. Coffee yield

In 2016-2017, coffee trees under *C. camphora* produced the lowest yields ($2380 \pm 160 \text{ g.tree}^{-1}$) (Fig 6). In comparison, all other coffee trees yielded on average 2760 to 2930 g.tree^{-1} . In 2017-2018, coffee yields ($4460 \pm 270 \text{ g.tree}^{-1}$) were on average 60% higher than that of the previous year ($2800 \pm 80 \text{ g.tree}^{-1}$). These yields were equivalent to 3.7 and 2.3 t.ha^{-1} in green coffee beans, respectively, based on a density of 5000 coffee trees. ha^{-1} and a 6-to-1 cherry to bean ratio. In 2017-2018, coffee trees under *C. camphora* once again produced the lowest yields ($2760 \pm 380 \text{ g.tree}^{-1}$), significantly lower than those of all other coffee trees (4650 to 5710 g.tree^{-1}), irrespective of shade intensity.

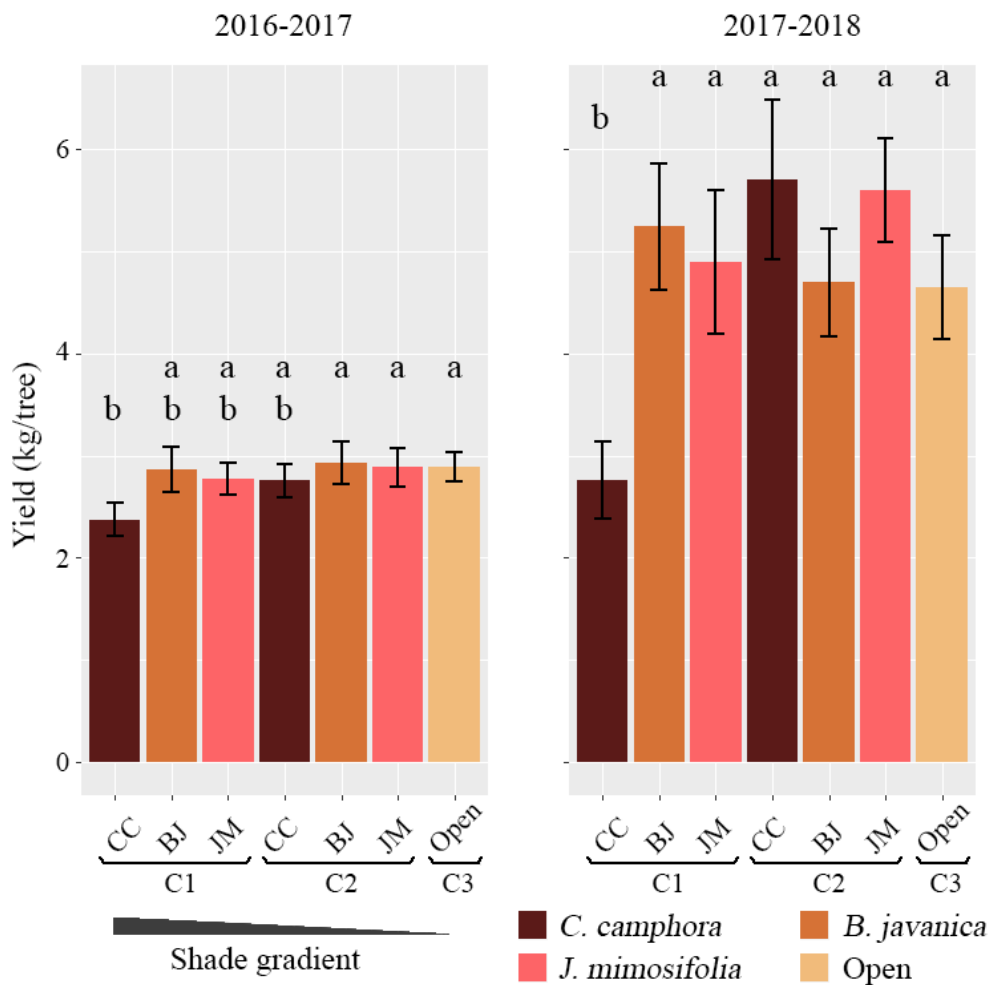


Figure 5-6: Coffee yields for two consecutive years in three coffee-agroforestry systems (*B. javanica*, *C. camphora* and *J. mimosifolia*), at different distance from shade trees (C1: below shade tree canopy, C2: at the edge of shade tree canopy, C3: open coffee) (mean \pm se, letters indicate significant groups)

5.3.5. Coffee quality

No significant differences in physical and organoleptic attributes were detected amongst shade treatments and coffee categories. On average, 68.6 ± 0.9 cherries were collected per 100 g of coffee cherries harvested. Once processed, green beans weighted $643 \pm 2 \text{ g.L}^{-1}$, and $74 \pm 1\%$ of bean weight was of size 16 or higher. All organoleptic attributes were rated between 7.2 and 7.6 out of 10, and no defects were detected. Total scores of coffee cupping ranged from 80.6 to 82.5, averaging 81.6 ± 0.1 out of 100.

Shade tree species, coffee category, coffee yield, percentage of aborted fruits, DD, ET_c and ET_0 , cherry density, and green bean density did not significantly explain variability in cupping scores. Coffee organoleptic attributes were best explained by month of harvest and green bean size (Figure 5-7). These two variables explained 37% of variability in coffee cupping scores. Coffee samples from mid-harvest (January) were those most positively correlated with high scores in acidity, aftertaste, body, flavor, sweetness, and total scores. Coffee samples collected during the latest round of harvest (February), were those most negatively correlated with these attributes. This resulted in higher total cupping scores for coffee samples harvested in January than those harvested in February (Figure 5-8). Total cupping scores were also positively correlated with percentages of large green beans, mostly through higher scores in fragrance and aroma (Figure 5-7). However, there was no significant difference between the percentages of large beans found in coffee samples grouped by harvest date (Figure 5-8).

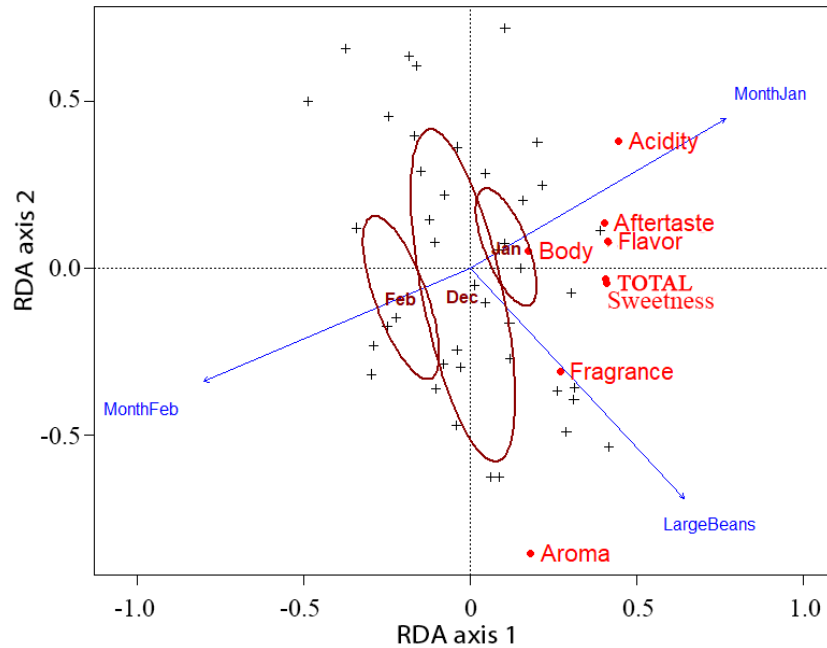


Figure 5-7: RDA for organoleptic quality of coffee beans constrained by shade (*B. javanica*, *C. camphora*, *J. mimosifolia* and open coffee), coffee category (C1 to C3), coffee yield, percentage of aborted fruits, DD, ET_C and ET₀, month of harvest peak and physical quality indicators. Axis 1 and 2 represent 35.6% and 1.5% of the total variation

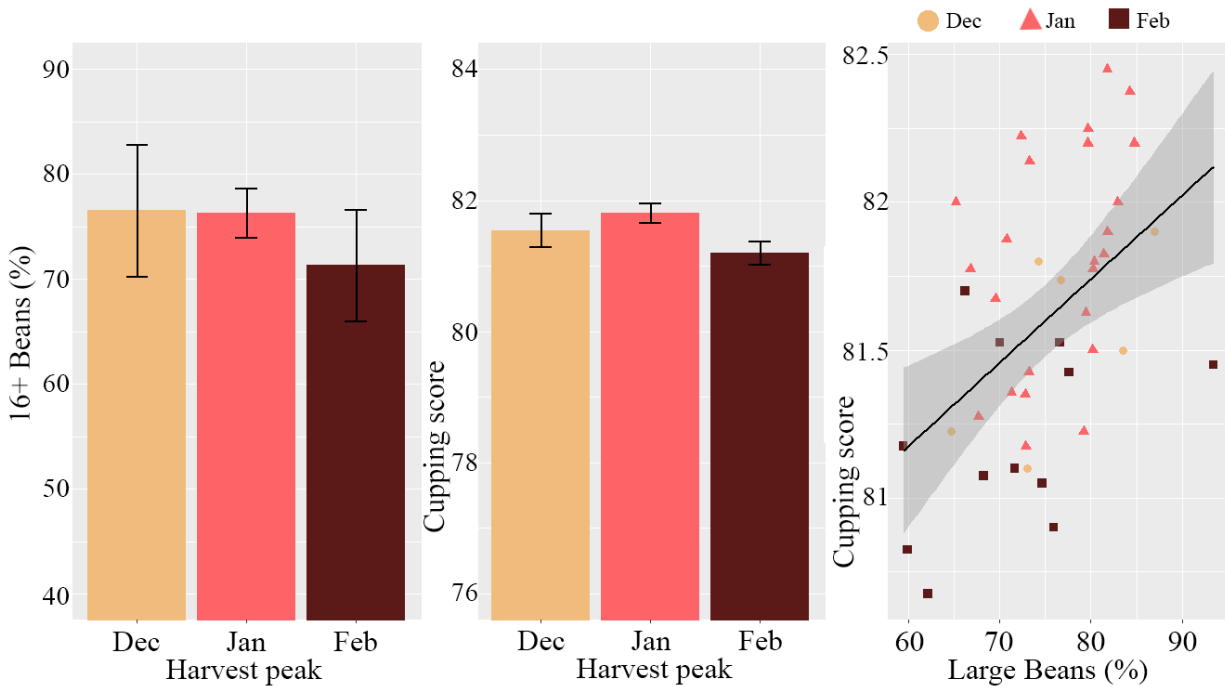


Figure 5-8: Pairwise relationships between percentages of large beans, month of harvest peak and total cupping scores (mean \pm se)

5.4. Discussion

5.4.1. Shade and micro-climate

J. mimosifolia had a high spreading canopy shade and provided a light shade intensity similar to that provided by *Inga densiflora* trees in Costa Rica, for which LAI were measured between 1.0 in the dry season and 1.3 in the wet season (Siles et al. 2010). On the other hand, *C. camphora* had a low and compact canopy shape, and provided by far the densest shade intensity of all three tree species, with LAI slightly higher than that of tall *Erythrina poeppigiana* trees (Charbonnier et al. 2013). For *E. poeppigiana*, LAI was estimated around 5.2 and light interception under the canopy ranged from 40 to 75%. This range of light interception is often considered the upper limit of acceptable shade, all the more under near-optimal growing conditions such as those found in the study area (Beer et al. 1998). This was a first indication of the excessive competition for light from *C. camphora*, which resulted in lower coffee yields under its canopy.

Although young, shade trees impacted micro-climate in ways similar to those recorded in more mature agroforestry systems. Their impact was more noticeable in reducing diurnal fluctuations in air temperatures and buffering extreme temperatures than in reducing average air temperature (Lin 2007). Buffering low temperatures was particularly important during the December cold spell, when shade trees maintained coffee trees just above freezing temperatures. This protective effect from shade trees was highlighted and confirmed through visual assessment in February, with fewer damages recorded below shade trees than in open areas.

Lastly, young shade trees significantly increased air relative humidity and decreased VPD under their canopies during daytime. This might have contributed to lowering photoinhibition (Batista et al. 2012) and maintaining coffee daily net photosynthesis despite lower irradiance intensities under shade trees. For instance, Franck and Vaast (2009) showed that coffee daily net photosynthesis under 55% shade was similar to that measured in open conditions, and that low irradiance under 81% shade only contributed to a 20% decrease in photosynthesis. Similarly, Ronquim et al. (2006) evidenced that on a clear days coffee trees only achieved around 1/3rd of their potential daily photosynthesis, mostly due to low stomatal conductance under high VPD, while on cloudy days, VPD was on average 0.5kPa lower, and coffee trees achieved daily net photosynthesis close to their potential.

5.4.2. Fruit development cycle

In line with our second hypothesis, flower set decreased with shade intensity. Coffee trees under the dense shade of *C. camphora* had only around half the flower set (7900 ± 1790) of coffee trees in open conditions (14860 ± 1580). A similar impact of mature shade trees has been noted in coffee agroforestry systems (Beer et al. 1998; DaMatta 2004), with some studies highlighting even more dramatic effects. For instance, Franck and Vaast (2009) noted a decrease from 4620 flowers in full sun down to 605 under 81% shade, therefore an 87% decrease in flower set. In Kenya, coffee trees under 50% shade only had 21% of the initial flower set recorded in full sun, due to a decrease in the number of nodes and number of flowers per node (Cannell 1976; 1985). Calculated on absolute numbers instead of percentages, our study displayed an even higher reduction of flower set. This reflects the very intensive coffee practices in the present study site, with highly productive Catimor cultivars and large fertilizer inputs, as well as a highly productive year within a biannual cycle.

By the end of the growing cycle, only 25 to 41% of flower buds resulted in ripe cherries. Most fruits aborted between June and September, when they entered the expansion stage and became a priority sink for carbohydrates (Bote and Jan 2016; Cannell 1971). During that stage, cherries can represent up to 72% of all dry weight increment in coffee trees and up to 95% NPK uptake (Cannell 1985). A minimum 20 cm² leaf-to-fruit ratio is then needed to balance carbohydrate source and sink and sustain fruit expansion, otherwise coffee trees shed fruits and, in more extreme cases, suffer from die-back (Bote and Jan 2016; Cannell 1985). For instance, coffee trees with LAI around 3 m².m⁻² (Charbonnier et al. 2013), planted at a density of 5000 trees.ha⁻¹ and adequately managed, could theoretically support the growth of 3000 cherries, similar to the final fruit loads recorded in November in the present study. Interestingly, in the present study, percentages of aborted fruits from die-back and *C. coffeanum* recorded in September were similar irrespective of fruit set and shade intensity (Figure 5-5). This result highlights the absence of major water or nutrient deficits in the summer. This interpretation is further supported by the fact that water limitations during the expansion stage usually translates to smaller beans at harvest (Cannell 1985; Carr 2001), while the percentages of large beans in the present study were similar irrespective of fruit set and shade intensity ($74 \pm 1\%$). The impact of shade nonetheless became visible in November, in line with our second hypothesis, as coffee trees under light shade and in open conditions continued shedding fruit between September and November, while coffee trees under denser shade maintained fruit loads similar to those recorded in September (Figure 5-5). This indicates that shade trees did provide positive externalities and lowered coffee trees' stress during the bean filling and maturation stages. Considering that temperatures started declining from September onward (Figure 5-1), this stress was probably induced by high nutrients and carbohydrate

sinks from coffee cherries (Bote and Jan 2016; Cannell 1971) , or from low leaf-to-fruit ratios in open conditions (Beer et al. 1998; DaMatta 2004; Vaast et al. 2006) , rather than caused by high temperatures (DaMatta et al. 2018). This result also indicates that farmers should adjust their second round of fertilizer inputs to better meet the needs of coffee trees.

5.4.3. Fruit growing period and coffee yield

In accordance with our first hypothesis, shade delayed both blossom peak and harvest peak. Since both these phenophases were similarly delayed by 2 to 3 weeks, there was no marked effect on DAF, approximating 280 days under all shade regimes. In contrast, most other studies found that shade delayed ripening by 4 to 6 weeks (Tolessa et al. 2017; Vaast et al. 2008) , with a marked effect on DAF (Geromel et al. 2008).

DD and total ET_c were most impacted by *C. camphora*, with values respectively 12 and 10% lower than those recorded in open conditions. This indicates that the canopy of *C. camphora* is too dense, and is therefore detrimental to coffee production. This interpretation is further supported by the fact that coffee yields were lower under *C. camphora* ($2760 \pm 380 \text{ g.tree}^{-1}$) than under all other shade regimes (4650 to 5710 g.tree^{-1}). Still, detrimental impacts from *C. camphora* might diminish with time, as trees grow in height, extend their canopy widths, and are pruned to decrease shade intensity (Vaast et al. 2008).

Shade had no visible impact on degree days, yield, or alternate production pattern, with the exception of coffee trees below *C. camphora*. DD under the light shade of young *B. javanica* and *J. mimosifolia* were within 5% of values recorded in open conditions and yields were not statistically different from those of open conditions. These results are mostly in line with studies on fruit set manipulation. In Costa Rica and in Brazil, reducing initial fruit set by 25% did not impact coffee production cumulated over 2 years, while reducing fruit set by 50% only reduced yield by 25 to 28% (DaMatta et al. 2008; Vaast et al. 2006). In Ethiopia, coffee trees with 25% and 50% fruit sets yielded slightly less than control trees in the first year but over-yielded control trees over 2 cumulated years (Bote and Jan 2016) . Similarly, coffee trees under *B. javanica* and *J. mimosifolia* had approximately 25% lower fruit sets but similar yields to coffee trees in open conditions, while an approximate 50% reduction in fruit set under *C. camphora* trees resulted in a 32% yield decrease over the two cumulated crop cycles, 2016-2017 and 2017-2018. These results also support the conclusion that Arabica coffee is a shade-adapted species (Franck and Vaast 2009). . Furthermore, considering that coffee yields are often higher in full sun than under shade in optimal growing conditions (Siles et al. 2010; Vaast et al. 2006) ; lower in full sun than under shade in sub-optimal conditions

(Liu et al. 2018; Vaast et al. 2008) and similar in open conditions and under light shade in the present study, it appears that the present coffee system behaves similarly to a system under near-optimal conditions (Beer et al. 1998; Bosselmann et al. 2009; Rahn et al. 2018).

Coffee yields measured in 2017-2018 were similar to local average yields (Zhang et al. 2014), but significantly higher than those measured in most other studies worldwide. For instance, in Costa Rica, the average national yield reaches 1.7 to 2.0 t.ha⁻¹, and high yields under optimal conditions reach an approximate 3 t.ha⁻¹ (Siles et al. 2010; Vaast et al. 2006). These high yields reflect the near-optimal growing conditions and the intensive management practices, and explain the marked biannual pattern observed between 2016 and 2018, with years of low production alternating with years of high production (Beer et al. 1998; DaMatta 2004). Only coffee trees below the dense shade of *C. camphora* had lower and constant yields over the two consecutive years, therefore indicating a balance between vegetative and reproductive growth.

5.4.4. Coffee quality

Very few differences were detected in physical and organoleptic attributes. Elevation and cultivars are commonly cited as the two most influential factors impacting coffee quality (Bertrand et al. 2006; Guyot et al. 1996), followed by fruit load (Bote and Vos 2017; Cannell 1974; Vaast et al. 2006), soil and climatic factors related to a geographical origin (Aguilar et al. 2012; Avelino et al. 2005; Avelino et al. 2002; Laderach et al. 2007) and shade (Bosselmann et al. 2009; Tolessa et al. 2017; Vaast et al. 2006). In this study, elevation, cultivar, as well as soil and climatic factors were all similar; only shade intensity varied across treatments. This explained the relative homogeneity in quality of all coffee samples. Furthermore, Bertrand et al. (2006) explained that new cultivars, such as Catimor, are more vigorous than traditional varieties, and therefore less impacted by environmental factors. Time of harvest was the most discriminating factor to explain cup quality scores, with the highest scores achieved by samples taken from December and January, corresponding to early and mid-harvest, in line with Tolessa et al. (2017).

Here again, results tend to confirm that the present coffee system behaves similarly to a system under near-optimal conditions. Elevation and shade, which similarly impact coffee quality (Vaast et al. 2006), only had a limited effect (Avelino et al. 2005; Steiman et al. 2011; Worku et al. 2018). The present study hence shows that *B. javanica* and *J. mimosifolia* provided positive externalities only four years after their introduction—through buffering high temperatures in summer and cold spells in winter, and lowering coffee trees' stress under their canopies during the bean filling and maturation stages—without negatively

impacting coffee yield and quality through light competition. In addition to these measured ecosystem services, shade trees have also been shown to provide a range of other services, such as contributing to income diversification (Jassogne et al. 2012) and preservation and/or restoration of soil fertility in coffee farms. These two shade tree species therefore appear as suitable options for the agro-ecological intensification of coffee farms. On the other hand, *C. camphora* provided positive externalities and maintained coffee quality, but also hindered coffee yield. This shade tree species should therefore be actively managed, in particular through pruning activities to lower shade intensity of its dense canopy and reduce its negative impact on coffee yield.

5.5. Conclusion

This study demonstrates that, only four years after their introduction in former monoculture coffee farms, young shade trees impacted coffee production in a way similar to that of mature shade trees, albeit over far smaller areas. Shade trees can therefore not only bring long-term benefits but also short-term ones during the transition period from monoculture to mature agroforestry systems. In the growing conditions found in Pu'er Prefecture, young shade trees buffered extreme climatic events, lowering coffee stress from high temperatures in summer (-3 to -6°C) and from cold spells in winter (+0.5 to +1°C). Fruit sets and subsequent losses during the bean filling and maturation stages decreased with shade intensity, while blossom peaks and harvest peaks shifted by two to three weeks. Furthermore, coffee trees located either at the edge of shade trees or below *B. javanica* and *J. mimosifolia* produced similar yields over two consecutive harvests as well as similar coffee quality to coffee trees in open conditions. *Cinnamomum camphora*, however, hindered coffee production with its low and compact canopy.

Young *B. javanica* and *J. mimosifolia* were shown to provide positive externalities without negative impacts on coffee yield and quality. In addition, shade trees are known to provide numerous ecosystem services, such as improving soil fertility, supporting higher biodiversity, and supplementing coffee incomes. This study hence supports the use of these species for agro-ecological intensification of coffee systems. The present results also highlight the fact that management practices must be adapted to individual shade tree species in order to maximize their positive externalities and lower their negative impacts. In the case of shade trees with dense canopies resulting in excessive shade intensity for coffee production, such as *C. camphora*, pruning must become an essential component of coffee farming management practices. The introduction of shade trees should also be complemented with changes in fertilization practices, in order to better adapt fertilizer inputs to coffee needs and to take advantage of improved soil fertility under shade

trees. Altogether, the introduction of shade trees and changes in management practices would contribute to the production of more sustainable coffee in Pu'er Prefecture.

CHAPTER 6 - Summary of the research

The present research focused on studying the ecosystem services provided by the most common shade tree species in coffee farms in southern Yunnan, only a few years after their introduction. In the first study (Chapter III), I carried out tree inventories to characterize shade tree biodiversity in coffee farms. I also documented farmers' local ecological knowledge in order to get a broad understanding of the ecosystem services and disservices provided by the 28 most common shade tree species in coffee farms. In the following section (Chapter IV), I set up a field experiment to study the specific impacts of three shade tree species – *Bischofia javanica*, *Cinnamomum camphora* and *Jacaranda mimosifolia* - on soil fertility, only four years after their introduction. Lastly, in Chapter V, I recorded the impacts of these same shade tree species on micro-climate, coffee yield and coffee quality.

6.1. Shade tree biodiversity

Shade tree inventories revealed an unexpectedly high level of diversity in the coffee farms of Pu'er and Xishuangbanna Prefectures. Diversity was high both at the farm level (average of 15 tree species per farm) and at the landscape level (with an estimated 162 tree species, similar to that documented in tropical mountain forests in southern Yunnan). This finding highlights the good prospects for biodiversity conservation in coffee-agroforestry systems. Still, a limited number of economically profitable tree species dominate the coffee landscape, and 84 of the 162 total tree species were only encountered in one or two coffee farms. Therefore, these species are particularly vulnerable to the decision-making process of a select few farmers.

6.2. Relevance of the shade tree species promoted by local governments

Nine shade tree species were promoted by the local governments of Pu'er and Xishuangbanna Prefectures, namely: *Alstonia scholaris*, *B. javanica*, *Cerasus cerasoides*, *C. camphora*, *Delonix regia*, *Dimocarpus longan*, *Litchi chinensis*, *Macadamia integrifolia* and *Mangifera indica*. These species were all highly favored by coffee farmers for their perceived economic potential, as well as the protection that they provided from environmental hazards. I also identified additional tree species valued by coffee farmers for the ecosystem services they provided, which could be added to the list of promoted species, such as *Artocarpus heterophyllus* and *Diospyros kaki*. Furthermore, I upgraded an online tool (www.shadetreeadvice.org) to complement the list of promoted shade tree species and provide tailored advice to farmers, based on their specific needs and their local ecological context.

6.3. Impact of young shade trees on soil fertility

Chapter IV demonstrated that *B. javanica*, *C. camphora* and *J. mimosifolia* all had a positive impact on soil fertility in the 0-20cm soil layer only four years after their introduction. This positive impact was attributed to leaf litter and tree below-ground activity. In addition, soil water profiles showed that rainfalls were sufficient to meet both coffee trees and shade trees needs for water resources.

Higher soil chemical fertility (higher pH, SOM, total N, available P and exchangeable Ca concentrations) was measured below shaded coffee than below open coffee. Furthermore, soil biological communities (fungi, bacteria, and nematodes) and soil enzyme activities (BG, NAG and ACP) were always similar or higher under shade trees than in open areas. The positive impact of shade trees on soil biology was particularly visible during the dry season, highlighting a buffering effect of shade trees on seasonal variations in soil biological communities. This chapter thus evidenced that young shade trees can quickly contribute to preserving and/or restoring soil fertility, which appears particularly important considering the documented trend of soil degradation in intensively managed coffee farms.

6.4. Impacts of young shade trees on micro-climate

Chapter V shows that *B. javanica*, *C. camphora* and *J. mimosifolia* all buffered extreme temperatures under their canopies: maximum temperatures decreased by 3 to 6°C in summer, and minimum temperatures increased by 0.5 to 1°C in winter. This proved especially important to protect coffee trees from leaf damage when a cold spell hit the study area in December 2017. Young shade trees hence appear suitable to decrease the vulnerability of coffee farmers to extreme climatic events, which will keep increasing in frequency due to climate change.

6.5. Impacts of young shade trees on coffee yield and coffee quality

Fruit set was positively correlated with light intensity. Coffee trees below shade trees thus had lower fruit sets than in open conditions, but also lower subsequent losses during the expansion stage, the bean filling stage, and the maturation stage of coffee cherries. As a result, fruit loads and yield at harvest were similar under *B. javanica*, *J. mimosifolia*, and in open conditions. Only coffee trees located below *C. camphora* had lower fruit loads and lower yield, highlighting the fact that while *Coffea arabica* is a shade-adapted species, too much shade still negatively impacts yield. Consequently, shade trees providing less shade intensity – *B. javanica* and *J. mimosifolia* with LAI lower than 2 – are suitable as such for coffee production, while shade trees with dense canopies – *C. camphora* with LAI higher than 5 – require

management practices to lower competition for light. Lastly, shade trees had no marked effect on the physical, chemical, or organoleptic quality of coffee. This last result reflects the fact that growing conditions in Pu'er Prefecture are already near-optimal and that the ecosystem services provided by shade trees thus only have a limited impact on coffee production.

6.6. Recommendations

Throughout this PhD thesis, I demonstrated that correctly selected and managed young shade trees provided more positive externalities than negative ones. In particular, they contribute to biodiversity conservation, to preservation and/or restoration of soil fertility, and to the buffering of extreme temperatures. Furthermore, provided that their canopies are not too dense, shaded coffee trees yield similarly to open coffee trees. The large-scale conversion program from monoculture coffee systems to coffee-agroforestry systems initiated by local governments in Pu'er and Xishuangbanna Prefectures therefore seem a relevant program to prepare the coffee sector to face upcoming challenges.

Nonetheless, based on the present results, I would add several recommendations to further increase the benefits of this program.

- 1) Additional shade tree species should be added to the list of promoted shade tree species, including *A. heterophyllus* and *D. kaki*;
- 2) The list of recommended shade tree species should be tailored to each farmer's needs and constraints in order to maximize the locally most important ecosystem services. This can be done using the online tool www.shadetreeadvice.org;
- 3) The conversion to agroforestry systems should be complemented by a decrease in fertilizer inputs, which are currently exceeding coffee needs and causing soil degradation and downstream pollution;
- 4) Emphasis should be put on the above-ground management of shade trees, in particular the pruning of shade trees with dense canopies timed with the coffee production cycle, so as to lower competition for light and ensure high yield in emerging coffee-agroforestry systems.

6.7. Future research

The many findings of this PhD research should be complemented with a long-term follow up of the provision of ecosystem services by shade trees and their impacts on coffee yield and quality. Indeed, the transition from monoculture coffee systems to agroforestry systems at such a large scale is unprecedented and provides a unique opportunity to study the impacts of shade trees at the landscape level at the point of introduction into coffee farms. Long term follow-up is also necessary to document the emerging

competition between shade trees and coffee trees as shade trees grow, and adapt management practices accordingly until an equilibrium point is reached. Indeed, the present study of farmers' ethnobotanical knowledge revealed knowledge gaps regarding the impact of mature trees on soil fertility, coffee yield, coffee quality and pests and diseases control.

Further research should also be carried out to document the impacts of shade trees on the main pests and diseases of the study areas, namely *Hemileia vastatrix*, *Colletotrichum coffeanum* and *Xylotrechus quadripes*. Shade trees are already known to lower damages from *X. quadripes* but their impacts on *H. vastatrix* are still subject to debate. Furthermore, climate change might further exacerbate pest and disease outbreaks. Research is thus needed to provide locally adapted management practices that will complement and support the current ecological intensification of coffee farms in southern Yunnan Province.

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Forest management, Forestry laws, Forestry economics, Social sciences
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*Urbanism, Management, Decision-making (model building, simulation and optimization)
Forestry and Statistics applied to forestry, GIS*
- **Bachelor's degree in mathematics and physics** (2005-2007), at Lycée Saint Louis, France
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Work and research experience

- **Carbon sequestration and forestry officer**
 - Apr 2011 – Feb 2015, with Initiative Développement (NGO), in Kunming
*Feasibility study for a carbon-forest project in Yunnan Province
Selection of the planting models, management of partnerships
Implementation (local nurseries, land selection, planting activities, monitoring)
Carbon certification under the Gold Standard*

- **Consultant**

- Jun-Aug 2013, with Planète Urgence, Indonesia
Assessment of the opportunity for certification of a mangrove reforestation project in Borneo Island under a carbon standard
- Nov 2012, with Gold Standard, Germany
Member of the advisory panel for the carbon standard for community-based forestry projects

- **Research assistant**

- Feb-Mar 2011, at Montpellier University, France and India
Territorial diagnosis and prospective of the coffee sector in Kodagu District
- Nov-Dec 2010, at ENGREF, France and Germany
Potential for wood energy in European forests
- Sep 2010, at ENGREF Guyana, France
Field inventories in mangroves
- Apr-Aug 2010, at CIFOR & University of Kisangani, Democratic Republic of Congo
Modeling of rattan's ecology

Language skills

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CONFERENCES

- The 27th International Conference on Coffee Sciences (ASIC). Portland (September 16-20, 2018)
Impact of Recent Large Scale Conversion from Intensive Monoculture Coffee Systems to Agroforestry Systems on Soil Fertility in Yunnan Province, China (Poster presentation)
- Mountain Future Conference. Kunming (June 4-8, 2018). *Using coffee farmers' ecological knowledge for providing locally relevant advice on the selection of shade tree species in Yunnan Province, China* (Oral presentation)
- First Dali Binchuan Zhukula International Coffee Forum. Dali (June 15-17, 2017) (Attendance)
- The 26th International Conference on Coffee Sciences (ASIC). Kunming (November 13-17, 2016)
Using local knowledge to link shade tree species composition to the provision of ecosystem services in coffee plantations in Yunnan Province, China (Poster presentation)
- Mountain Future Conference. Kunming (June 1-4, 2016) (Attendance)
- 全球气候变化背景下的生态农业-中法合作研讨会 – Conférence franco-chinoise sur l'agro-écologie dans le contexte du changement climatique. Beijing (June 3-5, 2015). *Risks and opportunities for coffee-agroforestry systems in Yunnan Province under climate change* (Oral presentation)

PUBLICATIONS

Rigal C, Vaast P, Xu J (2018) Using farmers' local knowledge of tree provision of ecosystem services to strengthen the emergence of coffee-agroforestry landscapes in southwest China. PLOS ONE 13(9): e0204046. <https://doi.org/10.1371/journal.pone.0204046>

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Rigal C, Xu J, Hu G, Minghua Q, Vaast P. Coffee production and quality during the transition period from monoculture to agroforestry systems in near optimal conditions, in Yunnan Province (manuscript in preparation)

Fortunel F, **Rigal C**, Xu J, Hu Y. A Geohistory of Coffee Development in the Region of Yunnan Province, China (under review by Asia Pacific Viewpoint)