THE EFFECTS OF TREE DIVERSIFICATION ON SOIL FERTILITY AND PRODUCTIVITY IN COCOA CULTIVATION SYSTEMS OF SOUTHEAST SULAWESI

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presented by

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Abstract

Theobroma cacao (cocoa) is one of the world's most important tree-grown cash crops. Grown in the humid tropics, cocoa supports the livelihoods of countless smallholder farmers, but also contributes to increased land-use degradation dynamics in areas often characterized by high biodiversity. While it is known that the inclusion of shade trees in agricultural systems can influence surrounding soils and crops, trade-offs between ecological and economic benefits associated with the inclusion of shade trees in cocoa agroforests are still not well understood. Moreover, while many studies have assessed the advantages of diverse cocoa agroforests, few have focused on the effects of tree diversification on soil fertility along a gradient, or on the effects of individual shade trees in tropical agroforests. The principal objective of my dissertation was therefore to assess the interactions between shade trees, cocoa trees and soils and to quantify how shade trees affect long-term soil fertility and cocoa productivity in cocoa agroforests.

The research presented in this dissertation focuses on i) biophysical interactions between shade trees, cocoa trees and soil, and ii) relationships between farmer knowledge of above- and below-ground processes and on-farm management decision-making processes. In a first study, I examined the effects of tree diversity at the farm level by quantifying changes in soil aggregation, nutrient stocks, and microbial community composition across a diversity gradient ranging from cocoa monocultures to complex cocoa agroforests, using secondary and primary forests as a reference. In a second study, I examined the effects of tree diversity at the individual tree level, and quantified changes in soil fertility, cocoa tree growth and yields under individual shade trees from 11 species commonly found in Southeast Sulawesi. In a third study, I evaluated the perceptions and local knowledge of smallholder farmers with regards to soil fertility and the interactions between shade trees, cocoa trees and soil.

One key finding from my research was the lack of a direct relationship between increasing tree diversity and improvements in soil properties in cocoa plantations. This result indicates that complex cocoa agroforests might not contribute as significantly to soil restoration after land degradation as previously thought. A second important finding from my research was that at the individual tree scale, shade trees did have positive effect on soil fertility, and were not linked to significant decreases in cocoa yields. This suggests that for farmers, shade tree diversification might not necessarily imply a decrease in cocoa-based

incomes, although this is dependent on shade tree species and traits. It moreover demonstrates that management approaches focusing on individual trees in smallholder farms might be more relevant than those focusing on entire "tree-based" systems. A third important finding from my research was that while farmers in Southeast Sulawesi had extensive knowledge about soil fertility and the effects of shade trees on soil fertility indicators and cocoa tree development, they were not necessarily aware of some of the more indirect benefits of shade trees for cocoa productivity. As such knowledge gaps might constitute barriers to adoption of sustainable management practices in cocoa farms, identifying and addressing them could potentially lead to improved adoption rates in these systems.

Zusammenfassung

Theobroma cacao (Kakao) gehört zu den weltweit bedeutendsten Anbaukulturen. Kakao wächst vor allem in den feuchten Tropen und unterstützt den Lebensunterhalt zahlreicher Kleinbauern. Gleichzeitig trägt grossflächiger Kakaoanbau jedoch auch zu zunehmenden Landnutzungsveränderungen bei – insbesondere in Gebieten die durch ihre große biologische Vielfalt gekennzeichnet sind. Man weiß, dass in landwirtschaftlichen Systemen das Einfügen von Schattenbäumen die umliegenden Böden und Kulturpflanzen beeinflussen kann. Jedoch ist der Ausgleich zwischen ökologischen und ökonomischen Vor- und Nachteilen von Schattenbäumen in Kakaoanbausystem bisher noch wenig erforscht. Während zahlreiche Studien die Vorteile von Kakao-Agroforstsystemen im Vergleich zu Monokulturen bewertet haben, gibt es nur wenige Erkenntnisse über die Auswirkungen von erhöhter Baumartenvielfalt auf Bodenfruchtbarkeit und Kakaoerträge, sei es in Funktion der „Mischdichte" entlang eines Gradienten oder durch die spezifischen Auswirkungen von einzelnen Schattenbäumen verschiedener Arten. Das Hauptziel dieser Forschungsarbeit ist daher, Zusammenhänge zwischen erhöhter Anpflanzung von Schattenbäumen und Kakaobäumen und Böden zu ermitteln. Ein weiteres Ziel dieser Arbeit ist, zu quantifizieren, inwiefern Schattenbäume langfristig die Bodenfruchtbarkeit und die Erträge in Kakao Plantagen beeinflussen können.

Die vorgestellten Studien fokussieren sich auf i) biophysikalische Zusammenhänge zwischen Schattenbäumen, Kakaobäumen und Böden; sowie ii) Auswirkungen von lokalem Wissen und empirischer Erfahrung der Kleinbauern auf Entscheidungen im Betrieb. In einer ersten Studie wurden die Einflüsse von erhöhter Baumartenvielfalt in Kakaoanbausystemen untersucht, indem Messungen von Bodenaggregation, Nährstoffbeständen und Bodenmikroorganismen entlang eines von Kakaomonokulturen bis hin zu komplexen Kakaomischkulturen reichenden Gradienten der Baumartenvielfalt ausgeführt wurden. Zum Vergleich wurden Sekundär- und Primärwälder als Referenzökosysteme einbezogen. In einer zweiten Studie wurden die individuellen Einflüsse von 11 häufig in Sulawesi angepflanzten Schattenbaumspezies auf Bodenfruchtbarkeit, Kakaobaumwachstum und Kakaoerträge bewertet. In einer dritten Studie wurden die Wahrnehmungen und lokalen Kenntnisse der

Kleinbauern in Bezug auf Bodenfruchtbarkeit und auf Interaktion zwischen Schattenbäumen, Kakaobäumen und Böden ausgewertet.

Eine wichtige Erkenntnis meiner ersten Studie ist, dass sich keine Anzeichen einer direkten Beziehung zwischen zunehmender Baumartenvielfalt und Verbesserungen der Bodeneigenschaften in Kakaoplantagen ergaben. Dies deutet darauf hin, dass das Anpflanzen von Schattenbäumen verschiedener Arten in Kakaomischkulturen nicht - wie bisher angenommen - maßgeblich zur Wiederherstellung der Bodenfruchtbarkeit nach Bodendegradierung beiträgt. Eine zweite wichtige Erkenntnis aus meinen Ergebnissen ist, dass einzelne Schattenbäume durchaus einen positiven Effekt auf Nährstoffbestände und Bodenaggregation haben können, und überdies keine erheblichen negativen Auswirkungen auf die Kakaoerträge zeigen. Diese Feststellung ist wichtig, denn sie zeigt, dass eine zunehmende Baumartendiversifizierung für Kleinbauern nicht unbedingt eine Verringerung der Erträge bedeutet. Sie deutet auch an, das die Verwaltung einzelner Bäume in Kleinbauernbetrieben wichtiger sein könnte als die Verwaltung eines gesamten "baumbasierten" Systems. Ein drittes wichtiges Ergebnis dieses Forschungsprojekts ist, dass die Kleinbauern im Südosten Sulawesis durchaus umfangreiche Kenntnisse über Bodenfruchtbarkeit an sich und über die Auswirkungen von Schattenbäumen auf Bodenfruchtbarkeitsindikatoren und Kakaobaumentwicklung haben. Jedoch waren sie sich oft nicht der indirekten und vor allem langfristigen Vorteile von Schattenbäumen für die Produktivität der Kakaobäume bewusst. Da solche Wissenslücken erhebliche Hindernisse für die Übernahme nachhaltiger Anbaustrategien verkörpern können, ist es wichtig, sie zu identifizieren und anzusprechen, mit dem Ziel, die Akzeptanz solcher Strategien bei den Kleinbauern zu verbessern.

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Chapter 1 :
General introduction

1.1 The global context of cocoa cultivation

Theobroma cacao (cocoa), an understory forest tree species endemic to western Amazonia, is an important tropical commodity at the global level (Donald, 2004; Franzen and Mulder, 2007). The cocoa tree thrives in sub-tropical climates and is traditionally grown under primary forest or planted fruit tree shade (Franzen and Mulder, 2007). Currently, cocoa is predominantly grown in West Africa, which produces more than two-thirds of the world's crop, as well as in Southeast Asia and Latin America (Hartemink, 2005; Ruf, 2011). Cocoa is mostly cultivated by smallholder farmers (Donald, 2004), who largely depend on the income from cocoa production for their livelihoods.

The stability of the global cocoa sector is threatened by three fundamental challenges. First, due to boom and bust cycle dynamics, the world's principal cocoa growing regions have seen significant yield declines in recent years due to increased pressures from soil degradation, ageing trees, climate change and pest and disease occurrences (Clough et al., 2009). This increases the economic vulnerability of smallholder cocoa farmers. Second, these issues are exacerbated by significant increases in global demand for raw cocoa beans, related to increasing demand in fast-growing regions such as India and China (e.g. Squicciarini and Swinnen, 2016). The incentives for smallholder farmers are thus to increase production at all costs, whereas coordinated efforts towards the adoption of more sustainable management methods remain lacking. Finally, the expansion of agriculture in the humid tropics is one of the leading drivers of deforestation. Cocoa cultivation areas, which cover more than 9 million ha globally (FAOSTAT, 2011), mostly overlap with tropical biodiversity hotspots (Clough et al., 2009) and therefore constitute a direct threat to global biodiversity conservation and climate change mitigation efforts. To address these concerns, the development and adoption of long-term sustainable management strategies for cocoa systems is crucial.

1.2 Can complex cocoa agroforests increase ecosystem resilience?

Researchers and policy-makers have long debated about how to best address trade-offs between poverty alleviation and biodiversity conservation in the context of cocoa cultivation (Franzen and Mulder, 2007). The diversification of cocoa plantations has been proposed as a solution to promote sustainability both from an economic and ecologic perspective. While cocoa monocultures are more attractive to farmers due to higher initial yields and economic benefits, they have been shown to be ecologically unstable systems: as they age, increasing crop losses due to pests and disease, and decreasing crop yields due to aging trees and soil deterioration, lead to decreasing cocoa returns (Belsky and Siebert, 2003). Mixed agroforests are thought to provide long-term benefits by promoting ecosystem diversity and associated ecological benefits, thus increasing overall system resilience (Belsky and Siebert, 2003; Franzen and Mulder, 2007). In a recent review, Tscharntke et al. (2011) reported multiple benefits associated with shade trees intercropped with cocoa, which include improved habitat connectivity, biodiversity conservation, ecosystem restoration, microclimate regulation, pest and disease reduction, farmer income diversification, increased ecosystem resilience to climate fluctuations and increased nutrient cycling efficiency.

Nevertheless, complex cocoa agroforests do not reach the same levels of biodiversity, above-ground vegetation biomass, and ultimately associated ecological benefits of primary forests (Siebert, 2002; Clay, 2004), although they do retain higher species richness than annual croplands (Zapfack et al., 2002). Therefore, many of the perceived ecological benefits of agroforests are highly dependent upon the type of land-use systems (i.e. undisturbed forests versus annual croplands) that they are compared to (Montagnini and Nair, 2004; Franzen and Mulder, 2007). To date, the question still remains open to what extent complex cocoa agroforests can contribute to increased environmental sustainability, particularly in terms of soil fertility.

1.3 Nutrient cycling and storage in perennial cropping systems

The long-term sustainability of agricultural systems is highly dependent on soil health and a soil’s capacity to support plant growth (e.g. Vanlauwe et al., 2015). Soil fertility is determined by key physical, chemical and biological properties, including texture, bulk density and infiltration, water holding capacity, aggregate stability, pH, cation exchange capacity, soil organic matter (SOM) content, nutrient stocks, microbial biomass, etc. (Doran and Parkin, 1994a). In tropical perennial cropping systems, fertilizer inputs by farmers are often minimal (Zaia et al., 2012a). For this reason, long-term soil fertility and availability of plant-essential nutrients in these ecosystems is highly dependent on the storage and recycling of inorganic nutrients from SOM (Tiessen et al., 1994).

Following decomposition, broken down organic matter from above-ground and below-ground plant residues is stabilized within soil aggregates, where it constitutes a major pool of plant-essential nutrients. Soil aggregates are important for long-term nutrient storage and carbon sequestration because of their ability to physically protect organic compounds from degradation by microbial organisms in the soil (Tisdall and Oades, 1982). The occlusion of nutrients into “stable” soil aggregates reduces soil nutrient losses through mineralization, erosion or leaching. Hence, increased soil aggregate formation contributes to enhancing soil fertility (Schmidt et al., 2011). According to the now widely accepted model described by Tisdall and Oades (1982), there are four size-categories for soil aggregates: large macroaggregates (>2000 μm), small macroaggregates (250-2000 μm), microaggregates (53-250 μm), and free silt and clay particles (<53 μm). Macroaggregates consist of SOM and soil particles physically held together by plant roots and fungal hyphae as well as inorganic binding agents. It has been suggested that microaggregates are formed within macroaggregates, where they are protected from disturbances and degradation (Six et al., 2000). This makes them important indicators for C and nutrient storage capacity in soils (Six and Paustian, 2014). The stability of macroaggregates is determined by the chemical and physical properties of their components as well as by soil disturbances and microbial activity (Tisdall and Oades, 1982). Aggregate turnover rates are thus impacted by agricultural activities and the chemical composition of plant residues (Tisdall and Oades, 1982).

Aggregate formation is driven not only by the overall availability of SOM in the system but also by complex interactions between soil macro-fauna (e.g. earthworms), plant root architecture and exudates, and soil microbial activity (Fonte et al., 2012; Six and Paustian, 2014). Microbial organisms constitute an essential component of SOM pools (Wall et al., 2015) and actively influence SOM cycling rates by catalyzing decomposition and mineralization processes (Swift et al., 1979). Physical and chemical changes in soil properties contribute to providing energy, substrates and biodiversity to support biological activity, affecting the richness and functional diversity of microbial communities in the soil (i.e. Tisdall and Oades, 1982; Schmidt et al., 2011). Soil microbiota are thus likely to respond directly to changes in above-ground vegetation and soil environmental conditions (Bending et al., 2002; de Graaff et al., 2015). For this reason, microbial community size and structure are important indicators for changes in nutrient cycling processes following land-use change and degradation (Lacombe et al., 2009; Zaia et al., 2012a; Tiemann et al., 2015).

Perennial cultivation systems are thought to be more sustainable than annual cropping systems due to reduced soil erosion and improved nutrient recycling (Hartemink, 2005). Indeed, trees alter soil physical, chemical and environmental conditions through root penetration, increased and diversified SOM inputs from the decomposition of litter residues and root decay (Swift et al., 1979; Tscharntke et al., 2011) or changes in soil surface temperature and soil moisture under their canopy (Rhoades, 1996). However, in the context of improving soil fertility in cocoa cultivation systems, data quantifying differences in soil fertility between monocultures and complex agroforests still remain lacking, and the effects of tree diversification are still poorly understood.

1.4 Benefits of tree diversification for soil fertility

An extensive body of literature has focused on quantifying the benefits of maintained plant species diversity for ecosystem resilience (e.g. Hooper et al., 2005). Increased plant diversity can contribute to altered litter decomposition rates and changes in substrate quality and thus indirectly impact soil microbial communities and functions (Scherer-Lorenzen et al., 2007). Higher plant functional diversity at the ecosystem level results in spatial and temporal resource partitioning and resource use complementarity (Mäder et al., 2002; van Ruijven and Berendse, 2005b; Zeugin et al., 2010). This in turn can minimize losses through leaching and erosion, stabilize plant-available nutrient pools (Cotrufo et al., 2013) and lead to an overall increase in average plant productivity and improved nutrient recycling (Ahenkorah et al., 1987a; Hooper et al., 2005).

The majority of studies examining the effects of plant species diversity on soil fertility parameters have been carried out in temperate grassland ecosystems and/or under controlled experimental settings (Tilman et al., 1996; Vilà et al., 2005a; Scherer-Lorenzen et al., 2007). In tree-based systems, evidence has indicated that trees with deeper roots can function as safety nets for surrounding vegetation, minimizing leaching via stratification and reaching nutrients in deeper soil horizons (Van Noordwijk and Purnomosidhi, 1995; Isaac et al., 2014). Increased tree species diversity can also enhance carbon sequestration (Montagnini and Nair, 2004; Jose, 2009) through increased C inputs from litter plus root decay (Palm, 1995; Smiley and Kroschel, 2010; Thoms et al., 2010).

The effects of shade trees on their surroundings are highly dependent on selected tree species (Beer, 1988; Isaac et al., 2005; Somarriba et al., 2013). There is high variability in tree morphology in terms of input quantity and quality, canopy shape and rooting architecture related to individual shade tree development and age, and to fundamental differences between shade tree species. Such variation in functional traits is likely to affect ecosystem functions, including water and nutrient use efficiency (Van Noordwijk et al., 2015), symbiotic associations with soil microbiota (Grayston and Prescott, 2005; Lejon et al., 2005) or microclimate regulation (Isaac et al., 2007). In tropical agroforests, the inclusion of shade trees of different species can thus be expected to impact both soil fertility and cocoa tree productivity. Nevertheless, data about the effects of tree diversity in cocoa agroforests remains scarce.

1.5 Tradeoffs for smallholder cocoa farmers

The expansion of cocoa cultivation areas happens at the cost of natural forest conversion to agroforests or monocultures and is generally fueled either by migrant fluxes or by related changes in land tenure (Weber et al., 2007). Declining productivity in cocoa plantations remains a central issue and may well drive farmers to clear new land instead of increasing the sustainability of already existing plantations (McGrath et al., 2001; Clay, 2004). This dynamic is often exacerbated by generational changes in farming communities, with younger generations of farmers moving to new land or switching to different crops to maintain cost and labor effectiveness (Ruf, 1995; Clough et al., 2009). Smallholders do not have the resources to compete with large-scale producers and are particularly vulnerable to environmental and economic risks linked to land degradation and biodiversity loss (Tscharntke et al., 2012).

Recent findings have indicated that agrobiodiversity conservation and yield productivity are not necessarily mutually exclusive (Clough et al., 2011) – particularly under moderate shade levels (Tscharntke et al., 2011). This is very encouraging as it suggests that there might be an opportunity to develop sustainable management approaches that address biodiversity conservation concerns without negative livelihood impacts for smallholder farmers. Despite such evidence, cocoa farmers are still not very likely to adopt diversification measures in their cocoa plantations. Globally, many farmers are moving away from complex agroforests and favoring conversion to cocoa monocultures (Belsky and Siebert, 2003; Ruf, 2011). A study conducted in central Sulawesi (Belsky and Siebert, 2003) highlighted subsistence farmers' tendencies to base decision-making on short-term productivity benefits, in an effort to address immediate economic pressures. Low adoption rates of sustainable practices might therefore be attributed to the initial high yields associated with monoculture cultivation. There might also be a substantial knowledge gap in farmers' understanding of ecological factors that affect cocoa tree productivity, and farmers might perceive potential ecologic and economic benefits provided by complex agroforests as secondary (e.g. Ruf, 2011).

Studies conducted in different parts of the world - Burkina Faso, Laos, Latin America - have shown that there is often a discrepancy between local farmer perceptions and scientific assessments regarding soil fertility status (Barrios and Trejo, 2003; Gray and Morant, 2003; Saito et al., 2006). More specifically, while farmer classification of soil physical properties tends to match scientific classifications (Saito et al., 2006), there are frequently discrepancies in linking soil fertility with yield and productivity (Gray and Morant, 2003). Soil fertility may not be perceived as an important indicator for productivity by smallholders, who may prioritize other management factors (Gray and Morant, 2003) such as pest control or fertilizer application. Additionally, findings related to the relationships between soil fertility and crop productivity are not always communicated effectively to farmers. Understanding and addressing the gap between local and formal knowledge systems might thus be an important step towards increased acceptance and adoption rates of improved farming practices that address farmer priorities and aim to overcome perceived yield-biodiversity tradeoffs (Pattanayak et al., 2003; Meijer et al., 2015; Smith-Dumont et al., 2017).

1.6 The study area: Southeast Sulawesi

Indonesia is currently the third global producer of cocoa (FAOSTAT, 2011). Sulawesi is a relatively recent cocoa-growing region; following the Indonesian cocoa boom of the 1980s (McMahon et al., 2015), more than 60% of the country's cocoa is currently grown across more than 400,000 smallholder farms on the island of Sulawesi (Panlibuton and Meyer, 2004; McMahon et al., 2015). As a recent "migration frontier," the island of Sulawesi is facing a particular set of pressures related to increased land conversion for agricultural and mining activities. Additionally, while in West Africa most native forests have already been degraded, in Southeast Sulawesi much of the island, particularly in mountainous areas, is still under tropical forest cover (Cannon et al., 2007). These forests are home to an incredible diversity of endemic species of plants, insects and birds. Unfortunately, this is rapidly changing due to the expansion of logging activities, land clearing for cash-crop cultivation and the degradation of converted areas via unsustainable management practices.

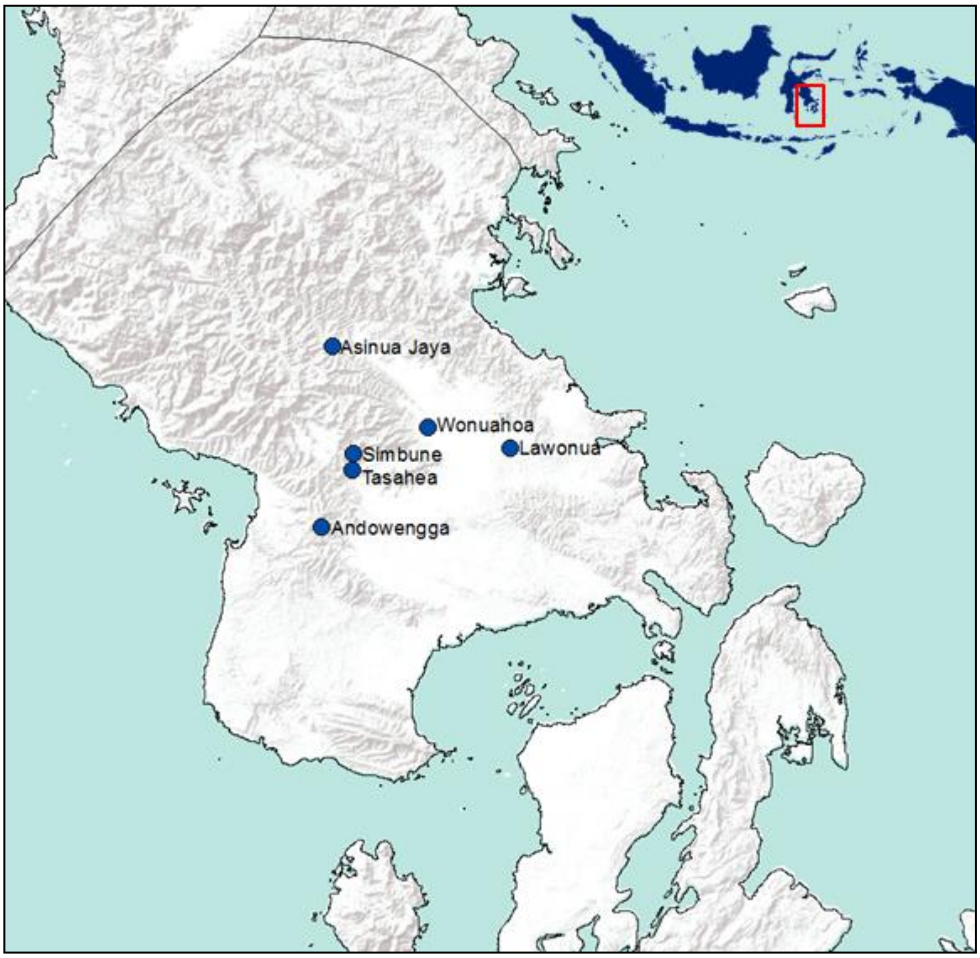

Figure 1.1. *Map of the study area: Southeast Sulawesi, Indonesia*

Field work for this dissertation was conducted in six communities located in the Kolaka and Konawe provinces in Southeast Sulawesi (Fig. 1.1). In the floodplains, the agricultural landscape is dominated by paddy rice, as well as maize and vegetable production. Mountain ranges are still widely forested, although at forest frontiers, deforestation and land-use changes are occurring rapidly. Valleys and hillsides are dominated by cocoa agroforests, although there has been a recent expansion of palm-oil, rubber and teak plantations. The region provides optimal geological and climatic conditions for cocoa farming (Wood and Lass, 1985; Juhrbandt et al., 2010). Soils are dominated by weathered *orthic acrisols* in the mountains and *dystric fluvisols* in the floodplain (FAO-UNESCO, 1979). Annual precipitation is 2080 mm (1982 - 2012 average) and is highly seasonal, with most rain falling during the wet season from January to June. Mean daily temperatures range between 25 °C and 28 °C, depending on time of the year and elevation (Climate-Data.org, 2016).

1.7 Dissertation Outline

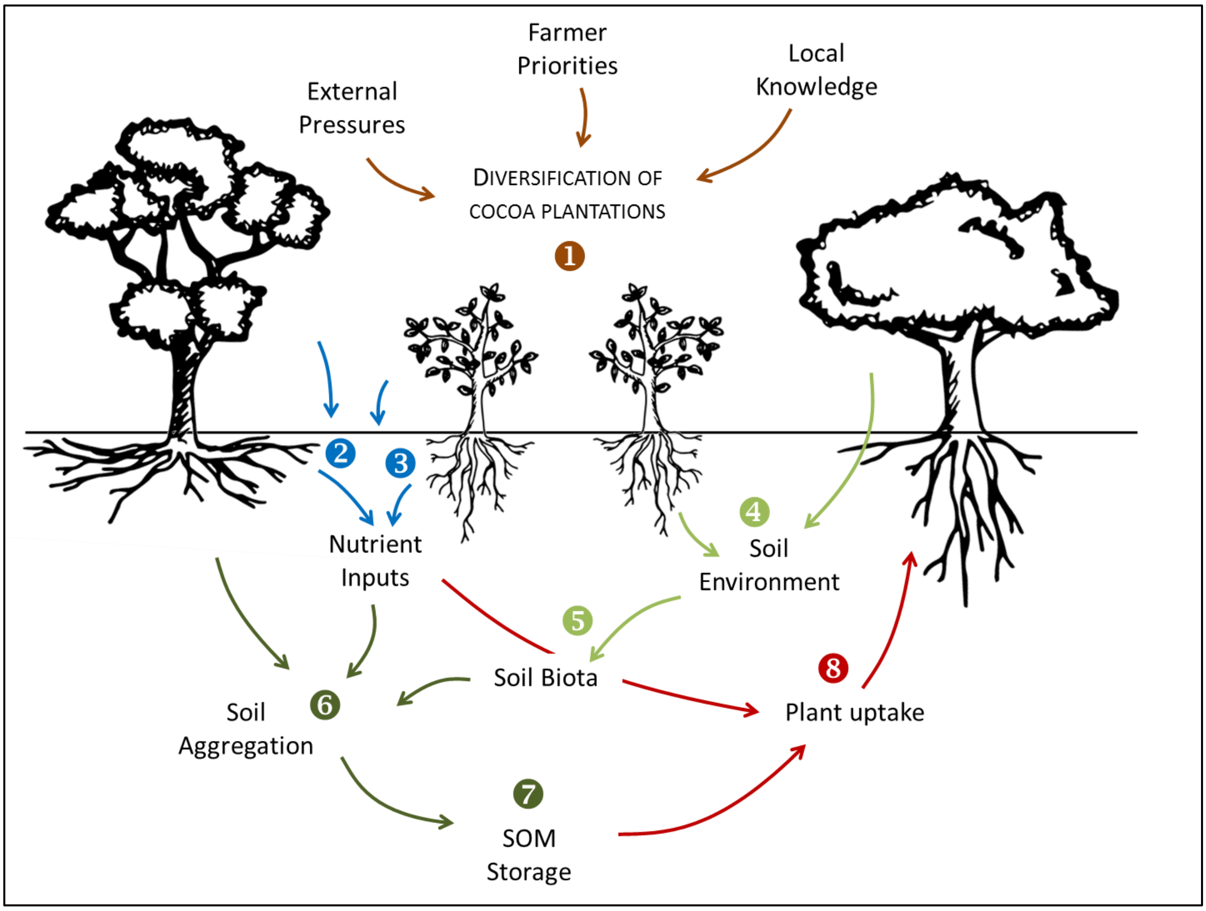

Figure 1.2. Conceptual Framework detailing the effects of diversification in cocoa cultivation systems on soil fertility and nutrient cycling processes.

Farmer adoption of diversification practices is likely to be influenced by the interaction of external pressures, household priorities and local knowledge about nutrient cycling and crop productivity ①.

Increased tree diversity in cocoa plantations can be expected to lead to: ② *increased nutrient inputs from plant and root residues;* ③ *alterations in litter chemistry and root exudates; and* ④ *regulation of soil environmental conditions such as soil moisture content and temperature.*

Such changes impact ⑤ *the functional diversity and size of soil biota and* ⑥ *the formation and stabilization of soil aggregates, which play an important role for* ⑦ *the long-term storage of nutrients and soil organic matter (SOM).*

Alterations in soil structure, nutrient contents and microbial abundance in turn play an important role in maintaining plant-essential nutrient pools, enhancing plant uptake rates and ultimately crop yields ⑧.

Research objectives and framework

The principal objective of this dissertation was to evaluate the potential of diverse *Theobroma cacao* (cocoa) agroforests as sustainable cocoa cultivation systems, according to the framework detailed in Figure 1.2. I quantified the effects of tree diversity at different scales in cocoa agroforests in Southeast Sulawesi, Indonesia. The FAO's definition of the concept of "sustainability" integrates biophysical and socio-economic principles (FAO, 2017). For this reason, the research approach presented here includes a two-fold approach. I first focused on biophysical interactions between vegetation and soil, investigating the effects of shade trees on soil fertility and cocoa productivity at the individual tree level and at the plot level across a tree-diversity gradient. I then focused on the human aspects of cocoa cultivation and evaluated the relationships between farmer knowledge of shade tree impacts on cocoa trees and soil fertility, and decision-making regarding farm management practices. The underlying aim of my research was to contribute to an improved understanding of the effects of human-induced land-use changes on soil fertility in tropical agricultural systems.

Chapter 2: Changes in soil fertility across a tree diversity gradient in cocoa plantations

In a first study, I examined the effects of tree species diversity on soil fertility and microbial community structure at the plot scale to assess whether tree diversification could contribute to soil restoration after deforestation. I quantified changes in soil fertility indicators (soil properties, nutrient contents, and soil microbial community composition) along a gradient of shade tree diversity ranging from cocoa monocultures to complex cocoa agroforests in southeast Sulawesi, using primary and secondary forests as references. Through this study, the following questions were addressed:

1. Does soil fertility, as indicated by soil nutrient stocks, aggregate stabilization and the abundance and diversity of soil microbes, improve with increasing tree species diversity in cocoa agroforests?
2. To what extent can cocoa agroforests contribute to soil restoration after primary forest loss due to deforestation activities?

Chapter 3: Soil fertility and cocoa growth and productivity under common shade tree species

In a second study, I focused on the different mechanisms through which individual shade trees might affect soil fertility and cocoa productivity. I quantified changes in soil fertility (as indicated by soil nutrient contents and aggregate stabilization), cocoa yields and cocoa tree biomass under individual shade trees which were selected from 11 tree species commonly intercropped with cocoa in Southeastern Sulawesi. The following questions were addressed in this study:

1. What is the effect of individual shade trees on the soil fertility under their canopy?
2. What is the effect of shade trees on the growth and productivity of neighboring cocoa trees?
3. Do different shade tree species have different effects, and are quantifiable differences related to specific shade tree traits?

Chapter 4: Farmer perceptions of plant-soil interactions in cocoa agroforests

In a third study, I present a case study about local knowledge of smallholder cocoa farmers in Southeast Sulawesi. The goal of this study was to evaluate the linkages between local knowledge and smallholder decision-making processes in cocoa production systems. I conducted individual interviews with smallholder farmers and documented their knowledge about soil fertility indicators, nutrient cycling processes and the interactions between shade trees, cocoa trees and soil in cocoa agroforests. I also collected data regarding farmers' fertilizer preferences, additional income sources and perceived barriers to improved cocoa production. Through my case study I addressed the following questions:

1. What are farmers' perceptions about soil fertility attributes, shade tree and soil interactions and shade tree effects on cocoa tree development and productivity?
2. How does farmers' knowledge compare to scientific literature?
3. What is the relationship between local knowledge about ecological processes, management decisions and other external pressures?

Chapter 2 : **Does shade tree diversity increase soil fertility in cocoa plantations?**

Abstract

Complex agroforests have been promoted as a potential solution to address trade-offs between environmental conservation efforts and the need for increased agricultural productivity for smallholder farmers in the tropics. However, the effects of tree diversification on soil fertility in tropical agroforests remain unclear. In this study, we examine whether tree diversification in cocoa plantations is associated with soil fertility benefits and can contribute to soil restoration after deforestation. We tested for positive associations between increasing tree species diversity and increased soil aggregation, soil nutrients and microbial communities across a diversity gradient ranging from cocoa monocultures to complex cocoa agroforests. Secondary forests and primary forests were used as reference ecosystems. Increase in tree diversity within cocoa plantations did not increase soil fertility parameters in topsoil layers or cocoa yields. Mean soil C contents were 8% lower, mean weight diameter of aggregates 48% lower and total bacterial biomass 35% lower in cocoa plantations than in primary and secondary forest systems, whereas soil P content was 22% higher. Across all land-use systems, microbial biomass was greater in sites with higher soil carbon contents and soil aggregation. This suggests soil function restoration in terms of microbial communities, soil C and aggregate stabilization in secondary forests. However, in cocoa plantations tree diversification alone may not be an effective solution to mitigate soil degradation after deforestation. Rather, preserving remaining forests or promoting farming approaches that allow for secondary forest regeneration (e.g. implementing forest strips and regular fallow rotations) might have a more substantial impact on soil health.

Authorship and status of manuscript

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2.1 Introduction

Agroforests have been proposed as a potential solution to bridge biodiversity conservation efforts and the need for increased agricultural productivity in tropical countries (Tscharntke et al., 2012). Benefits of intercropped shade trees are thought to range from microclimate regulation (Beer et al., 1998b) to alternative income sources for farmers (Tscharntke et al., 2011) or improved nutrient cycling efficiency (Schroth, 1998). Increasing tree species diversity is thought to maintain soil fertility through several mechanisms. For example, differences in input quantity and quality, rooting architecture and other functional traits among tree species can lead to altered litter decomposition rates and changes in substrate quality, which can indirectly impact soil microbiota (Scherer-Lorenzen et al., 2007). Increasing tree species diversity at the ecosystem level can also improve resource use complementarity, minimizing nutrient losses through leaching and erosion and potentially improving nutrient recycling and nutrient availability for crops at the ecosystem level (Ahenkorah et al., 1987b; Mäder et al., 2002; van Ruijven and Berendse, 2005a). Although studies conducted in Togo (Dossa et al., 2008) and Ghana (Ofori-Frimpong et al., 2007) have found improved soil fertility in complex coffee or cocoa agroforests compared to monocultures, data remains lacking about cumulative effects of increasing richness and abundance of tree species ("tree diversification") on soil fertility in tropical agroforestry systems.

While soil fertility is determined by many key physical, chemical and biological properties (Doran and Parkin, 1994b), microbial communities' role in the regulation of important nutrient cycling processes such as decomposition or aggregate formation is well recognized (e.g. Swift et al., 1979; Six et al., 2004). Many studies have documented soil microbial communities' responses to changes in vegetation composition (e.g. Wardle et al., 2004), and we similarly expect increases in tree diversity to impact soil microbial activity in cocoa agroforests. Soil microbial communities are also highly sensitive to environmental changes and are thus useful indicators for changes in soil conditions caused by land-use change (Six et al., 2006). However, few studies have documented the effects of increasing tree diversity on microbial communities in tropical agroforestry systems.

As a result, the overall benefits of increased tree diversity on soil fertility in cocoa agroforests remain ambiguous. On one hand, increased plant species diversity has been directly linked to spatial and temporal resource partitioning and improved functional complementarity (Hooper and Vitousek, 1997; van Ruijven and Berendse, 2005a). For example, certain tree roots can function as safety nets, minimizing leaching via stratification and recycling nutrients from deeper soil horizons to soil surface layers (Van Noordwijk and Purnomosidhi, 1995). However, intercropped trees in agroforests might also compete with crops for nutrients (Sanchez, 1995a) or light resources (Clough et al., 2011). A majority of the data suggesting a positive effect of plant species diversity on soil processes has been derived from experimental studies conducted in controlled plantation trials and/or in temperate grassland ecosystems (Tilman et al., 1996; Scherer-Lorenzen et al., 2007). While such studies are invaluable in determining causal relationships between plant diversity and below-ground processes, they may not easily translate to other natural environments and cropping systems. In contrast, insights derived from observational studies conducted in real-world farming systems are scarce, yet could provide complementary information that helps us understand the functioning of agroecosystems processes under field conditions (Vilà et al., 2005b)**.**

Indonesia is currently the third largest global cocoa exporter, and more than 60% of the country's cocoa is grown on the island of Sulawesi, which faces increasing rates of deforestation and agricultural expansion (McMahon et al., 2015). The region thus constitutes a relevant case study for the potential effects of cocoa agroforest diversification on soil fertility. After an initial period of high productivity, cocoa farmers in Sulawesi are now faced with rapidly declining cocoa yields linked to unsustainable management practices, increased pest and disease incidence and increased soil degradation (McMahon et al., 2015). This decline in productivity has led farmers to abandon existing plantations and seek out new land, leading to further deforestation and threatening remaining rainforest areas. Improving the sustainability of established cocoa plantations in the region should thus be a priority.

Our principal objective is to determine whether tree diversification in cocoa plantations can provide soil fertility benefits and contribute to soil restoration after deforestation, ultimately contributing to the increased sustainability of cocoa cultivation systems in Southeast Sulawesi. To quantify the effects of tree diversification on soil fertility in cocoa plantations we compared soil fertility indicators (total carbon (C), nitrogen (N), phosphorus (P), available

P, pH, cation exchange capacity (CEC), base saturation, soil aggregation, bulk density and phospholipid fatty acid (PLFA) composition) along a gradient of increasing tree species diversity. To assess the extent to which cocoa agroforests might contribute to soil restoration following deforestation, we further examine how the effects of tree diversification on soil fertility in cocoa plantations compare to soil fertility levels in secondary and primary forests.

2.2 Material & methods

Description of the study

We conducted our study in the Konawe province in Southeast Sulawesi, Indonesia (3.58°S, 122.30°E), where *Theobroma cacao* (cocoa) is the most prevalent cash crop. While traditionally cocoa plantations are often established by thinning primary forests (Tscharntke et al., 2011), in Sulawesi cocoa seedlings are planted on land completely cleared from forests by manual cutting of trees and undergrowth. Following plot establishment, *Gliricidia sepium* (gliricidia) trees are commonly intercropped with cocoa seedlings, mainly to provide shade protection. In older plots, farmers reduce the number of gliricidia trees, but fruit and timber trees are sometimes planted to supplement incomes. Thus, much of the cocoa in the region is grown in agroforests with varying levels of tree diversity.

Table 2.1. *Soil texture range across three communities in Southeast Sulawesi that were selected as study locations for our study. Means and standard errors are shown for percentage sand, silt and clay contents.*

Site	Plots	Sand (%)	Silt (%)	Clay (%)
1. Wonuahoa	18	27.8 ± 8.7	37.1 ± 5.9	36.0 ± 5.3
2. Asinua Jaya	15	37.0 ± 6.7	30.2 ± 9.9	32.9 ± 4.2
3. Lawonua	15	18.2 ± 7.2	46.9 ± 18.5	34.9 ± 13.5

Study sites were selected in the communities of Lawonua, Wonuahoa and Asinua Jaya. Soils in the region are dominated by weathered *orthic acrisols* in the mountains and *dystric fluvisols* in the floodplain (FAO-UNESCO, 1979), and the selection of three separate villages allowed us to test our hypotheses across different soil types in the study area (Table 2-1).

Annual precipitation is 2080 mm (1982 - 2012 average) and is highly seasonal, with most rain falling during the wet season from January to June. Mean daily temperatures range between 25°C and 28°C, depending on time of the year and elevation (Climate-Data.org, 2016).

Plot selection and characterization

We selected twelve cocoa plots measuring 30 m x 30 m in each village (for a total number of 36 cocoa plots) to represent the variation in shade tree cover and tree species diversity observed in the study region ("diversity gradient", Fig. 2.1a).

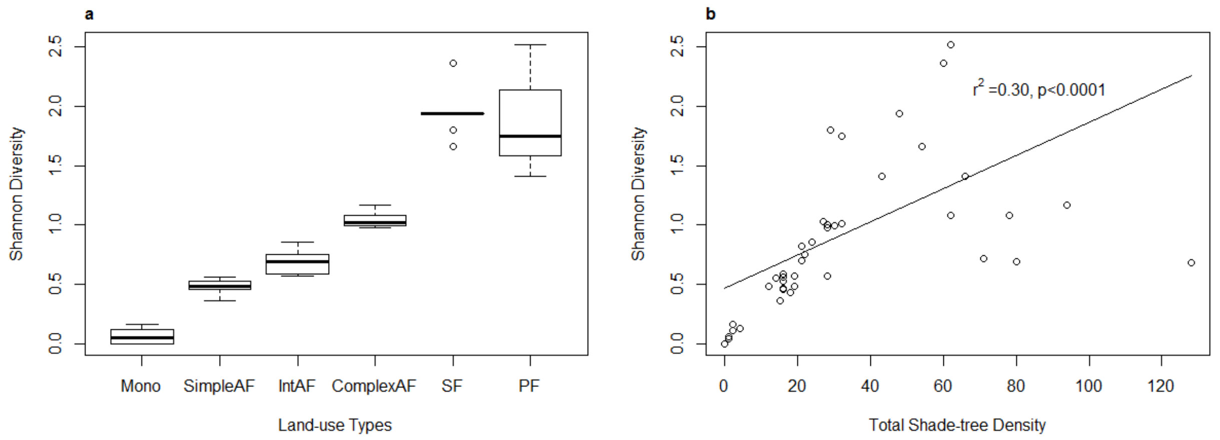

Figure 2.1. *Box-plot distribution of tree diversity quantified by Shannon diversity index across land-use typologies: monoculture (Mono), simple agroforest (SimpleAF), intermediate agroforest (IntAF), complex agroforest (ComplexAF), secondary forest (SF) and primary forest (PF) (a); and relationship between Shannon diversity and total shade-tree density per plot, across all plots (b). Horizontal lines are medians, boxes show the interquartile range (25^{th} to 75^{th} percentiles of observations). Whiskers show the full range excluding outliers.*

To obtain an adequate diversity gradient ranging from low to high tree species diversity, selected plots were evenly distributed across the following typologies, which we defined based on the number of intercropped tree species per plot: cocoa monocultures, simple agroforests, intermediate agroforests and complex agroforests (Table 2.2). In simple agroforests, the most common species intercropped with cocoa was gliricidia, followed by banana (*Musa paradisica*). In intermediate agroforests, cocoa was typically intercropped with 3 to 4 fruit or timber tree species. In complex cocoa agroforests, cocoa was intercropped with about 5 to 9 tree species. Most cocoa plots were established within 3 to 5 years of each other, and on average cocoa trees in our study plots were 13 years old (Table 2.2).

Table 2.2. *Site characteristics across cocoa, secondary and primary forest plots in the study area of Southeast Sulawesi: distribution of plot typologies across communities (Site); number of total replicates for each typology (N); shade tree density and standard*

Plot typology	Site [a]	N	Tree density (ha^{-1}) [b]	Fertilizer intensity	Plot age (years)	Cocoa yield ($kg\ ha^{-1}$)
Cocoa monoculture	1, 2, 3	9	44 ± 77	low:1 (plot), medium: 4, high: 2	12 ± 3	67-1786
Simple Agroforest	1, 2, 3	8	567 ± 489	low: 4, medium: 1, high: 2	12 ± 3	50-1071
Intermediate Agroforest	1, 2, 3	10	244 ± 167	low: 2, medium: 1, high: 4	13 ± 3	143-1920
Complex Agroforest	1, 2, 3	9	400 ± 222	low: 3, medium: 2, high: 3	14 ± 3	18-1920
Secondary forest	1, 2, 3	9	533 ± 89	--	fallow for 10+ years [2]	--
Primary forest	1	3	511 ± 167	--	--	--

[a] Wonuahoa (1); Asinua Jaya (2); Lawonua (3)
[b] Total number of trees for secondary and primary forests per hectare

To compare soil properties between cocoa plantations and forested areas, we selected three secondary forest plots in each community and three additional primary forest plots in Wonuahoa, leading to a total of 48 plots. Secondary forest systems were established at least 10 years after abandonment of old cocoa fields. They were dominated by a mix of domesticated crop trees (*Theobroma cacao*, *Gliricidia sepium*, *Gmelina arborea*) and local forest trees (*Mischocarpus sundaicus*, *Albizia procera*, etc.). Selection criteria for primary forest plots included plots that had more difficult access for farmers and appeared to be undisturbed both in terms of soil and vegetation. Tree species composition in these primary forests plots was dominated by local species (*Castanopsis buruana*, *Aporosa purpurescens*, etc.). All cocoa and secondary forest plots were identified and sampled between March and June 2014 and all primary forest plots in May 2015. Four plots across the diversity gradient in cocoa plantations and one secondary forest plot were re-sampled in 2015 to verify that 2014 and 2015 data sets are comparable. We compared total soil C, N and P content and found no significant differences between the two years. To minimize the risk of bias across all selected cocoa and forest sites we only included plots with homogenous vegetation cover and soils. Wherever possible we excluded plots located on sloped terrain or those that contained visible man-made structures or disturbances (e.g. hills or trenches).

In each plot we recorded total number of tree species (s) and proportion (p) of individuals per species to quantify tree diversity using the Shannon Diversity index (Shannon and Weaver, 1964):

$$\underline{\textbf{Shannon} - \textbf{Wiener Index} = -\sum_{i-1}^{s} p_{\mathrm{i}} \ln p_{\mathrm{i}}}$$

We also counted all cocoa trees within the 30 x 30 m plot perimeters. Our plot diversity categories formed an excellent gradient in Shannon diversity of trees across all plots (Fig. 1a). Therefore, from here on, we used the Shannon index values as the variable for tree diversity.

While our study examines the effects of Shannon diversity on soil fertility parameters, we additionally identified and quantified confounding site and management factors that may have influenced our results: shade tree density, above-ground biomass (AGB), plot history and fertilizer use. Total shade tree densities were determined by counting individuals with a stem diameter at breast height (DBH) of ≥ 10 cm located inside our plots (Table 2.2). Above-ground biomass was calculated for a sub-sample of plots located in the community of Wonuahoa, based on measured DBH and height of individual trees (see Appendix 1 for detailed methodology). As both shade tree density and AGB were significantly correlated with Shannon diversity across our plots (Fig. 2.1b, Appendix 1), we tested whether inclusion of these factors as covariates in initial statistical analyses influenced our results; however, this was not the case. We therefore focus our results and discussion on effects of tree diversity.

Farm age, management intensity and land-use history were recorded through semi-structured farmer interviews, which included cross-checking certain answers to verify obtained information. Fertilizer use intensity was determined based on reported frequency of application events per year, reported amounts of fertilizer per application and extrapolated number of total cocoa trees per ha based on the number of trees counted per plot. Additionally, yield estimates were directly reported by farmers and were standardized to kg of dried harvested beans per ha per year. Fertilizer intensity, plot age, and yields did not vary significantly between land-use typologies (Table 2.2).

Soil sampling and analysis

We quantified soil fertility levels in cocoa plantations selected along a tree species diversity gradient, as well as in secondary and primary forest plots. The bulk of cocoa roots is concentrated in the top 30 cm of soil (Hartemink, 2005), and up to 60% of cocoa fine-roots are located in the top 15 cm of soil (Muñoz and Beer, 2001). The effects of forest conversion and site management on soil C have been found to be most significant in the topsoil (e.g. Schroth et al., 2002) and we similarly found no significant relationship between tree diversity and soil nutrient pool sizes in deeper soil layers (all $p>0.08$, results not shown). We therefore focus our results and discussion on the impacts of tree diversification in topsoil layers.

In each of our 48 total plots, we collected a total of 15 soil samples at two depths (0-15 cm and 15-30 cm) every 5 m along a systematic grid. Surface litter layer material was gently cleared before sampling. All samples were composited to obtain one sample per depth per plot and gently processed through an 8mm sieve to remove rocks, macro-fauna, roots and woody debris. About 150 g per sample were sealed into airtight bags immediately after sampling and refrigerated at 4°C for phospholipid fatty acid (PLFA) analysis; the rest was air-dried and transported to ETH Zürich, where all samples were finely ground for subsequent analyses.

We used a hammer corer (Ø 5.5 cm) to collect nine intact cores (0-15 cm) for aggregate fractionation along the same systematic grid in each plot. Cores were stored to preserve soil structure, and sub-samples were taken to determine soil moisture content and bulk density. Cores were then carefully sieved through an 8 mm sieve by gently breaking soil clumps along natural planes of weakness (Six et al., 1998) and composited to yield one sample per plot. All core-composites were air-dried and immobilized in solid containers to avoid disrupting particle size structure during transport to ETH Zürich.

Samples were fractionated by means of wet sieving to determine aggregate stability and aggregate size-distribution, based on the methodology adapted from Elliott (1986), as described by Fonte and Six (2010). Separated fractions were oven-dried at 60°C and weighed to determine aggregate size-distributions. We calculated Mean Weight Diameter (MWD), which was used as an index for mean aggregate size, based on the proportions of large macroaggregates (LM; >2000 μm), small macroaggregates (sM; 250-2000 μm), microaggregates (m; 53-250 μm) and free silt and clay (s+c; <53 μm) particles (Van Bavel, 1950):

$$\mathbf{MWD} = \mathbf{2}(\mathbf{LM}) + \mathbf{1.125}(\mathbf{sM}) + \mathbf{0.1515}(\mathbf{m}) + \mathbf{0.0265}(\mathbf{s} + \mathbf{c})$$

At ETH Zürich, we determined total soil C and N concentrations using a dry combustion analyzer (CN-2000; LECO Corp., St Joseph, MN). Total and Mehlich I P were determined colorimetrically after heat digestion with H_2O_2, H_2SO_4, Se and Li_2O_4S (method adapted from Anderson and Ingram (1994b)) and Mehlich I extractions (Mehlich, 1953), respectively. We determined soil pH for all composite samples in a soil-water suspension using a pH meter. Soil texture (hydrometer method) and CEC and exchangeable base saturation were determined at Biotrop Laboratories in Bogor, Indonesia, via NH_4OAc extraction buffered at pH 7, using an atomic absorption spectrophotometer for Ca^{2+} and Mg^{2+} and a flame photometer for K^+ and Na^+. Nutrient stocks were calculated based on the bulk density values determined for each plot.

Microbial community structure and biomass assessment

Phospholipid fatty acid (PLFA) fingerprinting was used to determine the presence and distribution of different soil microbial groups. PLFAs were extracted from field-moist samples (15 g equivalent dry matter) following standard methodology adapted from Zelles and Bai (1993). After PLFA extraction and preparation, each sample was analyzed as a fatty acid methylester (FAME) via gas chromatography mass spectrometry (GC/MS) (GC 6890 MSD 5973, Agilent Technologies, Santa Clara, CA, USA). Individual FAME identification was based on retention time and comparison with a mass spectral database of standard compounds (Gattinger et al., 2003). We selected known PLFA biomarkers to indicate common groups of micro-organisms: Gram-positive (Gram+ve) bacteria (i15:0 ; a15:0 ; i17:0 ; a17:0), Gram-negative (Gram-ve) bacteria (16:1ω7 ; 16:1ω9c ; 16:1ω9t ; 18:1ω11 ; 17:0cy ; 19:0cy), arbuscular mycorrhizae (AM) fungi (16:1ω11), saprophytic fungi (18:2ω6c) and soil protozoa (20:3 ; 20:4 ; 20:5) (White et al., 1996; Olsson, 1999; Thoms et al., 2010). Total bacterial biomass was determined by adding the n15:0 fatty acid and all PLFA markers representing Gram+ve and Gram-ve bacteria; cyclo-propyl fatty acids (17:0cy; 19:0cy) were included as indicators of environmental stress (Frostegård and Bååth, 1996; White et al., 1996; Zelles, 1997). Total PLFA biomass was determined by calculating the sum of all selected biomarkers (expressed in nmol g^{-1} soil dry matter).

Statistical analyses

To test the effect of tree diversity on soil fertility indicators along a tree diversity gradient in cocoa plantations, we fitted our data into linear mixed-effects models using the *lme* function in R (Pinheiro et al., 2017). As we found no significant interactions between Shannon diversity and soil texture for any tested variable (all $p > 0.1$), the interaction factor was removed from all analyses. It therefore appears that farmers' planting decisions were not related to preferential selection of sites with differing soil conditions in our study area. Nevertheless, variability in soil nutrient contents has been linked with soil texture (Six et al., 2006; Zaia et al., 2012b). Our final statistical model therefore included Shannon diversity and soil texture as fixed variables and further included village as a random blocking factor to minimize masking effects by other environmental factors. Soil properties (C, N, P, pH, CEC and aggregation) and soil microbial community abundances (as indicated by PLFA groups) were set as response variables. Soil microbial community composition has been linked to variability in soil pH (Bossio et al., 1998; Thoms et al., 2010). We initially used pH as an additional covariant for PLFA analyses but removed it from final analyses because pH did not have an influence on our results.

Differences in soil properties and microbial communities between cocoa, secondary and primary forest plots ("land-use types") were assessed using analysis of covariance (ANCOVA). ANCOVA models were fitted using the *robustbase* (Maechler et al., 2016) packages in R (R Development Core Team 2014, version 3.1.1), and soil texture was used as a covariate (Table 2-1). Natural log- or inverse-transformations were applied where needed to meet assumptions of normality for all analyses. We further applied the Tukey-Kramer HSD tests for pair-wise comparisons of means ($p < 0.05$) between land-use typologies.

Statistical analyses of the PLFA data were carried out using the *vegan* package in R (Oksanen et al., 2017), including known PLFA biomarkers for common groups of micro-organisms. We carried out a non-metric multidimensional scaling (NMDS) analysis using Bray-Curtis dissimilarity (Faith et al., 1987) to relate PLFA biomarker abundance to tree diversity and chemical plus physical properties. This analysis was carried out across all plots, including secondary and primary forests. Variables for tree diversity and chemical and physical soil properties were then tested in post-hoc correlations with axes 1 and 2 of the PLFA biomarker NMDS analysis to determine which of these variables best explained the variation in PLFA data. The significance of all post-hoc correlations was assessed via permutation tests (n=999) (McCune et al., 2002). Based on NMDS results (Appendices 2 & 3), we then determined a reduced dataset of significant indicators for PLFA and soil properties (total C, bulk density and MWD) and performed simple linear regressions on these variables across all plots to compare influences of soil properties on PLFA groups.

2.3 Results

Tree diversity effects on soil nutrient contents

Despite the wide-range of recorded Shannon index values along the diversity gradient in cocoa plots (0 to approximately 1.4), tree diversity was not significantly related to total soil C-contents in the topsoil layer (0 - 15 cm) (Table 2.3, Fig. 2.2a). We found no significant association between total soil N-levels and tree diversity (Table 2.3, Fig. 2.2b), whereas total P decreased significantly with increasing tree diversity (Table 2.3, Fig. 2.2c).

A comparison across all three land-use types (cocoa, secondary and primary forest) revealed significantly higher levels of Shannon diversity in secondary and primary forests (Fig. 2.1a). Total soil C was significantly higher in secondary forests than in cocoa plantations (Fig. 2.2e). Total soil N and P levels were higher in cocoa plots than in primary forest plots, whereas differences between cocoa plots and secondary forest plots were not statistically significant (Fig. 2.2f and Fig. 2.2g).

Cocoa yields did not vary with increasing tree species diversity (Table 2.3) or fertilizer inputs ($F=0.1$, $p=0.71$). We found no significant relationship between soil physical and chemical properties and fertilizer inputs; or between tree diversity and pH, Mehlich I P and CEC along the diversity gradient in cocoa plots (data not shown).

Table 2.3. *Results from a linear mixed-effect model analysis examining the changes in yield and soil fertility indicators in topsoil layers (0 - 15cm) along a gradient of increasing shade tree diversity ("Diversity") across 36 cocoa plots in Southeast. (*** p<0.001, ** p<0.01, * p<0.05, . p<0.1)*

RESPONSE VARIABLES	EXPLANATORY VARIABLES	NUM DF	DEN DF	F	P
log(Yield) (kg ha^{-1} of dried beans)[a]	Diversity	1	24	0.3	0.62
	Soil Texture	1	24	0.0	0.91
Soil total C (kg ha^{-1})	Diversity	1	30	0.1	0.72
	Soil Texture	1	30	1.1	0.30
Soil total N (kg ha^{-1})	Diversity	1	30	0.4	0.55
	Soil Texture	1	30	0.1	0.79
Soil total P (kg ha^{-1})	Diversity	1	30	4.4	**0.04 ***
	Soil Texture	1	30	0.8	0.40
Mean Weight Diameter (mm)	Diversity	1	30	0.1	0.72
	Soil Texture	1	30	0.2	0.65
Total PLFA (nmol g^{-1})	Diversity	1	30	0.3	0.59
	Soil Texture	1	30	7.5	**0.01 ****
Gram-ve bacteria (nmol g^{-1})	Diversity	1	30	0.2	0.63
	Soil Texture	1	30	10.7	**0.004 ****
Gram+ve bacteria (nmol g^{-1})	Diversity	1	30	0.9	0.35
	Soil Texture	1	30	8.5	**0.01 ****
1/ AM fungi (nmol g^{-1})	Diversity	1	30	0.2	0.64
	Soil Texture	1	30	3.5	0.07.

[a] Yield estimates are based on values directly reported by farmers and were standardized to kg of dried harvested beans per year per ha.

Tree diversity effects on soil aggregation

We found no increase in soil aggregate stability (i.e. MWD) with increasing shade tree diversity in cocoa plots (Table 2.3, Fig. 2.2d). We also found no significant differences in large macroaggregate (LM) proportions and C-storage-within-LM between cocoa plots with varying tree diversity levels (all p>0.08). A comparison across land-use types showed increased proportions of LM and decreased proportions of microaggregates in forest plots in comparison to cocoa plots. Within the LM fractions, total aggregate-associated soil C and P levels were highest in primary and secondary forest plots (Fig. 2.3).

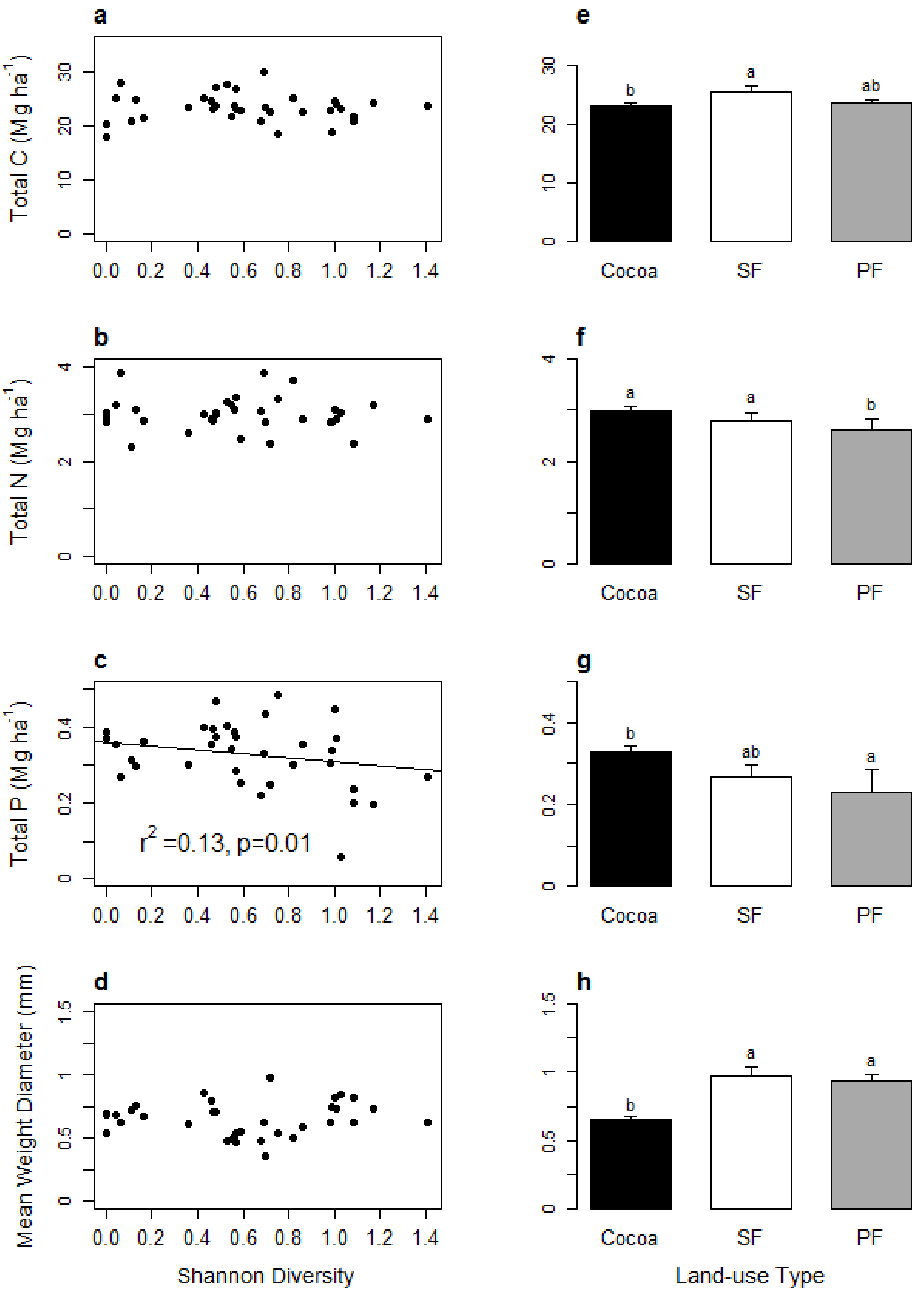

Figure 2.2. *Variation of total C, total N and total P in Mg ha-1 at 0-15 cm depth, and mean weight diameter (mm) along the "diversity gradient" in cocoa plots (indicated by Shannon Diversity) (a, b, c, d); and between cocoa, secondary (SF) and primary forest (PF) plots (e, f, g, h). Mean Weight Diameter" is a measure of mean soil aggregate size. The solid line in each graph represents a significant effect of diversity on soil variables ($p<0.05$). Bars represent mean values for each land-use type ± standard error. Letters indicate significant differences between land-use types for each of the measured soil variables.*

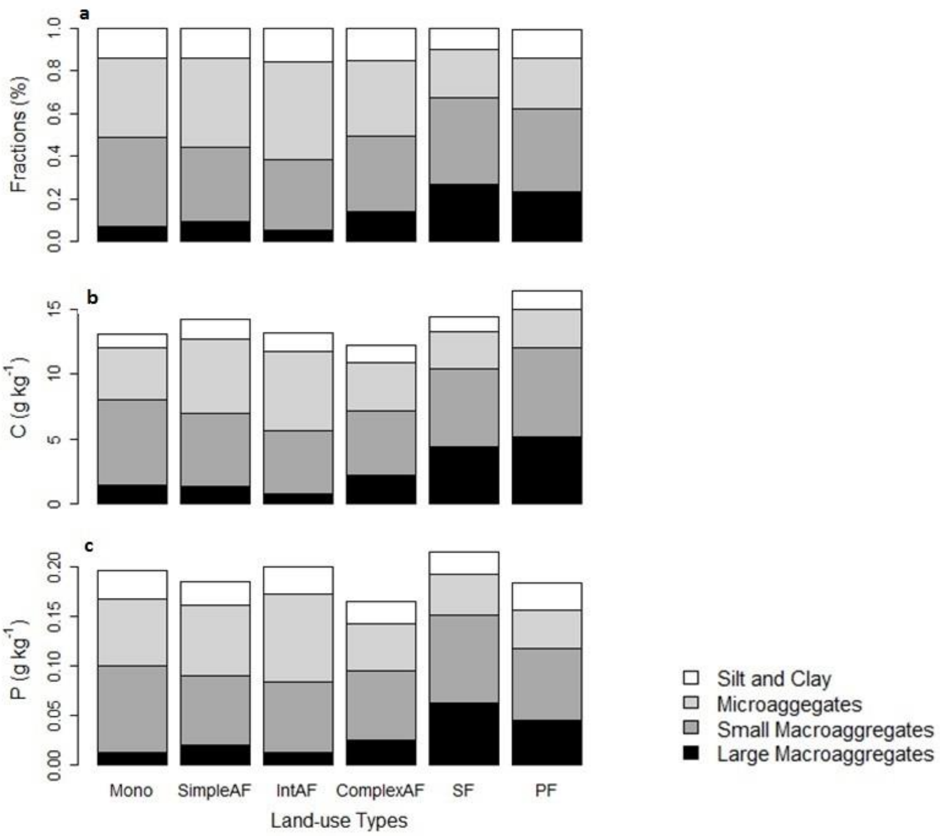

Figure 2.3. *Proportion of aggregate fractions (a), total C-within-fractions (b), and total P-within-fractions (c) found across all examined land-use typologies: monoculture (Mono), simple agroforest (SimpleAF), intermediate agroforest (IntAF), complex agroforest (ComplexAF), secondary forest (SF) and primary forest (PF).*

Tree diversity effects on microbial communities

We found no significant relationship between tree diversity and total PLFA biomass, PLFA abundance for Gram-ve bacteria, Gram+ve bacteria or AM fungi along the diversity gradient in cocoa plots (Table 2.3, Fig. 2.4). We found two significant differences in PLFA abundance across land-use types. First, total PLFA biomass and PLFA abundance for Gram-ve bacteria were highest in secondary forest plots. For total PLFA, the difference between secondary and primary forests was not statistically significant (Fig. 2.4e & Fig. 2.4f). Second, PLFA abundance for Gram+ve bacteria and AM fungi was significantly lower in cocoa plots than in secondary and primary forests (Fig. 2.4g & Fig. 2.4h).

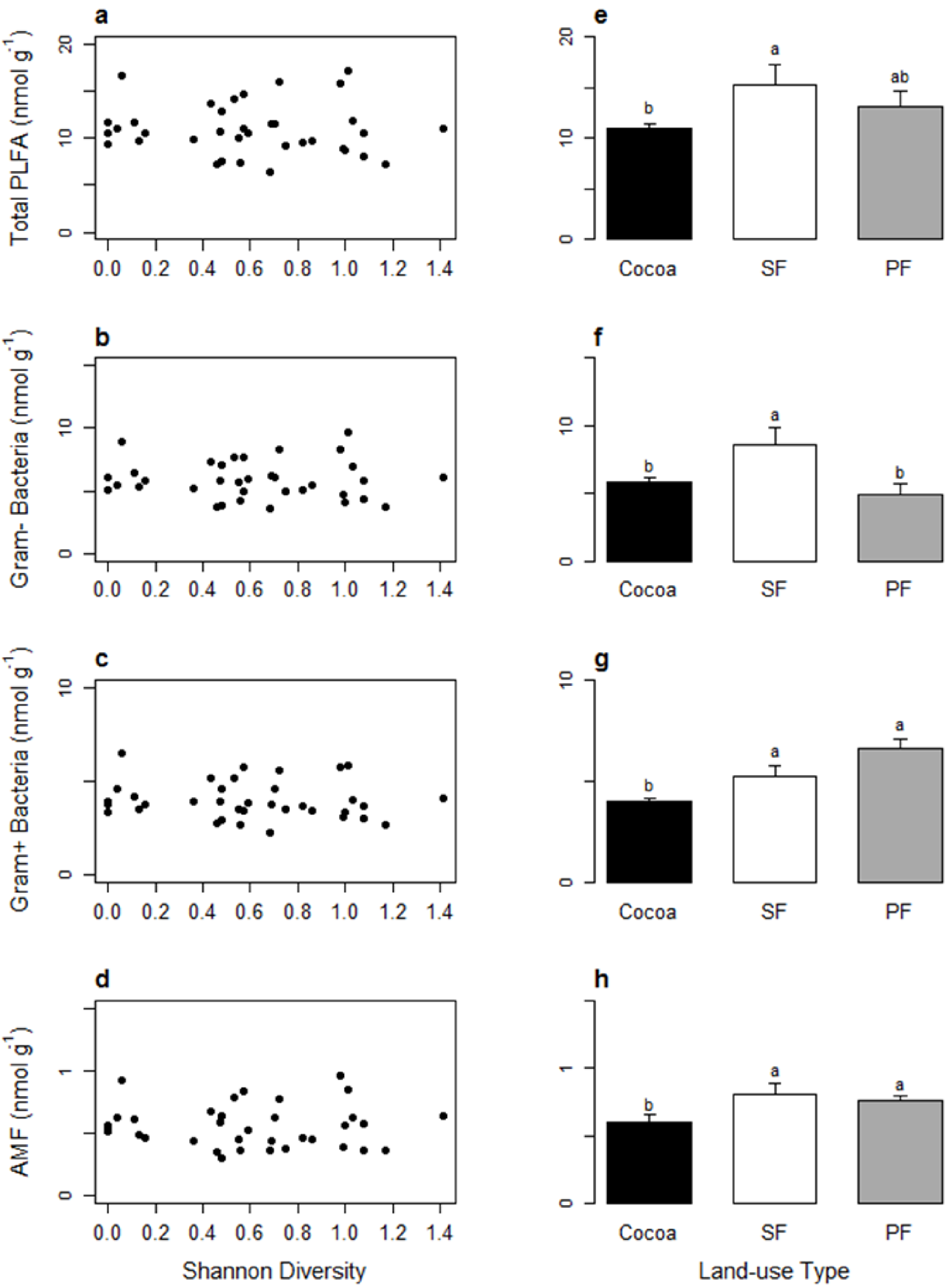

Figure 2.4. *Variation of total PLFA biomass and PLFA specific biomarkers for Gram negative (Gram-), Gram positive (Gram+) bacteria and arbuscular mycorrhizal fungi (AMF) in nmol g-1 along the "diversity gradient" in cocoa plots (indicated by Shannon Diversity) (a, b, c, d); and between cocoa, secondary (SF) and primary forest (PF) plots (e, f, g, h). Bars represent mean values for each land-use type ± standard error. Letters indicate significant differences between land-use types for each of the measured soil variables.*

Soil properties and changes in microbial communities

Our NMDS analysis did not result in clear groupings of plots based on either tree diversity or land-use types alone (Table A.1). Other factors appear to drive observed differences in microbial communities, even though tree diversity was significantly correlated with differences in PLFA abundances in the NMDS post-hoc correlations (Appendix 3). The post-hoc correlations for PLFA marker abundance showed that total C, bulk density and MWD were the only soil properties significantly correlated with differences in PLFA composition and abundance (Appendix 3). A subsequent regression analysis of total C and MWD with PLFA markers showed significant positive correlations between total soil C content and bacterial PLFA and AM fungi PLFA, and between soil MWD and PLFA of saprophytic and AM fungi (Table 2.4).

Table 2.4. *Results of linear regression analyzing analysis between phospholipid fatty acid (PLFA) markers for and total soil carbon (C) and mean weight diameter (MWD) across cocoa, secondary forest, primary forest plots (n=48) in Southeast Sulawesi. MWD is a measure of mean soil aggregate size. PLFA markers for bacteria, saprophytic fungi and arbuscular mycorrhizal fungi (AMF) were included. Shown are R^2 and P-values. (******* p<0.001, ****** p<0.01, ***** p<0.05, **.** p<0.1).*

	C	MWD
Total PLFA	**0.33 *****	0.14
Bacterial PLFA	**0.35 *****	0.14
Log(Fungi)	**0.08 ***	**0.20 ***
1/AMF	**0.35 *****	**0.12 ***

2.4 Discussion

Tree diversity did not change soil fertility in cocoa plantations in Southeast Sulawesi

We found no significant relationships between increased tree species diversity and total soil C, N, soil aggregation (MWD), or microbial group abundances across our cocoa plots. These results were not entirely surprising as existing studies comparing simple and complex cocoa- or coffee-based agroforestry systems have either found no significant differences for soil organic C stocks (Noponen et al., 2013; Jacobi et al., 2014; Blaser et al., 2017), CEC and total soil N (de Souza et al., 2012), or aggregate distribution (Gama-Rodrigues et al., 2010); or have yielded inconclusive results (Haggar et al., 2011; Häger, 2012). In the next sections we discuss three potential explanations for our results.

First, our data suggests that tree species diversity alone did not have a significant effect on soil properties and microbiota in Southeast Sulawesi. However, differences in Shannon diversity were significantly higher between cocoa plots and forest plots than among cocoa plots (Fig. 2.1a), and our results indicate significant differences in soil fertility parameters between land-use systems (Fig. 2.2 & 2.4). We therefore postulate that increased species diversity in selected cocoa plantations may not have altered litter inputs or resource use efficiency rates enough to lead to measurable differences in soil properties and microbial community composition and abundance among cocoa plantations of varying diversity. Shade tree density was greater in forest plots (Fig. 2.1b) and the range of AGB in cocoa plots (750-5000 kg $plot^{-1}$) was much smaller than the AGB range in forest plots (5000-17,000 kg $plot^{-1}$) (Appendix 1). Nevertheless, controlling for variation related to shade tree density and AGB across cocoa plantations did not significantly change our results.

Second, benefits of increasing tree species diversity might not be measurable over the average lifetime of a cocoa farm in Southeast Sulawesi, and this might be exacerbated by persistent effects related to previous land-use. Studies along chrono-sequences in cocoa agroforests have shown significant differences in soil fertility between plots established at different times (Smiley and Kroschel, 2010; Dawoe et al., 2014). At our study sites, selected cocoa plots were of relatively uniform age (Table 2.2) and plot age was not likely a confounding factor for our results. However, it is possible that our plots were too young to show significant effects of increased shade tree diversity. Additionally, individual trees in forest ecosystems influence soil nutrient distributions over their lifetime, contributing to long-term spatial heterogeneity of soil properties, and these effects can persist for years following land-use change activities (Døckersmith et al., 1999; Diekmann et al., 2007). Observed spatial variation of C, N and P pools within our plots were unrelated to current distribution of shade trees (Wartenberg, unpublished). We therefore hypothesize that persistent effects linked to previous forest cover might have masked potential benefits increased tree diversification on soil fertility in our cocoa plantations (Blaser et al., 2017).

Third, the effects of tree diversity on soil properties may have been confounded by external factors such as variation in site characteristics or farm management practices, particularly for P dynamics. Controlling for soil texture and study site (village) did not change the outcome of our results. Controlling for fertilizer application also did not significantly alter the observed relationships between tree species diversity and microbial communities, MWD, soil C and soil N. However, the observed negative correlation between soil total P and diversity ($F=4.4$, $p=0.04$, see Table 2.3) became more significant when fertilizing intensity was used as a covariant ($F=5.4$, $p=0.03$), confirming that fertilizer application may have confounded negative effects of tree diversity on soil P. Further study on management factors influencing P dynamics in cocoa agroforests could therefore yield useful insights. Nevertheless, our results still do not indicate a significant effect of increasing tree diversity on soil C, N, MWD or soil microbiota.

Overall, we find that increasing tree species diversity did not measurably increase soil fertility in cocoa farms aged 10-15 years (Table 2.2), and likely over the average lifetime of cocoa farms in Southeast Sulawesi. While benefits of increasing tree species diversity for soil health might become more apparent over longer time scales, this may not be immediately relevant for smallholder farmers in the study region who are dependent on short- to mid-term income security to sustain their livelihoods.

Soil degradation after forest conversion

We found significant evidence of soil degradation in terms of soil aggregation, SOM content and microbial abundances in cocoa plantations compared to reference forest ecosystems. Soil aggregation was significantly lower in cocoa plots compared to primary forests (30% for MWD and 19% for C within macroaggregates) and secondary forests plots (33% and 7%, respectively). Decreased MWD values indicate a decrease in the long-term SOM storage capacity in cocoa plots, likely caused by ecological disturbances associated with the establishment of cocoa plantations after deforestation (Roshetko et al., 2007). The magnitude of C losses we recorded were in line with previous literature: a meta-analysis carried out by Guo and Gifford (2002) found an average decrease of 13% in soil C stocks after conversion of primary forest to plantation, whereas in Central Sulawesi, above-ground C was found to decrease by 75% (Steffan-Dewenter et al., 2007) to 88% (Smiley and Kroschel, 2010) after conversion from primary forest to cocoa agroforests.

AM fungi abundance was similarly decreased in cocoa plots compared to forest plots (Fig. 2.2h and Fig. 2.4h). Across all our sites, soil aggregation and AM fungi (Table 2.4) were positively correlated, highlighting the linkages between microbial abundances and aggregation dynamics (Miller and Jastrow, 2000). Soil P was significantly decreased in primary forest systems compared to cocoa plantations in our study area. This could be linked to the fertilizer effects discussed previously. Alternatively, McGrath et al. (2001) suggest that after tropical forest clearing and burning, P previously stored in AGB is transferred to the soil, leading to short-term soil P accumulation. Increased AM fungi abundances in primary forests compared to cocoa plantations (Fig. 2.4) could have led to higher P uptake rates in forest systems (Thompson, 1987; Muleta et al., 2008) although more research is needed to corroborate this.

In tropical forests, SOC sometimes accumulates over thousands of years, whereas reforestation efforts alter soil C levels at the decadal/century time scale (Mehta et al., 2013b). Due to slow soil recovery rates, levels of “reference ecosystem” (primary forest) soil fertility cannot be easily recovered despite tree planting (Detwiler, 1986). Our results indicate that in our study area, soil degradation following land-use change was not offset by planting more diverse tree species in cocoa agroforests, at least at the measured time-scale. It is likely that confounding factors related to differences in vegetation cover or land-use history had more influence on soil microbial dynamics and soil nutrient storage processes than tree species diversity alone. Increasing the diversity of shade trees in cocoa agroforests thus appears to have a limited potential for soil restoration following deforestation, particularly in the short- to middle-term. Based on our findings, we recommend that policies and management efforts should target not only soil restoration in complex agroforests but, more importantly, the prevention of further land degradation, e.g. by prioritizing the sustained use of already cleared areas or by minimizing incentives for further deforestation.

Ecosystem recovery after land-use change and disturbance

In accordance with existing literature we expected to find significantly lower soil fertility levels in secondary forests compared to primary forests (van Noordwijk et al., 1997; Steffan-Dewenter et al., 2007). However, we found no significant differences in soil C levels between secondary (25.6 Mg ha^{-1}) and primary forests (23.6 Mg ha^{-1}), whereas mean soil C was significantly higher in secondary forests compared to cocoa plots of varying levels of diversity (23.3 Mg ha^{-1}). This might be due to the presence of more labile C in secondary forest systems, as increased resource availability in secondary forests (Vilà et al., 2005b) might have promoted higher accumulation of plant-derived organic matter in topsoil layers. AGB stocks have been shown to increase rapidly in secondary forests after farm abandonment (Feldpausch et al., 2004), and we similarly found that AGB was increased in secondary forest plots compared to cocoa plots (Appendix 1).

Total PLFA biomass was also highest in secondary forests (Fig. 2.4e). This may have been driven by an increase in Gram-ve bacteria (Fig. 2.4f), which have been shown to prefer more labile sources of organic material than Gram+ve bacteria (Kramer and Gleixner, 2008). We also observed an incremental increase in Gram+ve bacteria across land-use systems (Fig. 2.4f) and found no significant differences in AM fungi abundances or MWD between secondary and primary forests (Fig. 2.2h). These dynamics suggest a recovery in microbial function and long-term SOM accumulation processes in secondary forests compared to cocoa plantations, indicating that these systems could potentially contribute to long-term soil restoration after deforestation.

2.5 Conclusions

Cocoa plantations in Southeast Sulawesi were found to have consistently lower soil C, MWD and microbial abundances than both primary and secondary forests. Our findings indicate that in our study region, increasing tree species diversity (and hence the diversification of plant-based inputs) was not the principal determinant of variation in soil fertility. Our data did not allow us to identify the mechanisms that cause the observed differences between cocoa plantations and reference forest ecosystems. Nevertheless, based on our results, we postulate that in secondary and primary forest systems of Southeast Sulawesi, differences in other factors related to vegetation cover and land-use history might significantly contribute to altered litter decomposition rates and substrate quality compared to cocoa plantations, leading to significant differences in soil nutrient contents, aggregation, and bacterial and fungal abundance between land-use systems.

We conclude that, while the diversification of cocoa agroforests might have the potential to provide significant benefits for biodiversity conservation and farmer livelihoods (e.g. Tscharntke et al., 2011), it is not a solution to mitigate the negative impacts of deforestation on soil ecosystem health in cocoa plantations. In forests soils, nutrient stabilization and accumulation occur over very long time-periods. Following soil degradation after deforestation, the effects of increased species diversity from monocultures to cocoa agroforests do not appear to lead to measurable improvements in soil fertility over the lifetime of an average cocoa farm. However, our data suggests that secondary forests might be beneficial for soil function restoration in terms of microbial communities, soil C and aggregate stabilization. Hence, we recommend that in Southeast Sulawesi, or in regions facing similar pressures related to deforestation and land degradation, farm sustainability guidelines focus on secondary forest regeneration within the agricultural landscape, for instance by implementing forest strips and regular rotations to allow ecosystem recovery after intense farming periods.

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Chapter 3 :

Soil fertility and *Theobroma cacao* growth and productivity under commonly intercropped shade tree species in Sulawesi, Indonesia

Abstract

The inclusion of shade trees in agricultural cropping systems can have a significant influence on surrounding soils and crops, with variations in specific tree traits impacting microclimate and soil fertility. Still, trade-offs between ecological and economic benefits associated with the inclusion of shade trees in cocoa agroforests are not well understood. To gain understanding about the interactions between shade and cocoa trees in cocoa agroforests, we conducted a field study in Southeast Sulawesi, where we quantified the effects of individual shade trees from 11 commonly intercropped species on cocoa performance indicators (above-ground biomass and yields) and soil fertility indicators (total soil carbon, nitrogen, phosphorus contents and soil aggregation). We found that shade trees were associated with a net positive effect on soil fertility, a negative effect on cocoa tree growth and no net effect on cocoa yields. There were significant differences between shade tree species in the magnitude of these effects: *G. sepium* (gliricidia) had significantly positive effects on yields but less on soil fertility, whereas *N. lappaceum* (rambutan) and D. *zibethinus* (durian) had significantly positive effects on some soil fertility indicators but not on yields. Our results importantly indicate that the inclusion of individual shade trees does not necessarily constitute a direct trade-off for farmers in terms of yield losses, and that the management of individual shade trees at low densities in cocoa farms could be beneficial. Nevertheless, our results also indicate high variation in the effects of different tree species. Due to complex interactions between different traits, the development of shade tree planting guidelines for improved cocoa cultivation, based on shade tree morphology and functional traits, may prove difficult and would require further research. Evaluating the trade-offs associated with different shade tree species in terms of ecosystem resilience and yield improvements thus remains important for the selection of locally suitable shade tree species in cocoa agroforests.

Authorship and status of manuscript

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3.1 Introduction

On a global scale, smallholder *Theobroma cacao* (cocoa) cultivation systems are facing increasing production pressures related to factors such as soil degradation or pest and disease outbreaks (Vaast and Somarriba, 2014). The inclusion of shade trees in cocoa agroforests has been heralded as a solution to these issues, with proposed benefits ranging from increased livelihood sources to improved nutrient cycling processes and increased ecosystem resilience (e.g. Beer et al., 1998a; Somarriba et al., 2013). However, shade trees are also likely to compete for light or nutrient resources with neighboring crops or trees (Sanchez, 1995b), and to date it remains unclear to what extent the benefits and disadvantages associated with shade trees impact soil fertility and yield productivity in cocoa agroforests.

Studies by Zinke (1962) or Rhoades (1996) have indicated that isolated trees in savanna ecosystems can improve the soils around them by providing protection from direct solar irradiation and by increasing aboveground and belowground organic inputs, which can in turn improve vegetation growth under tree canopy. It is, however, difficult to extrapolate from such studies to tropical agroforestry systems, as data collected in different cropping systems and under different environmental conditions systems may not directly translate to tropical agroforests (Lejon et al., 2005). Various studies have examined soil nutrient storage dynamics under individual trees (Zinke, 1962; Rhoades, 1996; Finzi et al., 1998) and different tree species (Binkley, 1995). Still, to our knowledge, studies of the effects of individual trees on aggregate stability, an important indicator for long-term soil fertility, remain scarce (e.g. Lehmann et al., 2001), whether in temperate or in tropical ecosystems.

In the context of cocoa agroforests, few studies have quantified in detail the effects of intercropped trees on soil fertility and neighboring cocoa trees. The benefits or disadvantages of shade trees are highly dependent on selected tree species and local climate (Beer et al., 1998a; Isaac et al., 2005). The variability in morphological traits of shade trees, such as canopy shape, litter chemistry or root system attributes, is likely to affect cocoa growth and productivity either directly via competition for light (Isaac et al., 2007), water or nutrients (Van Noordwijk et al., 2015), or indirectly via changes in soil chemistry (Binkley and Giardina, 1998) and microbial associations (Grayston and Prescott, 2005). Certain shade tree species can also contribute to pest and pathogen control at the ecosystem level (van Noordwijk et al., 2004).

Canopy shape and density are important modulators of light and microclimate conditions (Lindner et al., 2010), as variations in light, temperature and humidity can occur as a response to reduced solar irradiation underneath tree canopies (Isaac et al., 2007). In cocoa plantations, cocoa yields are highly dependent on solar irradiation levels, particularly in environments where nutrient availability is not a limiting factor (Cunningham and Arnold, 1962; Beer et al., 1998a; Isaac et al., 2007). Quality and quantity of litterfall impact soil fertility by modulating soil organic matter inputs and decomposition processes, and have been shown to vary substantially between tree species (Sariyildiz et al., 2005; Hobbie et al., 2006). Although most studies of the effects of different tree species on chemical soil properties have focused on temperate single-species forest stands (Rhoades, 1996), changes in litter quantity and chemistry among shade-tree species can similarly be expected to indirectly affect cocoa tree growth and development by changing soil nutrient availabilities. Roots and root-associated fungi are another important source of soil organic matter in agroforests (van Noordwijk et al., 2004). To date it remains difficult to assess root interactions between shade and cocoa trees due to lacking data about tree root architecture and tree root turnover rates for tropical agroforestry species (Van Noordwijk et al., 2015), and to the complexity and heterogeneity of interactions between roots, microbial organisms and site-specific field conditions. For instance, while Beer (1987) discusses the risks of significant root competition for moisture and nutrients between cocoa and shade trees, trees with deeper roots are also known to access water and nutrients from deeper soil layers (Van Noordwijk and Purnomosidhi, 1995; Bayala et al., 2008), leading to increased substrate availability for microbial communities (Cardoso et al., 2003) and improved soil fertility (Ramachandran Nair et al., 2009). However, the cumulative outcome of these effects has rarely been documented.

More generally, while some tree-associated traits, such as extensive shallow rooting systems and dense spreading canopies, are thought to lead to direct resource competition between trees and crops, others, such as nitrogen-fixing (N-fixing) capacity, are thought to improve soil fertility and therefore provide indirect benefits to understory crops (Rhoades, 1996). There is, however, little consensus in current literature about how to optimize agroforestry design based on a holistic evaluation of the effects of separate shade tree traits. To our knowledge, no existing studies have studied how tree-traits such as root structure or canopy shape might influence the general outcome of tree-crop interactions in cocoa agroforests.

An improved understanding of the interactions between shade trees and cocoa trees in cocoa agroforests would contribute valuable knowledge needed to optimize the sustainability and resilience of tropical agroforestry systems. The goal of our study was to both quantify the effects of individual shade trees on soil fertility and cocoa productivity in Southeast Sulawesi and to test whether observed differences might be linked to functional traits (absolute height, canopy height, canopy area, litter nutrient contents, rooting depth and above-ground biomass (AGB)) of the shade trees. We hypothesized that: i) cocoa productivity (as indicated by AGB and yields) would decrease under shade tree canopy, due to increased competition for both light and soil resources; ii) soil fertility (as indicated by total carbon (C), nitrogen (N), phosphorus (P) and soil aggregation (MWD)) would increase under shade tree canopy; iii) that the magnitude of these effects would vary significantly between species due to differences in functional traits.

3.2 Methods

Description of the study area

We conducted our study in the Konawe province of Southeast Sulawesi, Indonesia (3.58°S, 122.30°E), where cocoa is the most prevalent cash crop. Experimental sites were selected in smallholder farms located in the community of Wonuahoa, where soils are predominantly *orthic acrisols* (FAO-UNESCO, 1979). Mean annual precipitation is 2080 mm (1982 - 2012) and highly seasonal, with most rain falling in the January to June period. Mean daily temperatures range is 25°C to 28°C, depending on time of the year and elevation (Climate-Data.org, 2016).

Table 3.1 *Description of shade tree species and their functional traits: rooting depth, canopy shape (tree and canopy height, canopy area and above-ground biomass (AGB)) and litter nutrient concentrations (litter C, N, P, Ca2+, and C:N). The values displayed are mean values ± standard deviations.*

Species	Family	Common name	Rooting depth[1]	Tree Height (m)	Canopy Height (m)	Canopy Area (m^2)	AGB (kg)	Litter C ($g\ kg^{-1}$)	Litter N ($g\ kg^{-1}$)	Litter P ($g\ kg^{-1}$)	Litter Ca ($g\ kg^{-1}$)	Litter C:N
1. *Theobroma cacao*	Malvacea	Cocoa	Shallow	5.3 ± 0.9	2.4 ± 1.0	20 ± 7	21 ± 14	431 ± 18	16.4 ± 4.4	1.4 ± 0.3	6.4 ± 3.0	27.7 ± 7.5
2. *Gliricidia sepium*	Fabaceae	Gliricidia	Shallow	10.5 ± 1.6	3.4 ± 1.7	40 ± 30	56 ± 38	464 ± 6	27.2 ± 1.7	1.8 ± 0.2	9.7 ± 0.7	17.1 ± 1.0
3. *Nephelium lappaceum*	Sapindaceae	Rambutan	Shallow	12.7 ± 1.9	3.9 ± 0.8	69 ± 24	332 ± 229	469 ± 10	11.0 ± 2.7	1.8 ± 0.6	13.6 ± 2.3	44.6 ± 10.4
4. *Lansium domesticum*	Meliaceae	Langsat	Shallow	16.7 ± 3.3	3.2 ± 1.1	41 ± 13	495 ± 211	418 ± 16	15.0 ± 2.7	1.4 ± 0.2	9.9 ± 3.8	28.6 ± 5.4
5. *Durio zibethinus*	Malvacea	Durian	Deep	12.8 ± 2.2	3.5 ± 0.3	33 ± 16	537 ± 316	459 ± 7	17.3 ± 1.3	1.8 ± 0.4	8.6 ± 1.6	26.7 ± 2.0
6. *Artocarpus heterophyllus*	Moracea	Jackfruit	Deep	14.0 ± 3.9	3.7 ± 1.6	63 ± 48	526 ± 434	391 ± 9	13.0 ± 2.9	1.2 ± 0.2	8.9 ± 2.1	31.1 ± 6.1
7. *Neolamarckia cadamba*	Rubiacea	Jabon	Deep	21.6 ± 5.1	7.2 ± 1.9	136 ± 72	1262 ± 785	503 ± 19	15.9 ± 1.4	1.5 ± 0.1	5.4 ± 1.6	31.9 ± 2.9
8. *Psidium guajava*	Myrtaceae	Guava	Shallow	6.8 ± 1.9	2.1 ± 0.4	40 ± 25	84 ± 108	484 ± 10	10.4 ± 0.9	1.5 ± 0.1	7.0 ± 2.5	46.7 ± 3.5
9. *Mangifera indica*	Anacardiacea	Mango	Deep	11.2 ± 4.6	4.1 ± 2.0	41 ± 25	348 ± 387	415 ± 25	12.1 ± 3.8	1.3 ± 0.3	9.3 ± 2.1	36.3 ± 8.2
10. *Parkia speciosa*	Fabaceae	Petai	Shallow	13.5 ± 0.8	6.7 ± 0.9	64 ± 25	138 ± 30	NA	NA	NA	NA	NA
11. *Cocos nucifera*	Arecaceae	Coconut	Deep	10.2 ± 5.4	3.5 ± 2.3	39 ± 18	300 ± 283	468 ± 14	13.2 ± 2.8	1.5 ± 0.2	3.1 ± 1.5	36.5 ± 6.2
12. *Gmelina arborea*	Lamiacea	White Teak	Shallow	14.4 ± 4.9	4.8 ± 1.8	60 ± 26	322 ± 288	435 ± 27	11.8 ± 3.4	1.5 ± 0.2	9.3 ± 1.0	38.5 ± 8.0

[1] References: (Ruhigwa et al., 1992); Van Noordwijk and Purnomosidhi (1995); (Wahid, 2000); Lehmann (2003); Hartemink (2005)

Shade tree selection and characterization

We selected 11 of the most commonly intercropped shade tree species found in cocoa farms in Southeast Sulawesi: *Gliricidia sepium, Nephelium lappaceum, Lansium domesticum, Durio zibethinus, Artocarpus heterophyllus, Anthoccephalus cadamba, Psidium guajava, Mangifera indica, Parkia speciosa, Cocos nucifera,* and *Gmelina arborea* (Table 3.1). *Theobroma cacao* trees were included as the baseline in our analyses. All trees selected for this study were located geographically close to each other in cocoa plots of similar ages (7 to 12 years since establishment). Neighboring farmers had access to the same sources of plant material and likely planted similar combinations of cocoa varieties. For each species we selected 3 to 5 replicates, summing up to a total of 56 individual trees.

We selected isolated shade trees which were separated from the edge of adjacent canopies by at least 10 m. As cocoa farmers generally determined the planting locations of shade trees based on species-specific spacing recommendations from extension agents the selection of tree-planting location in microsites with favorable soil properties is highly unlikely All sampling sites were located in the same valley and on soils with similar texture (clay loam).

Shade tree and cocoa tree metrics

For all shade trees, we recorded diameter at breast height (D; in cm) and tree height (H; in m), measured with a Haglöf ECII hypsometer. We then estimated above-ground biomass (AGB) based on specific wood density (ρ), D and H for each individual shade tree according to the following allometric equation developed by Chave et al. (2014):

$$\mathbf{AGB_{est} = 0.0673 \times (\rho \times D^2 \times H)^{0.976}}$$

We additionally recorded lower canopy height (m) for each shade tree. Canopy area (m^2) was estimated based on radius (m) measurements in four directions from each shade tree trunk. Shade tree species were classified according to their rooting depth: deep vs. shallow (Table 3.1). We collected litter samples under each individual shade tree in April through May 2015, using 50 x 50 cm mesh litter traps placed directly under tree canopy at 50 cm above the ground. Litter samples were collected 2 to 3 weeks after installation of the traps, and then air-dried and ground in a coffee grinder. Samples were then transported to ETH Zürich and analyzed for C- and N-contents using dry combustion (CN-2000; LECO Corp., St Joseph, MN). Ca^{2+} concentrations were determined using wet digestion with HNO_3 and H_2O_2 and emission spectroscopy (ICP-OES 5100, Agilent Technologies, Santa Clara, CA).

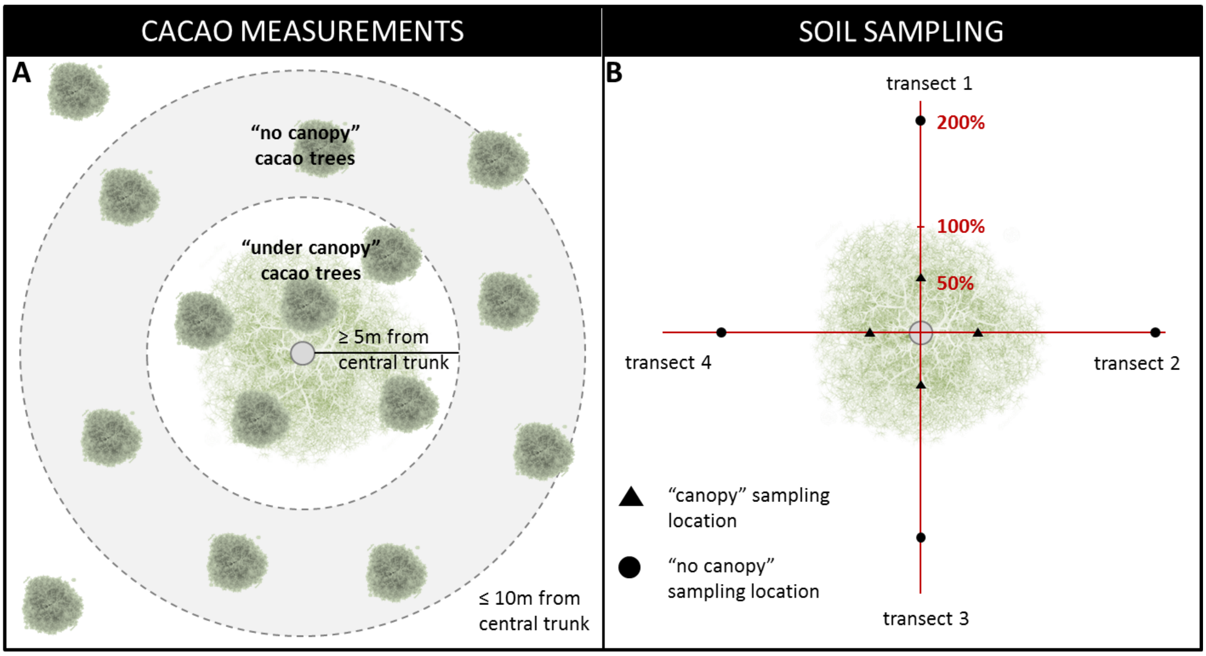

Figure 3.1. *Visual representation of the field design for a) measurements of T. cacao productivity and b) soil sampling.*

Around each individual shade tree, cacao trees were marked in two circular subplots. All cacao trees located under the shade tree canopy (and up to a maximum distance of 5 m from the central shade tree trunk) were marked as "under canopy", whereas cacao trees located in open areas (and at a maximum distance of 10 m from the central shade tree trunk) were marked as "no canopy" (Fig. 3.1a). For all selected cacao trees, we recorded the distance of each cacao tree from the central shade tree trunk, as well as Dand height. AGB was then estimated based on the same allometric equation as above. Potential yields for each individual cacao tree (N=898) was determined by pod counts in April - May 2015, between the end of pod maturation and the start of cacao harvest in Sulawesi.

<u>Soil sampling and analysis</u>

At each individual shade tree site, as well as for the cocoa control sites, we laid out four perpendicular transects radiating out from the central tree trunk (Fig. 3.1b). We collected four topsoil (0-15 cm depth) samples each for two locations: at 50% of shade-canopy diameter ("canopy"), and at 200% of shade-canopy diameter in open areas ("no canopy"). At each site, samples were composited to obtain one sample per depth per location, processed through an 8 mm sieve to remove rocks, macro-fauna and large organic material, and then air-dried. All samples were then transported to ETH Zürich, where they were passed through a 2 mm sieve and finely ground for subsequent analysis.

For the five most common tree species (*G. sepium, N. lappaceum, L. domesticum, D. zibethinus, A. heterophyllus)* and for *T. cacao* control plots, we also collected 4 intact cores (0-15 cm) per location ("canopy" and "no canopy") for aggregate fractionation using a hammer corer (Ø 5.5 cm). Weight, soil moisture content and bulk density were determined for each individual core. Cores were then carefully sieved through an 8 mm sieve by gently breaking soil clumps along natural planes of weakness (Six et al., 1998), and composited, yielding one sample per location. All samples were air-dried and packed in solid containers to avoid disrupting aggregate structure during transport to ETH Zurich. Samples were then fractionated using wet sieving methodology (adapted from Elliott (1986) and described in Fonte and Six (2010)) to determine stable aggregate size-distribution. Mean weight diameter (MWD), which we used as an index for median aggregate size, was calculated based on the proportions of large macroaggregates (LM; >2000 μm), small macroaggregates (sM; 250-2000 μm), microaggregates (m; 53-250 μm), and free silt and clay (s+c; <53 μm) particles (Van Bavel, 1950):

$$\mathbf{MWD} = \mathbf{2}(\mathbf{LM}) + \mathbf{1.125}(\mathbf{sM}) + \mathbf{0.1515}(\mathbf{m}) + \mathbf{0.0265}(\mathbf{s} + \mathbf{c})$$

Soil nutrient concentrations were determined for "canopy" and "no canopy" composite samples under 11 species and *T. cacao* (N = 12 Species * 2 Locations * 3-5 Replicates = 112), as well as for "canopy" and "no canopy" aggregate fractions under 5 species and *T. cacao* (N = 6 Species * 2 Locations * 5 replicates * 4 aggregate fractions = 240). Total soil C and N concentrations were determined at ETH Zürich, using a dry combustion analyzer (CN-2000; LECO Corp., St Joseph, MN). Total soil P was determined colorimetrically after heat digestion with H_2O_2, H_2SO_4, Se and Li_2O_4S extraction (method adapted from Anderson and Ingram (1994a)).

Statistical analyses

We used a split-plot design to test how shade trees in cocoa agroforests affect soil nutrient contents (total C, N and P, and C- and N-within-aggregate-fractions), soil aggregation (indicated by MWD), and *T. cacao* above-ground biomass (cocoa AGB) and yields. We specifically tested i) differences in soil parameter values under shade tree canopies, relative to open reference positions ("tree effect"), and ii) whether the magnitude of this effect differed between the selected shade tree species ("species effect"). Our data was fitted into linear mixed-effects models using the *lme* function in R (Pinheiro et al., 2016). We used location and shade tree species as our fixed variables, and assigned replicates for each shade tree species as random effects. For each response variable, we subsequently ran two-tailed t-tests to assess whether the "tree effect" under each shade tree species was significantly different from zero. To visualize the magnitude of the effects on soil C-, N- and P-contents, and MWD, we calculated the difference between measured "no canopy" and "canopy" values.

We performed linear regressions to assess i) whether cocoa AGB and yields changed with increasing distance from the trunks of shade trees; and ii) whether differences in cocoa AGB and yields were directly related to changes in soil N- and P-contents. For both of these analyses, shade tree species was used as a covariate. To assess whether observed differences between different tree species could be ascribed to difference in shade tree functional traits, we further carried out multiple linear regressions to explore interactions between the effects of shade trees in cocoa agroforests and variation in the shade tree traits selected for our dataset (Table 3.1). We first tested for significant relationships between relevant shade tree traits (litter nutrient contents, rooting depth, tree and canopy height, canopy area and AGB) and cocoa AGB and cocoa yields. We then similarly tested for significant relationships between relevant shade tree traits (litter nutrient contents, rooting depth) and soil nutrient contents and aggregation. Model assumptions were checked for all analyses using both visual and statistical tests; robust models were chosen to control for the influence of outliers, using the *robustbase* (Rousseeuw et al., 2015) package in R (R Development Core Team 2014, version 3.1.1).

3.3 Results

Shade tree effect and species effect on cocoa biomass and yield

There was a significant negative effect of shade trees on mean cocoa AGB, which was on average decreased by 40% under shade trees compared to open areas. The magnitude of this "tree effect" differed significantly between species (Table 3.2, Fig. 3.2a). Under the canopies of *N. lappaceum*, *L. domesticum*, *M. indica* and *G. arborea*, the decrease in cocoa tree AGB was significantly different from zero, and under *G. sepium* and *C. nucifera* the decrease was marginally significant (Fig. 3.2a). We observed a slight but significant increase in cocoa AGB with increasing distance from the shade tree trunk (r^2=0.11, p<0.001).

While average yields across all sites appeared to decrease under shade tree canopy compared to open areas (Fig. 3.2b), this trend was not statistically significant and differences between species were only marginally significant (Table 3.2). At the species level, the decrease under canopy was only significantly different from zero under *D. zibenthinus* and marginally significant under *N. lappacceum*. We also observed a marginally significant increase under *G. sepium* (Fig. 3.2b). Our data showed no correlation between cocoa yields and distance from shade tree trunk (r^2=0.07, p=0.2).

Cocoa AGB and yields were not correlated with each other or with soil fertility variables (results not shown). Variation in shade tree traits (tree height, lower canopy height, canopy area, AGB, rooting depth and litter nutrient contents) was not correlated with changes in cocoa AGB or cocoa yields (results not shown).

Table 3.2. *Results from linear mixed effect model analysis examining the changes in total soil carbon (C), nitrogen (N) and phosphorus (P), soil aggregation (MWD), and T. cacao above-ground biomass (AGB) and yields (Yield), associated with shade-tree presence ("tree effect") and differences between shade tree species ("species effect"). Abbreviations are: between group (numerator) degrees of freedom (Num DF); within group (denominator) degrees of freedom (Den DF); F-value (F); P-value (P).*

Response variables	Explanatory variables	Num DF	Den DF	F	P
Cocoa Above-Ground Biomass (kg)					
	Tree	1	84	15.7	**< 0.001**
	Species	11	84	4.0	**< 0.001**
	Tree x Species	11	84	0.3	0.97
Cocoa Yield (# fresh pods)					
	Tree	1	84	3.4	0.15
	Species	11	84	1.5	0.07
	Tree x Species	11	84	0.9	0.56
Total soil C (g kg^{-1})					
	Tree	1	84	6.3	**0.01**
	Species	11	84	2.4	**0.01**
	Tree x Species	1	84	0.7	0.72
Total soil N (g kg^{-1})					
	Tree	1	44	4.3	**0.04**
	Species	5	44	6.1	**< 0.001**
	Tree x Species	5	44	0.8	0.66
Total soil P (g kg^{-1})					
	Tree	1	84	0.6	0.52
	Species	11	84	1.1	0.37
	Tree x Species	11	84	0.3	0.99
Mean Weight Diameter (mm)					
	Tree	1	84	26.0	**< 0.001**
	Species	11	84	2.7	**0.04**
	Tree x Species	11	84	7.0	**< 0.001**

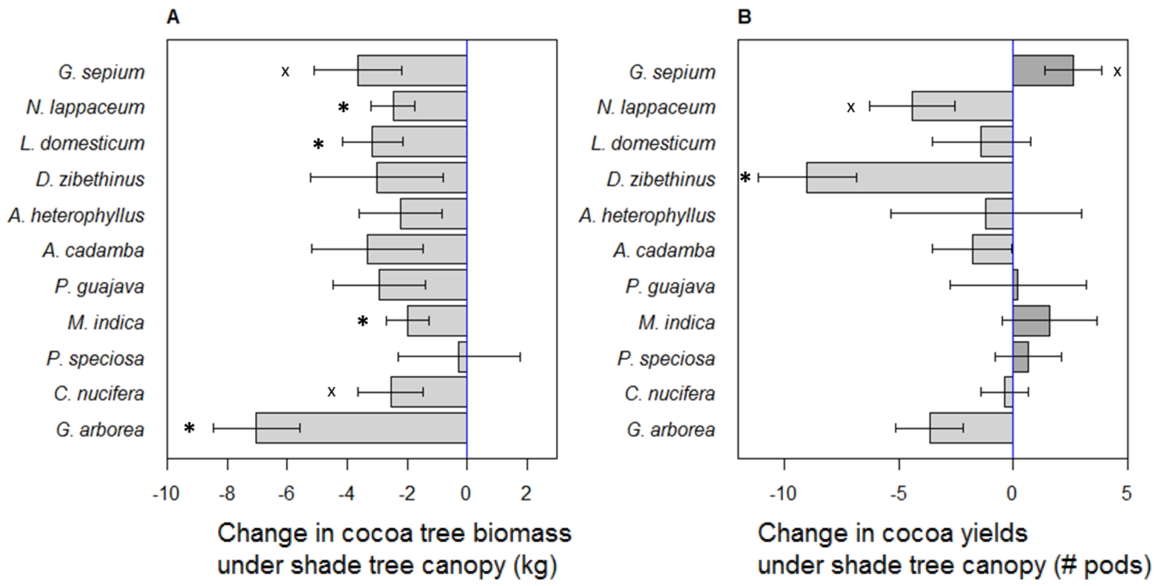

***Figure 3.2** Mean difference in cocoa tree a) yields (Nr. of pods) and b) above-ground biomass (AGB) under shade-tree canopy for 11 different shade-tree species intercropped with Theobroma cacao. Mean differences for each species were calculated as the difference between mean cocoa AGB and cocoa yields measured under the canopy of individual shade trees and paired open locations. Bars represent one standard error of the mean. For each species, asterisks (*) indicate a "tree effect" significantly different from zero ($p \leq 0.05$); crosses (x) indicate trends in "tree effect" ($p \leq 0.10$).*

<u>Shade tree effect and species effect on soil total C-, N- and P-contents</u>

Overall, shade trees had a positive effect on total soil C concentrations (Table 3.2), which significantly increased by 6% under shade trees relative to open areas. However, the magnitude of this "tree effect" significantly differed between shade tree species. Mean soil C was marginally increased under *G. sepium* and significantly increased under *N. lappaceum* (3.6 g C kg^{-1} under shade compared to an increase of 1.5 g C kg^{-1} or less for all other species; Fig. 3.3a).

Similarly, total soil N was significantly increased under shade trees compared to adjacent open areas by about 4% on average across all species (Table 3.2). The magnitude of this "tree effect" significantly differed between shade tree species but was not significantly different from zero for any of the shade tree species. We did observe a marginally significant increase under *N. lappaceum* and *M. indica* (Fig. 3.3b). Soil N contents under shade trees were not correlated with shade tree litter N contents (r^2=0.01, p=0.48).

Even though total soil P levels appeared to increase under "canopy" for most species, neither the mean "tree effect" nor the mean "species effect" on soil P content were statistically significant (Table 3.2). Nevertheless, the increase in soil P was still significantly different from zero under *N. cadamba* (Fig. 3.3c). This result likely did not scale up to an overall "species effect" due to the high degree of variation between replicates under shade trees for all other species (Fig. 3.3c). Soil P contents were not correlated with shade tree litter P contents (r^2=0.00, p=0.92).

Shade tree effect and species effect on soil aggregation

We found a significant positive "tree effect" as well as a significant "species effect" on MWD, which was increased by an average of 12% under shade trees compared to open areas. We also found a significant interaction between tree and species effect on MWD (Table 3.2). There was a trend of decreased MWD under *T. cacao* and increased MWD under *G. sepium.* The increase in MWD under shade trees was only significantly different from zero for *N. lappaceum* and *D. zibenthinus* (Fig. 3.3d). MWD was positively correlated with soil C (r^2=0.33, p<0.0001) and soil N (r^2=0.23, p<0.0001). Moreover, MWD was significantly increased under shade trees with increased litter Ca^{2+} contents (r^2=0.28, p=0.003) and under shade trees with increased litter C/N ratios (r^2=0.15, p=0.03). We also found a significant parabolic effect of shade tree height (r^2=0.32, p=0.02) on MWD, with MWD values maximized under shade trees with heights ranging between 10 to 15 m, and a positive correlation between increasing canopy area and increasing MWD (r^2=0.23, p=0.01).

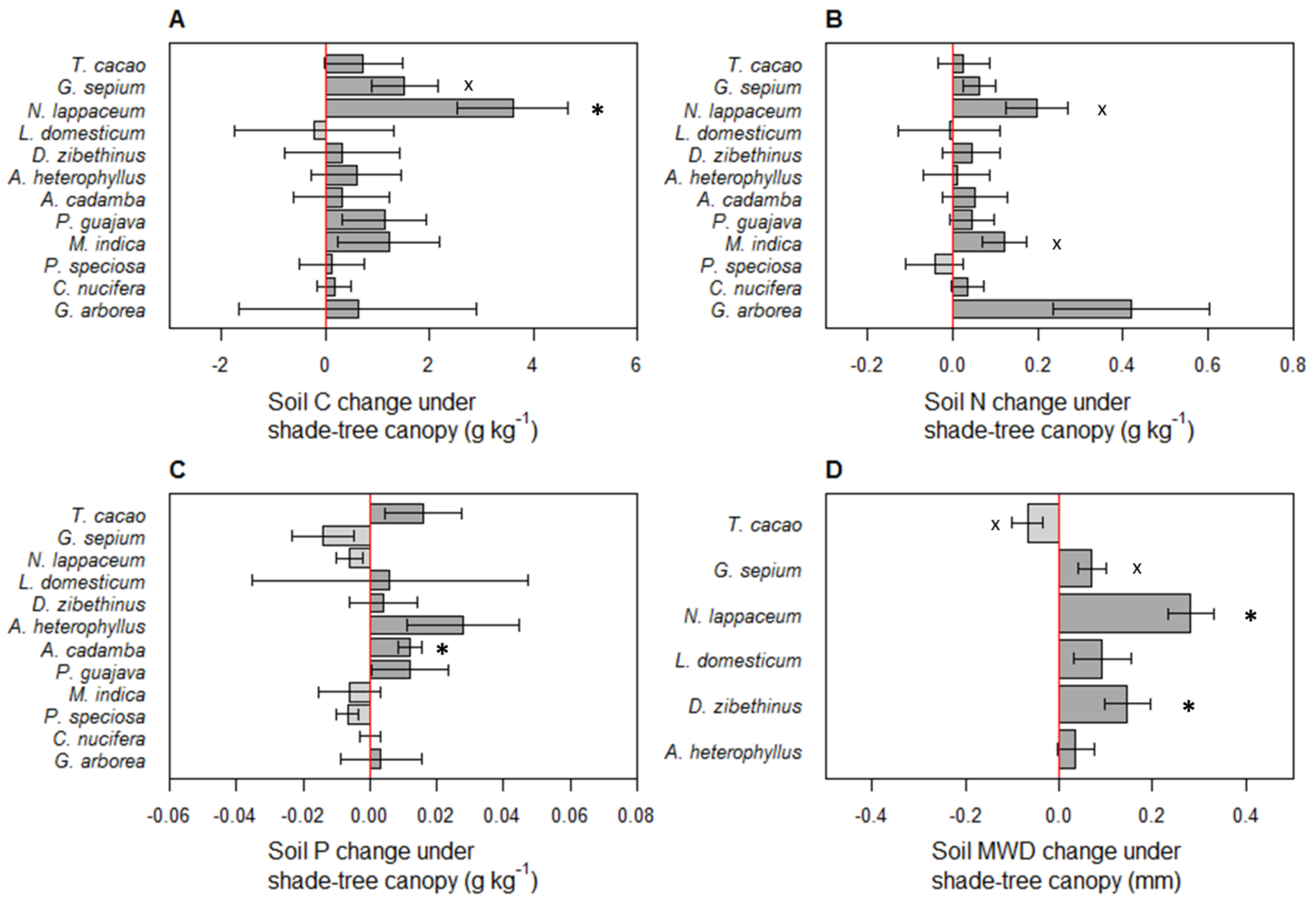

Figure 3.3 *Mean difference in soil a) ca Mean difference in soil a) carbon (C), b) nitrogen (N) and c) phosphorus (P) content and d) mean weight diameter (MWD) in the topsoil layer (0-15 cm) under shade-tree canopy for 11 different shade tree species and the control species T. cacao. Mean differences were calculated as the differences between mean soil parameter values measured under the canopy of individual shade trees and paired open locations. Bars represent one standard error of the mean. For each species, asterisks (*) indicate a "tree effect" significantly different from zero ($p \leq 0.05$); crosses (x) indicate trends in "tree effect" ($p \leq 0.10$).*

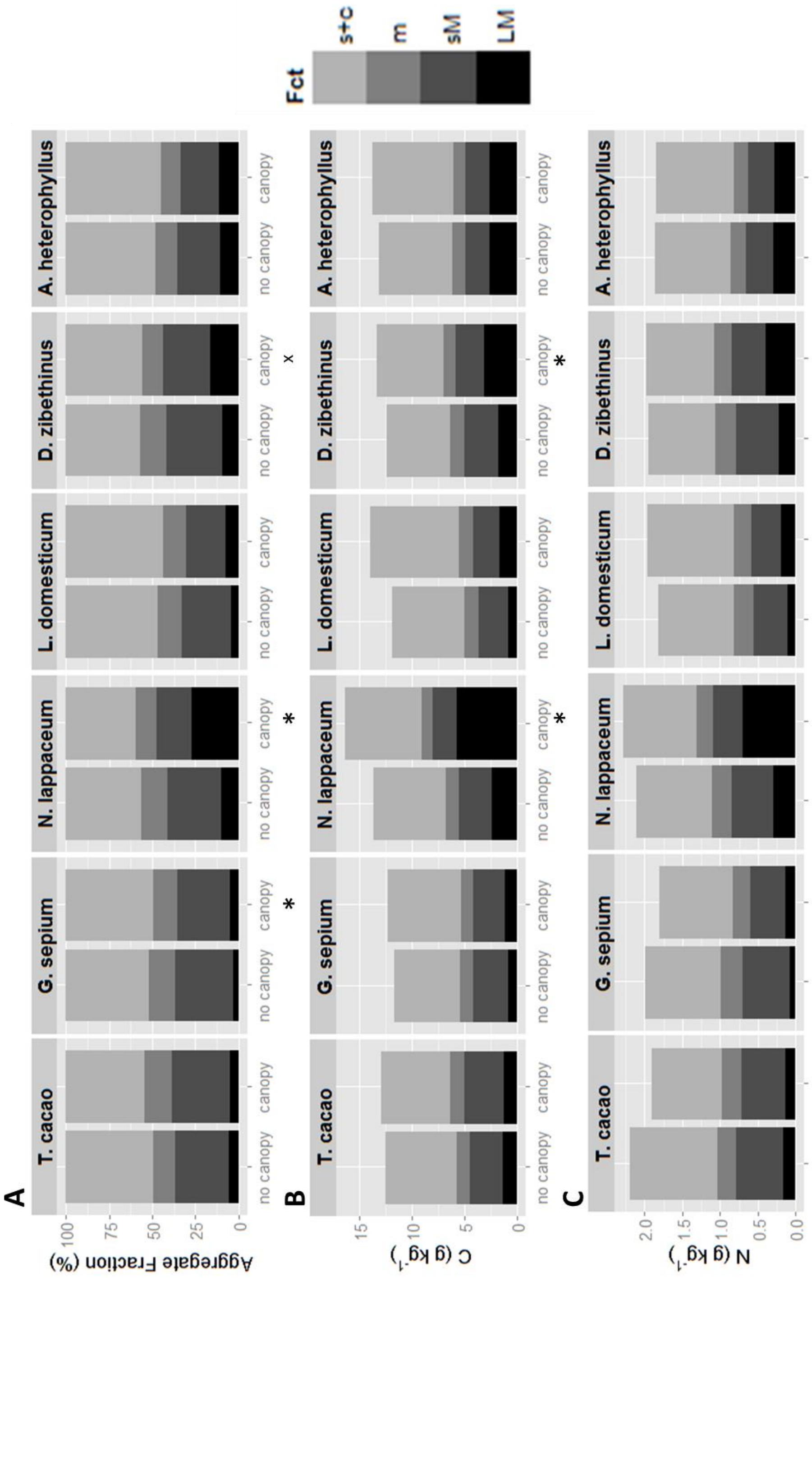

Figure 3.4 *Mean differences in a) aggregate fraction proportions, b) C- contents within-aggregates and c) N-contents within-aggregates for five shade tree species commonly intercropped with Theobroma cacao in Sulawesi, Indonesia. The different fractions (Fct) represented are: large macroaggregates (LM; >2000 µm), small macroaggregates (sM; 250-2000 µm), microaggregates (m; 53-250 µm), and free silt and clay (s+c; <53 µm) particles. For each species, asterisks (*) indicate a "tree effect" significantly different from zero ($p \leq 0.05$); crosses (x) indicate trends in "tree effect" ($p \leq 0.10$). Both significant effects and trends are indicated for the LM fraction only.*

An analysis of different soil aggregate size classes showed a positive "tree effect" as well as a significant "species effect" on large macroaggregate (LM) and microaggregate (m) proportions, and C- and N-contents within LM and m fractions. Variations in small macroaggregate (sM) and silt-and-clay (s+c) fractions were not correlated with shade tree presence or shade tree species. The mean proportion of LM ($F=10.9$, $p=0.002$) and m ($F=7.1$, $p=0.01$) fractions significantly increased under shade trees. The increase in LM proportion under shade tree canopy compared to open areas was significantly different under *G. sepium* and *N. lappaceum*, and marginally significant under *D. zibethinus* (Fig. 3.4a). C-content within LM fractions ($F=12.2$, $p=0.001$) also increased under shade trees. The increase in C-content within LM was significant under *N. lappaceum* and *D. zibenthinus* compared to open areas (Fig. 3.4b). Similarly, N-content within LM ($F=10.6$, $p=0.002$) and m ($F=11.3$, $p=0.002$) fractions increased under shade trees relative to open areas. The increase in N-content within LM fractions was significant under *G. sepium* and *N. lappaceum*, and marginally significant under *D. zibethinus*, compared to open areas (Fig. 3.4c).

3.4 Discussion

<u>Shade trees negatively affect *T. cacao* growth, but have limited effects on yields</u>

Shade trees had a significant negative effect on the growth of cocoa trees as cocoa tree AGB decreased by an average of 40% under shade canopy compared to open areas (Fig. 3.1a). While these results confirm observations by Blaser et al. (2017) or Koko et al. (2013) they contrast with those of Isaac et al. (2007), who found increased cocoa AGB under shade trees. This discrepancy might be related to differences in canopy structure and density between the shade tree species investigated in the two studies. Structural differences in shade-tree canopies likely lead to differences in below-canopy light levels and microclimate. As cocoa trees are known to respond to changes in incident light and microclimate (Almeida and Valle, 2007) such differences might have substantial effects on the growth of cocoa trees. Similarly to Koko et al. (2013), we found that cocoa AGB increased with planting distance from shade trees, confirming that close proximity to shade trees has a negative effect on cocoa tree growth. Our results provide further evidence that light might be an important limiting factor for cocoa tree growth.

We found that on average, cocoa yields were not significantly decreased under shade trees as compared to open areas. Based on our results, individual shade trees might thus have less of a direct negative influence on yields than often assumed, although the extent to which negative effects do occur is likely dependent on differences in tree morphology across individuals and species. Studies examining the relationships between plant composition and crop yields in mixed agroforests have documented significant negative effects of shade tree presence on cocoa yields at the systems scale (Clough et al., 2011; Waldron et al., 2015; Blaser et al., 2017), but no direct relationship has been found between increased shade tree diversity and yields in cocoa agroforests (Clough et al., 2011; Wartenberg et al., 2017). Reported negative effects of shade trees on cocoa yields thus appear to be related to an additive effect of shade trees, as indicated by shade cover extent or density, rather than to shade tree presence or diversity per se.

Cocoa trees might benefit from shade tree presence at low densities, and negative effects on yield with increasing shade tree abundance might be related to an increase in resource competition between trees and understory crops as shade tree densities increase. The extent to which benefits or disadvantages of specific shade trees might scale-up to the plot level might be influenced by differences in individual tree morphology, although we found no evidence of a direct effect of shade tree canopy shape on cocoa yields at the individual tree level. Additionally, unlike cocoa AGB, cocoa fruit development and maturation may be primarily affected by factors that are only indirectly related to individual shade tree presence, such as pollination intensity (Groeneveld et al., 2010), internally-caused fruit-wilt due to nutrient deficiencies, and high pest and disease incidence (Bos et al., 2007), which have all been shown to significantly contribute to the loss of cocoa pods at all stages of development.

Isolated shade trees increase soil fertility

Soil C and N, as well as soil MWD, were significantly increased under shade trees (Fig. 3.3). These results echo previous studies which have found that isolated trees in acacia agroforests or savanna ecosystems contribute to increased total C and N pools in the topsoil (Zinke, 1962; Radwanski and Wickens, 1967; Pandey et al., 2000), and confirm that shade trees can have measurable positive effects on soil fertility even in perennial systems. Increased soil C- and N-contents under shade trees could be linked to increased organic inputs from litterfall (Beer, 1988), buffered microclimates under tree canopies and resulting increases in decomposition rates (Belsky et al., 1989; Steffan-Dewenter et al., 2007), and increased root activity (Schroth, 1998) under shade tree canopies.

Increased soil organic matter (SOM) content and changes in microclimate conditions can further lead to increased substrate availability and changes in soil environmental conditions. These changes can influence SOM decomposition rates and microbial activity (Swift et al., 1979; Bending et al., 2002; Zaman and Chang, 2004). Soil aggregate formation is known to be driven by mechanisms related to the interaction of soil micro- and macro-fauna and plant roots and exudates (Fonte et al., 2012; Six and Paustian, 2014), as well as to the overall availability of SOM in the system (Kong et al., 2005). In our study, the observed increase in soil aggregate size (indicated by MWD) under tree canopies therefore suggests an increase in nutrient cycling activities and organic matter storage under shade trees.

<u>Shade tree effects on soil fertility are highly variable between shade tree species</u>

We observed high variability in the net change in soil nutrient concentrations and MWD under different shade tree species (Fig. 3.3), which is consistent with existing literature (Bossuyt et al., 2001; Giardina et al., 2001; Lehmann et al., 2001). We found no relationship between rooting depth and soil properties. Additionally, neither canopy shape (tree height, canopy height, canopy area and tree AGB) nor litter nutrient contents were correlated with variation in soil nutrient contents. This is consistent with the results of Vivanco and Austin (2008), who reported that differences in litter quality and decomposition rates between tree species in Argentina did not translate to differences in SOM concentrations. Differences in soil C-, N- and P-contents under different species might instead have been related to changes in total litterfall quantities under different trees although further research is needed to corroborate this. Our results ultimately highlight the complexity of plant-soil interactions and the difficulty of disentangling direct relationships between tree species diversity and soil nutrient cycling mechanisms in farmed landscapes (Vivanco and Austin, 2008).

Our results do provide some insights regarding soil aggregation pathways under different tree species. MWD increases were maximized under shade trees with large canopy area and median-height of 10-15 m, which suggests that soil aggregation was optimized under moderate levels of shade. Changes in soil temperature and moisture content are directly related to changes in canopy density (e.g. Isaac et al., 2007). As soil microbes are highly sensitive to environmental changes (Six et al., 2006), differences in microclimate between shade trees with different canopy structures might have an indirect effect on microbial-regulated processes such as soil aggregate formation (Tisdall and Oades, 1982; Miller and Jastrow, 2000).

Additionally, MWD and large macroaggregate (LM) proportions were significantly increased (Fig. 3.4a) under the canopies of *N. lappaceum* (rambutan), which had elevated litter CN ratios and litter calcium levels compared to other species (Table 3.1). Lower quality litter is thought to contribute to increased long-term SOM stabilization due to slower decomposition and aggregate turnover rates (Bossuyt et al., 2001; Six et al., 2001). In addition, calcium has been shown to catalyze the formation of physical bonds and to stimulate microbial activity (Chan & Heenan, 1999; Six et al., 2004) by altering soil acidity (Reich et al., 2005), and has been recognized as a key driver of soil aggregation and SOM stabilization processes. We thus hypothesize that both increased litter CN and litter calcium contributed to increased long-term aggregate stabilization under rambutan.

C- and N-distributions in aggregate fractions under tree canopies also varied between species. Under rambutan, *G. sepium* (gliricidia) and *D. zibethinus* (durian) trees, there was a significant increase in C- and N-storage in LM fractions compared to open areas (Fig. 3.3). We measured elevated litter CN ratios and high calcium levels only in rambutan litter (Table 3.1), and found that changes in total soil C and N pools in the whole soil were not reflected in C- and N-storage-within-aggregate dynamics except under rambutan (Fig. 3.3 & 3.4). We did not measure increased total N contents under gliricidia. The high litter quality of gliricidia trees, as indicated by low CN ratios (Table 3.1), may have contributed to significantly increased aggregate turnover rates (e.g. Six et al., 2001) under gliricidia canopies. This may have led to increased short-term, rather than long-term, N-storage within macroaggregates. Under rambutan and durian, aggregate formation and C-stabilization within LM fractions might also have been related to changes in soil biological activity. Two separate studies conducted in Kalimantan (Smith et al., 1998) and Malaysia (Naher et al., 2013) found evidence associating durian and rambutan with vesicular arbuscular mycorrhizae (AM) root colonization. Increased AM root colonization could thus be an important factor distinguishing durian and rambutan from other species, and might have resulted in improved aggregation and C stabilization under their canopies.

Interactions between shade tree functional traits and implications for cocoa productivity

While we found effects of shade trees on cocoa tree performance and soil fertility, we also found that the magnitude of these effects differed significantly between shade tree species. However, we were not able to directly link this variation to specific shade tree traits. Nevertheless, we suggest that there are interactions between shade tree traits, and that certain traits have a more dominant effect than others.

For example, gliricidia trees are often cited as beneficial in agroforestry settings due to their N-fixing capacity (e.g. Tscharntke et al., 2011). Our results largely confirmed this, as we found increased N-contents-within-large-macroaggregates in soils under gliricidia (Fig. 3.3 & Fig. 3.4). We also expected to find increased cocoa AGB and yields under gliricidia compared to other shade trees. Surprisingly, cocoa AGB decreased under gliricidia canopies. As lower canopy height for mature cocoa and gliricidia were not significantly different in our plots (Table 3.1), the two species might be competing for light. Still, cocoa yields were slightly increased under gliricidia (Fig. 3.2b). Our results thus suggest that under gliricidia, benefits from increased nutrient inputs outweighed potential disadvantages related to light competition.

A comparison of the effect of different species on cocoa yields showed that durian had the most negative effect on yields (Fig. 3.2a). In contrast, the measured increase in soil aggregation under durian trees indicated a significant improvement in soil structure. Similarly, rambutan had a net negative effect on both cocoa AGB and yields but a significantly positive effect on soil C and MWD, indicating a high potential for soil fertility improvement. The individual durian and rambutan trees in the cocoa plots selected for this study had relatively high AGBs and low canopy heights (Table 3.1), indicating relatively dense canopies – this might have led to reduced light availability for nearby cocoa trees. The potential benefits to cocoa trees from increased soil fertility (Fig. 3.1 & Fig. 3.2) might have thus been "canceled out" by light competition under durian and rambutan canopies in our plots.

3.5 Conclusions

In Southeast Sulawesi, shade trees had a positive net effect on soil fertility and a negative net effect on cocoa tree growth. However, we found that cocoa yields were not significantly decreased under shade trees. Shade tree traits such as litter quality or morphology were also found to have significant effects on short-term and long-term soil nutrient storage, confirming the potential for soil improvements under shade trees. Our results indicate that shade tree inclusion in perennial cropping systems is a viable approach to increase the economic and ecologic sustainability of cocoa cultivation systems, particularly when planted at low densities. However, our findings also suggest the existence of complex trade-offs between shade tree traits in cocoa farms. We conclude that the development of shade tree planting guidelines based on general morphology and functional traits may prove difficult and would require further research. In the meantime, we recommend that targeted evaluations of the costs and benefits associated with local shade tree species in tropical agroforests could help generate relevant planting recommendations for farmers in different regions.

Our results confirm that gliricidia is a good addition in cocoa agroforests in Sulawesi, as it can be expected to contribute to enhanced yields. More surprisingly, we found evidence suggesting that durian and rambutan might be useful species in the context of long-term soil restoration, as they measurably improved soil properties under their canopies. As we found decreased cocoa yields under both species, management recommendations targeting improved cocoa farming practices would have to address the potential adverse effects of these two species on productivity. However, durian and rambutan trees produce fruit commonly consumed throughout Southeast Asia. In areas where soil restoration is a priority, the establishment of durian- or rambutan-based plantations or agroforestry systems might thus constitute an interesting alternative to cocoa for farmers, although future research would have to address the optimization of incentive schemes and access to markets.

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Chapter 4 :
Farmer perceptions of plant-soil interactions can affect adoption of sustainable management practices in cocoa agroforests: a case study from Southeast Sulawesi

Abstract

Despite extensive research focused on increasing the sustainability and productivity of agricultural systems in the tropics, adoption rates of improved management solutions often remain low among smallholder farmers. To address this, we evaluated how local knowledge and perceptions influenced decision-making processes among smallholder cocoa farmers. We conducted individual semi-structured interviews with 72 cocoa farmers in Southeast Sulawesi and documented local knowledge about soil fertility indicators, nutrient cycling processes, and the interactions between shade trees, cocoa trees, and soils in cocoa agroforests. We further collected data regarding farmers' fertilizer preferences, additional income sources and perceived barriers to improved cocoa production. We found that farmers' understanding of biophysical interactions in Southeast Sulawesi was accurately matched with scientific literature. Our findings also highlight potential knowledge gaps about how specific tree species affect soil fertility, cocoa trees, and ultimately cocoa yields. Nevertheless, our results suggest that cocoa farmers in Southeast Sulawesi approach decision-making in a holistic way by integrating personal observations about trees and soils, information from external sources, and socio-economic limitations and priorities. Low farmer awareness of the direct benefits of shade tree inclusion for improved yields and income security likely contributes to low adoption rates of systematic diversification practices. Therefore, the identification of local knowledge gaps, coupled with targeted knowledge dissemination, could contribute to an increase in the long-term adoption rates of more sustainable cocoa cultivation practices.

Authorship and status of manuscript

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4.1 Introduction

There are currently approximately 2.5 billion smallholders worldwide (IFAD 2013) who represent the backbone of global agriculture (Tscharntke et al., 2012) yet are particularly vulnerable to food insecurity. Smallholder farmers generally rely on annual yields to sustain their livelihoods and frequently do not have access to economic or social safety nets (Barrett and Bevis, 2015). Researchers and practitioners have stressed the linkages between rural poverty, food insecurity and soil degradation for several decades (Sanchez et al., 1997; Tilman et al., 2002; Barrett and Bevis, 2015). Nevertheless, soil degradation and the related decline in food production remain central issues in vulnerable agrarian regions and are exacerbated by poor management practices, population growth (Vanlauwe et al., 2015) and climate change (Mbow et al., 2014). The development of more sustainable crop production practices targeted at empowering smallholders through long-term reduction of poverty and soil degradation is therefore crucial. Tropical agroforestry systems are frequently cited as a potential solution to these issues, as they are believed to offer the potential to integrate incomes and enhanced ecosystem resilience and functioning (e.g. Franzen and Mulder, 2007; Tscharntke et al., 2012; Mbow et al., 2014). This is particularly relevant for cash crops such as cocoa or coffee, which are shade-tolerant understory tree species traditionally grown in agroforests (Schroth et al., 2004).

Farmer-driven initiatives aiming to improve the sustainability of cocoa cultivation, for instance through diversification, are an important vehicle to improve rural livelihoods. However, to promote the adoption of locally appropriate management approaches in these systems, it is first necessary to understand the drivers of smallholders' decision-making processes (Barrett and Bevis, 2015). A number of studies have examined rural incentive structures (e.g. Shiferaw et al., 2009) and the socioeconomic and environmental factors that drive land-use change and farm management in rural tropical areas (Clough et al., 2016). Such research has shown that smallholders often base their management decisions on factors which can include but are not limited to their understanding of ecologic processes. Smallholders often integrate their observations of biophysical processes with external sources of information (from other farmers, extension agents, etc.) to guide farm-related management decisions (Pauli et al., 2012; Villamor et al., 2014; Mulyoutami et al., 2015). There is also a growing body of literature exploring the role of local knowledge for sustainable farm development (e.g. Isaac et al., 2009; Raymond et al., 2010; Meijer et al., 2015).

The differences between local and scientific knowledge on soil fertility have been discussed extensively, along with the different criteria by which farmers from around the world classify soils (e.g. Talawar and Rhoades, 1998; Joshi et al., 2004; Dawoe et al., 2012). While farmer classifications of soil physical properties have been shown to match scientific assessments (Saito et al., 2006), farmer knowledge frequently diverges from scientific consensus when it comes to relating ecosystem services (e.g. enhanced soil fertility) to changes in crop productivity (Barrios and Trejo, 2003; Gray and Morant, 2003). Such knowledge gaps might be caused by farmers' limited access to information, but can also highlight aspects of ecosystem functions not yet fully understood by formal science.

In the context of cocoa cultivation, the benefits of mixed agroforestry systems have been widely studied from ecologic and economic perspectives. To date, scientists have come up with a plethora of findings and recommendations aimed at improving the sustainability of cocoa cultivation (Franzen and Mulder, 2007; Tscharntke et al., 2011; Clough et al., 2016). Despite this, long-term adoption rates remain low in most cocoa producing countries (Ruf, 2011; Martini et al., 2016). In Indonesia, cocoa farmers are moving towards intensification of their farms, and simple cocoa agroforests interplanted with single species, such as coconut, gliricidia or patchouli, are prevalent (Feintrenie et al., 2010; Rahmanulloh et al., 2012). Limited adoption of farm diversification practices might be related to our limited understanding of the drivers of smallholders' decision-making. Indeed, policy and agricultural extension solutions might not sufficiently take into account local knowledge and perceptions about yield-related ecosystem services (e.g. improved nutrient cycling, pest and disease control, etc.) commonly associated with agroforests (e.g. Ruf, 2011).

Systematic integration of local and scientific knowledge could improve our understanding of the mechanisms through which soil fertility changes can impact crop productivity (Gray and Morant, 2003) and promote the application of participatory approaches (i.e. multi-stakeholder workshops or knowledge exchange between farmers and researchers or policy-makers) which have been shown to increase adoption rates of sustainable farming practices (Smith-Dumont et al., 2017). Several studies have separately assessed local knowledge about soil fertility and soil management (Barrios and Trejo, 2003; Dawoe et al., 2012); and the influence of farmer perceptions and other factors on adoption rates of agricultural management practices in smallholder farms (Pattanayak et al., 2003; Meijer et al., 2015). To our knowledge, few studies have bridged both areas of research by examining the extent of local knowledge about ecological processes, and relating this to external farm-related pressures and management decisions (Wyckhuys and O'Neil, 2007; Isaac et al., 2009; Smith-Dumont et al., 2017).

In this case study we conducted interviews in 72 cocoa farming households in Southeast Sulawesi to understand farmers' perceptions of biophysical processes related to tree-soil-cocoa interactions. Our objectives were to i) identify and document farmers' knowledge and perceptions about visible soil fertility attributes, shade tree and soil interactions, and shade tree effects on cocoa tree development and productivity; ii) compare farmers' knowledge about biophysical processes and the interactions between different ecosystem components with scientific literature; iii) determine to what extent the optimization of ecological processes is taken into account by farmers in comparison with external pressures (e.g. input availability, market-driven price fluctuations). Our aim was to provide information about the relationship between local knowledge and smallholder decision-making processes in cocoa cultivation systems and to contribute to the development of more sustainable and locally-appropriate management recommendations.

4.2 Methodology

Study area

This study was conducted in the Konawe and Kolaka provinces in Southeast Sulawesi (3.58°S, 122.30°E). The agricultural landscape of the region is dominated by paddy rice, maize and vegetable production. Surrounding mountain ranges are still widely forested, although at forest frontiers, deforestation and land-use changes are expanding rapidly. Soils in Southeast Sulawesi are predominantly *orthic acrisols* in mountainous areas, and *dystric fluvisols* in the floodplains (FAO-UNESCO, 1979). Mean daily temperatures range between 25°C to 28°C and the rainy season lasts from January to June, with an average annual precipitation of about 2080 mm (Climate-Data.org, 2016). We selected six cocoa-producing communities in the study area: Wonuahoa, Asinua Jaya and Lawonua in Kolaka province; and Tasahea, Andowengga and Simbune in Konawe province. All communities were included in the scope of the World Agroforestry Centre (ICRAF)'s Agroforestry and Forestry in Sulawesi

(AgFor) project, which aims to improve rural livelihoods and enhance sustainable natural resource management by focusing on agroforestry systems.

Communities in Southeast Sulawesi have been classified into three different typologies: local, local/migrant, and transmigrant (Janudianto et al., 2012). Wonuahoa and Simbune are local villages and most households belong to the Tolaki ethnic group which is indigenous to Southeast Sulawesi. Lawonua, originally established in the 1930s, is a local/migrant village and has a mix of local Tolaki families and Bugis migrants from south Sulawesi. In Tasahea, Asinua Jaya and Andowengga, most families are transmigrants from south Sulawesi or other Indonesian islands (Bali or Java).

Cocoa, which was introduced in the region in the 1980s, is the principal livelihood source for most households, followed by paddy rice and pepper (Janudianto et al., 2012). Cocoa agroforests are, for the most part, established directly on previously forested areas which are cleared gradually by manual cutting of trees and undergrowth. The agroforests in the region consist of mixed stands of cocoa intercropped with various shade trees.

Survey design and description of variables

In June and July 2015, we conducted semi-structured farmer interviews with 72 smallholder cocoa farmers. Twelve farmers were selected from each of the six communities listed above using random stratification within strata defined by occupation (cocoa farmers) and gender. While it was difficult to identify female cocoa farmers willing to be interviewed individually, we ensured that at least one third of respondents in each village were women. For each respondent, we recorded age, gender, farmer group membership status, place of birth and education level (Table 4.1). All interviews were conducted individually in Bahasa Indonesia, with the assistance of a local translator, and lasted approximately 45 to 60 minutes each.

Table 4.1. *Description of study respondents in Southeast Sulawesi grouped by community (n=12 per community). Farmer group membership refers to respondents' membership in a local farmer group or cooperative.*

Community	*Gender*		*Years of Education*	*Age*	*Farmer Group Membership*	*Years farming cacao*
	M	*F*				
Tasahea	67%	33%	9 ± 5	44 ± 7	100%	19 ± 7
Andowengga	83%	17%	8 ± 4	47 ± 12	67%	19 ± 6
Simbune	75%	25%	11 ± 3	48 ± 10	75%	19 ± 11
Wonuahoa	67%	33%	8 ± 4	43 ± 12	75%	9 ± 7
Lawonua	67%	33%	7 ± 4	41 ± 13	75%	15 ± 6
Asinua Jaya	50%	50%	11 ± 3	40 ± 12	58%	14 ± 5
Total	68%	32%	9 ± 4	44 ± 11	75%	16 ± 8

Our questionnaire was composed of closed- and open-ended questions. For open-ended questions, responses were classified into categories after the interviews were completed to facilitate and standardize data analysis. Questions focused on six topics: farmer and household history (see Table 4.1), soil fertility indicators, shade tree impacts on soil fertility, shade tree impacts on cocoa, access to extension services and limiting factors for cocoa productivity. To understand farmer perceptions of significant soil fertility indicators, we selected seven commonly used soil fertility indicators: stone content, soil color, soil litter layer, soil structure, macro-fauna content, soil texture and water-holding capacity/porosity (e.g. Doran and Parkin, 1994a; Pauli et al., 2012). For each indicator, study participants were asked to indicate optimal soil conditions, using visual vignettes for each indicator. We then asked participants to rank indicators according to their perceived importance for cocoa production.

We asked all survey participants open-ended questions about a) attributes of shade trees that can modify soil indicators, and b) participants' perceptions about shade tree impacts on soil fertility and cocoa development. Responses were coded and classified into the following categories: shading and protection, cocoa tree health, nutrients and resources, root systems and pest and disease occurrence. Based on observations in the field and on discussions with farmers, farming extension agents and AgFor project staff, we identified six shade tree species commonly inter-cropped with *Theobroma cacao* (cocoa) in Southeast Sulawesi: *Gliricidia sepium* (gliricidia), *Nephelium lappaceum* (rambutan), *Durio zibethinus* (durian), *Mangifera* *indica* (mango), *Gmelina arborea* (white teak) and *Lansium domesticum* (langsat). Respondents were asked to evaluate the effects of each species on soil fertility and cocoa trees. We then coded answers and classified them into three soil characteristics (soil structure, soil nutrients, and soil moisture) and four cocoa tree characteristics (pest and disease occurrence, shade and protection, cocoa pod yields, and cocoa tree growth). We also recorded common secondary uses for all shade tree species and asked farmers how they had acquired knowledge about shade tree selection, planting practices, ongoing management and fertilization application. Respondents were further asked about their membership in farmer associations, their preferences regarding organic and chemical fertilizer application and the principal obstacles that they viewed as limiting to cocoa productivity.

Data Analysis

All data was analyzed for the entire population of respondents. We first used frequency distribution analysis to quantify responses for the following groups of variables: respondent characteristics, soil fertility indicators, shade tree effects, knowledge extension, fertilizer use and obstacles to cocoa production. Because our data did not have the normal distribution assumed for common statistical procedures, we used non-parametric Kruskal-Wallis one-way analysis of variance (ANOVA) models to evaluate differences based on village, education level and membership status within farmer groups. This was carried out for the following dependent variables: i) ranking of soil fertility variables; ii) preferences regarding soil fertility indicators; and iii) general perceived effects of shade trees on soil fertility and cocoa. Similarly, we used a non-parametric Kruskal-Wallis ANOVA to test for significant differences in farmers' responses regarding the perceived effects of different shade trees species on soil and cocoa characteristics. All analyses were carried out using SPSS software for Windows (version 22.0.0).

4.3 Results

Respondent characteristics

Out of 72 interviewed farmers, 68% were male and 32% were female. Farmer age ranged from 25 to 70 years old with a mean age of 44 years (Table 4.1). Eighty-five percent of respondents reported completing at least a primary-level education; six percent reported having received no formal education. Most farmers owned less than five ha of land (82%) and were members of local farmer associations (74%). Respondents in Wonuahoa had on average fewer years of experience in farming cocoa than those in other villages (Table 4.1). Ninety-seven percent of farmers reported that they owned their land, although formal aspects of land ownership varied significantly among villages. In Simbune and Asinua Jaya most farmers inherited their land, whereas in other villages land was mostly purchased.

Farmer perceptions regarding soil fertility indicators

Soil structure, thickness of litter layer, soil macro-fauna content and soil color were identified as the most important indicators for soil fertility (Table 4.2). While we asked farmers about general macro-fauna contents, most respondents focused on the presence of "worms" (*cacing*) for this indicator. When asked about soil structure, respondents differentiated between "looseness" (*tanah gembur*) and "hardness" (*tanah keras*). Farmers expressed clear preferences for looser, dark soils and for medium-to-thick litter layers and "worm" presence within their plots (Table 4.2). We observed no significant variation in farmers' perceptions of soil fertility according to farmer group membership (data not shown). Farmers with highest education levels reported a preference for darker soils (H=8.4, p=0.04). While there were no significant differences in ranking of important fertility indicators between villages, there were significant differences between villages in the ways farmers evaluated soil fertility based on litter content (H=13.9, p=0.02) and stone (*batu*) content (H=12.1, p=0.03). In the three villages of Kolaka district, at least 50% of interviewed farmers preferred high litter contents on their farms, whereas in communities located in Konawe district at least 50% preferred having either low litter contents or no litter at all. In Lawonua, all respondents except one indicated stone content as a positive indicator for soil fertility, whereas in Wonuahoa and Asinua Jaya 58% and 67% of farmers indicated stone content as a negative indicator. Given the differences in soil between communities, these significant differences in farmers' perceptions might reflect environmental variability in their plots.

Shade tree benefits for soil fertility

Shade trees were perceived to modify soil fertility through several mechanisms or processes: by providing shade and protection (58% of respondents), through litter-fall and resulting nutrient inputs (42%), through root systems (22%) and by regulating soil moisture (13%). Fifteen percent of respondents indicated that they did not know about such mechanisms.

Responses were not associated with differences in community, education levels or farmer group membership (data not shown).

Table 4.2. *Ranking of soil fertility indicators considered as the most important for cocoa cultivation by respondents in Southeast Sulawesi (n=72) and commonly reported describing factors of a good soil for cocoa cultivation. The ranking ranges from 1 (most frequently ranked as most important) to 7 (least frequently ranked as most important).*

Rank	*Soil fertility indicators*	*Description of good soil for cocoa cultivation for each indicator*							
1	Soil structure	Loose	72%	Medium:	24%	Hard	4%		
2	Thickness of litter layer	Thick layer	51%	Thin layer	36%	None	13%		
3	Macro-fauna	Some	49%	Many	43%	None	8%		
4	Soil color	Black-brown	88%	Yellow-white	10%	Red	3%		
5	Water holding capacity	Low	61%	None	38%	High	1%		
6	Soil texture	Gritty/sandy	40%	Smooth/silty	49%	Sticky/clayey	18%	Don't know	1%
7	Stone content	Some	53%	None	39%	Many	6%	Depends	3%

A detailed assessment of farmer responses indicated a good understanding of potential effects of shade trees on soil fertility indicators (Table 4.3). Farmers perceived significant differences between shade tree species in their effects on soil structure ($H=35.5$, $p<0.001$). Gliricidia was associated with beneficial effects on soil structure by 65% of respondents (Fig. 4.1a). Ten farmers perceived gliricidia leaves to be beneficial as compost, and 12 farmers perceived gliricidia to have a positive effect on soil moisture. Rambutan and langsat, on the other hand, were associated with negative effects on soil structure by 58% and 44% of respondents respectively. Perceived disadvantages of rambutan and langsat were related to soil compaction and structure, as many farmers observed “harder” soils under these species and both species were said to “eat nutrients” and contribute to water competition with neighboring cocoa trees. For mango, durian and white teak, most respondents observed no positive or negative effects (Fig. 4.1).

<u>Shade tree benefits for *Theobroma cacao*</u>

Shade trees were perceived to influence neighboring cocoa trees through the following mechanisms or processes: providing shade and protection (67% of respondents), impacting cocoa tree health and growth (34%), affecting cocoa pod development and yields (26%), affecting nutrient availability for cocoa trees (22%), changing pest and disease occurrence (17%) and regulating water and nutrient availability for cocoa trees (8%). Fifteen percent of respondents indicated that they did not know about such mechanisms. Between villages there were significant differences in farmer perceptions of tree effects on shade protection (H=12.6, p=0.03) and yields (H=13.0, p=0.02). In Tasahea, Andowengga and Lawonua, most farmers associated shade trees with increased canopy protection, whereas in the other villages less than 50% of farmers reported this. Wonuahoa was the only village where no respondents reported associations between shade trees and cocoa yields. We found no differences in responses related to education levels or farmer group membership status (data not shown).

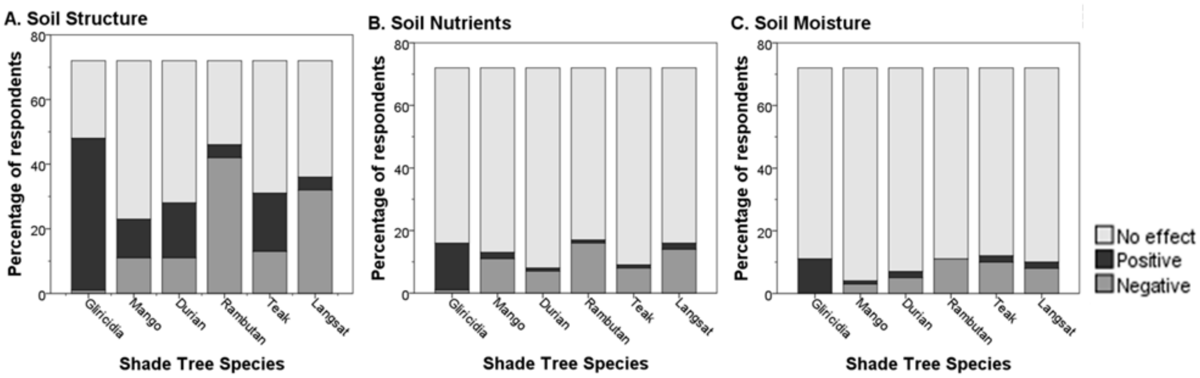

Figure 4.1. *Perceptions regarding the effects of six common shade tree species on a) soil structure; b) soil nutrient contents; and c) soil moisture, as reported by smallholder cocoa farmers in Southeast Sulawesi (n=72).*

Farmers perceived significant differences between shade tree species in their effects on shade protection (H=29.8, p<0.001), pest and disease occurrence (H=18.6, p=0.002) and yields (H=16.6, p=0.005). Gliricidia was associated with an increase in cocoa yields by 21% of respondents, whereas all other species were associated with decreased yields by 22 to 58% of respondents (Fig. 4.2a). Most farmers perceived shade trees to have no effects on cocoa tree growth (Fig. 4.2b) or pest and disease occurrence (Fig. 4.2c), although mango, durian and rambutan were reported to have a negative effect on pest and disease more frequently than other species. The shade provided by gliricidia and durian was perceived to be beneficial for cocoa trees by 39% and 21% of respondents, whereas the shade provided by mango and white teak was reported by 22% and 24% of farmers to have negative effects on cocoa (Fig. 4.2d). Twenty-eight percent of respondents pointed out the importance of pruning gliricidia properly and recognized that excessive shade caused by insufficient pruning could lead to both decreased cocoa yields and decreased cocoa tree health and black pod infections.

Of the 97% of respondents who had gliricidia in their plots, only two did not plant it there themselves. For the other species, 85% of respondents planted durian, 75% planted rambutan, 68% planted mango, 57% planted langsat and 47% planted white teak in their cocoa plots. A smaller proportion of farmers reported avoiding planting some tree species because they disliked them: 24% for mango, 21% for rambutan, 39% for white teak and 14% for langsat. Other desirable shade trees commonly mentioned by participants were *Musa musa* or banana (26% of respondents), *Cocos nucifera* or coconut (17%) and *Hevea brasiliensis* or rubber (4%).

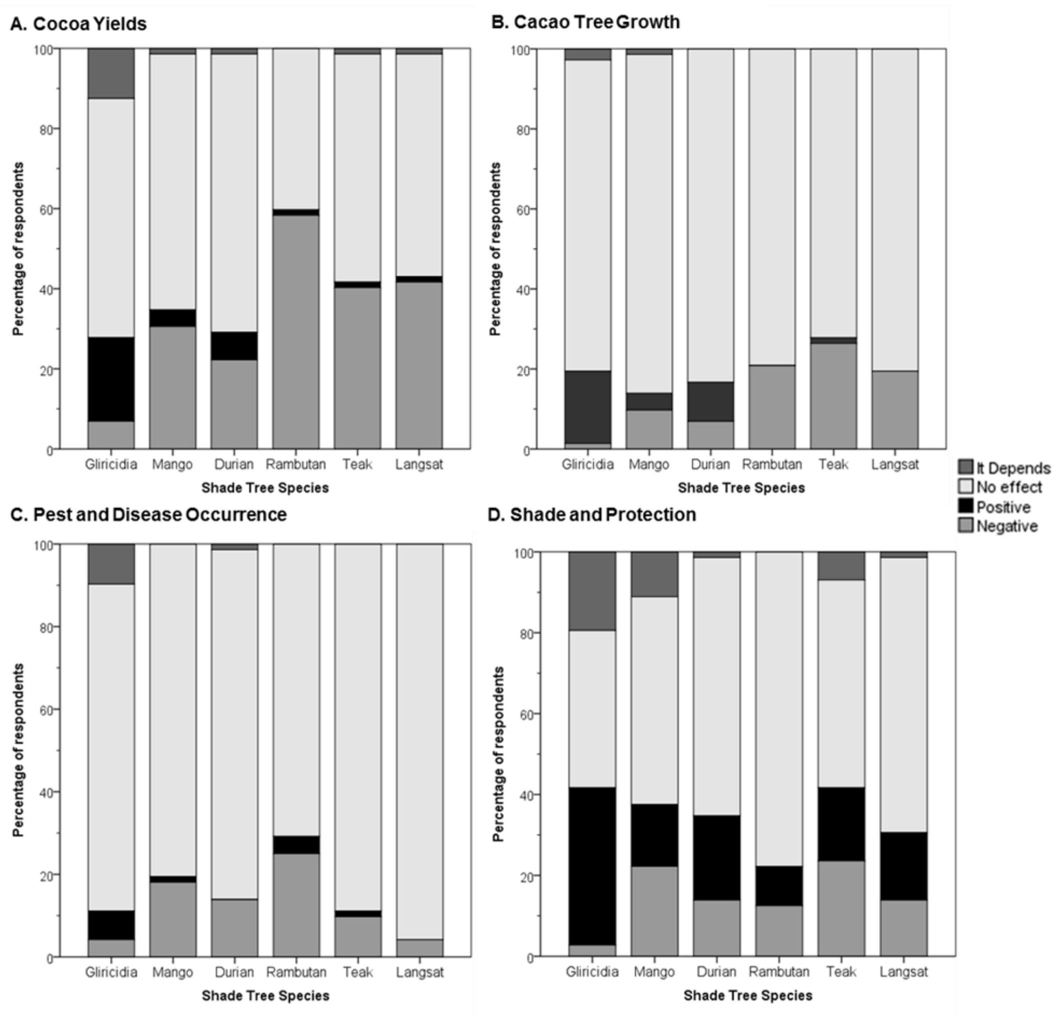

Figure 4.2. *Perceptions regarding the effects of six common shade tree species on a) cocoa yields; b) cacao tree health; c) shade protection; and d) pest and disease occurrence, as reported by smallholder cocoa farmers in Southeast Sulawesi (n=72).*

Table 4.3. *Selection of responses from smallholder cocoa farmers selected in six communities of Southeast Sulawesi, detailing their understanding of a) soil fertility indicators; and b) the linkages between shade trees, soil fertility and cocoa tree development.*

a)

	In-line with current scientific knowledge	Established scientific knowledge and references	No direct match with current scientific knowledge
Water-holding capacity	"too much water is bad for plants" "it's better if water just passes through"	• Ideal conditions for plant growth occur when there is adequate aeration in soil pore-space (e.g. no waterlogging), and adequate drainage. e.g. *Brady & Weil, 13th ed.*	"too much water makes pods turn red" "no water is better"
Worm content	"worms eat soil litter and loosen the soil" "worms lead to more bacteria, and a lot of soil "bacteria are good" "litter increases worm content"	• Earthworms can contribute to decomposition and mineralization of soil organic matter in plant litter, improved soil porosity and aggregation, and the stimulation of microbial activity. e.g. *Blouin et al. 2013*	"black ants are good, but cacao doesn't like worms"
Soil color	"darker soils indicate healthier soils" "soil color, litter layer and soil texture should be friends [synchronized with each other]"	• Soil color is an indicator of soil characteristics, and can be influenced by organic matter, water contents, etc. e.g. *Brady & Weil, 13th ed.*	"white soil gets very hard if it doesn't rain" "red soil is bad for cacao – branches tend to die"
Stone content	"the soil tends to be looser if there are no stones" "stones disturb cacao roots"	• Stony soils have been considered as unsuitable for cocoa. e.g. *Ruf et al. 1998*	"some stones are good because stones cool the soil" "it's good for cacao if there are some stones – this means that the cacao will get heavier pods"
Litter content	"many leaves are good for the little roots of the cacao tree which come up to take food from the leaves' "litter can hold water in the soil and cool it" "humus is a sort of fertilizer and replaces chemical fertilizer"	• A thick layer of litter and organic residues can contribute to decreased nutrient leaching in areas characterized by high rainfall. e.g. *Beer et al. 1988* • Soil organic matter decomposition provides substrates for microbial activity, and humus increases a soil's capacity to store plant-available nutrients. e.g. *Brady & Weil, 13th ed.*	"litter makes new pods in the cacao" "it's better if the soil is clean under the cacao tree before fertilizer is applied so that there is no reaction with fertilizer"
Soil texture	"clay soil gets too dry and hard and kills cacao" "soils that are too sandy or too sticky [clayey] are not ideal for plants	• Clay soils have a high nutrient-holding capacity but can get too sticky when wet or too hard for cultivation when they are dry. Sandy soils have lower nutrient-holding capacity and do not hold soil moisture well. e.g. *Brady & Weil, 13th ed.*	"if the soil is too clayey, there will be a lot of cacao leaves but no pods"
Soil consistency	"loose soil is good for cacao roots which are able to spread more easily"	• Loose "granular" non-compacted soil structure allows for good plant root development. e.g. *Brady & Weil, 13th ed.*	"while looser soil can be healthier, in the dry season harder soils keep in nutrients better"

b)

	In-line with current scientific knowledge	Established scientific knowledge and references	No direct match with current scientific knowledge
Shading & protection	"when cacao is young it needs shade, when it gets older it doesn't need shade anymore" "shade trees cool down and loosen the soil" "too much shade and too little shade are both bad" "there is a connection between too much shade and black pods"	• Shade trees compete with neighboring plants (e.g. cocoa trees) for growth resources but may also provide benefits such as microclimate amelioration or improved soil structure / fertility. e.g. *Hartemink et al. 2005 ; Belsky et al. 1989* • Young cocoa seedlings are generally established under denser shade which is then removed as the cocoa trees mature. e.g. *CRIG Ghana Cocoa Manual* • Black pod infection in cocoa trees is generally exacerbated by high humidity and poor airflow (e.g. under heavy shade). e.g. *Beer 1987 ; World Cocoa Foundation Cocoa Manual*	"the leaves of durian, mango and langsat are hard to decompose" "if shade trees are too close, branches can fall on cacao and kill it"
Cocoa tree health	"shade trees can improve cacao leaf growth" "Shade tree litter provides food for cacao trees"	• Shade trees might improve crop (e.g. cocoa) phenology through improvement of microclimatic conditions. They might also contribute to soil fertility through increased SOM from litterfall or improved nutrient recycling. e.g. *Beer 1987*	"cacao and shade trees should be the same age as this balances the soil" "cacao pods are harder under rambutan" "durian and mango don't match with cacao" "under rambutan and langsat cacao trees get yellow leaves"
Shade tree roots	"shade tree roots can disturb cacao trees" "shade tree roots improve water-holding capacity" "hold together the soil" "brings vitamin to other plants" "roots make competition for nutrients"	• Shade tree roots can improve soil drainage and aeration, or recycle nutrients not available to crops (e.g. cocoa). e.g. *Beer 1987 ; Van Noordwijk & Purnomosidhi 1995* • Shade tree roots can compete for moisture or nutrients with crops (such as cocoa). e.g. *Beer 1987*	"gamal [gliricidia] roots have oxygen in them and provide it to the cacao" "the farmer can change soil fertility conditions but the tree can't" "shade tree roots harden the soil" "the shade tree trunk affects soil water – bigger trunks mean drier soils" "rambutan takes water through its long roots" "langsat can change soil pH"
Pest and disease	"shade trees attract more birds which can reduce pest and disease" "shade trees increase the risk of black pod [fungus] infection"	• Shade trees can reduce pest and disease incidence through increases in natural enemies e.g. *Beer 1987 ; Pumarino et al. 2015* • Black pod infection in cocoa trees is generally exacerbated by high humidity and poor airflow (e.g. under heavy shade). e.g. *Beer 1987 ; World Cocoa Foundation Cocoa Manual*	"rambutan attracts wild pigs" "rambutan attracts too many worms" "rambutan worms go to cacao; cacao worms go to durian"

Shade trees as additional income sources

In addition to shade protection, farmers reported various uses for the shade tree species included in our questionnaire. Gliricidia trees were used as pepper stakes by 63% of respondents and for firewood by 58%. A majority of respondents indicated that crops from fruit-bearing shade tree species were used primarily for household consumption: mango (67% of respondents), durian (85%), rambutan (81%) and langsat (81%). These same crops were also sold to supplement household incomes. White teak was used as construction material by 43% of respondents, and was cited as a supplemental source of household income by 17% of respondents (Fig 4.3).

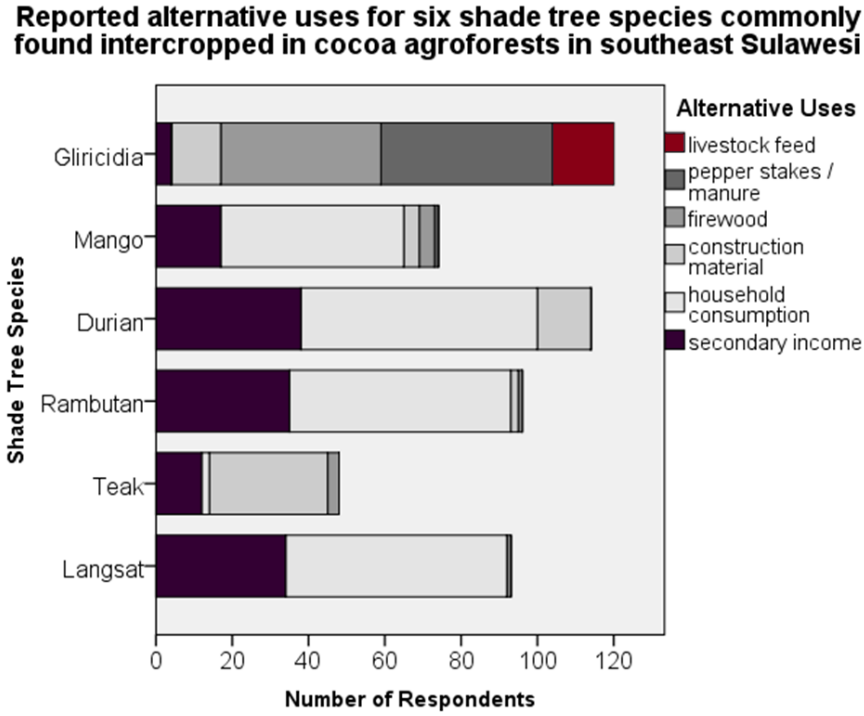

Figure 4.3. *Reported alternative uses for six common shade tree species found in cocoa agroforests in southeast Sulawesi. The values shown are cumulative, as respondents often cited more than one use per tree.*

When asked about alternative income sources to cocoa production, farmers frequently referred to some of the shade tree uses mentioned above. The most commonly cited additional income sources were the cultivation of other crops, which included pepper (54% of respondents), fruit and vegetables intercropped with tree crops (19%), patchouli intercropped with tree crops (15% of respondents) and annual crops (maize or rice) (14%). Seven percent of respondents reported livestock as an additional income source. In Asinua Jaya, logging was an important livelihood source (personal observation), although due to the illegal nature of this activity only five farmers admitted openly that it contributed to their incomes. In Lawonua, three farmers reported that working on large palm oil plantations was the most important income source in their households. Farmers reported that these other income sources often contributed more to their household income than revenues from cocoa production.

Factors influencing fertilizer use

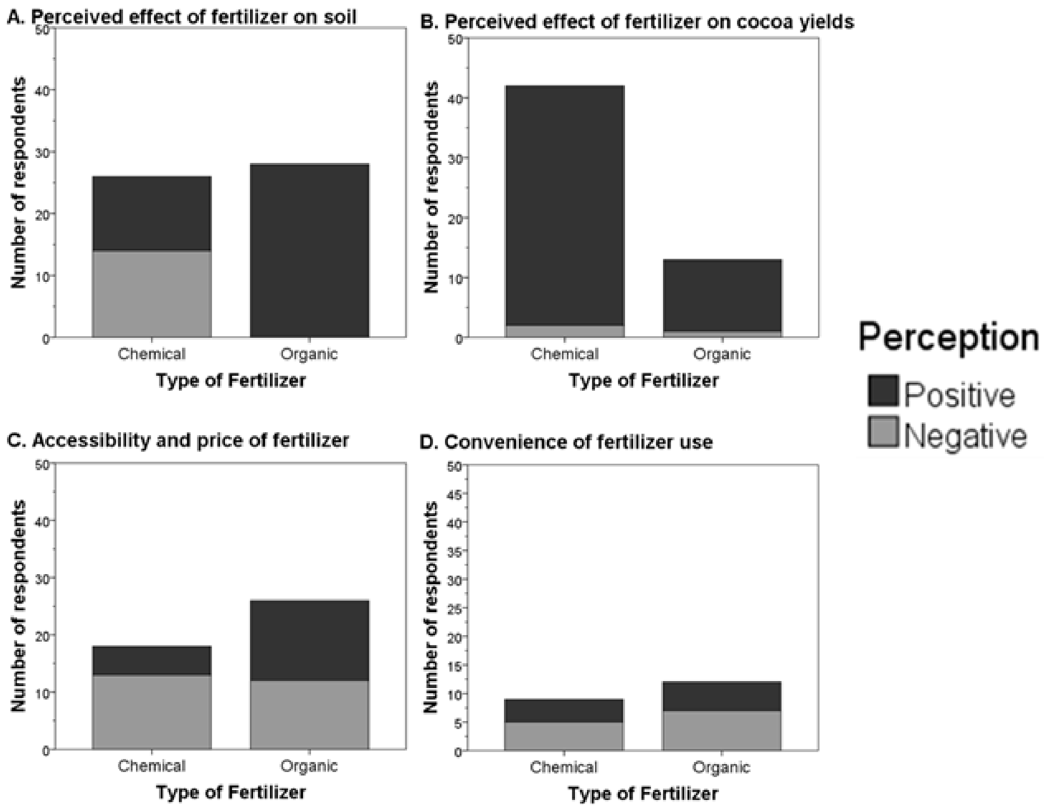

Figure 4.4. *Perceptions of chemical and organic fertilizer in terms of a) effect on soils; b) effect on cocoa yields; c) market and cost accessibility; and d) convenience and efficiency of use, as reported by smallholder cocoa farmers in Southeast Sulawesi (n=72).*

Fifty-four percent of farmers reported using a mix of both chemical and organic fertilizer (which generally consisted of green manure and compost). Twenty-one percent of farmers (21%) used only chemical fertilizer, 15% used only organic fertilizer, and 10% used no fertilizer. Farmers associated organic fertilizer with positive effects on soil (39% of respondents), whereas chemical fertilizer was perceived to have positive effects on soil by

17% of respondents and negative effects by 19% (Fig. 4.4a). In contrast, 56% of respondents cited the positive effects of chemical fertilizer on cocoa yields compared to 17% for organic fertilizer (Fig. 4.4b). More farmers found that organic fertilizer was more accessible and affordable compared to chemical fertilizer (Fig. 4.4c). Few farmers cited convenience of use as a factor determining which kind of fertilizer they preferred (Fig. 4.4d). Sixteen farmers reported using organic fertilizer after receiving external guidelines, whereas only 4 farmers reported using chemical fertilizer because of external information.

External farm management guidelines predominantly originated from government programs, although local farmer networks and AgFor also played an important role (Table 4.4). Only 7% of respondents reported receiving no information on the addressed topics. Less advice was received about shade tree management practices than about shade tree selection, planting densities and fertilizer application (Table 4.4).

Table 4.4. *Proportion of smallholder farmers interviewed in Southeast Sulawesi (n=72) who reported receiving knowledge or advice about the topics of shade tree selection, shade tree management, planting densities and fertilizer application.*

Knowledge topic		***Source of knowledge***					***No knowledge exchange reported***
		Farmer group	*AgFor (ICRAF)*	*Other NGOs*	*Government*	*Other*	
Shade tree selection		38 %	19 %	3 %	43 %	4 %	22 %
Shade tree management		26 %	14 %	1 %	32 %	10 %	39 %
Planting densities		38%	18 %	4 %	42 %	8 %	24 %
Fertilizer application		32 %	18 %	3 %	40 %	8 %	24 %

<u>Limiting factors for cocoa production</u>

The factors constraining cocoa production most often mentioned were: crop damage due to pest and disease (93% of respondents), low cocoa selling prices (32%), decreased tree productivity (28%), aging cocoa trees (24%), unfavorable weather conditions (19%) and soil degradation (8%) (Fig. 4.5).

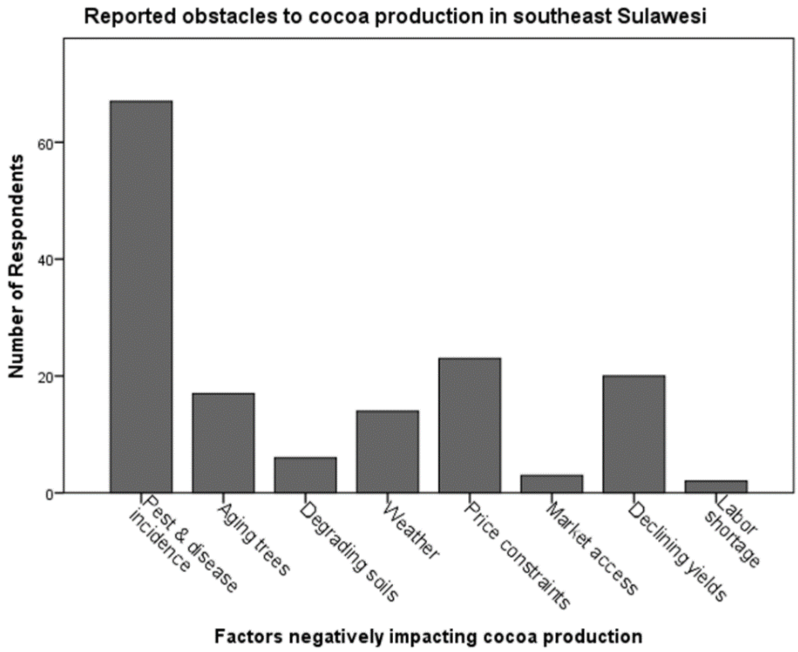

Figure 4.5. *Commonly reported constraints that negatively impacted cocoa production in smallholder plots in 2014/2015 in six communities of Southeast Sulawesi.*

4.4 Discussion

<u>Farmers' knowledge about soil fertility and soil-tree-cocoa interactions</u>

Respondents in our study reported using soil physical properties (structure and color), and biological properties (quantity of litter and "worms") as indicators for soil fertility. Smallholders expressed a clear preference for dark, loose soils, which echoes previous farmer knowledge assessments in West African cocoa agroforests (Talawar and Rhoades, 1998; Isaac et al., 2009; Dawoe et al., 2012). In general, farmers' assessments of soil fertility were consistent with existing literature (Table 4.3). Farmers frequently associated different soil properties, such as high litter contents and increased soil nutrients and "worm" contents (Table 4.3). This suggests a holistic understanding of the significance of different soil properties in the context of cocoa cultivation. Similarly, local knowledge about the interactions between shade trees, soil fertility and neighboring cocoa trees was in line both with previous studies of farmer perceptions of tree-crop interactions (e.g. Albertin and Nair, 2004; Anglaaere et al., 2011) and with scientific literature (Table 4.3). Farmers recognized shade trees' dual effects in cocoa agroforests, acknowledging the benefits provided by shade trees, including microclimate regulation and increased organic inputs from litterfall, as well as disadvantages related to increased resource competition with neighboring cocoa trees.

Farmers also considered indicators not commonly addressed by scientific studies (Table 4.3). This has been the case in other regions where farmers were acutely aware of processes directly tied to crop productivity, such as the risk of physical damage caused to cocoa trees by falling branches from shade trees (Atkins and Eastin, 2012; Lamond et al., 2016) or the negative implications of yellow leaves or tall and narrow trunk shapes for cocoa tree growth and development (Isaac et al., 2009). Similarities in farmer perceptions regarding physical soil properties (Joshi et al., 2004) and the usefulness of shade trees in coffee or cocoa agroforests (Albertin and Nair, 2004; Anglaaere et al., 2011; Gyau et al., 2014) have been observed across different regions. Our case study provides additional evidence indicating that there are commonalities in the ways cocoa farmers across the globe identify indicators for soil fertility and cocoa tree health.

Farmers' knowledge is not always consistent with quantitative data from the same study area

While we found significant overlap between local knowledge and scientific knowledge, there were several instances where farmer perceptions diverged from established scientific knowledge. Farmer understanding of the influence of soil quality on cocoa productivity did not match with common biophysical findings (Table 4.3). Even among farmers, our data indicated contrasting views and perceptions regarding the effects of shade trees on soil fertility. For example, some farmers cited preferring high amounts of litter, while others preferred none (Tables 4.2 & 4.3). Such differences could be related to knowledge gaps in farmers' understanding of nutrient cycling processes – or, alternatively, to real-world variation in context and experiences which might have shaped farmers' perceptions and preferences.

Nevertheless, a high proportion of respondents associated shade trees with a measurable decrease in cocoa yields, citing excessive shade and resource competition as explanations for this negative interaction. These results contrast with an observational study conducted by Wartenberg et al. (in preparation) in the community of Wonuahoa, in which individual shade trees of various species (gliricidia, rambutan, durian, mango, white teak and langsat) were shown to contribute to increased soil fertility and decreased cocoa tree biomass but had no significant effect on cocoa yields. In this same study gliricidia was the only species associated with increased cocoa yields, and the highest increases in soil fertility were measured under rambutan and durian. One explanation for this difference in results might be that Wartenberg et al. (in preparation) specifically selected isolated shade trees in cocoa agroforests, whereas farmers responses might be influenced by their observations of the effects of shade trees planted at higher densities.

A majority of respondents in our case study associated both rambutan and langsat with soil hardening (Fig. 4.1a, Table 4.3). In contrast, a comparison of changes in soil bulk density and moisture contents under shade trees shows no changes under rambutan and significant improvements in soil moisture and bulk density under langsat (Appendix 5). Discrepancies between local and scientific knowledge are not unusual (e.g. Gray and Morant, 2003) and, in this case, might be related to farmers' strong associations between the physical appearance of root systems and the perceived effects on soil quality. In Southeast Sulawesi, respondents described the root structure of rambutan and langsat trees as "long", "strong", "shallow" or "spreading", in line with existing literature (Watson, 1982; Calvo, 1994; Van Noordwijk and Purnomosidhi, 1995). Smallholders tend to associate visible root systems with an increase in resource competition between shade trees and crops, as has been documented previously in both Java (Joshi et al., 2000) and Nepal (Joshi et al., 2004). In our study area, our results could also indicate that farmers under-estimate the extent to which rambutan or durian can improve soil indicators that we used to assess soil fertility.

Generally, the farmers that we surveyed tended to possess a good understanding of ecosystem components and processes directly visible to the naked eye, such as litter decomposition or worm activity (Talawar and Rhoades, 1998). However, farmer understanding of less visible processes, such as microbial activity or N-fixing through root nodules, is often less accurate (e.g. Grossman, 2003; Joshi et al., 2004). Additionally, the proportion of farmers that associated gliricidia with increased cocoa yields was significantly lower than the number of farmers who recognized the positive effects of gliricidia on soil fertility (Fig. 4.1 & Fig. 4.2a). As this was not the case for other species, we postulate that farmer' strong positive perception of gliricidia may have been influenced by external knowledge sources.

Local knowledge is influenced by environmental conditions and external information

Our data showed that there were significant differences between the six selected communities regarding respondents' reported prioritization of soil indicators and their perceptions of different shade tree species. Such differences might arise because of variation in local soil conditions (Halbrendt et al., 2014; Meijer et al., 2015) or in cultural context between villages (e.g. Weber et al., 2007). For example, farmers in Lawonua had a different perception of stone content in their soils than other farmers. Lawonua is located in a floodplain with *dystric fluvisols*, whereas other villages are located in more hilly areas characterized by *orthic acrisols* (FAO-UNESCO, 1979). Farmer preferences might reflect differences in soil conditions at the landscape level relating to sedimentation and weathering processes (Van Straaten, 2006; Brady and Weil, 2013), although more data would be needed to corroborate this. Additionally, there were clear distinctions across the six communities selected for this study in terms of represented ethnicities (Janudianto et al., 2012). In Southeast Sulawesi, significant differences have been reported between Tolaki or Bugis households regarding local knowledge and perceptions about cocoa farm management. As a consequence of migration dynamics, increased communication between both ethnic groups has been shown to strongly influence cocoa cultivation approaches (Weber et al., 2007; Mulyoutami et al., 2015). We postulate that farmers who migrated to Southeast Sulawesi from other islands (e.g. Java or Bali) might similarly arrive with differing experiences and assumptions than farmers from Southeast Sulawesi.

Local knowledge is also strongly influenced by information derived from external sources (Martini et al., 2016). In our case study, farmers reported that information received on the addressed topics mainly originated from government programs, other farmers and to some extent AgFor project extension agents (Table 4.4). The Indonesian government has provided targeted support of cocoa projects in the region since the 1980's through projects like the Program Gerakan Nasional Percepatan Revitalisasi Kakao (GERNAS) seedling program

(Martini et al., 2013). Government-led extension services and programs should therefore be considered an important focal point for future knowledge transfer. Similarly to Martini et al. (2013), we found that formal schooling or training was not cited as a source of information about farming management. It was therefore not surprising that we found no relationship between educational level and local knowledge about soil-tree-crop interactions and management practices. However, according to our results, information was also transferred through informal exchanges between local farmer groups and through AgFor/ICRAF agents during practical field activities. This echoes the findings originating from the same study area presented in Martini et al. (2016) and indicates that both of these groups represent important entry-points for future knowledge transfer.'

Knowledge and perception can impact farmers' management decisions

Farmer use of fertilizers in Sulawesi illustrates the extent to which farmer knowledge and perceptions of ecosystem processes can influence management decisions (Fig. 4.4). A significant proportion of interviewed farmers were aware of the benefits of organic fertilizer in terms of long-term soil health, accessibility, affordability, and efficiency. Respondents demonstrated awareness of the negative effects of chemical fertilizer on long-term soil fertility (through "hardening" of the soil), although chemical fertilizers were also perceived to have a more positive and "faster" effect on cocoa yields by directly providing "food for cocoa trees". While more farmers applied only chemical fertilizers (21%) compared to those who applied only organic fertilizer (15%), it was notable that most farmers (54%) tried to address perceived trade-offs between organic and chemical fertilizer use by applying a mix of both in their plots. Farmers thus seem to be receptive to the adoption of more "ecologically" oriented solutions where relevant, particularly if these can be directly linked to increased crop production and incomes. This result points towards the value of flexible conservation farming approaches that allow farmers to tailor the way they integrate sustainable and "conventional" management practices to fit their needs. Such approaches could increase adoption rates and encourage simultaneous mitigation of long-term soil depletion and prioritization of crop productivity to support farmers' livelihoods (Swift et al., 2004; Tscharntke et al., 2011; Mbow et al., 2014).

Wartenberg et al. (in preparation) find that the effects of gliricidia on soil fertility in cocoa agroforests were only marginally significant when compared to other species, such as rambutan. In contrast, we found that farmers tended to associate gliricidia with positive effects not only on cocoa yields but also on cocoa tree growth and general soil fertility. Farmers may overestimate of the benefits of gliricidia. Our results could also indicate that indicators used to assess soil fertility benefits by farmers and by scientists do not capture the same things. Reported farmer preferences were directly reflected in planting choices, as gliricidia was the species most commonly interplanted with cocoa trees, followed by durian. Gliricidia and other N-fixing trees have been promoted actively by both government- and project-based extension programs since the 1980s and 1990s, based on their capacity to improve soils and thus positively influence smallholder farming systems (Roshetko, 2001). Such policies likely contributed to the positive perception of the species by farmers. Surprisingly, while other species like rambutan or mango were often associated with negative effects on soils and cocoa, more than half of respondents still chose to plant individuals of these species on their plots. Both species were reported to contribute to household incomes, which suggests that the inclusion of specific shade tree species in cocoa plots could be driven primarily by economic considerations.

Adoption barriers to more widespread shade tree diversification in Southeast Sulawesi

Nevertheless, the principal barriers to cocoa production in Southeast Sulawesi were pest and disease incidence and low cocoa selling prices (Fig. 4.5). Both factors can be expected to play a significant role for decision-making in cocoa plot management. Nevertheless, farmers did not perceive increased tree diversification to address these barriers by decreasing pest and disease incidence, improving cocoa yields, or increasing selling prices. This lack of an association between shade tree diversification and yield or income improvements might be one of the principal adoption barriers for more widespread diversification at the farm level.

While cocoa selling prices are determined by external markets, scientific evidence suggests that the diversification of agroforests might reduce yields losses from pest and disease incidence (Pumariño et al., 2015). Nevertheless, the effects of shade trees on pest and disease vectors are complex and associated with trade-offs in terms of overall yield benefits (Schroth et al., 2000; Bos et al., 2007; Tscharntke et al., 2011). In Southeast Sulawesi, research suggests that while shade trees in cacao agroforests can indeed reduce the occurrence of certain pests, increased humidity under shade tree canopy may contribute to increased black pod infections in the absence of adequate pruning (Martini et al. in prepration). It remains unclear whether farmers' lack of recognition of the benefits of shade trees for pest and disease management (Fig. 4.2c) can be attributed to poor understanding of the mechanisms through which shade trees can be beneficial in this context – or simply to a lack of benefits at the farm level. Addressing this "dual" knowledge gap through further research is crucial. If shade trees can be managed to effectively contribute to pest and disease reduction, targeted recommendations could provide smallholders with incentives to include shade trees in their farms, while also significantly contributing to their long-term income security.

4.5 Conclusions

We found that farmers' understanding of biophysical interactions in Southeast Sulawesi was quite elaborate and generally aligned with science-based findings. However, local perceptions of the effects of specific shade tree species within cocoa agroforests did not reflect scientific findings originating in the same study-area. This could point to gaps either in local knowledge or in science-based literature, which remains scarce in cocoa ecosystems. Smallholders in Southeast Sulawesi might value different ecosystem services (e.g. short-term soil improvements, yield increases, pest and disease reduction) than those that have been addressed in existing scientific studies. Nevertheless, smallholders appear to approach decision-making in a holistic way by integrating personal observations about biophysical processes with external information and socio-economic pressures and priorities. The relationship between knowledge and management decisions thus appears to be quite complex. We suggest that, in addition to continued improvement of top-down policy development that addresses external socio-economic pressures faced by smallholders, further research on the relationship between farmer knowledge and decision making remains invaluable. Low farmer awareness of direct benefits of shade tree inclusion for cocoa yields likely contributes to low adoption rates of systematic diversification practices. Identifying and addressing local knowledge gaps via targeted knowledge dissemination could potentially improve long-term adoption rates of such practices. In parallel, further science-based exploration of concepts reflected in farmer knowledge is still needed.

Acknowledgements

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Chapter 5 :
General discussion

5.1. Summary of dissertation

The principal objective of this dissertation was to evaluate whether increased tree diversification can improve the long-term sustainability of cocoa cultivation systems in terms of soil fertility and productivity. In my approach, I considered drivers of farmers' management decisions and the consequences of such decisions on soil fertility at two different spatial resolutions (plot-level and tree-level), using a case study based on smallholder cocoa farms in Southeast Sulawesi.

I first focused on the effects of tree diversity at the plot level by quantifying changes in soil aggregation, soil nutrient contents and microbial community composition across a diversity gradient ranging from cocoa monocultures to complex cocoa agroforests. Secondary and primary forests were used as reference ecosystems (Ch. 2). A key finding from this study was the lack of a direct association between increasing tree diversity and improvements in soil properties in cocoa plantations, which indicates that complex cocoa agroforests might not contribute as significantly to soil restoration after land degradation as previously thought. Rather, other variables related to vegetation cover (i.e. above-ground biomass, shade tree density or stand age) might have a more direct effect on soil fertility processes than tree species diversity alone. However, my results did suggest that promoting the establishment of secondary forests could be a promising avenue for the restoration of soil functions in degraded areas.

In a second study, I focused on the effects of individual shade trees on surrounding soils and cocoa trees, by quantifying changes in soil fertility, cocoa tree growth and yields under individual shade trees from 11 species commonly found in Southeast Sulawesi (Ch. 3). My results showed that individual trees had a positive effect on soil fertility but a negative effect on cacao tree growth, likely because of competition for light resources. Surprisingly, I found no significant relationship between shade tree presence and cocoa yields. This is significant as it confirms that the inclusion of diverse shade trees in cocoa agroforests does not necessarily entail significant yield-related trade-offs for smallholder farmers (Clough et al., 2011). My results further illustrate that the effects of trees on their surroundings is highly dependent on the species. While there were indications of relationships between tree traits (e.g. litter chemistry, crown shape) and soil fertility parameters and cocoa growth, the interactions between different traits appear to be complex. For this reason, the evaluation of different pathways through which trees might affect soil and crop yields remains important for the selection of suitable shade tree species in specific environments.

Understanding how changes in tree diversity can influence soil fertility and crop productivity in cocoa farms is important. In the context of sustainable farm management, it is, however, also crucial to understand the drivers of farmers' planting and management decisions at the farm level. In my third study, I therefore evaluated the perceptions and local knowledge of smallholder farmers with regard to soil fertility and the interactions between shade trees, cocoa trees and soil (Ch. 4). Survey responses revealed that while local knowledge about soil fertility indicators was elaborate and accurately matched with common scientific findings, there were notable discrepancies in linking ecosystem processes with cocoa productivity. Farmers in Southeast Sulawesi, however, integrate ecologic concerns into their decision-making, even though direct economic pressures generally outweigh those concerns. Therefore, targeted knowledge dissemination aimed at addressing local knowledge gaps and relating science-based ecosystem benefits to direct income improvements could significantly contribute to an increase in the long-term adoption rates of sustainable cocoa management practices.

In summary, my results highlight the complexity of biophysical interactions linking *Theobroma cacao*, shade trees and soil fertility. They also confirm that farmers' planting and management decisions can have a substantial impact on soil fertility. The implementation of more sustainable farming practices requires farmer participation, and my results indicate that smallholders' knowledge and perceptions of ecological processes play an important role in cocoa farming system functioning. More broadly, my results contribute to the discussion of how cocoa cultivation systems could be optimized to integrate biodiversity conservation and farmer livelihoods in tropical rural environments. In the following sections, I briefly discuss i) how spatial and temporal heterogeneity in soil fertility might have influenced my results; ii) the significance of my results in the context of conservation biology and climate change mitigation; and iii) the implications of my findings for future farm-management approaches.

5.2. Temporal and spatial variability of soil properties

Spatial heterogeneity of nutrient concentrations in agroforests

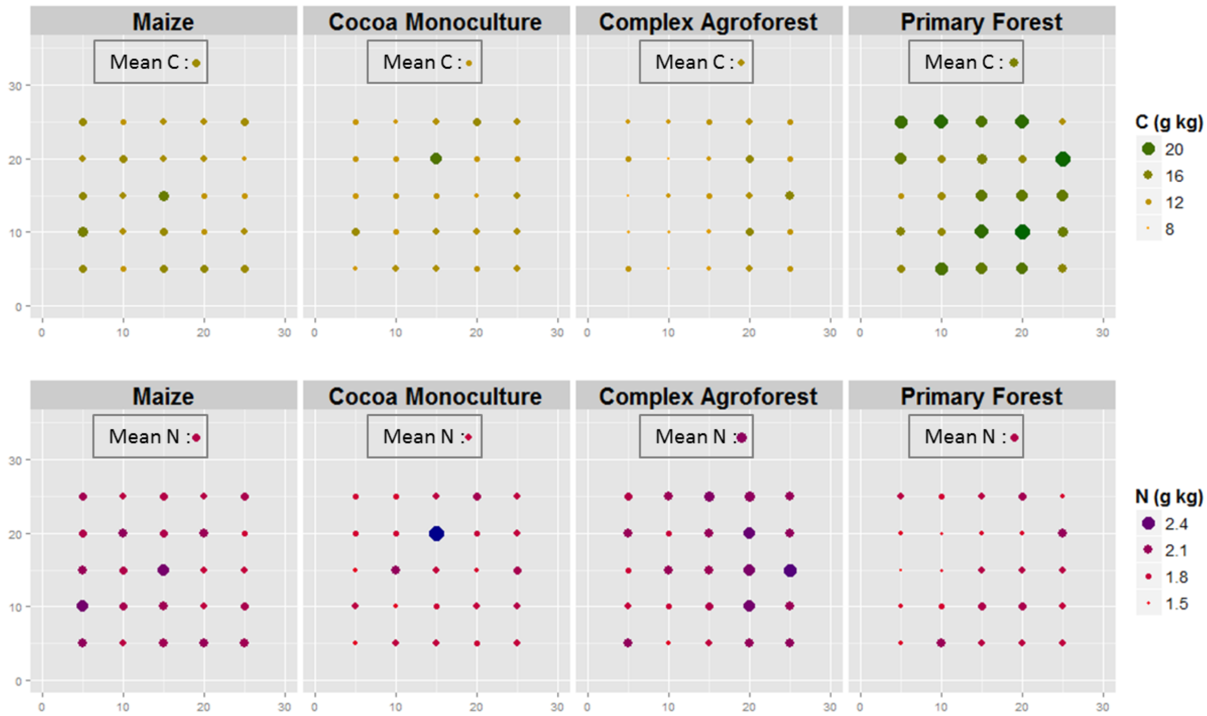

Figure 5.1 Spatial representation of heterogeneity *within* plots for soil total carbon (C) and total nitrogen (N) concentrations across four land-use systems: maize, cocoa monoculture, complex cocoa agroforest, and primary forest. “Mean” values were calculated by averaging C and N contents for all sampled points for each land-use system.

The inclusion of individual shade trees in cocoa agroforests had a positive effect on soil fertility directly under shade tree canopy area (Ch. 3). This was the case for soil carbon (C) and nitrogen (N) concentrations, soil aggregation, and C- and N-storage within large macroaggregates, indicating changes in the long-term storage of nutrients under shade trees in agroforests. It was, however, surprising that these results did not scale up to the field level. Indeed, in cocoa cultivation systems there was no evidence of a positive effect of increased tree species diversity on soil fertility when I quantified the effects of tree diversity across a gradient (Ch. 2). One potential explanation for this could be that increased soil nutrient contents around individual trees were canceled out by decreased soil nutrient contents away from trees, leading to averaged values at the field level. To test this further, an additional analysis was carried out to quantify soil C and N variation at the plot level: soil samples were taken at a 5 x 5 m resolution in 12 plots, distributed evenly across four types of land-use systems (cocoa monocultures, complex cocoa agroforests, primary forest plots and maize plots). The results indicate high spatial heterogeneity in these variables at the plot level (Fig. 5.1), and higher variation *within* plots than *between* land-use systems. Moreover, variation in soil C and N contents was not correlated with the locations of shade trees or other plot landmarks, indicating that the lack of an effect of tree diversity at the plot level cannot be attributed to averaged effects of individual shade trees. It is therefore more likely that variation in inherent soil properties and/or site history might strongly influence present soil conditions and/or have masked the effects of trees on soil properties (Fraterrigo et al., 2005; Vilà et al., 2005a; Van der Putten et al., 2009).

At what time scale are changes in perennial ecosystems measurable?

Additionally, most of the cocoa plots selected for the comparison study across a diversification gradient were established recently and within a few years of each other. Indeed, cocoa plot ages averaged about 13 years since initial establishment across all three study sites in Konawe province (Ch. 2). This relative uniformity in the age of cocoa plots in the region is related to the widespread introduction of cocoa in the 1980s through governmental programs like the Program Gerakan Nasional Percepatan Revitalisasi Kakao (GERNAS) (Martini et al., 2013). In contrast, secondary forests at the study sites were left fallow for at least 10 years after cultivation, and primary forests in Sulawesi are much older. The substantial differences in soil aggregation and C stocks between cocoa and forest plots might therefore be related to these significant differences in plot-age and in vegetation successional stages (Roshetko et al., 2007; Mehta et al., 2013a). My data did indicate that improvements of soil fertility might be measurable after relatively short time-spans directly underneath the canopies of individual shade trees (Ch. 3). Similarly, I observed differences in soil microbial community composition which might have been related to land-use changes (Ch. 2). Nevertheless, my findings suggest that there might be a time-lag in the way the effects of trees on soil chemical properties (i.e. nutrient stocks and aggregation) scale up to the field-, farm- or landscape-level.

5.3. Implications for ecosystem resilience and biodiversity conservation

Relevance for ecosystem restoration

Surprisingly, my results showed that soil phosphorus (P) stocks decreased with increasing tree diversification (Ch. 2). Farmers are more likely to add external fertilizer inputs to monocultures, which are more heavily managed, and this might have contributed to increased phosphorus inputs. For other measured indicators, however, my results indicated that tree diversification did not lead to improved soil fertility in cocoa cultivation systems (Ch. 2). Differences between cocoa monocultures and agroforests in terms of above-ground and below-ground biodiversity and biomass remained minimal in comparison with primary forests (Ch. 2). It thus appears that increasing tree diversity in cocoa cultivation systems does not have a measurable impact in terms of restoring soil fertility, at least in the short term. However, as cocoa is a tree crop, even in monocultures the presence of trees can contribute to improved ecosystem health via litter inputs, root activity and microclimate regulation (Hartemink, 2005). In comparison with more intensive systems such as rice paddies or maize fields, cocoa cultivation systems might thus be more sustainable in the long term (Dechert et al., 2004). Additionally, measured improvements in soil fertility under secondary forest (Ch. 2) were encouraging, as they indicate that increasing the use of fallows might be a possibility for restoring long-term soil fertility in degraded areas.

Soil organic matter storage and carbon sequestration

While above-ground biomass is the most immediate compartment for C accumulation following assimilation, at the global scale more C is stored in soils than in the atmosphere or in vegetation (Schmidt et al., 2011). This C is predominantly found in the form of soil organic matter (SOM), and soil aggregation is an important indicator for a soil's capacity of long-term SOM storage. The measured increases in soil C-contents and aggregation under individual shade trees in cocoa agroforests (Ch. 3) confirm that trees do not simply contribute to C-immobilization and storage through biomass increases, but can also promote increased C-storage in the soils around them. My findings indicate that certain tree species increase soil aggregate formation and SOM storage more than others (Ch. 3), although further research is needed to better understand what mechanisms might have led to these differences. Nevertheless, in all cocoa cultivations systems, soil C-contents and aggregation were consistently lower than in primary forests (Ch. 2). Hence, the diversification of cocoa cultivation systems might not be an effective solution to address soil fertility losses and C emissions resulting from land-use change activities.

5.4. Implications for farm-management approaches

How aware are farmers of the potential benefits of shade tree inclusion in agroforests?

Cacao yields were not significantly impacted by shade tree presence at the tree level (Ch. 3) or at the plot level (Ch. 2). These results echo previous findings which have indicated that the inclusion of additional tree species in cocoa cultivation systems does not necessarily lead to cocoa yield declines (Clough et al., 2011). Instead, existing literature suggests that other factors such as pollination intensity and pest and disease occurrence play a more important role in determining cocoa yield outcomes in Southeast Sulawesi (Bos et al., 2007; Groeneveld et al., 2010). When it comes to farm management, farmers' principal concerns often revolve around productivity and income security, and my findings indicated that in Southeast Sulawesi, the biggest perceived threats to future yield expansion were related to substantial losses from pest and disease occurrence (Ch. 4). Farmers in Brazil perceive shade as a protection against pest and disease occurrence, whereas this is not the case in Indonesia (Tscharntke et al. 2011). This discrepancy might be related either to a gap in farmer knowledge in Indonesia, or to substantial environmental differences between the two regions.

Addressing trade-offs and developing solutions with farmers for increased sustainability

My results also showed that both i) the effects of shade trees in cocoa agroforests (Ch. 3) and ii) the way they are perceived by farmers (Ch. 4) can vary significantly between species. While species like *Nephelium lappaceum* (rambutan) or *Durio zibethinus* (durian) have a significant effect on soil fertility improvements, from a cocoa farmer's perspective these benefits are outweighed by negative associations with cocoa yields. Conversely, species like *Gliricidia sepium* (gliricidia) have marginal effects on soil fertility but contribute directly to increased cocoa yields. The priorities of scientists and farmers might thus not always be lined up, and there are sometimes contradictions between scientific recommendations or science-based policies and farmer preferences (Franzen and Mulder, 2007). To ensure adoption of sustainable management solutions, it is therefore imperative to promote practices that address farmer concerns directly, for instance by encouraging the use of participatory approaches that actively include farmers.

5.5. Outlook

The findings presented in this dissertation give some new insights into the drivers of smallholders' decisions regarding tree diversity in cocoa agroforests and the effects of these decisions on soil fertility changes and cocoa yields. While the diversification of shade trees in cocoa cultivation systems did not appear to contribute significantly to soil restoration or C-sequestration at the plot level, complex agroforests are still likely more sustainable than annual cropping systems or monocultures in terms of general ecosystem resilience. On the other hand, secondary forests were found to improve soil properties compared to cocoa agroforests and might thus constitute a more adequate solution to address soil degradation issues. While reforestation efforts might mitigate soil fertility losses in already degraded areas, they are often costly and complicated (Le et al., 2014; Baynes et al., 2015). Instead, local and global policy efforts should target to halt continued expansion into limited remaining forested areas and rather promote the intensification and restoration of existing systems. This is particularly relevant for tropical regions with high endemic biodiversity.

My results also highlight several key issues that remain unresolved and warrant future research. First, while shade trees had a positive effect on soil fertility at the individual tree scale, this did not scale up to the plot level. This was likely exacerbated by the high degree of variation for soil properties within plots and highlights the strong influence of site history and inherent soil properties on present-day soil conditions. This finding raises an important question, which is particularly relevant for areas threatened by soil degradation: how can agroforest design be optimized to better scale up the positive effects of shade trees on soil fertility? My findings suggest that improvements in soil fertility in perennial ecosystems may occur too slowly to be measurable in a short-term study; however, the interpretation of my results also remains limited as the data collected represents a "snapshot" in time. In perennial ecosystems, organic matter turnover occurs at much slower rates than in annual systems, and additional information about long-term implications of diversification would be quite valuable. Future research would thus benefit from long-term on-farm trials specifically designed to test how positive effects of individual shade trees might scale up to the plot-level. Such research could be coupled with laboratory-based research to elucidate some of the mechanisms through which specific shade tree species can contribute to increased SOM stabilization.

Second, I found no indication of a direct influence of shade trees on yields in my study systems, although there was variation in the effects of different species. Nevertheless, shade trees might have more indirect effects on cocoa yields by affecting additional ecosystem services such as pollination or pest and disease control. While these issues were not addressed within the scope of this dissertation, more research is needed to understand these interactions at the ecosystem level. Moreover, future research should focus on an improved understanding of farmer perceptions and needs. The establishment of direct linkages between ecosystem benefits provided by trees and increased income opportunities should moreover be communicated effectively to farmers, as this would increase the likelihood that scientific findings will be translated into locally-appropriate practices and adopted in the long term.

Third, the propagation of species like rambutan and durian could have useful applications for soil restoration and climate change mitigation efforts in Southeast Asia, due to their apparent role in improving SOM storage (Ch. 3). The results of farmer surveys showed that even though these species are commonly interplanted in cocoa agroforests, they are perceived to reduce cocoa yields (Ch. 4). To address this, farmers diversify cocoa systems with other species such as gliricidia (Ch. 3), but further research on the trade-offs and benefits of specific intercropped species in cocoa systems could lead to the development more sustainable cocoa cultivation approaches. Additionally, an interesting alternative approach might be to consider promoting rambutan- or durian- based agroforestry system, although future research would have to address the economic aspects of such an approach and the importance of other external factors such as land availability. More generally, instead of focusing on the diversification of agroforests centered on specific cash-crops, policies could shift towards increased valuation of landscape-level diversification which could be optimized based on local environmental conditions and farmer priorities. A first step towards this would be strengthening communication and knowledge transfer channels between farmers, scientists and policy makers at the local, national and international level.

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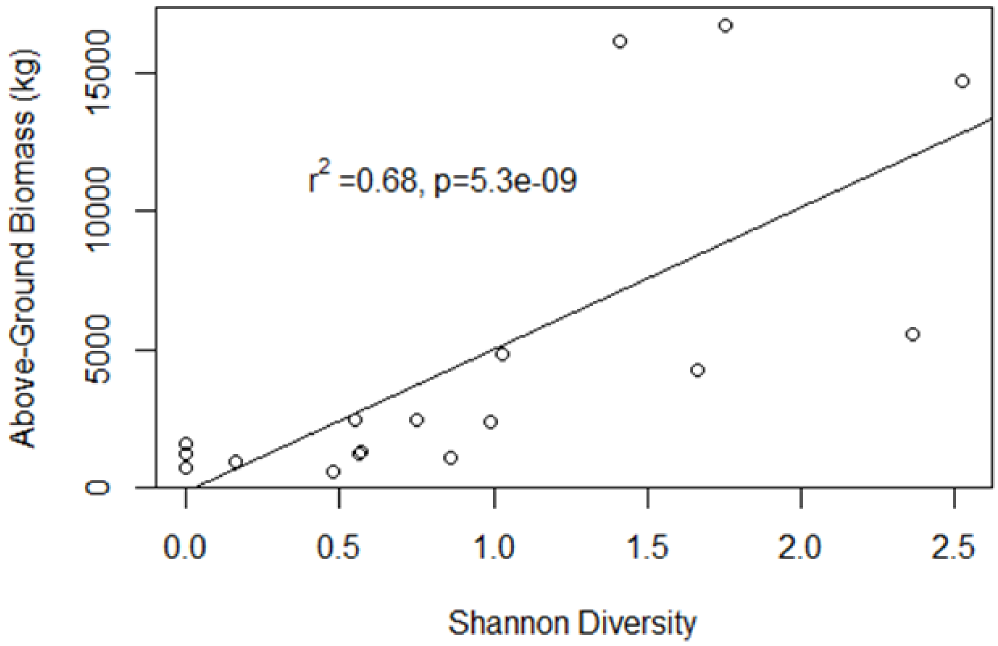
Appendix 1



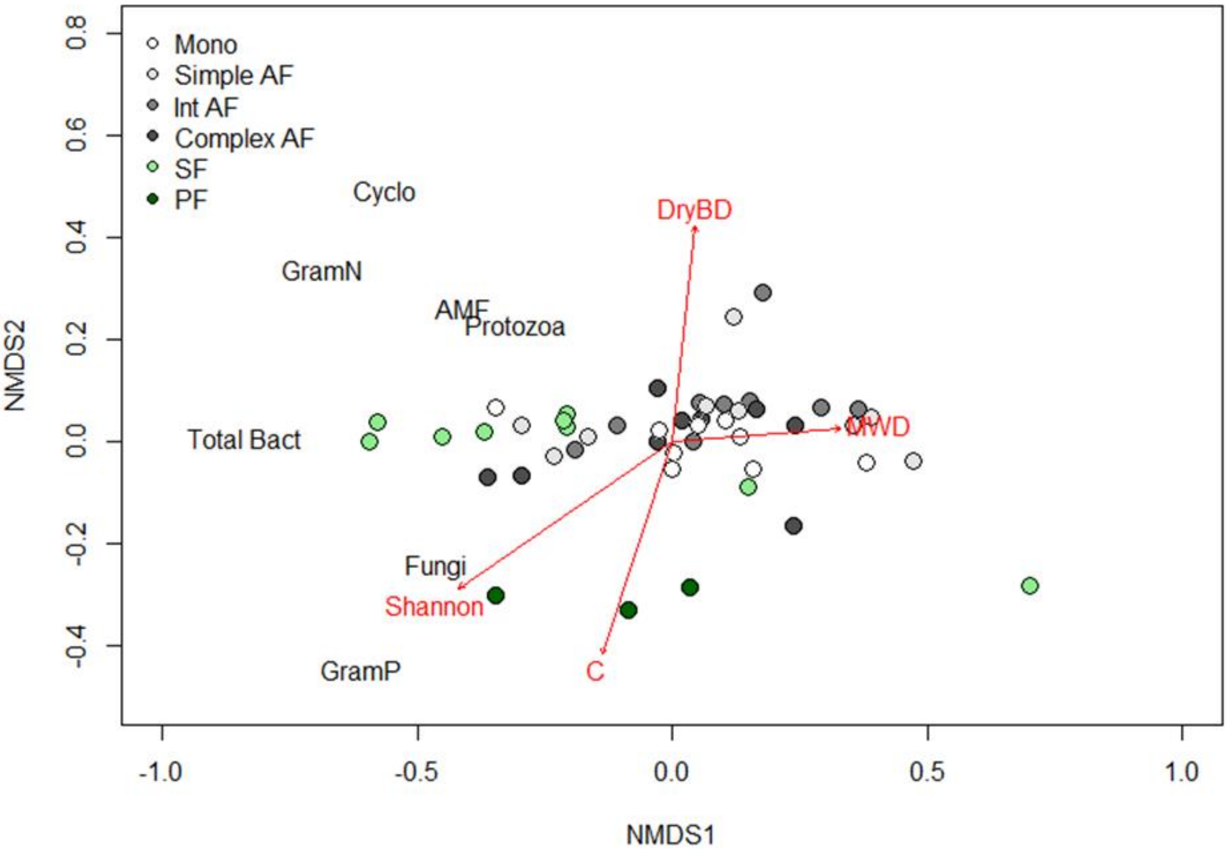
Correlations between total above-ground biomass and Shannon diversity

Above-ground tree biomass was quantified in all plots located in Wonuahoa (n=18). For *Theobroma cacao*, we used a methodology similar to the one developed by Smiley and Kroschel (2010), where tree trunk diameter at breast-height (DBH) and estimated height (H) were recorded for a subsample of at least 30 randomly selected individual trees per plot . These values were averaged used to determine mean cocoa tree biomass in each plot. For all other trees we sampled all trees with DBH ≥ 10cm found within the 30 x 30 m plot perimeters. For each tree, we recorded DBH (cm), and height (m) measured with a Haglöf ECII hypsometer. Above-ground tree biomass was estimated from specific wood density ρ, DBH D, and tree height H using the following allometric equations developed by Chave et al. (2014):

$$\mathrm{AGB_{est}} = 0.0673\ \times (\rho\ \times D^2 \times H)^{0.976}$$

Given the lack of data regarding tree taxonomy and distribution in Sulawesi's primary and secondary forests (Culmsee et al., 2011), we substituted an average of specific wood density values where tree species identification was not possible.

Appendix 2



Non-metric multidimensional scaling (NMDS) analysis showing the effects of tree diversity and soil properties on soil microbial community composition as determined via PLFA fingerprinting (Stress = 0.07, a stable solution was found after 20 random starts).

Each circle represents a separate plot, with different colors indicating land-use types: monoculture (Mono), simple agroforest (SimpleAF), intermediate agroforest (IntAF), complex agroforest (ComplexAF), secondary forest (SF) and primary forest (PF).

Red arrows indicate the effect of the variables most significantly correlated with PLFA variation and NMDS axes: total soil C (C), mean weight diameter (MWD), Shannon Diversity (Shannon) and bulk density (DryBD). The degree of variation in microbial group representation across all plots is indicated by the position of each microbial group label on the graph for the following microbial groups: Gram+ bacteria (GramP), Gram- bacteria (GramN), total bacteria (Total Bact), cyclo-propyl fatty acids (Cyclo), saprophytic fungi (Fungi), arbuscular mycorrhizal fungi (AMF).

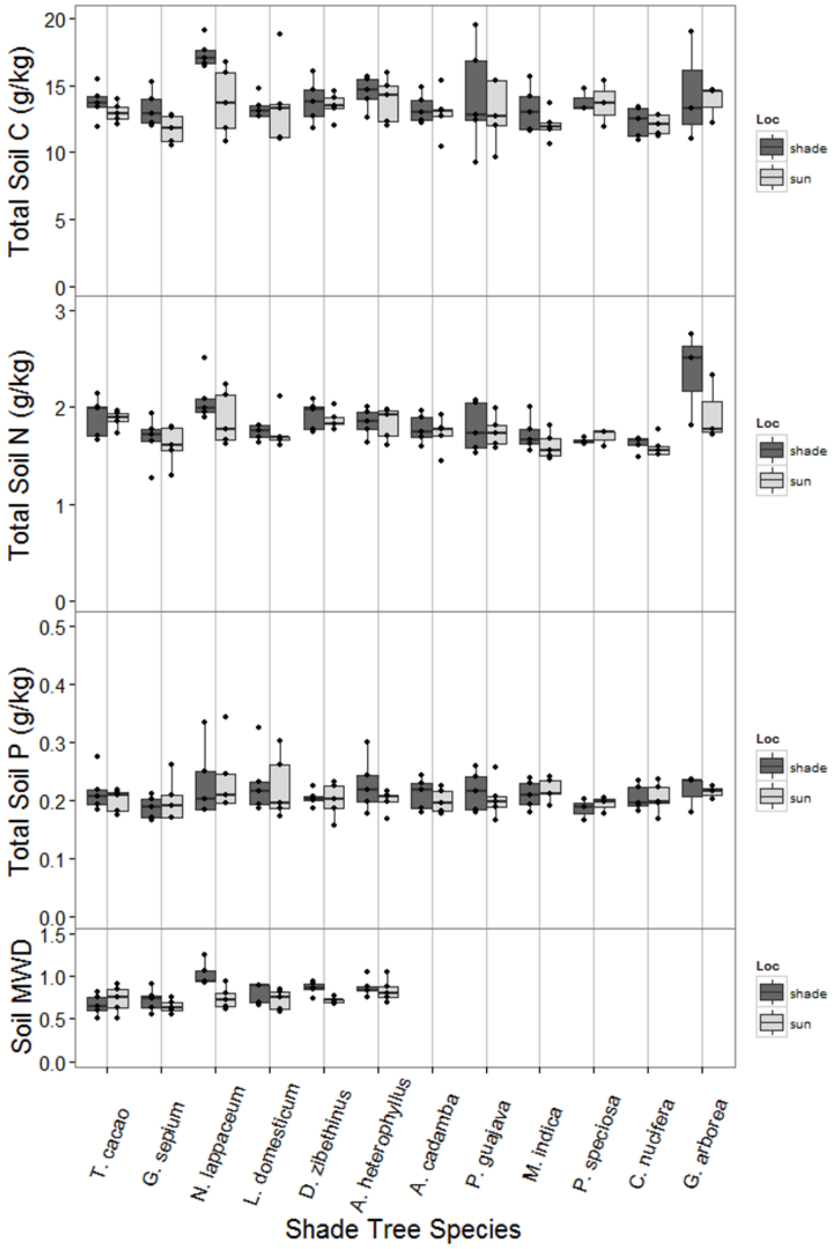
Appendix 3

Post hoc correlations coefficients for microbial lipid composition, and the most significant chemical and physical soil properties across cocoa, secondary and primary forest plots, showing the first and second axes of the NMDS analysis.

	NMDS1	NMDS2	R^2	P
PLFA Subgroups				
Gram Positive bacteria	-0.80	-0.59	0.92	**0.001** ***
Gram Negative bacteria	-0.90	0.45	0.90	**0.001** ***
Total bacteria	-1.00	0.01	0.95	**0.001** ***
Cyclo-propyl fatty acids	-0.76	0.65	0.90	**0.001** ***
Saprophytic fungi	-0.89	-0.45	0.38	**0.001** ***
Arbuscular Mycorrhizal Fungi	-0.84	0.54	0.34	**0.001** ***
Shade Tree Diversity				
Shannon Index	-0.31	-0.95	0.23	**0.005** **
Chemical Soil Properties				
pH	-0.48	-0.88	0.04	0.431
Total Carbon	-0.82	-0.57	0.31	**0.002** **
Total Nitrogen	-0.64	0.77	0.07	0.214
Total Phosphorus	-0.72	-0.69	0.06	0.240
Available Phosphorus	0.43	0.90	0.04	0.406
Base Saturation	0.34	-0.94	0.00	0.982
Cation Exchange Capacity	-0.56	-0.83	0.07	0.235
Physical Soil properties				
Bulk Density	0.10	0.99	0.21	**0.003** **
Clay Content (%)	-0.65	0.76	0.01	0.866
Mean Weight Diameter	-0.36	-0.93	0.25	**0.003** **

*** $P<0.001$, ** $P<0.01$, * $P<0.05$, . $P<0.1$

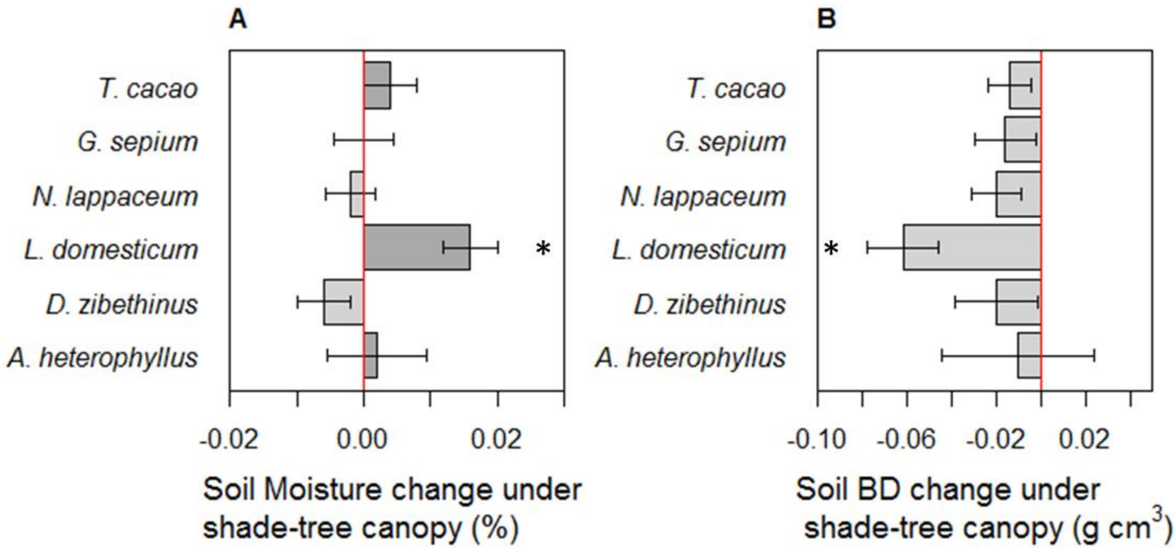
Appendix 4



Soil carbon (a), nitrogen (b), and phosphorus (c) contents; and mean weight diameter (or MWD) (d) in the topsoil layer (0-15 cm) obtained under shade-tree canopy (shade) and full sun (sun) for 11 different shade-tree species and our control *T. cacao*.

The data is displayed as boxplots with dark horizontal lines representing the mean, the box representing the 25th and 75th percentiles, the whiskers the 5th and 95th percentiles, and dots representing outliers.

Appendix 5



Mean difference in a) soil moisture and b) bulk density (BD) in the topsoil layer (0-15 cm) under shade tree canopy for five shade tree species and our control species *T. cacao*.

A hammer corer (Ø 5.5 cm) was used to collect four intact cores (0-15 cm) per location ("canopy" and "no canopy"). Each core was weighed individually and soil moisture content and bulk density were determined. Mean differences were calculated as the differences between mean soil parameter values measured under the canopy of individual shade trees and paired open locations. Bars represent one standard error of the mean. Asterisks indicate for which shade tree species the difference between "canopy" and "no canopy" locations was significantly different from zero (only t-test results with p-values < 0.05 are shown).

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Wartenberg, A.C., Blaser, W.J., Gattinger, A., Roshetko, J.M., Van Noordwijk, M., Six, J., 2017. Does shade tree diversity increase soil fertility in cocoa plantations? Agriculture, Ecosystems & Environment 248, 190-199.
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Zinke, P.J., 1962. The pattern of influence of individual forest trees on soil properties. Ecology 43, 130-133.

EDUCATION

Swiss Federal Institute of Technology (ETHZ); Zürich, Switzerland, in collaboration with **March 2013 - March 2017**
the World Agroforestry Centre (ICRAF); Bogor, Indonesia
Doctoral Student, Department of Environmental Systems Sciences
Study of a) the effects of tree species diversity on soil restoration after deforestation; b) shade tree interactions with soil and cocoa yields for common tree intercrops; and c) farmer perceptions in smallholder cacao agroforests of Sulawesi, Indonesia.

Columbia University – School of International and Public Affairs; New York, NY **2008 - 2009**
MPA in Environmental Sciences and Policy
Focus: Forestry & agroforestry systems, sustainable food production

University of Texas; Austin, TX **2004 - 2008**
BA in Latin American Studies & BS in Human Biology
Focus: Geography

Pontificia Universidad Católica del Perú; Lima, Perú **Aug – Dec 2006**
Academic Exchange Program (taught in Spanish)

PROFESSIONAL EXPERIENCE

Agriculture and Rural Development in the Latin American Region; World Bank; Washington, D.C. **September 2009 – August 2011**
Haiti Portfolio: project design & management; grant writing; communication and operational support

- *Rural and Urban Community Development Program*
- *Housing Reconstruction and Cash for Work*
- *Strengthening of Extension of Agricultural Public Services*
- *Avian Flu Control and Prevention*
- *Gender & Nutrition Strategy*
- *Financial Literacy Course for Women*

Agricultural Innovation Portfolio: project appraisal & management; writing and research support

- *Agricultural Innovation and Services Project (Bolivia)*
- *Vision of the Agricultural Sector by 2020 (Chile)*
- *Report on Ecological Agricultural Inputs*

Biodiversity in the World Bank Portfolio: policy analysis and research support

- *2010 World Bank Environmental Strategy : Inclusion of Biodiversity in Carbon Finance projects*

Payments for Ecosystem Services (PES) Team at Columbia University; New York, NY **January – May 2009**
Consultancy for Forest Trends & Wildlife Conservation Society

- *Assessed PES efforts through research of 10 international case studies*
- *Contributed to design, formatting and written content of analytic report*

Wildlife Survival Team at Columbia University; New York, NY **August – December 2008**
Workshop on policy analysis & recommendations for a proposed bill to the US Congress

- *Management of 12-member team*
- *Outputs included public final briefing and final report publication of 40 page report*

INTERNSHIPS/RESEARCH ASSISTANTSHIPS

Indonesian Nature Foundation (LINI); Sanur, Indonesia **March – May 2012**
Development of communication strategy and website design for community-based coral reef restoration & protection projects in Bali

International Fund for Agricultural Development (IFAD); United Nations HQ Liaison Office; New York **September – October 2011**
Participation in high level meetings on food security & gender issues, development of policy briefs

Hibiscus Production in Sénégal, Millennium Villages (UNDP /Columbia University & Earth Institute) **June – July 2009**
Value-chain analysis of small-scale hibiscus production by women's farmer groups

Institut National de la Recherche Agronomique (INRA); Paris, France **June – July 2009**
Research and writing support for project about international agriculture approaches

Instituto del Bien Común; Lima, Perú **August – October 2006**
Review of local testimonies for policy development of national protected areas in the Amazon region

LANGUAGES

German – native language
French, English – native level proficiency
Spanish – full professional proficiency
Bahasa Indonesia – elementary proficiency

OTHER SKILLS

General – Word, Excel, Power-point, basic html coding, graphic design (Adobe Suite)
Mapping – GIS
Statistical analysis – Full proficiency in R & SPSS
Field research – participatory rural development; design and implementation of interviews at different stakeholder levels; biomass & biodiversity surveying; litter sampling; soil sampling
Laboratory research – phospholipid fatty acid analysis (PLFA); soil fertility assessments (aggregation, macro- & micro-nutrient content analysis)

PUBLICATIONS

Wartenberg C.A., Blaser W.J., Gattinger A., Roshetko J.M., Van Noordwijk M., Six J., "Does shade tree diversity increase soil fertility in cocoa plantations*?" Agriculture, Ecosystems & Environments* 248C (2017) pp. 190-199.

Wartenberg C.A., Blaser W.J., Roshetko J.M., Van Noordwijk M., Six J., "Soil fertility and *Theobroma cacao* growth and productivity under commonly intercropped shade tree species in Sulawesi, Indonesia" (*in preparation)*.

Wartenberg C.A., Blaser W.J., Janudianto, Roshetko J.M., Van Noordwijk M., Six J., "Farmer perceptions of plant-soil interactions can affect adoption of sustainable management practices in cocoa agroforests: a case study from Southeast Sulawesi" (in review with *Ecology & Society)*.

Wartenberg C.A. (2010) "Analysis of organizational structure within women's working groups, related to quality/bio production of Hibiscus sabdariffa (bissap) at the Millenium Villages Project Site in Senegal." Internal report.

Wartenberg C.A. (2011) "Ecological Agricultural Inputs: World Bank LCSAR Analytical Paper." Internal report.

World Bank LCSAR Group, Ministerio de Agricultura de Chile (MINAGRI, Fundación para la Innovación Agraria (FIA) del Gobierno de Chile. (2011) « Una Visión de la Innovación Agraria en Chile hacia el 2030 » & « Plan de Acción Chile 2030 »