Shedding Light on Shade

Reconciling Livelihoods and Biodiversity in Coffee Agroforests

Rosalien E. Jezeer

Dit proefschrift werd mede mogelijk gemaakt met financiële steun van Hivos in het kader van het Business for Biodiversity programma, Academy of Ecosystem Services (Utrecht University) en Tropenbos International.

ISBN: 978-90-8672-082-8

Design & Layout: Juanita Franco, Tropenbos International

Photos: Rosalien Jezeer

Illustrations: ©Jeneses Imre / ©Adobe Stock

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Licht werpen op schaduw
Verenigen van biodiversiteit en bestaanszekerheid in koffie agroforests
(met een samenvatting in het Nederlands)

Iluminar las sombras
Conciliación de los medios de subsistencia y la biodiversidad en sistemas agroforestales con café
(con un resumen en español)

Proefschrift

ter verkrijging van de graad van doctor
aan de Universiteit Utrecht
op gezag van de rector magnificus, prof. dr. H.R.B.M. Kummeling,
ingevolge het besluit van het college voor promoties
in het openbaar te verdedigen
op vrijdag 13 juli 2018 des middags te 2.30 uur

door

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geboren op 26 juni 1986 te Arnhem

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General Introduction

Driven by a growing world population and higher overall living standard, global demand for agricultural crops is increasing (Tilman et al., 2011). Many of the world's food is produced by smallholders, but they are facing increasing pressures from environmental degradation as well as from globalisation and climate change. Consequently, one of the main challenges of the coming decades is to develop agricultural systems that produce food and income to sustain smallholder livelihoods in the tropics, without compromising ecosystem functioning, including biodiversity conservation. There is a need for improved understanding of the relations between agricultural production, conservation of biodiversity and other ecosystem services, and smallholder livelihoods. The overall objective of this thesis is therefore to obtain a better understanding on possible trade-offs and double benefits between economic and environmental outcomes of smallholder management systems and to improve our understanding of farmer decision making. This first chapter presents the context of the current debate and introduces coffee and cocoa agroforestry systems as models to explore possible trade-offs and double dividends. In this thesis, a case study of smallholder coffee systems is presented, and therefore, the introduction partly focuses on coffee systems.

1.1. Intensification of smallholder agriculture in the tropics

Millions of smallholders in the tropics depend on tree crops such as palm oil, cocoa, rubber and coffee for their daily livelihoods (Schroth et al., 2011). Traditionally, these tree crops have been grown under forest canopies or intercropped with a diverse set of other trees, making use of local knowledge and locally available resources rather than relying on external inputs. In recent decades, however, there has been a trend towards intensification by increasing inorganic nutrients, introducing new crop varieties and replacing biological weed and pest control with pesticides to remove limitations to crop productivity. This movement towards conventional monoculture systems is driven by the expected higher crop yields and economic performance of intensified systems, aiming to increase short term income (Clough et al., 2011; Siebert, 2002). Although these intensification practices have been successful to meet increasing global food demands by increasing the productivity per unit area, these practices come at the expense of long-term maintenance of ecosystem services relevant for agricultural production (Foley et al., 2011). Intensified farming systems are known to cause environmental problems such as loss of biodiversity and soil fertility (Perfecto and Vandermeer, 2015), compromising the ecological resilience and long-term productivity of these intensified production systems. This holds especially true for smallholders in the tropics as they are often located in biodiversity-rich areas (Myers et al., 2000) and depend strongly on crop cultivation for their livelihoods. Smallholders are therefore particularly vulnerable to stressors such as pest and disease incidence and volatile market prices, while climate change is expected to exacerbate their vulnerability (Morton, 2007). The challenge is to develop agricultural systems that produce food and income to provide, or even improve, smallholder livelihoods in the tropics, without compromising ecosystem functioning, including biodiversity conservation. In response, there are agricultural approaches that seek to reconcile economic and environmental performance, in particular described in agro-ecological practices, i.e. the application of ecological concepts and principles to the design and management of sustainable agricultural systems (Gliessman, 1992). Where conventional intensification is directed towards high-input agriculture and low diversity systems which lead to a trade-off between economic and environmental performance, agro-ecological systems are often more diverse and rely less on external inputs. Rather, these systems rely more on biodiversity and other ecosystem services, in pursuit of achieving dual benefits or even synergies between local development and biodiversity conservation and associated ecosystem services (Altieri, 2002; Gliessman, 1992).

1.2. Agroforestry systems

Agroforestry systems (i.e., integration of trees and other large woody perennials into farming systems; Schroth et al., 2004) are often put forward as agroecological systems that provide a promising approach to deal with the twin challenges of local development and conservation of biodiversity and other ecosystem services (Atangana et al., 2014a; Perfecto et al., 2005; Philpott et al., 2007; Schroth et al., 2004; Waldron et al., 2012). Worldwide, agroforestry systems cover approximately 50% of the agricultural area (Kumar et al., 2014), and in many tropical landscapes agroforestry systems represent a large part of the agricultural area. At the same time, agroforestry systems are the major ecosystems that resemble natural forest in these tropical landscapes (Bhagwat et al., 2008; Schroth et al., 2004). There is ample evidence that agroforestry systems have a considerable potential to conserve biodiversity (Harvey et al., 2006; Moguel and Toledo, 1999; Rice and Greenberg, 2000), as complex agroforestry systems have been reported to sustain species richness equivalent to more than 60% of that of natural forests (Bhagwat et al., 2008; De Beenhouwer et al., 2013).

Agroforestry systems are often applauded for their biodiversity conservation value, however, these systems are foremost intended to improve farmers' livelihoods by increasing overall productivity, profitability and sustainability (Atangana et al., 2014b). According to the World Bank (2008), the improvement of these three aspects of smallholder farming is a key pathway out of poverty, emphasising the potential of agroforestry practices to alleviate poverty and strengthen smallholder resilience. Within coffee and cocoa systems, shade trees can provide multiple benefits (Tscharntke et al., 2011). First of all, not only is the overall biodiversity enhanced, but also functional biodiversity, which can increase productivity and ecological resilience. For example, cross-pollination can increase coffee yield by up to 50% compared with self-pollination (Krishnan et al., 2012; Tscharntke et al., 2011) and biological control can reduce pest or herbivore outbreaks (Kellerman et al., 2008; Perfecto et al., 2004; Philpott and Armbrecht, 2006). Second, shade trees play an important role in erosion control and weed control (Staver et al., 2001) and the maintenance of soil productivity by stimulating litter decomposition (Jose, 2009; Tscharntke et al., 2011), which reduces the need for fertilizers and herbicides (Vaast et al., 2006). Third, shade trees can mitigate the effects of climate change by enhancing a favourable micro-climate (Ehrenbergerová et al., 2017; Lin, 2007) and increased carbon storage (Atangana et al., 2014b; De Beenhouwer et al., 2016; Ehrenbergerová et al., 2016). Lastly, shade trees can generate additional products such as timber, firewood and fruits, providing important contributions to farmers' livelihoods, especially in times of low coffee prices or low coffee productivity (McNeely and Schroth, 2006; Rice, 2008; Souza et al., 2010; Tscharntke et al., 2011). Thus, besides enhanced biodiversity conservation, shade trees have the potential to improve farmers' livelihoods by stabilising their income and increasing their overall resilience (Atangana et al., 2014b).

Benefits provided by shade trees are thus both direct and indirect, making it more complex to quantify the economic performance of agroforestry systems compared to conventional intensified systems. Moreover, the general perception of lower economic performance of agroforestry systems is often based on incomplete analysis as commodity prices can be higher due to improved bean quality (Muschler, 2001; Vaast et al., 2006) while costs are often not accounted for, and neither are benefits of other products, even though multiple studies showed that shade tree products can significantly contribute to farmers' income (Cerda et al., 2014; Gobbi, 2000; Wulan et al., 2008). Also, an increased awareness about the negative environmental effects of intensification has given rise to new markets for environmentally-friendly coffee in consuming countries. This has resulted in an array of certified sustainable seals such as Rainforest Alliance and Fair Trade for crops as coffee and cocoa. Some of these promote the inclusion of shade trees, and provide access to nice markets with a price premium (Siles et al., 2010). Assessing the economic performance of agroforestry systems is more complex than for conventional intensified systems as the benefits provided by shade trees are both direct and indirect in terms of other products and ecosystem services, making it difficult to fully quantify the total benefits. At present, there is a need for comprehensive economic studies that take multiple benefits from agroforestry systems into account.

1.3. Potential to reconcile livelihoods and biodiversity conservation

Despite these known benefits, there is still a tendency towards intensification of cultivation of tropical tree crops, including cocoa, palm oil, rubber and coffee as the biodiversity benefits of agroforestry systems are often assumed to come at the cost of lower yields than under full sun conditions (Perfecto et al., 2005). Some studies consequently state that agroforestry, representing a form of extensive land use, cannot meet the growing demand for food; therefore, they argue in favour of agricultural intensification to minimize the conversion of natural habitats, which is considered a land-sparing strategy (Chandler et al., 2013; Gabriel et al., 2013; Green et al., 2005; Phalan et al., 2011). There are, however, several studies that show that in some agroforestry systems high crop yields and high biodiversity can coexist (Clough et al., 2011; Gordon et al., 2007), so that dual benefits are achieved. To this regard, it is often advocated that agroforestry systems can be designed to optimize both biodiversity and economic benefits without adding pressure on natural habitats, which is considered a land sharing strategy (Clough et al., 2011; Scherr and McNeely, 2008; Tscharntke et al., 2011). This debate is however not as straightforward as proposed here, as increased crop yields do not guarantee land sparing, while land sharing schemes do not guarantee biodiversity benefits on agricultural lands (Phalan et al., 2011). Optimal land management strategies in the framework of the land-sharing land-sparing debate depend on the trade-offs between crop productivity and conservation of biodiversity and other ecosystem services (Phalan et al., 2011; Tscharntke et al., 2012). The examples illustrate the high variability between the economic-environmental relationships, suggesting there is potential for the identification of agroecological systems that reconcile smallholder livelihoods and maintenance of ecosystem services, including biodiversity conservation (Figure 1). Our understanding of the mechanisms underlying these relationships is however limited (Balvanera et al., 2006; Bommarco et al., 2013). There there is ample evidence supporting the ecological importance of agroforestry systems for biodiversity conservation (De Beenhouwer et al., 2013), yet evidence of the trade-offs between the economic and environmental performance or their potential double dividend is lacking as there are only few multidisciplinary studies that quantify both (Bisseleua et al., 2009; Clough et al., 2016; Gordon et al., 2007; Pinoargote et al., 2017). More insight in the relations between crop productivity, biodiversity conservation and smallholder livelihoods is needed to identify systems that can minimise trade-offs between economic and environmental performance or even provide double dividends.

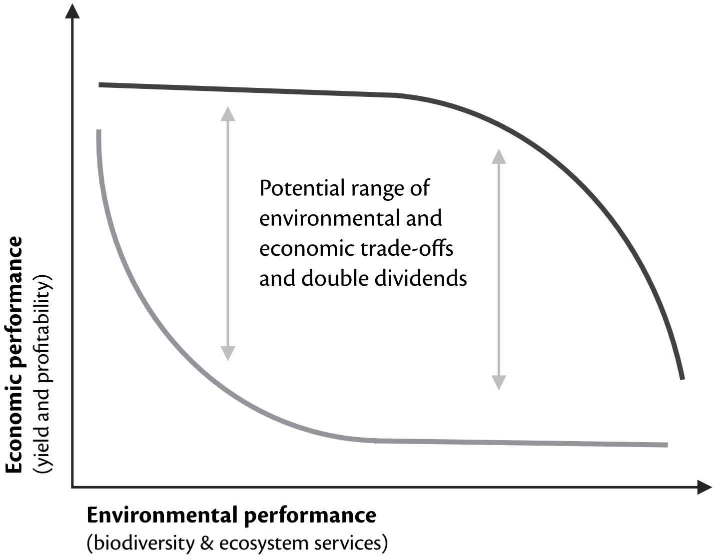


Figure 1. The relationship between environmental performance (biodiversity and other ecosystem services; x-axis) and economic performance (e.g., yield, income, benefit cost ratio (BCR); y-axis). Adapted from Tscharntke et al., 2012).

1.4. Coffee and cocoa cultivation

Traditionally, coffee and cocoa are grown under a dense canopy of various indigenous shade tree species (Tscharntke et al., 2011) and together, these crops cover a substantial amount of the world's agroforest area (O'Brien, Timothy and Kinnaird, 2003; Perfecto and Vandermeer, 2008; Tscharntke et al., 2011). Furthermore, with export values of around US$12 and 11 billion per year for cocoa and coffee respectively, these crops represent important economic activities for producing countries (Vaast et al., 2016). Together, coffee and cocoa cover an area of approximately 20 million ha worldwide, of which around 80% is cultivated by smallholders with a farm size of a few hectares or less (Vaast et al., 2016). Altogether, over 30 million rural households are involved in the global production of coffee and cocoa (Ovalle-Rivera et al., 2015). Biodiversity benefits associated with shaded coffee and cocoa practices are well researched and it is clear that these systems hold considerable potential to conserve biodiversity (Bhagwat et al., 2008; De Beenhouwer et al., 2013). Complex coffee and cocoa agroforestry systems have been known to contribute to conserving plant (Beukema et al., 2007; Häger et al., 2014), bird (Beukema et al., 2007; Mas and Dietsch, 2004), arthropod (Harvey et al., 2006) and mammal diversity (Caudill and Rice, 2016). Since coffee and cocoa are often cultivated in areas with high levels of biodiversity and carbon stocks, intensification of these systems is associated with multiple negative environmental impacts due to the loss of ecosystem services. The role of coffee and cocoa systems in maintaining biodiversity is becoming increasingly important in these (often) highly fragmented landscapes, especially since forests continue to be encroached to establish new coffee and cocoa agroforestry systems (Magrach and Ghazoul, 2015).

Despite these known biodiversity benefits, the global coffee and cocoa sector are no exception to the worldwide intensification trend. Driven by fluctuating prices and increasing demand for cacao and coffee on the world market, and increasing local human population, coffee and cocoa farmers intensify the traditional coffee and cocoa agroforestry management and/or expand the cultivated land area (Defries et al., 2010; Laurance, 1999). These dynamics are further explored for coffee systems.

1.5. Coffee cultivation

1.5.1. Crop characteristics

Only two out of the 103 species of the genus *Coffea* are commercially viable; Robusta coffee (*Coffea canephora*) and Arabica coffee (*Coffea arabica L.*; Davis et al., 2006). Both species originate from Africa, Ethiopia, but have spread to landscapes throughout the tropics over the past centuries. Ten countries account for approximately 88% of the worlds coffee production; Brazil, Vietnam, Colombia, Indonesia, Peru, India, Uganda, Mexico, Ethiopia and Honduras - 37% of which is Robusta coffee (ICO, 2017). Robusta grows at low elevation (0–800 m), is more tolerant to growth in full sun and exhibits higher yield and pest resistance. Arabica coffee grows at higher elevations (600–1.500 m) and produces higher quality coffee beans than Robusta, making Arabica beans more suitable for specialty markets (Bacon, 2005). Coffee plants are very sensitive to changes in temperature, rainfall and irradiation (Lin, 2007). The optimal temperature range for Arabica coffee is 18–21 °C (Lin, 2007) and already small changes in temperatures and water availability can affect photosynthesis as well as the reproductive growth (Cannell, 1975). Also, coffee is not resistant to frost, limiting elevations and latitudes at which coffee can be cultivated (DaMatta, 2004). Coffee growth, production and photosynthesis of the plant thus require specific physical and ecological conditions, making this plant highly sensitive to changes in climate (Bunn et al., 2015), making it likely that climate change will affect the suitable areas to grow Arabica coffee (Bunn et al., 2015; Magrach and Ghazoul, 2015). Moreover, since the average lifespan of a coffee plantation is about 30 years (Wintgens, 2012), existing coffee plantations may already experience the climate change foreseen by global circulation models (Bunn et al., 2015).

1.5.2. Intensification of coffee systems

Worldwide, there is a strong tendency to intensify coffee plantations by reducing or eliminating shade trees, planting higher densities of new varieties and using agrochemical inputs (Bosselmann, 2012; Jha et al., 2014; Perfecto et al., 1996). All these efforts are aimed at increasing production and short-term income (Juhrbandt, 2010; Rice and Greenberg, 2000; Siebert, 2002; Tscharntke et al., 2011) and are in part driven by lower expected crop yields under shaded conditions due to competition for light, water and nutrients in the soil between shade trees and coffee shrubs (Beer et al., 1998; Meyfroidt et al., 2014; Perfecto and Vandermeer, 2015). The intensification trend is further accelerated by the perception that higher shade levels lead to increased incidence of coffee leaf rust (*Hemileia vastatrix*), a disease associated with a 10-70% reduction in coffee harvest in several countries during the latest outbreak in 2012-2013 (Avelino et al., 2015).

However, evidence supporting the coupling of increased shade levels with decreased crop yields is scarce (Jha et al., 2014) as there is high variability in reported relations between shade levels and productivity. Multiple studies have shown a negative relation between coffee and cocoa yields and shade (Jaramillo-Botero et al., 2010; Vaast et al., 2006), while several studies found no relation between shade and productivity (Boreux et al., 2016; Cerda et al., 2016; Meylan et al., 2017). Importantly, productivity is highly influenced by climate, soil conditions and pest and disease pressure (DaMatta, 2004). In sub-optimal conditions, studies showed that in full-sun systems there was higher water stress (Lin, 2010), lower flowering success (Lin et al., 2008), lower bean quality as a result of incomplete bean filling (Vaast et al., 2006) and reduced soil fertility (Hairiah et al., 2006), while natural pest and disease control was likely decreased as full-sun systems are associated with lower biodiversity (Kellerman et al., 2008; Perfecto et al., 2004; Philpott and Armbrecht, 2006; Vandermeer et al., 2014). To counter these effects, use of irrigation, fertilizers and pesticides are needed for full-sun systems in sub-optimal conditions. Consequently, DaMatta (2004) concludes that due to the eco-physiological constraints of coffee, the benefits of shade increase as the environment becomes less favourable for coffee cultivation for both Arabica and Robusta.

Following the intensification trend, worldwide large shares of coffee (40%) areas are currently being managed without shade, and only less than a quarter of such area with multi-layered, diversified shade (Jha et al., 2014). Broadly stated, there are two competitive management strategies in coffee production systems, namely conventional intensification which is directed towards high input agriculture and low diversity systems, whilst food production in agroforestry systems, representing an agroecological system, relies more on the biodiversity and associated ecosystem services of these more diverse systems and less on external inputs (Tscharntke et al., 2012). It has to be recognised that this is a simplification as many of the coffee systems may lie anywhere within this continuum of management strategies, ranging from low to high inputs, and from monoculture, full-sun systems to agroforestry systems with complex vegetation structures (Figure 2). Due to this variety, coffee systems are suitable as model systems to study the impact of different management strategies on farmer livelihoods and ecosystem services. Besides shade, management intensity also influences relations between crop yield and other ecosystem services, as increased frequency of management activities (Rice, 2008) such as weeding and pruning, and increased organic and chemical input as fertilizers, insecticides and herbicides are reported to negatively affect biodiversity (Lin et al., 2008; Tscharntke et al., 2005). As both input management and shade management can affect productivity, biodiversity and other ecosystem services, it is necessary to study the effect of both simultaneously (Hernández-Martínez et al., 2009), which is rarely done.

1.5.3. Farmer decision making

Given that smallholder farmers can adopt different management strategies with different environmental and economic outcomes, a better understanding of the opportunities and constraints that farmers experience and the role of stressors is therefore fundamental to gain insight in drivers of the adoption of these different management strategies. Although increased yields and farmers' income are assumed to be important drivers of decision making (Edwards-Jones, 2006; McGregor et al., 2001), research has shown that many other criteria are included when making decisions (Feola and Binder, 2010). Smallholder farmers can adopt different management strategies to pursue objectives that can range from maximizing economic performance to minimizing risks, and from stabilizing income to maintaining food security (Schroth and Ruf, 2014). At the same time, farmer decision making can be facilitated or constrained by the assets they have, for example social, economic, cultural and biophysical resources (Bravo-Monroy et al., 2016). Smallholder farmers may also change management strategies in response to external factors, including external stressors and shocks that are outside the control of the household, in particular price fluctuations, pest and disease pressure and extreme climate events. Not all farmers respond to shocks in the same way and in the dynamic and complex context of global environmental change and individuals are rarely responding to only one shock or stressor at any one time (Eakin et al., 2009). Improving our understanding of the effects of livelihoods assets, experienced shocks, and risk perception on farmer decision making is important to support farmers in developing management strategies that enhance overall economic and environmental performance, especially in the context of global change and uncertainty.

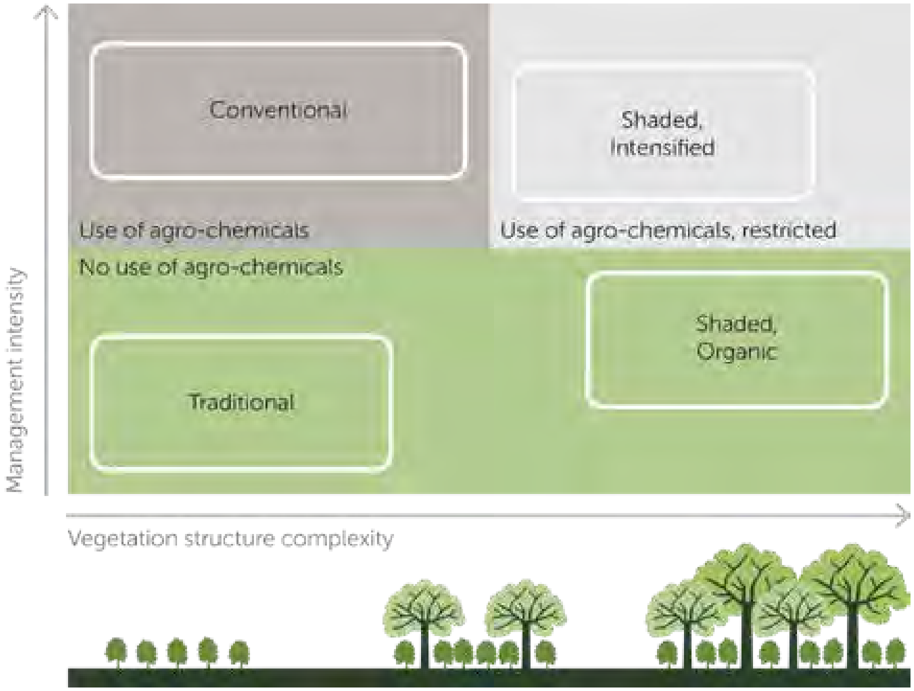


Figure 2. Schematic overview of coffee management systems, according to vegetation structure complexity and management intensity (Jezeer and Verweij, 2015).

1.6. Objective and research questions

Given the economic and ecological importance of small scale agricultural systems in tropical countries, there is a need for multidisciplinary studies that quantify economic and environmental performance simultaneously, to obtain insights as to how the two goals can be reconciled. Further, there is a need to identify opportunities and constraints faced by smallholder farmers for the adoption of different management strategies. The overall objective of this thesis was therefore to assess the economic and environmental outcomes of smallholder management systems to identify trade-offs and seek opportunities for double dividends, as well as to identify opportunities and constraints faced by smallholder farmers for the adoption of different management strategies. In this thesis, coffee and cocoa systems are used to study the impact of different management strategies on economic and environmental performance and seek to identify possible trade-offs and double benefits between biodiversity conservation and local development. There is an emphasis on coffee systems as a case study on smallholder coffee farmers in San Martín, Peru is used. To this end, the following research questions are addressed:

I. What is the *environmental performance* of coffee and cocoa systems with different shade and input management?
II. What is the *economic performance* of coffee and cocoa systems with different shade and input management?
III. Can *trade-offs or double dividends* be identified between environmental and economic performance of coffee and cocoa systems with different shade and input management?
IV. What is driving *smallholder decision-making* regarding the adoption of different shade and input management strategies for coffee systems?

1.7. Outline of the thesis

The research questions are addressed in Chapters 2 through 5 (Table 1). In **Chapter 2**, a meta-analysis is used to address **research questions I, II and III**. To this regard, economic (i.e., profitability in terms of net revenue and cost-efficiency in terms of benefit cost ratio, BCR) and biodiversity performance of small-scale shaded coffee and cocoa plantations are compared to intensified conventional ones. This chapter includes 23 studies on coffee and cocoa plantations over a 26 year period. In **Chapter 3, research questions I and III** are addressed. In this chapter, the relationship between coffee yields, butterfly species richness and above-ground carbon storage are examined, while accounting for soil fertility and yield losses due to pests and diseases. For this chapter, a case study was used on smallholder coffee plantations in the department of San Martín, Peru. To this regard, data was collected by a farmer survey (in 162 farms) and by plot measurements (in a subsample of 62 farms), and plantations represent a range in shade and input management. The same case study was used in **Chapter 4**, to address **research questions II and III**. In this chapter, a comprehensive economic analysis of Arabica coffee farming systems is presented. To this regard, coffee yields, costs, net income and benefit-cost ratio (BCR) values are presented for of 162 small-scale Peruvian coffee plantations under different shade and input management practices along an elevation gradient. In **Chapter 5, research question IV** is assessed. To this regard, the sustainable livelihoods framework is used to seek how livelihood assets of smallholders influence the adoption of management strategies (shade and input) and how are they affected by risks and shocks, for a case study of smallholder coffee producers in San Martín, Peru. Furthermore, farmers' motives to change shade and input management strategies are explored. In **Chapter 6** a summary of each chapter and its main findings is presented, followed by answers to the each of the four research questions, including recommendations for further research. Lastly, recommendations for policy makers and practitioners are presented. The remaining part of the introduction presents a description of the case study region.

Table 1. Overview of research questions and chapters in which they are addressed in Chapters 2-5.

	Research question			
Chapter	I. Environmental performance	II. Economic performance	III. Trade-offs and double dividends	IV. Farmer decision making
3 Meta-analysis on profitability and cost-efficiency of shaded coffee- and cocoa systems	●	●	●	
4 Research paper on trade-offs between yield, butterfly diversity and carbon sequestration in smallholder coffee plantations in Peru	●		●	
5 Research paper on the economic performance of smallholder coffee plantations in Peru under different shade and input management		●	●	
6 Research paper on the influence of livelihood assets, experienced shocks and perceived risks on adoption of shade and input management strategies for smallholder coffee systems in Peru				●

1.8. Case study of smallholder coffee production in Peru

1.8.1. The Peruvian coffee context

In recent decades, the production of Peruvian coffee has increased substantially and coffee has become the main agricultural export product at national level. Currently, coffee generates more revenue than any other crop. Exports have increased from 2 million bags in the ‘90s to about a 5 million bags this year with a total export value of approximately USD 700 million, all Arabica coffee. Coffee is cultivation on approximately 425.000 hectares of land and is grown at 600 to 2.000 meters above sea level. Most farms are located in the country’s highland tropical forests, in the regions of Piura, Amazonas, Cajamarca, San Martín, Huánuco, Junín, Pasco, Ayacucho, Apurímac, Cusco and Puno. About 223.000 families are involved in coffee production and the supply chain involves more than 1 million people (CENAGRO, 2012). The majority of the Peruvian coffee farmers (about 80%) are not organised in farmer associations and the average farm size is 2.75 ha (CENAGRO, 2012).

In Peru, only 13% of the plantations are managed without shade, a large share (60%) is managed with simplified shade while the remaining 23% is managed as diverse agroforestry systems (Vargas and Willems, 2017). Although shade levels in Peru are high compared to other coffee producing countries, most shade trees in coffee plantations are planted after land clearing, especially trees of the genus *Inga*.

The expanding coffee production and the trends towards intensification has left its mark on the landscape as increased production is frequently realised through the establishment of new plantations often in previously forested areas.

Peruvian coffee farmers are facing multiple challenges similar to many small-scale coffee farmers' worldwide. First of all, coffee price volatility is a major challenge as coffee prices more than tripled from 2004 to 2011, yet almost dropped again by half in 2013 (Larrea et al., 2014). Additionally, pests and diseases pose major risks as the recent coffee rust outbreak peaked in 2013 in Peru (Avelino et al., 2015) and caused approximately a 40% reduction in national production. Lastly, Peru appears to be especially exposed to changing climate conditions due to the presence of the El Niño phenomenon and its mountainous topography (Vargas, 2009). Temperatures in San Martín are expected to increase with approximately 2 degrees by the year 2050 and rainfall is expected to be more variable (Vargas, 2009). Thus, Peruvian small-scale farmers are under pressure due to volatile coffee prices and increased pests and diseases pressure, which is likely exacerbated by climate change (Morton, 2007).

1.8.2. Study region

The effect of expansion and intensification of coffee cultivation is reflected in high deforestation rates throughout Peru, but in particular in the department of San Martín. In this department, 25-30% of all Peruvian coffee is produced by about 35.000 families on 90.000 hectares. This region is located in the northeast of Peru (Figure 3) and most of its original land cover consisted of tropical forests and wetlands. However, by the end of the 20th century, the region started to see a rapid increase in deforestation rates. It currently holds the highest deforestation rate in Peru of more than 10.000 hectares per year (Valqui et al., 2015), and it is estimated that 30% of the total primary forest area - which comprises 1.6 million hectares - has already been converted into agriculture (Rodriguez, 2010). This rapid conversion was caused mainly by government efforts to connect the region with the rest of the country through the construction of roads as well as changing legislation and capacity building programs. Thus, many farmers switched from growing coca to coffee and cocoa. Furthermore, it accelerated the influx of migrants from economically depressed rural areas in the Andean highlands of San Martín as the number of migrants more than doubled in 10 years. As a result, migrants represented more than 30% of the total population in San Martín at the beginning of the '90s. If the current deforestation trend continues, San Martín could lose most of its forest by 2050 and along with it the ecosystem services it provides. Due to the environmental and economic impacts of coffee production in San Martín, it is important to seek opportunities to reconcile conservation practices and local development, especially since the effects of environmental degradation are becoming more visible. Moreover, the study region was not only selected for the importance of the Peruvian coffee sector, but also for the presence of a wide variety in management of smallholder coffee systems as well as large stretches of natural forests and national parks which are amongst the most biodiverse areas in the world (Myers et al., 2000) and containing high carbon stocks (Asner et al., 2014). As these conditions are similar to many of the world regions where coffee is grown (Perfecto et al., 1996), this makes the region of San Martín an interesting case to study possible trade-offs and double dividends between environmental and economic performance for coffee regions worldwide.

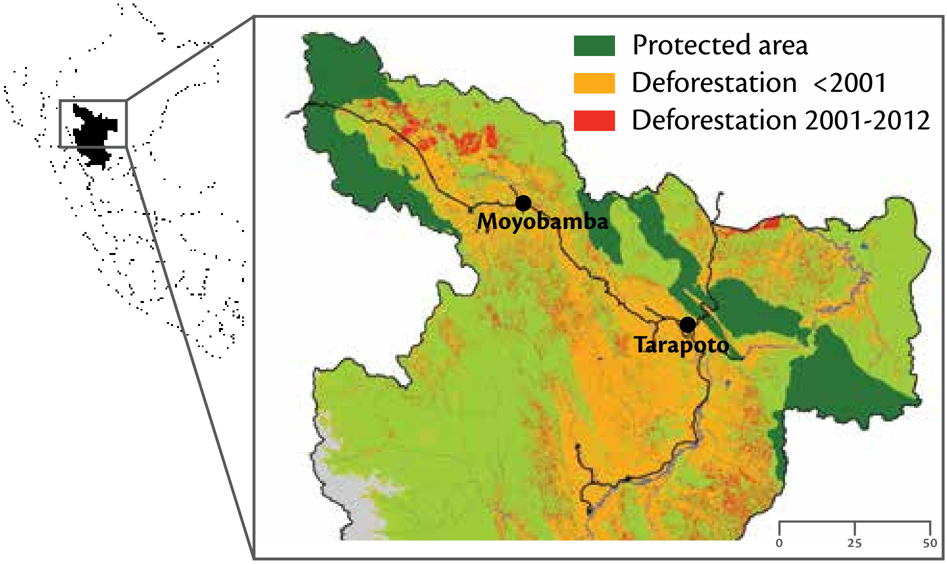
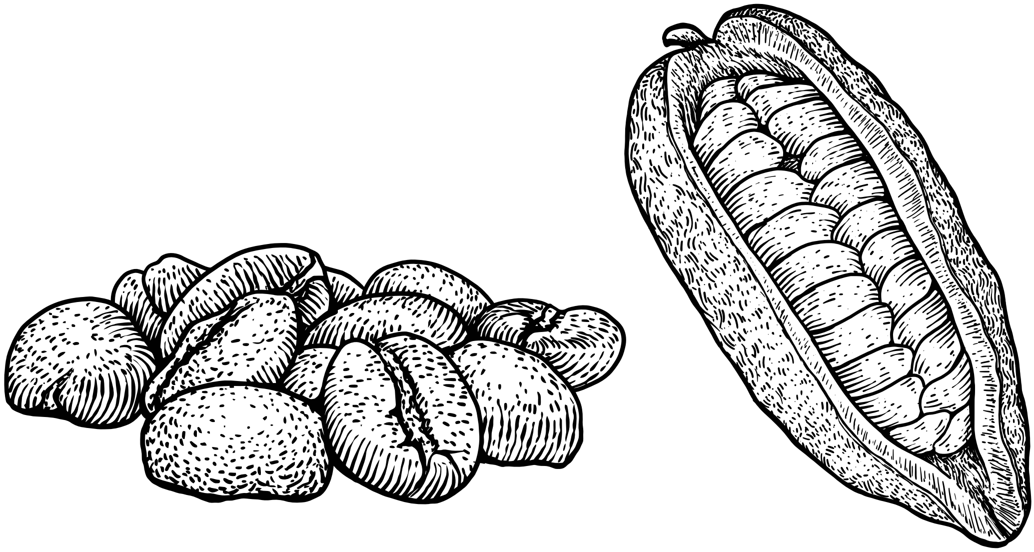


Figure 3. Map of San Martín, depicting deforestation and protected areas.



2

Shaded coffee and cocoa – double dividend for biodiversity and small-scale farmers

Jezeer, Rosalien E., Verweij, Pita A., Santos, Maria J., Boot, Rene G.A.

*This paper has been published in Ecological Economics (2017), 140, 136-145 **

** This chapter differs slightly from the published article*

Abstract

This paper compares financial and biodiversity performance of small-scale shaded coffee and cocoa plantations versus intensified conventional ones. We conduct a meta-analysis including 23 studies on coffee and cocoa plantations over a 26 year period. Our results show that, contrary to common perceptions, profitability and cost-efficiency are higher for small-scale shaded systems. Despite the lower yields for shaded systems, the lower costs per area and higher price per kilogram of coffee or cocoa causes shaded systems to perform better financially. This finding shows that the traditional indicator 'yield' is an inaccurate measure of financial performance when studying diversified systems, and that the more detailed indicators as net revenue or benefit-cost ratio should be used instead. A few studies specifically reported on the relationship between biodiversity and financial performance, providing divergent results, yet various papers showed a promising optimum relationship for intermediate levels of shade. Because shaded systems are known to correlate positively with biodiversity, we postulate that they can offer competitive business opportunities for small-scale farmers, while also contributing to biodiversity conservation. Still, there is a pressing need for multidisciplinary studies to quantify financial and biodiversity performance simultaneously and to identify opportunities for scaling up shaded systems.

2.1. Introduction

Tropical agroforestry is seen as a promising approach to reconcile biodiversity conservation and local development (Atangana et al., 2014b; Perfecto et al., 2005; Philpott et al., 2007; Schroth et al., 2004; Waldron et al., 2012). Together, coffee and cocoa represent an important component of the international commodity trade volume (Tscharntke et al., 2011), providing income for over 30 million smallholders, predominantly in developing countries (Ovalle-Rivera et al., 2015; Ponte, 2002). Traditionally, coffee and cocoa crops are grown under a dense canopy of various indigenous shade tree species, and these crops form a considerable amount of the world's area under agroforestry management (O'Brien, Timothy and Kinnaird, 2003; Perfecto and Vandermeer, 2008; Tscharntke et al., 2011). However, there is a strong tendency worldwide to intensify these traditional shaded systems by reducing or eliminating shade trees, planting higher densities of new coffee and cocoa varieties and using agrochemical inputs. All these efforts are aimed at increasing production and short-term income (Clough et al., 2011; Juhrbandt, 2010; Rice and Greenberg, 2000; Siebert, 2002). Consequently, worldwide the largest share of coffee and cocoa area is currently being managed without shade, and only less than a quarter with multi-layered, diversified shade (Jha et al., 2014). Thus, there are a variety of coffee and cocoa management systems along a gradient of intensification, ranging from low-input rustic agroforestry plantations with high levels of shade to high-input monoculture plantations without shade (Moguel and Toledo, 1999; Perfecto et al., 2005). Due to this variety, the coffee and cocoa agroecosystem is suitable as a model system to study the impact of agricultural intensification. Although there is ample evidence supporting the ecological importance of coffee and cocoa agroforestry systems for biodiversity conservation (De Beenhouwer et al., 2013), evidence of the trade-offs between the biodiversity performance and socio-economic benefits or their potential double dividend is lacking, as there are only few multidisciplinary studies that quantify both.

Biodiversity benefits associated with shaded coffee and cocoa practices are well researched. There is ample evidence that these systems have a considerable potential to conserve biodiversity, as complex agroforestry systems have been reported to sustain species richness equivalent to more than 60% of that of natural forests (Bhagwat et al., 2008; Harvey et al., 2006; Moguel and Toledo, 1999; Rice and Greenberg, 2000). However, there is no consensus on how productive and profitable these systems are in comparison to intensive, conventional management systems (Clough et al., 2011; Steffan-Dewenter et al., 2007). Some studies state that agroforestry, representing a form of extensive land use, cannot meet the growing demand for food; therefore, they advocate agricultural intensification to minimize the conversion of natural habitats (Chandler et al., 2013; Gabriel et al., 2013; Green et al., 2005; Phalan et al., 2011). Other studies, however, suggest that coffee and cocoa systems can be designed to optimize both biodiversity and economic benefits without adding pressure on natural habitats (Clough et al., 2011; Scherr and McNeely, 2008; Tscharntke et al., 2011).

Considering the economic and ecological importance of coffee and cocoa, it is important to gain more insight into the financial and biodiversity benefits, as well as into the opportunities to reconcile these. In this paper we synthesize currently known trade-offs between the biodiversity performance and financial performance of small-scale shaded plantations versus conventional coffee and cocoa plantations. We present the results of a meta-analysis including data of 23 different studies on shaded cocoa and coffee systems. The central question addressed is if the financial and biodiversity performances of small-scale shaded coffee and cocoa systems are similar or higher than those of conventional systems. To provide an answer to this question, we developed a meta-analytic framework computing a comprehensive database by calculating and including information on financial, economic and biodiversity performance indicators for a wide range of small-scale shaded coffee and cocoa systems. This analysis enabled us to make a better informed synthesis of the potential double benefits of shaded coffee and cocoa systems. We emphasized the financial performance as there is little consensus on the financial benefits, even though profitability is expected to be an important determinant for the choices of smallholder farmers (Pannell, 1999). In this paper, we discuss both the ecological and financial benefits of shaded coffee and cocoa cultivation as a function of shade management, and we provide recommendations for further research to enhance these benefits.

First, we compare shaded systems with conventional ones according to the results of the financial performance analysis. Second, we briefly discuss the different coffee and cocoa management systems in relation to biodiversity, with an emphasis on shade level and management intensity. Third, a systematic literature review is used to link biodiversity and financial performance of small-scale shaded coffee and cocoa systems. Finally, we discuss the implications of our findings for environmental policy and research.

2.2. Methodology

2.2.1. Literature search and data collection

We systematically searched for scientific and grey literature using the following search terms in Google Scholar: “Biodiversity AND shade AND agroforestry AND (tropics OR tropical) AND (product OR productivity OR profit OR profitability OR yield OR financial OR finance)”, of which the first 1,000 results were included. Studies were selected if they included (i) coffee or cocoa systems; (ii) an intensified conventional system and a shaded system and there is mentioning of difference in shade between the two systems in the paper; (iii) quantitative information on yield (kg ha^{-1}) and/or costs and benefits (monetary currency), in terms of e.g. input costs, net revenue, labour time and costs, or Benefit-Cost Ratios (BCR); and (iv) quantitative information on biodiversity performance in terms of species richness. These criteria were applied to both scientific and grey literature encountered in the first thousand Google Scholar results. Besides studies that included a direct indicator of biodiversity performance such as species richness, studies including proxy variables known for their correlation with biodiversity such as canopy closure and shade tree density (Bhagwat et al., 2008; Harvey et al., 2008) were also selected. Only papers including shade provided by trees were included, avoiding papers describing artificial shade, for example shade provided by cloth. For financial performance, indicators such as productivity and costs were used. Besides systems referred to in the encountered literature as shaded or agroforestry systems, a broader range was incorporated as ‘shaded systems’ including organic, certified, or low-input systems, only if there was mentioning of a certain level of shade management in the system. Furthermore, systems referred to as sun-grown, unshaded monoculture or uncertified were included as ‘conventional systems’ representing an intensified alternative system. The complete list of selected studies and extracted data is provided in Table A1 in the appendix. Data were extracted from articles, integrated into one database and converted to the same units of measurement: one hectare was used as the unit for surface area, one year as unit for time and US dollar as currency. Benefit-Cost Ratio (BCR; net revenue / costs) and net revenue (US\$ ha^{-1}) are used as main indicators of financial performance, as they provide insight into the dynamics between costs and benefits and the total profit per surface area. There were insufficient data on variables such as discount rate, plantation age and labour time and costs to take these explicitly into account and to analyse their effects separately. Coffee and cocoa yields are expressed in dry weight. If necessary, coffee fresh weight was converted to dry weight using a 4.6:1 ratio (Hicks, 2002). All cocoa studies presented dry weight figures. In addition, data on trees per hectare (trees ha^{-1}), costs per hectare (US$ ha^{-1}), gross revenue per hectare (US$ ha^{-1}) and net revenue per hectare (US$ ha^{-1}) were calculated when possible and included in the database. Shade tree density categories were defined according to number of shade trees per hectare (low<40, medium 41-100 and high>100 trees). Shade quality was identified according to shade tree density and the description of the system in the article.

2.2.2. Description of dataset and analysis

A total of 23 articles are included in this review; they were published between 1988 and 2014 and matched the inclusion criteria mentioned above. All selected articles contain data of a single conventional system and one or several shaded systems. Although some articles lacked a detailed description of shade tree density and species richness, it was clear that the shaded systems included in this analysis showed a large range in shade complexity and therefore quality. The shaded systems ranged from highly diverse shaded systems, often referred to as rustic systems (as characterized by Moguel & Toledo, 1999), to shaded monocultures systems where shade is provided by a single species. Each shaded system is paired to the unshaded conventional system in the article. Consequently, when one article describes more than one shaded case, the data used in the analysis for the conventional counterpart system are replicas. The basic units of analysis in the database were these paired cases, allowing for a comparison between a shaded system and a conventional system. Indicator analysis predominantly focused on paired cases within a study, expressed as a relative difference between the shaded and conventional system within one study. Most studies used field data, although some studies based their modelling on empirical data.

A subset of five articles contained continuous data and has therefore been reviewed separately. These articles contained data on both financial performance and biodiversity performance; they originated from different regions in Africa (2), Asia (1) and Latin America (2) and four of these concerned cocoa. The remaining 18 articles contained categorical data, allowing for quantitative analysis of financial performance by means of a meta-analysis. A total of 31 categorical paired cases were identified and numbered (Table A1), and these numbers are used to refer to the cases. Of these categorical data, three articles reported explicitly on biodiversity, resulting in a total of six cases that included data on biodiversity and financial performance. Table 1 presents an overview of the categorical dataset and the most important variables with corresponding units of analysis. A subset was made of all 20 cases that included BCR information, thus also forming a subset of the other indicators. Although we do not imply that coffee and cocoa systems are identical, we assume that the great similarities between the two systems (Beer et al., 1998; Tscharntke et al., 2012) allow for combined analysis, especially since this analysis involves pair-wise comparisons. Our data show no indication that we should question this assumption, but differences in results between the two crops are addressed when necessary.

Table 2. Selected articles as a result from the literature search, with corresponding number of cases per indicator. BCR = Benefit-Cost Ratio.

		# of articles	**# of cases**	**# cases BCR-subset**
Total dataset		**18**	**31**	
BCR	ratio	11	20	20
Yield	Kg ha^{-1}	14	25	15
Coffee shrub / cocoa tree density	# shrubs ha^{-1}, # trees ha^{-1}	10	14	9
Productivity per shrub / tree	kg shrub^{-1}, kg tree^{-1}	7	10	5
Costs	US$ ha^{-1}	8	15	15
Coffee price	US$ kg^{-1}	5	8	8
Gross revenue	US$ ha^{-1}	4	11	8
Net revenue	US$ ha^{-1}	10	19	15
Biodiversity	Species diversity & abundance	3	6	4

A total of 26 of the selected cases provide data from coffee plantations, compared to 5 cases of cocoa plantations. Of all categorical articles, 5 contained data from African plantations and 13 from Latin American plantations (Figure 4). Differences in mean indicator value (BCR, yield, tree density, productivity per tree, costs, product price and net revenue) between shaded and conventional systems were tested by conducting one-sided, paired sample t-tests (R software, version 3.0.2, R Core Team 2014). This analysis allowed for comparison of means between groups while taking the paired cases into account and p-values, t-values and degrees of freedom (*df*) are reported. One-way ANOVA tests were conducted to test for differences in variance in indicator value (BCR, yield, and net revenue) among the characterized low, medium and high shade tree densities (Table A1), for which p-values, F-values and degrees of freedom are reported (*df*).

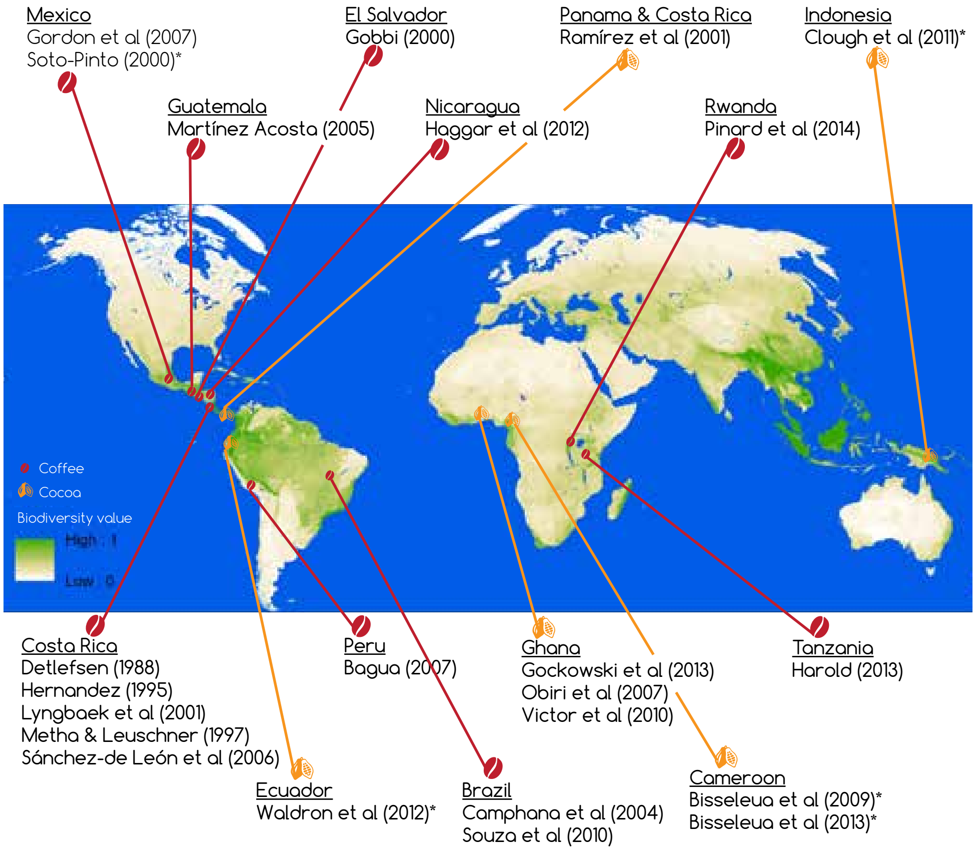


*Figure 4. Geographical locations of the study, plotted on a map showing the worlds' biodiversity hotspots from high (green) to low (white). *Indicates articles with continuous data. Map derived from: http://static1.squarespace.com*

2.3. Results

2.3.1. Financial performance

In this section, we analyse the financial performance of conventional and shaded coffee and cocoa systems, predominantly by presenting the results of the analysis of the BCR-subset. First, we present the results of the analysis of BCR and net revenue as main indicators of financial performance. Subsequently, the results regarding yield, cost and product price are presented and analysed in relation to BCR and net revenue, providing more insight into the underlying components of the financial performance of coffee and cocoa systems. An overview of the results is presented in Figure 5.

2.3.1.1. Net revenue and BCR

Our analysis showed that shaded systems were more cost-effective (BCR) and profitable (net revenue) than conventional systems, indicating a better financial performance. Data showed a trend ($p=0.06$; $t=1.62$; $df=19$) that average BCR of shaded systems 1.66 (± 0.22; n= 20) was higher than that of conventional systems 1.34 (± 0.15; n=11; Figure 5). Additionally, the average net return of shaded systems in the subset was significantly higher by 23% ($p<0.05$; $t=2.31$; $df=14$), showing a higher profit per hectare for farmers with shade trees planted between their coffee and cocoa plants. Despite differences in net revenue and BCR, the majority of cases were profitable; in other words, they had a BCR higher than 1.0 and gross revenues that were higher than the costs. No significant difference in net revenue ($p>0.05$; $F=0.72$; $df=10$), yield ($p>0.05$; $F=0.12$; $df=17$) or BCR ($p>0.05$; $F=1.98$; $df=11$) was found across different levels of shading (low, medium or high shade tree density).

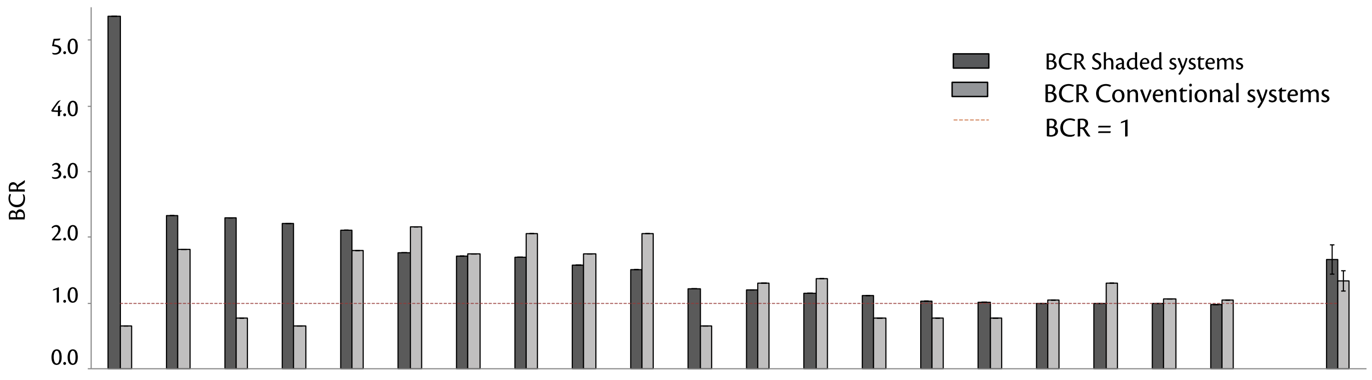
2.3.1.2. Yield

For 25 cases data were reported on yield, 15 of which also presented data on BCR (Table A1). Productivity per hectare for shaded systems decreased 26% compared to conventional systems ($p<0.001$; $t=-4.37$; $df=24$). This difference in yield is reflected by the higher coffee and cocoa tree density and higher per plant productivity for conventional systems. No significant difference in yield was found among low, medium and high shade tree densities ($p>0.05$; $F=0.12$; $df=17$). The average tree density was 32% higher for conventional systems, a difference which was significant ($p<0.001$; $t=-2.88$; $df=13$). Furthermore, data showed a trend towards higher average productivity for conventional systems per coffee shrub of cocoa tree by 18% ($p<0.10$; $t=1.38$; $df=9$).

To provide more insight into the underlying components of cost-effectiveness and profitability, it is important to examine the data of the 15 cases included in the BCR-subset that reported on productivity. Overall, yield per hectare was 25% lower for the shaded systems than for the conventional systems ($p<0.01$; $t=-3.06$; $df=14$), ranging from +59% to -79%. Of the 15 cases, 13 showed higher productivity per hectare for shaded systems in comparison to conventional systems, leaving two cases (nos. 14 and 16) with a higher yield for the shaded systems (22% and 59%, respectively). All shaded cocoa systems were less productive per hectare than their conventional counterparts, as yields were between 15% and 80% (n=3) lower for shaded systems. Comparable with the total dataset, the differences in the productivity of this subset can be explained by trend in a 10% lower coffee and cocoa tree density in the shaded systems ($p<0.10$; $t=-1.60$; $df=8$) combined with a non-significant difference of 19% lower productivity per tree ($p>0.10$; $t=2.8$; $df=5$).

2.3.1.3. Costs

A total of 15 cases, all within the BCR-subset, presented data on costs. On average, costs per hectare associated with shaded systems were 13.2% lower than for conventional systems, but this difference was not significant ($p>0.10$; $t=-1.03$; $df=14$). In these cost analyses, the level of detail differed between cases, as did the components included, such as labour costs, input costs, land prices and certification costs.



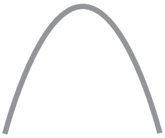
Case #	10	29	13	12	18	17	23*	21	24*	20	11	9*	26*	15	16	14	30	8*	19	31	Average	SE	n
Yield difference (%)	-28%	-39%	-41%	-13%	-44%			-45%		-35%	-51%	-22%	-15%	-21%	59%	22%		-80%	-22%		-25%***	8%	15
Trees ha^{-1} difference (%)		-23%			-34%	8%						0%	-36%				0%	0%	-8%	0%	-10%*	5%	9
Yield tree^{-1} difference (%)		-22%			-6%							-22%	32%					-80%			-19%**	18%	5
Costs difference (%)	-80%	-67%	-51%	-47%		-26%	34%	-65%	37%	-5%	-63%		82%	-38%	60%	23%			5%		-13%	13%	12
Price/kg difference (%)	0%	0%	64%			34%				0%				-2%	18%	20%			21%		17%*	8%	8
Gross revenue difference (%)		-39%	-9%			-11%	55%		46%					-26%	84%	40%					15%	15%	8
Net revenue difference (%)	68%	-5%	45%	81%		-39%	64%		50%		-30%	-17%	51%	-11%	115%	62%		-82%	-2%		23%**	14%	15

Figure 5. *BCR (y-axis) of shaded coffee and cocoa systems compared to conventional systems (x-axis, n=20). Dotted line represents break-even point of BCR = 1.0, where costs and net benefits are equal. Cocoa cases are indicated with (*). In the connected table, differences in yield (kg ha^{-1}), coffee tree density (trees ha^{-1}), productivity per tree (kg tree^{-1}), costs (US\$ ha^{-1}), price received per product (US\$ kg-1), gross revenues (US\$ ha^{-1}) and net revenues (US\$ ha^{-1}) are presented in percentages. Red cells indicate a negative difference for shaded systems compared to conventional systems, with all differences <-50% are marked in darker red, and green cells represent a positive difference, where darker green cells indicate a positive difference of >50%. SE and n of average values of all variables are presented. *** indicates a significant level of <0.01, ** of 0.05 and * of 0.10 derived from one-tailed t-tests.*

2.3.1.4. Product price

Besides productivity, an important determinant for net income is the price farmers receive per unit of product (expressed as US dollar per kilogram: US\$/Kg). Although most cases lacked data on product price, 10 coffee cases presented price per kilogram of coffee beans; four of these cases adopted the same coffee prices for the two different systems, resulting in identical prices for conventionally and shade-grown coffee. The remaining six cases presented prices per kilogram of certified coffee beans, resulting in a price premium for shade-grown coffee in these studies. With the exception of one case in which the coffee price was 2% lower for shaded systems (no. 15), all prices were higher for shaded systems, ranging from an 18-64% increase in dollar per kilogram. In these 6 cases there was a trend towards higher average prices for shaded coffee and cocoa by 26% per kilogram, than the price received by conventional farmers ($p<0.10$; $t=1.91$; $df=5$).

Table 3. Qualitative analyses of biodiversity and financial performance for five studies presenting continuous data. Relationship between biodiversity (x-axis) and financial performance (y-axis) indicators is presented abstracted and when available statistical data is included.

Biodiversity performance indicator (x-axis)	Financial performance indicator (y-axis)	
Shade	Yield	Income
	Bisseleua et al (2009) (R^2= 0.41, p=0.006) Soto-Pinto (2000) (R^2=0.68; p<0.001) Waldron et al (2012) (R^2= 0.69)	Waldron et al (2012) (R^2= 0.57)
	Clough et al (2011) (p<0.05)	Bisseleua et al (2013) (0.72 (p<0.0001)
Species richness	Yield	Income
	Bisseleua et al (2009)	Bisseleua et al (2009)
	Bisseleua et al (2013) (R^2=0.25; p<0.05)	
	Clough et al (2011)	

2.3.2. Biodiversity performance and financial performance

One of the main characteristics of intensification is the reduction or elimination of shade trees resulting in monoculture plantations without shade. Since the level of shade provided by shade trees is relatively easy to quantify and its relationship with biodiversity is well researched, shade is often used as a proxy indicator of biodiversity. Similarly, productivity in terms of yield of the main cash crop is often used as an indicator for financial performance. Consequently, cases that included these proxy indicators for biodiversity and financial performance are also presented here.

2.3.2.1. Shade, yield and income

All five continuous data studies included in this review explicitly studied the relationship between shade trees and productivity in terms of coffee or cocoa yield and/or income, yielding contrasting results (Table 3). Clough et al. (2011) found a negative relationship for cocoa production as yield decreased with an increasing percentage of shade. However, other studies show an optimum relationship (Bisseleua et al., 2009; Soto-Pinto et al., 2000; Waldron et al., 2012) for intermediate levels of shade. Two of these studies explicitly studied revenues in terms of income of systems with different levels of shade, again with contrasting results similar to the shade-yield relationships. Bisseleua et al. (2013) found a negative linear relationship between the level of shade and income, as income decreased with an increasing percentage of shade. Data presented by Waldron et al. (2012) indicate an optimum for intermediate levels of shade in relation to income for smallholder farmers.

2.3.2.2. Species richness, yield and income

Studies analysing the relationship between species richness and yield and/or income show divergent results. Bisseleua et al. (2013) found that there was a negative relationship between the diversity of native shade trees in cocoa plantations and productivity, although the correlation was relatively weak. This is in contrast to another study by Bisseleua et al. (2009), which reported an optimum relationship between species richness and yield as well as between species richness and income. This study observed the highest net income with intermediate ant species richness. Clough et al. (2011) found no relationship between species richness and yield. Furthermore, two papers containing categorical data included data on both species richness and BCR and net revenue (Table A2). Gordon et al. (2007; nos. 10-12) showed that bird diversity was between 120-306% higher in three shaded coffee systems ranging in complexity, whilst BCR and net revenue were also significantly higher for all three shaded systems despite an overall decline in yield. The same trend was found on coffee plantations in Nicaragua studies by Haggar et al. (2012).

2.4. Discussion

2.4.1. Management characteristics and biodiversity

Since there is a broad variety in coffee and cocoa management systems, these systems can be used to study the effect of intensification on both biodiversity and financial performance. Differences with respect to for example shade trees, input of agrochemicals, coffee and cocoa varieties and tree density can all be located along this gradient of intensification. Numerous studies investigated the relationship between the intensity of crop management and the biodiversity performance of coffee and cocoa systems, in order to determine the potential of agroforestry systems to conserve biodiversity, as well as the circumstances such as the quality of the matrix and management practices involved. Some studies reported a decline in biodiversity when coffee or cacao management intensifies (e.g. Faria et al. 2007; Gardner et al. 2009), whereas other studies did not find such an overall effect (e.g. Steffan-Dewenter et al. 2007; Gordon et al. 2007). Though the conservation of biodiversity is thus influenced by many different factors and outcomes are divergent, there are some clear messages that can be drawn from the literature. Overall, there is substantial evidence that naturally shaded systems have a great potential to conserve biodiversity (Bhagwat et al., 2008; Harvey et al., 2008). Although different taxa respond differently to habitat modification intensification of both of coffee and cocoa agroecosystems (Perfecto et al., 2003; Schroth et al., 2004), it is well known that a reduction of shade quality will have a negative effect on the biodiversity conservation potential. Species richness is typically highest in coffee and cocoa systems with high plant diversity, and structurally complex canopies. De Beenhouwer et al. (2013) performed a meta-analysis of 74 studies and concluded that there was a stronger decline in total species richness when comparing agroforestry systems with plantations (-46%) than when comparing forest with agroforestry (-11%), confirming the general idea that both plant and animal diversity in coffee and cocoa agroforests are higher than those of other agricultural land uses, but lower than in the original forest habitat. Species richness is thus often significantly related to plantation characteristics such as canopy closure, management intensity index, shade tree density and other vegetation characteristics (Clough et al., 2009; Marín et al., 2016; Schroth and Harvey, 2007). Such plantation characteristics are therefore often used as indicators of species richness, both in research and in certification practices. We therefore assume that the shaded systems included in our analyses offer a greater potential to conserve biodiversity than the conventional systems they are paired with. While we did include shade quality in the analysis by categorizing shade tree density (low, medium, high, Table A1), the lack of more detailed case descriptions of shade quality hampered an adequate analysis of its effect on both biodiversity and financial performance. It should be noted that there is a wide range in shade quality reported in the studies included in this analysis, ranging from very low shade tree density values of 12 trees per ha^{-1} (no. 9), to high shade tree densities of 400 trees per ha^{-1} (no. 4; Table A1), and from single to multiple species of trees. We consequently expect large differences in biodiversity performance within the pool of shaded systems. A more detailed and consistent description of shade and shade management practices across studies would help to overcome such shortcomings. Besides quality of shading practices, the same accounts for other management characteristics such as the use of agrochemicals and the quality of the surrounding matrix. Although these variables are known to have important effects on biodiversity, little is known about the effects of these *in situ* and *ex situ* plantation characteristics on the financial performance of these systems, and information on the trade-offs between economic and biodiversity performance is even scarcer.

2.4.2. Financial performance

In this study, financial performance was determined with both input and output indicators. First, the results of the analysis on financial performance are discussed in terms of profitability and cost-efficiency. Then, BCR and net revenue are broken down into their separate components to discuss the opportunities and disadvantages associated with shaded systems.

2.4.2.1. Profitability and cost-efficiency

With net revenue and BCR taken as financial performance indicators, shaded systems show a better financial performance as average net revenue and BCR were higher for cocoa and coffee systems intercropped with shade trees. Interestingly, the highest BCR (5.36) was found in a case describing extensive agroforestry sites (no. 10). This high BCR is not directly related to an improvement in yield, as the yield was 28% lower compared to the conventional reference system. However, the costs associated with the production of coffee (per ha per year) were 80% lower and net revenue was 68% higher (Figure 5). Coffee prices received per kilogram were assumed for the different systems and, consequently, were identical; therefore, these prices do not explain the difference in financial performance. In practice this means that a premium price as a result of certification could be an opportunity to further increase the cost-efficiency and profitability for these agroforestry cases. Case no. 10 is exceptional as the overall yield only poorly explains its financial performance. Despite higher BCR and net revenue of shaded systems, the yield values for shaded systems were on average 26% lower than for conventional systems. It is therefore interesting to consider the separate components of net revenue and BCR. Indeed, on the one hand shaded systems had lower average costs (13%), while on the other hand they received higher average gross benefits per hectare (17%), which is partly a reflection of the higher average price per kilogram of coffee or cocoa (17%).

2.4.2.2. Coffee and cocoa yield

The lower average yield (-26%) found for shaded systems in comparison to conventional systems is in accordance with the majority of the literature, confirming the negative linear relationship between shade and production of the main cash crop

(Foley et al., 2011; Seufert et al., 2012). Even though this is often directly attributed to a decrease in solar radiation (Campanha et al., 2004a; Vaast et al., 2006), there are an increasing number of studies showing that moderate shade levels have little effect on cacao and coffee plant productivity (Perfecto et al., 2005; Soto-Pinto et al., 2000). Other studies found that a shade cover of 23-38% could even have a positive effect on yield, and that yield remained stable at a shade cover between 38-48%, but that production was lower when shade cover exceeded 50% (Somarriba and Beer, 2010). This parabolic relationship is confirmed in a study by Bisseleua et al. (2009), who found that yield was positively influenced by a shade cover of 28-47%, that yield remained stable at a shade cover of 49-55%, and that yield decreased at a shade cover of over 60%. In agroforestry systems coffee and cocoa trees are planted beneath shade trees; however, coffee and cocoa trees are also frequently intercropped with perennials such as banana. Van Asten et al. (2011) showed that coffee–banana intercropping is much more beneficial for smallholders than banana or coffee mono-cropping, since the coffee yield was not affected and farmers gained additional income from the bananas, thereby offering a good business opportunity for small-scale farmers. Although banana plants in such a system are expected to provide shade and extra income, the difference in biodiversity conservation value compared to plantations with high quality shading should be taken into consideration.

2.4.2.3. Yield as an indicator of financial performance

Studies addressing the socio-economic impact of coffee and cocoa agroforestry systems often extract financial performance solely based on the yield of the main cash crop. This is not surprising, as yield is the common denominator of different systems. However, an important finding in this review is the absence of a direct relationship between coffee and cocoa productivity, both per surface area and per tree, and financial performance expressed as BCR and net revenue (Figure 5). This indicates a more complex relationship than is often assumed between yield and financial performance (Steffan-Dewenter et al., 2007), which questions the use of yield as a direct indicator of financial performance. Nonetheless, the relationship between yield and management characteristics (in this study shade provided by trees) provides important insight into the trade-offs for coffee and cocoa systems. Productivity data are indeed useful to predict financial performance, but results should be interpreted with due caution and in the right context.

2.4.2.4. Costs

Intensification of coffee and cocoa management systems is associated with an increase in agrochemical input and management intensity, which is expected to be reflected in higher costs, especially since prices of chemical fertilizers have increased over the last decade (ICC, 2014). Put reversely, Hoekstra (1987) described that agroforestry land-use systems have a higher output value at the same resource cost or have the same output value at a lower resource cost when compared to non-agroforestry land-use systems. We found similar results, as costs per hectare were 13.2% lower for the shaded systems in comparison to the conventional systems, partially explaining the better financial performance of shaded systems. These predicted dynamics are reflected in Gobbi (2000), who demonstrates that capital requirements for organic shaded systems are low and that these requirements increase with reduction in shade cover. Bisseleua et al. (2013) confirms this relationship as they found that higher input in studied cocoa farms does not necessarily result in a higher net return. Besides agro-chemical input, labour is often one of the major costs incurred in plantation management, while type and allocation of labour vary among different management systems. For example, the organic shaded systems in the study of Lyngbæk et al. (2001, no.19) required more labour than the conventional unshaded systems in this study, mostly because more hours were needed for fertilization and pest control and pruning of the shade trees. However, the lower input costs associated with the organic systems in this study compensated for the increase in labour requirements, resulting eventually in similar costs. Since small-scale farmers often have only limited access to resources and finance, shaded coffee and cocoa systems appear to be an attractive option for this group as shaded systems involve lower costs in the establishment and maintenance of the plantations. Additionally, a distinction between actual incurred costs of hired labour and opportunity costs of family labour in the economic analysis would be useful. Small-scale subsistence farming often relies more on family labour, avoiding costs associated with hired labour, in contrast to larger scale plantations which are often more intensively managed and rely more on hired labour, which comes at additional costs. Further research is therefore recommended on the effects of agrochemicals and environmental conditions on productivity, as well as the relative contribution of family and hired labour to costs incurred.

2.4.2.5. Coffee/ cocoa price and certification

An important determinant of income derived from plantations is the price per kilogram of produced coffee or cocoa received by the farmers. The price of shade-produced coffee or cocoa can be potentially higher due to increased quality and therefore suitability for specialty markets (Muschler, 2001; Vaast et al., 2006) as well as price premiums from environmental certification schemes. In this review, the price received per kilogram of dry coffee or cocoa beans was indeed higher (+18%) for farmers growing shaded coffee or cocoa compared to the price received for conventionally grown coffee. This partially explains the observed better financial performance for shaded systems. Price premiums received by small-scale farmers as a result of environmental certification thus seem to play an important role (Lyngbæk et al., 2001) and show potentially better economic prospects for small-scale farming, as the specialty coffee market has increased over the last decade and is expected to keep growing (Jha et al., 2014). Other research however argues that although the price premium can play a role, yields rather than these price premiums are most important for net income of coffee farmers in Mexico (Barham and Weber, 2012).

Overall, if farmers are to consider switching from a conventional to a shaded system, the presumed decrease in coffee or cocoa yield needs to be compensated by a price premium, irrespective of the difference in quality of the product. Although coffee prices are in part determined by quality, worldwide coffee and cocoa price fluctuations put farmers in a vulnerable position (Belsky and Siebert, 2003; Ponte, 2002). As shaded systems are more diverse than conventional systems, they are expected to show a lower sensitivity to changes in commodity prices, as income derived from other products can contribute greatly to the income of small-scale farmers (Rice, 2008). Unfortunately, the selected cases had only limited data on the benefits associated with diversification, which made it impossible to include this aspect separately in the quantitative analysis. Still, some cases addressed the benefits of additional income or income stability. An example is provided by Souza et al. (2010, case 29), where income derived from other products adds more than a third to the income derived from coffee (R$1792.00 from coffee and R$701.50 from other products). The same applies to cases 21 and 22, where income from timber and firewood accounts for more than 70% of the total income derived from shaded coffee plantations. Such additional income can reduce the sensitivity of farmers' livelihoods to fluctuations in commodity prices. This is illustrated by case 10, described by Gordon et al. (2007), who showed that a recent coffee price crash on the international market had a much greater impact on the net revenue of conventional (sun-grown) coffee plantations (30-fold decrease relative to the pre-crisis prices) than on the net revenue of the extensive agroforestry sites (2.9-fold decrease) and other shaded plantations (6.7-fold decrease). Concluding, although coffee and cocoa yield are presumed to be lower for shaded-systems, income from other products is expected to compensate for such losses while reducing farmers' vulnerability to the high price volatility of these two commodities, which should be included in financial analyses of these systems.

2.4.3. Trade-off between biodiversity performance and financial performance

Although there are only few studies directly linking biodiversity performance and financial performance, there are indications that shaded systems potentially combine increases in both types of performance. As previously discussed, shade trees positively correlate with biodiversity thereby also increasing the matrix quality on landscape level (Schulze et al. 2004). In this review, we have attempted to analyse this relationship not only directly, but also indirectly, by discussing the relationships between the different biodiversity and financial performance indicators (Table 3).

2.4.3.1. Shade, yield and income

The influence of shade on the productivity of coffee and cocoa systems is highly debated and results are varied (Table 3). It is an important observation that some studies suggest a parabolic shaped relationship between yield and shade, indicating an excellent opportunity for shaded systems to increase financial performance. A fitted quadratic model from Waldron et al. (2012) suggests that for cocoa plantations the tipping point of maximum productivity lies around 144 shade trees per hectare, a relationship confirmed by studies indicating an optimum between approximately 20% and 50% of canopy closure. Similar debate accounts for the relationship between shade and income (Table 3). However, it should be noted that income in some of these studies is often a more or less direct result of productivity of the main cash crop, as the yield is frequently simply multiplied by the price received per unit of product. Yet, an optimum relationship between shade and yield would provide good opportunities to reconcile biodiversity conservation and local development in the tropics, where extensive conversion of tropical forest and agricultural intensification are identified as major drivers of biodiversity loss and of reduced associated ecosystem services, including coffee and cocoa production systems (Foley et al., 2011).

2.4.3.2. Biodiversity and financial performance

With regard to the relationship between species richness and financial performance, the results are even more divergent; they are often addressed in terms of yield and farmer income (Table 3). Clough et al. (2011) confirm that smallholders of cocoa agroforestry systems are able to combine high agricultural yield and high biodiversity goals on-farm, as they did not find a negative relationship between species diversity and income. An exclusion experiment on cocoa systems in Indonesia found the highest yield coinciding with high levels of ants (Wielgoss et al., 2013), indicating opportunities for increased income with a higher performance on biodiversity; this was also indicated by the study by Bisseleua et al. (2009). Even though there are only few studies directly linking biodiversity performance and financial performance, there are indications that shaded systems potentially combine increases in both types of performance (Somarriba and Beer, 2010; Staver et al., 2001). Besides direct monetary benefits, such as income from other products and a price premium, shaded coffee and cocoa systems generate other, often indirect, benefits for their owners. Although there are contradictory studies (e.g. Avelino et al. 2012), it has been found that moderate levels of shade can reduce disease (López-Bravo et al., 2012) and can hinder fungal disease by creating windbreaks which slow the horizontal spread of coffee leaf rust spores (Soto-Pinto et al., 2002). Furthermore, agroforestry systems can mitigate changes in temperature and precipitation (Lin, 2007), whilst the shade trees function as a nutrient safety net and natural provider of fertilizer (Tscharntke et al., 2011) and thereby enhance soil fertility. The latter finding will limit the input of agrochemicals, which is especially important for smallholders due to the rising prices of chemical fertilizer. To draw more accurate and robust conclusions, further research is needed that focuses on the trade-offs between economic and biodiversity performance, including both direct and indirect benefits.

2.4.4. Data limitations and recommendation for future research

Despite the growing body of evidence suggesting that shaded systems can offer competitive business opportunities for small-scale farmers, knowledge remains limited on the conditions necessary for shaded systems to be competitive. A few main obstacles for detailed and robust analyses have become apparent in this review. First of all, there are only a limited number of multidisciplinary studies that include both financial and biodiversity data. Secondly, although a great deal of literature focuses on shaded systems, these studies frequently lack a baseline, as a conventional reference system is not always included. For instance, there is a large body of literature on shaded coffee systems in Mexico, yet the majority of these empirical studies focus on either ecological or economic components, do not include a reference system or report on economic performance only in terms of coffee yield. Thirdly, the few studies that comply with the standards mentioned above often include different categories or indicators, and the data collection methods are not always transparent. Although there is a clear continuum of coffee and cocoa management practices, researchers often develop their own characterizations of shade management practices. For example, the most-cited coffee biodiversity studies include more than 25 names to describe coffee-management systems (Philpott et al., 2008). This limits the comparability across case studies, thus preventing robust conclusions, while at the same time essential details, such as on shade quality and matrix are lacking. Yet, the importance of shade and matrix quality on the conservation of biodiversity should not be underestimated. A framework with a consistent terminology would allow for greater comparability across studies, leading to more robust, precise and conclusive findings. Further research is therefore recommended on the effects of agrochemicals and environmental conditions on productivity, as well as the relative contribution of family and hired labour to costs incurred.

2.5. Conclusion

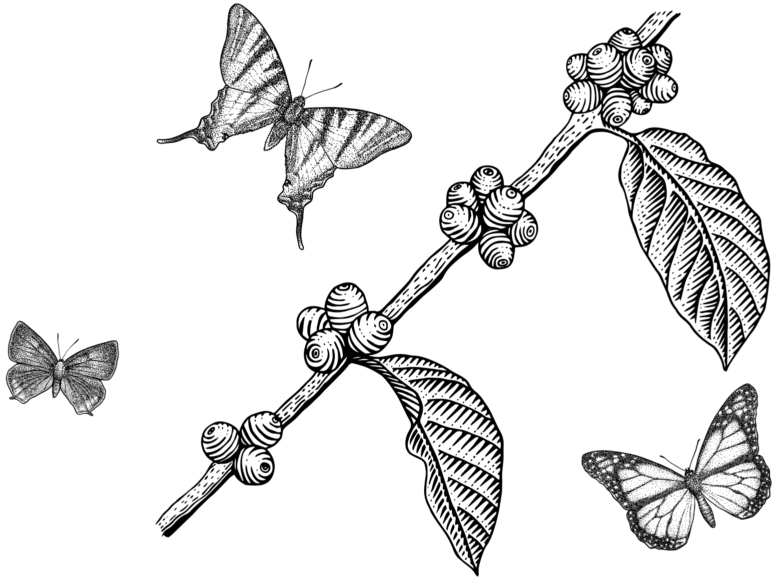
Although the relationship between productivity and financial performance may be straightforward for intensified monoculture land-use systems, this paper shows that this relationship is more complicated for diversified systems such as shaded coffee and cocoa plantations. As profitability in terms of net revenue and cost-efficiency in terms of BCR were higher for shaded systems, this review indicates that shaded systems can offer competitive business opportunities in comparison to the expanding sun-grown conventional plantations, and that there is a growing body of literature supporting this hypothesis. By analysing financial performance as a direct derivative of productivity for shaded coffee and cocoa systems, as conventional approaches dictate, other direct and indirect benefits are excluded, such as income from the shade trees and the ecosystem services provided by the shade trees. Additionally, costs associated with different management systems are often excluded from the analysis.

We therefore recommend using a more comprehensive indicator such as net revenue or BCR. A fruitful venue for further research would be to provide more insight into the relationship between the separate components of financial performance in relation to the management of shaded coffee and cocoa systems.

Despite a lack of consensus on financial performance of shaded coffee and cocoa systems, it is known that there is a positive relationship between shade trees and biodiversity. Furthermore, in this review we found indications that shaded systems can have a similar or even better financial performance than conventional systems, mainly due to lower costs and a higher price received for their products. Moreover, shaded systems are likely to contribute to greater economic stability of farmers' income, also due to opportunity to gain additional income from other products which reduces sensitivity to price volatility. Although case and site-specific conditions need to be taken into account, we have shown that shaded systems offer great potential to reconcile biodiversity conservation and local development. To address the lack of data, further validation of this relationship is necessary. We emphasize the need for comparable, long-term multidisciplinary studies, to quantify both financial and biodiversity performance, as well as to gain greater insight into the opportunities and challenges for scaling up.

2.6. Acknowledgements

This project was funded by Hivos, a Dutch non-governmental organisation, through the Business for Biodiversity project. We are also grateful to Tropenbos International for additional financial support. We would also like to thank two anonymous reviewers for their insightful comments and revisions.



3

Effects of shade and input management on coffee yield, biodiversity and carbon storage in smallholder plantations in San Martín, Peru

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René G.A. Boot, Yann Clough

Abstract

Tropical agroforestry systems provide a number of ecosystem services that help sustain crop production, improve farmers' livelihoods and conserve biodiversity. These benefits are, to a large extent, a function of management, but there is a need to further understand the relationships and combined effects of shade and input management (fertilizer and pesticides) on the provisioning of such ecosystem services and the potential trade-offs or synergies among them. To better understand the relationships between the three ecosystem services, coffee production, biodiversity and carbon storage, we examined the relationship between coffee yield, the butterfly species richness, and carbon storage, while accounting for soil fertility and yield losses due to pests and diseases. Data were collected on smallholder coffee plantations in the department of San Martín, Peru, along a gradient of shade and input management, by survey (in 162 farms) and by plot measurements (in a subsample of 62 farms). We found that coffee yields, forest butterfly species richness and aboveground carbon responded differently to shade and input management. Both carbon and butterfly species richness were higher in plantations with higher shade levels, yet importantly, we found no reduction in coffee yields with increasing levels of shade. This was independent of the trend that yield losses due to pests and diseases were lower when inputs were higher. We found neither trade-offs nor synergies between coffee yield, biodiversity and carbon storage. Input use, especially of fertilizers, was highest in low yielding sites, but was not related with either butterfly species richness or carbon. We also found that yield loss due to pests and diseases, in particular due to coffee leaf rust, were important constraints on coffee yield. The lack of trade-offs between yield, biodiversity and carbon implies that it is possible to maintain and enhance the provision of multiple ecosystem services without a reduction in coffee yields. We suggest that smallholder coffee farmers can enhance productivity by managing soil fertility pro-actively, prioritizing pest management, and planting rust-resilient Arabica varieties. We therefore conclude that when optimizing shade and input management for coffee production, increased carbon storage and/or biodiversity conservation in coffee plantations could be pursued simultaneously.

Key words: *Agroforestry systems; Arabica coffee; Butterfly richness; Ecosystem services; Pests and diseases; Soil fertility; Trade-offs*

3.1. Introduction

Tropical agroforestry systems have been argued to be environmentally-friendly, reconciling biodiversity conservation, food production and the delivery of other ecosystem services (Schroth et al., 2004). Complex agroforestry systems with multiple vegetation layers and tree species are valuable for nature conservation, as they provide habitat for a large number of species (Bhagwat et al., 2008). The biodiversity benefits of shaded agroforestry systems are often assumed to come at the cost of lower crop yields under shaded conditions compared to full sun conditions (Perfecto et al., 2005; Vaast et al., 2006). At the same time, several studies show that in some agroforestry systems high crop yields and high biodiversity can coexist (Clough et al., 2011; Gordon et al., 2007). Unfortunately, the mechanisms underlying the relationships between crop productivity, biodiversity conservation and other ecosystem services remain poorly understood (Balvanera et al., 2006). A growing world population, deforestation, climate change and commodity price volatility are expected to increase pressure on agricultural systems, highlighting the need to understand whether multiple ecosystem services can be provided simultaneously in agroforestry systems or which trade-offs these systems face.

Complex tropical agroforestry systems offer multiple benefits besides supporting high biodiversity. They not only generate cash income from the main crop, but can provide farmers with other products for sale or household use. Fruits, timber, firewood and other shade tree products contribute to smallholders' livelihoods, diversify their income and increase food security (Souza et al., 2010). Shade practices are also related to improved soil fertility (Tscharntke et al., 2011), weed control (Staver et al., 2001), a lower need for fertilizers and herbicides (Vaast et al., 2006), buffering of micro-climate extremes (Lin, 2007), enhanced carbon storage (Atangana et al., 2014a) and pollination and natural pest control (Perfecto et al., 2004). Despite the recognition that tropical agroforestry systems can potentially provide diverse ecosystem services, there is still limited understanding on the provision of multiple ecosystem services (including productivity) and about the potential trade-offs or synergies among them. The lower expected yields under shaded conditions due to competition for light, water and nutrients in the soil between trees and the main crop (Beer et al., 1998) drive agricultural intensification worldwide to increase crop yields and farmer income (Meyfroidt et al., 2014; Perfecto and Vandermeer, 2015).

The global coffee sector is no exception to this worldwide intensification trend; in 2010, less than a quarter of the global coffee sector was managed as diverse agroforestry systems with multi-layered, multi-species shade, 35% was managed with sparse shade, while the remaining 40% of coffee area lacked shade (Jha et al., 2014). About 20-25 million families are involved in global coffee production of which more than 70% are smallholders who farm on less than ten hectares (Jha et al., 2011). Besides reduced shade, intensified coffee systems increasingly rely on new high-yielding varieties, higher coffee plant density and chemical inputs (Tscharntke et al., 2011). In Latin America, coffee intensification is accelerated by the perception that higher shade levels lead to increased incidence of coffee leaf rust (*Hemileia vastatrix*), a disease associated with a 10-70% reduction in coffee harvest in several countries during the latest outbreak in 2012-2013 (Avelino et al., 2015). Although increased coffee yields and income are important drivers behind intensification practices (Perfecto et al., 2005), evidence supporting the coupling of increased shade levels with decreased coffee yields is scarce (Jha et al., 2014).

Besides shade, there are other factors which potentially influence trade-offs between productivity and other ecosystem services. Increased frequency of management activities such as weeding and pruning, and increased use of organic and especially chemical inputs as fertilizers, insecticides and herbicides are reported to negatively affect biodiversity (Lin et al., 2008; Tscharntke et al., 2005) and insect diversity in particular (Kremen and Miles, 2012; Potts et al., 2010). Incidence of pests and diseases and soil fertility may confound the direct effects of shade or input management on coffee yields. Pest and disease incidences have triggered farmers to change varieties and management regime (Jha et al., 2014). Lack of soil fertility is expected to be an important stressor as it may affect productivity (Tittonell et al., 2005), biodiversity and carbon storage (Moguel and Toledo, 1999; Siebert, 2002).

As both input and shade management can affect productivity, biodiversity and other ecosystem services, it is necessary to study the effect of both simultaneously (Hernández-Martínez et al., 2009), which is rarely done. Three recent studies by Allinne et al. (2016), Cerda et al. (2016) and Meylan et al. (2017) demonstrate that coffee agroforestry systems in Costa Rica provide for enhanced ecosystem services compared to full sun systems. At the same time these studies show complex and interactive effects of environmental conditions, input and shade management, and emphasize the need for more research spanning a wider range in altitude, shade and input management intensity in order to generalize findings.

Here, we investigate the potential synergies and trade-offs among coffee yield, butterfly species richness and carbon storage in Peruvian smallholder plantations under a range of shade and input practices. The study region was not only selected for the importance of the Peruvian coffee sector, but also for the presence of a wide variety in management of smallholder coffee systems as well as large stretches of natural forests and national parks which are amongst the most biodiverse areas in the world (Myers et al., 2000) and containing high carbon stocks (Asner et al., 2014). As these conditions are similar to many of the world regions where coffee is grown (Perfecto et al., 1996), this makes the region of San Martín an interesting case to study the relations between yield, biodiversity and carbon for coffee regions worldwide. Here we (i) assess the effects of shade and input management on coffee yield, butterfly species richness and carbon storage, while taking into account the yield losses due to pests and diseases and maintenance of soil fertility; (ii) identify possible synergies or trade-offs between ecosystem services: butterfly species richness and coffee yield, carbon and coffee yield, and butterfly species richness and carbon; and (iii) discuss shade and input management implications for smallholder coffee farmers. The conceptual way in which these variables are interconnected is presented in Figure 6. With this research we contribute to the understanding of how shade and input management in coffee systems affect the provisioning of multiple ecosystem services and the possible trade-offs and synergies among them.

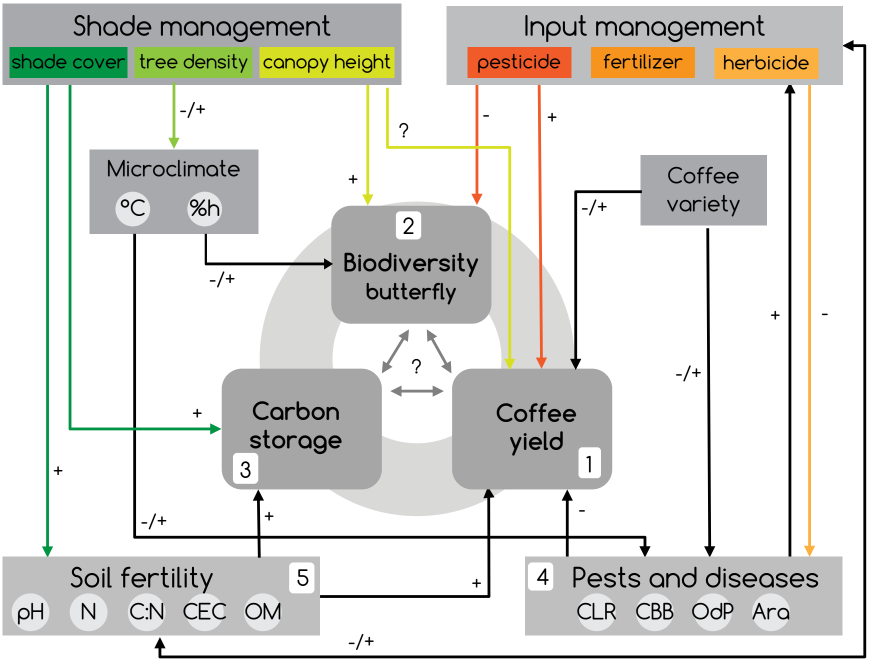

Figure 6. Conceptual diagram depicting expected relations, including synergies and trade-offs between coffee yields, biodiversity and carbon, and model description. We hypothesize positive effects of shade management on microclimate, butterfly biodiversity, carbon storage and soil fertility, yet effects on coffee yields are uncertain. This is because increased shade levels in coffee systems are associated with enhanced biomass (Atangana et al., 2014a), soil fertility (Tscharntke et al., 2011), buffering of micro-climate conditions (Lin, 2007), and provision of habitat (Bhagwat et al., 2008). We expect positive effects of input management on coffee yield, due to improved soil fertility and decreased incidence of pests and diseases, and negative effects of inputs on biodiversity. This is because input management is aimed at improving yields via fertilization (Castro-Tanzi et al., 2012) and decreasing yield losses due to pests and diseases via pesticide application (Cerda et al., 2016). Such external inputs, especially chemical products, are expected to have negative effects on biodiversity (Scherr and McNeely, 2008). °C= air temperature in degrees Celsius; %h= relative air humidity in %; N= Nitrogen; C:N= Carbon/Nitrogen ratio; CEC= soil cation exchange capacity; OM= organic matter; CLR= Coffee leaf rust; CBB= coffee berry borer; OdP= Ojo de pollo; Ara= Aranjero.

3.2. Materials and methods

3.2.1. Study region

The study area was located in the department of San Martín, Peru, which is one of the major coffee producing regions in the country, experiencing high deforestation rates (>20 000 hectares per year; Valqui et al., 2015). The coffee plantations included in this study were spread over an area of approximately 2000 km^2 (Figure 7a; 673-1497 m). Most plantations (n=143) were situated in the provinces Moyobamba and Rioja, which together form the 'Alto Mayo', a tropical highland with an average altitude of 1101 m (range 850-1497 m). For these higher elevation plantations, the average rainfall is 1512 mm per year, and the mean temperature 22.8°C. The remaining plantations (n=19) were situated in the lowland province of Picota, with an average altitude of 861 m (range 673 – 1001 m). The nearest weather station lies approximately 20 km from these plantations at an altitude of 218 m and reports a mean temperature of 26.5°C and a mean annual rainfall of 937 mm. For both regions, the dry season occurs between May and September (Gobierno Regional de San Martín, 2008). Most shade trees in coffee plantations are planted after land clearing, especially trees of the genus *Inga*.

3.2.2. Sampling and surveying methods

From April 2014 to August 2016, household surveys were conducted in 162 plantations to collect data on coffee management practices, shade (e.g. shade cover, tree species richness) and input management (e.g. type and amount of fertilizer, pesticides and herbicide use). Surveys were complemented with plot measurements in a subsample of 62 plantations (out of the 162 plantations surveyed), constituting a second dataset. Plantations were selected to cover the range of input and shade management implemented in the study area, ranging from full sun monoculture coffee to diversified shaded plantations and from high agro-chemical inputs to the use of organic inputs or without inputs (Figure 7; Table 4). Coffee plantations were selected based on field technician's knowledge of farmers shade and input uses, and we also consulted local databases on certification and organizational levels that recorded some information on shade and input. Only plantations with coffee shrubs older than three years were selected because this is when Arabica shrubs start producing marketable beans (Perfecto et al., 1996). Consequently, mean coffee shrub age was 8.9 years (range: 3-30 y). We only included smallholder plantations and the resulting average coffee plantation size was 2.74 ha (range: 0.5-13 ha) which is comparable to that of the average Peruvian coffee producer with an average coffee plantations size 3 ha (Bean and Nolte, 2017). We performed household surveys twice, in 2014 and again in 2016 because we wanted more information on the shade trees. The majority of the data used in this study was collected in 2014, and only shade tree species richness and density was obtained from the 2016 survey. In both cases we performed surveys using a semi-structured questionnaire and collected information on several variables as described below. The interviewers were trained by the same person and surveys lasted 45 to 60 minutes per farmer, most often plantation owners or tenants were interviewed. The interviewers assessed qualitatively if the farmers responded with confidence, and outliers were double checked. In 2016, data was collected and recorded in a smartphone/tablet app developed for this study, using ODK software (ODK Collect, version 1.4.10). The app included fields for each question, which provided guidance for the surveyors to minimise interview bias.

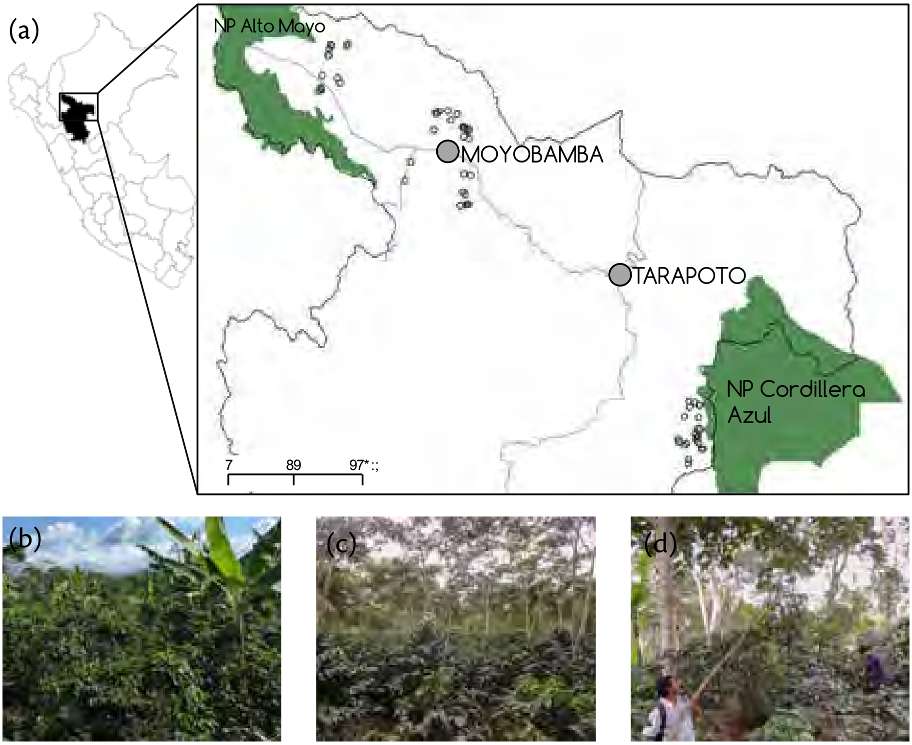

Figure 7. Study area and management regimes. (a) Study area in the region of San Martín, Peru. Open circles represent the locations of the plantations were plot measurement where made, grey-filled circles represent important cities, grey lines depict major roads and the dark green areas depict national parks. Region 1 refers to the area near Moyobamba, all north of Tarapoto, whereas region 2 refers to the area southeast of Picota, near the national park (NP) Cordillera Azul; (b) full sun monoculture management regime, sometimes sparsely intercropped with bananas during the first years, (c) single-species shade management regime, (d) diversified shade management regime.

In addition to the surveys, we conducted field measurements to obtain more detailed information on vegetation structure, soil fertility, biodiversity and microclimate. We established field plots in a subset of the farms (n=62) in 2014. Due to logistic and time constraints, these farms were selected so that they would reflect the same range in shade and input management as observed for the study area. Plots of 10x10 m (Picota, n=19) or 20x20 m (Alto Mayo, n=43) were set in representative areas of the farm. Four additional plots (20x20m) were set in the buffer zone of the national park Cordillera Azul to measure undisturbed forest conditions as a reference. Field plots were sampled from May to August in 2014 and 2015.

Within the sampling plot, all shade trees with a diameter at breast height >5 cm were identified to species level if possible, and otherwise to genus level. Species identification was done using a field guide (Pennington et al., 2004), and knowledge from local experts and farmers. We distinguished three groups of trees that provide shade yet are expected to contribute differently to ecosystem services, namely: (i) banana plants, plantains and palm trees; (ii) planted leguminous trees, predominantly of the genus Inga; and (iii) other trees (hereafter referred to as timber trees), both natural and planted. Tree species falling under each of these categories are listed in the Table A3 (in appendix). Tree height was measured with a Nikon Forestry Hypsometer. Level of shade (hereafter referred to as shade cover) was determined visually by estimating canopy cover on a scale of 0% to 100% (Samnegård et al., 2014). Visual estimation techniques have the potential of accurately estimating shade levels (Bellow and Nair, 2003) and are recommended when it is logistically difficult to collect canopy cover data above the tall coffee canopy using hemispheric lenses. Following the recommendations of Vittoz et al. (2010) to use highly trained observers for detecting changes in cover, we used at least two trained observers who cross-calibrated their estimates. Shade trees were rarely pruned and the shade measurements were taken once per plantation from May to August, which corresponds with the dry season. As shade trees are predominantly tropical evergreen trees, we have no reason to expect a large variation of shade cover throughout the year. The established sampling design resulted in two datasets: one dataset consisting of only survey data, and one dataset consisting of survey data complemented with plot data collected by field measurements for a subset of the plantations. We refer to these two data sets as "*survey*" (n=162) and "*survey+plot*" (n=62) respectively.

3.2.2.1. Shade and input management

Surveyors were asked about their management practices, namely shade tree species and approximate density (2016; trees ha^{-1}) and input management (cost of organic of chemical fertilizer, pesticides, and herbicides (2014; € ha^{-1} y^{-1}). Tree species richness was assessed with the 2016 survey by asking the farmers about the different types of trees and the number of shade trees present in their coffee farm. The farmers were also asked how difficult they thought it was to report the number and type of trees in their coffee farm (easy, medium or difficult). If they responded that they found this 'difficult' the answer was not included in the database. In addition, we used the field plots data on shade tree density and height (see above description) to improve and compare shade estimates from field surveys and farmer interviews. Shade tree density and species richness reported by farmers were correlated with the visually estimated shade cover per plot to assess the consistency across datasets (Figure A2). Most inputs, especially fertilizers, are used in solid form as well as liquid concentrates, thus we considered the total value of used input (€ ha^{-1} y^{-1}) as a proxy for the amount of inputs used. This included inputs given to the farmers free of charge, for example by the farmer association or the government. We also distinguished between organic and chemical input, as we expected strong positive effects on of these types of input on biodiversity (Gomiero et al., 2011). In addition, general farm characteristics were also recorded (e.g., size (ha), coffee shrub planting density (shrubs ha^{-1}) and age (y)), to be added in the modelling exercise as potential confounding factors (see below description for modelling setting).

3.2.2.2. Coffee yield

To measure coffee production as an ecosystem service, we used as proxy coffee yield. We asked farmers about harvested coffee yields (2010-2014; kg ha^{-1} y^{-1}), and coffee variety. Farmers were asked to report their coffee yields from 2010-2014 in terms of dried green coffee (known as café pergamino; 1 quintal = 56 kilogram). For coffee variety, we recorded the type of coffee varieties present at the plantation as reported by the farmer.

3.2.2.3. Butterfly species richness

As a proxy for biodiversity we measured butterfly species richness. Butterflies (*Lepidoptera*) can function as a proxy for biodiversity due to their sensitivity to micro-climatic changes in e.g. temperature, air movement, moisture and insolation (Bobo et al., 2006), thereby reflecting effects of shade cover, shade tree diversity; butterflies are also expected to be sensitive to pesticide use (Dolia et al., 2008). Butterfly species richness was estimated using transect counts (Christian H Schulze et al., 2004). One transect with a total length of 300m was walked by two observers per plantation at a pace of 12.5 m min^{-1} during 24 min, always between 9:30 and 15:30 h and without precipitation. All butterflies observed in a band of 3m to each side of the transect were identified based on wing characteristics. When identification was difficult, butterflies were netted and photographed for identification. If species level identification was not possible, the lowest level taxon was recorded instead. All measurements were taken in the dry season (from May to August) to avoid inter-seasonal variation. Butterflies were classified as forest or non-forest species, based on preferred habitat type obtained from information of different sources, including peer reviewed articles, books and websites (details in Table A4).

To account for weather variability, we recorded whether precipitation occurred before and after the sampling, and the day was sunny, medium-cloudy or cloudy. Simultaneously with walking the transect, we recorded air temperature (°C) and relative air humidity (%) at soil surface level over 30 minutes per plot using a thermo-hygrometer (TFA, Maxim II). Species accumulation curves were calculated to determine sampling completeness and reliability (Figure A1).

As the landscape matrix may influence farm species diversity (Häger et al., 2014; Ricketts et al., 2001), we measured landscape characteristics for each farm. The farm location was registered with a GPS (Garmin GPS 62s) and plotted in a geographical information system containing information on land cover and forest cover. Land cover maps were derived from an automated land cover classification of Landsat data from 2011. This map included six classes (urban areas, annual crop cultivation, perennial crops, pastures, primary forest and secondary forest) but we were only interested in primary and secondary forest as these land cover types more likely provide habitat for butterflies. Farm locations were used as centroids to 1000 m buffers, as this radius corresponds to butterfly home range sizes (Tufto et al., 2012) and is comparable to areas analysed in previous research (e.g., Steffan-Dewenter et al., 2002). Within the 1000 m-buffers, the percentage cover primary and secondary forest was calculated. For each farm we also calculated the distance to the nearest primary forest, and recorded its elevation with a GPS (Garmin GPS 62s).

3.2.2.4. Carbon storage

As a proxy for carbon storage we estimated above-ground biomass (AGB, Mg ha^{-1}). We estimated ABG for shade trees in the plots using an allometric equation for wet tropical forests that included specific wood density, DBH and tree height (Chave et al. 2014): $AGB= 0.0673 \ x \ (pD^{2})^{0.976}$, where D is the diameter at breast height (cm), H is the tree height (m) and p wood density (g cm^{-3}). Specific wood density of the trees was determined using the species-mean from the comprehensive global wood density database (Chave et al., 2009; Zanne et al., 2009), genus-mean or family mean. For the unidentified trees we assumed the global mean wood density for tropical forests in America (0.6 g cm^{-3}; Reyes et al., 1992). AGB of individual trees (kg tree^{-1}) was summed to obtain the total AGB per plot (kg plot^{-1}) and afterwards standardized to megagram per hectare (Mg ha^{-1}). Above-ground carbon storage was calculated as 50% of the AGB in Mg ha^{-1} (Hairiah et al., 2010).

3.2.2.5. Pests and diseases

We asked farmers about coffee yield loss due to pests and diseases, estimated as percent yield lost to the fungal pathogens coffee leaf rust, “ojo de pollo” (*Mycena citricolor*, OdP) and “aranjero” (*Pellicularia koleroga*, Ara) and to a pest beetle, the coffee berry borer (*Hypothenemus hampei*, CBB). Although only Arabica coffee is grown in this region, a subset of Arabica widespread varieties is more prone to coffee leaf rust than others. Costa Rica 95 from the Catimor family and Iapar 59 were recognized as more coffee rust- tolerant varieties, and Pache, Caturra, Típica, Borbón, Catuaí and Nacional as varieties more sensitive to coffee rust (Arrieta et al., 2016). We recorded the mix of varieties within one farm, and farms were classified as “*sensitive*”, “*resistant*” or “*mixed*”. The category “*sensitive*” had only one observation (n=1) and therefore was excluded from subsequent analyses.

3.2.2.6. Soil fertility

As proxies of soil fertility we measured soil organic matter (OM), nitrogen content (N), pH, cation exchange capacity (CEC) and C:N ratio in the field plots. For each plot, we took five random 500 g soil samples from the top layer (0-15 cm). Samples were thoroughly mixed and a sub-sample of approximately one kg was sent for standard soil laboratory analyses. See Appendix A1 for more detailed information on soil fertility measurements and Table A5 for lab procedures.

3.2.3. Data analyses

We used generalized linear models to evaluate the effects of shade and input management on coffee yield, butterfly species richness, and carbon storage, while accounting for yield losses due to pests and diseases and soil fertility. We used model selection procedures to selected the best set of models using coffee yield, butterfly richness and carbon as response variables and shade management, input use, micro-climate, yield loss due to pests and diseases, and soil fertility as predictor variables; farm elevation, coffee shrub age, and region were included as fixed factors to account for potential confounding effects. Vegetation and farm characteristics were included as random factors to account for potential confounding effects. To account for potential effects from neighbouring primary and secondary forest, distance to primary forest and forest cover (% primary and secondary forest in the 1km radius buffer around the farm) were included in the butterfly models. To check for potential effects of weather on butterfly species richness, we correlated precipitation and cloudiness on the day of the butterfly sampling with butterfly species richness. For coffee yields, two modelling runs were set, one with the survey data only and one with the *survey+plot* data. For more detailed information on the fitted models, see Figure 6 and Table A6.

The variables above-ground carbon, input expenses and forest and non-forest butterfly species richness were log-transformed to meet assumptions of homoscedasticity and normality of the residuals after adding the smallest value divided by two whenever observations included zero. We tested for correlations between the predictor variables using the Spearman's rank correlation (Table A7). Simultaneous inclusion of correlated variables in a given model was prevented.

We used multi-model ensembles to allow including multiple equally good models (Burnham and Anderson, 2002). We set several model sets, for each response variable and when including survey only or survey+plot data. For each model set, candidate models with all valid combinations of the predictor variables were generated and Akaike Information Criterion (AIC) values and AIC weights computed. Models were fit to a normal distribution. Full models were checked for (i) homogeneity of variance by plotting the standardized residuals against fitted values, (ii) absence of skewness through a normal Q-Q plot, and (iii) absence of outliers by plotting Cook's distances against the standardized leverages. Maximum likelihood parameter estimates were then obtained by model averaging across the best set of models, including all models with ΔAIC <2 (Burnham and Anderson, 2002). We used the packages lme4 (Bates et al., 2015), vegan (Oksanen et al., 2017) and MuMIn (Barton and Anderson, 2015) in R (version 3.0.2, R Core Team 2014). Finally, to identify possible synergies or trade-offs between ecosystem services, we correlated i) coffee yield and butterfly species richness; ii) butterfly species richness and carbon storage and; iii) coffee yields and carbon storage using the Spearman's correlation coefficient. To this correlation analysis we used the model residuals of generalised linear models fitted for coffee yields, butterfly species richness and carbon storage controlled for effects of altitude, coffee shrub age and region.

Table 4. Descriptive statistics of explanatory variables. Variables were measured with data from surveys (n=162), and field plots (n=62). Variables were measured with data collected via farmer surveys, unless stated otherwise. As for some farms we could not obtain a measurement, we report the number of observations per variable.

	unit	*mean*	*±SD*	*min*	*max*	*n*
General farm characteristics						
Farm size	ha	6.38	8.42	0.50	80.00	154
Productive coffee area	ha	2.74	1.96	0.50	13.00	154
Elevation	m a.s.l.	1070.31	171.74	673.00	1497.00	162
Coffee shrub age	year	8.75	4.56	3.00	30.00	159
Region	[Alto Mayo]; [Picota]					
Vegetation structure						
Coffee shrub density	shrubs ha^{-1}	3934.63	1139.65	1000.00	7000.00	154
Banana plant density (plot)	plant ha^{-1}	77.19	231.03	0.00	1400.00	54
Inga tree density	trees ha^{-1}	41.03	72.11	0.00	550.00	154
Inga tree density (plot)	trees ha^{-1}	126.85	161.28	0.00	700.00	54
Timber-species tree density	trees ha^{-1}	26.74	55.60	0.00	375.00	154
Timber-species tree density (plot)	trees ha^{-1}	74.54	94.36	0.00	375.00	54
Total tree density	trees ha^{-1}	71.34	97.13	0.00	600.00	154
Total tree density (plot)	trees ha^{-1}	193.51	131.14	0.00	600.00	54
Shade cover (plot)	%	36.76	26.74	0.00	80.00	54
Maximum canopy height (plot)	m	12.44	7.91	0.00	31.50	54
Coffee variety	[sensitive];[resistant];[mixed]					
Microclimate						
Air temperature (plot)	°C	26.52	2.48	21.20	34.20	52
Air humidity (plot)	%	77.42	7.10	61.00	93.50	53
Input management						
Total	€ ha^{-1} y^{-1}	149.74	196.90	0.00	1021.80	151
Fertilizer	€ ha^{-1} y^{-1}	123.93	174.29	0.00	951.60	140
Pesticide	€ ha^{-1} y^{-1}	34.07	77.25	0.00	468.00	128
Herbicides	€ ha^{-1} y^{-1}	6.67	26.21	0.00	249.60	138
Landscape configuration						
Distance to natural forest (plot)	m	2532.87	2121.47	0.00	7868.63	54
Forested area in 1km radius (ratio, 0-1) (plot)	%	0.41	0.16	0.12	0.76	54

3.3. Results

3.3.1. Shade and input effects on ecosystem services

Both carbon and butterfly species richness were higher in plantations with higher shade levels, yet importantly, we found no reduction in coffee yields with increasing levels of shade. While we found no effect of input on butterfly species richness and carbon, inputs were negatively related to coffee yields (Figure 8a-f). We found no significant correlations between i) coffee yields and forest butterfly species richness, ii) above-ground carbon and forest butterfly species richness, and iii) coffee yields and above-ground carbon (Figure 8g-i, Figure A4).

3.3.2. Coffee yield

Estimated yields averaged (±SD) 860±526 kg ha^{-1} y^{-1} and ranged between 112 and 2893 kg ha^{-1} y^{-1}. This large variation in coffee yields is probably related to the high incidence of coffee leaf rust, as well as to variation in coffee shrub age and elevation. Twelve models based on the *survey* data were equally good at explaining coffee yields, and this set of models included the null model. We found only trends towards negative relationships between coffee yield and coffee shrub age, yield loss due to pests and diseases, and elevation. These three variables were included in 12 and 6 models, respectively (Table 5 and Figure A4). From the *survey+plot* dataset, three best models were identified to explain coffee yields, all of which included significant negative effects of chemical fertilizer expenses and coffee shrub age. Two of the three models also included a trend for a negative effect of shade tree density on coffee yields (Table 5).

3.3.3. Butterfly species richness

We observed 2689 individuals, of which 92% could be identified to the species level. Altogether, 147 butterfly species from six different families were identified, 40 non-forest species, and 107 forest species (see Table A4 for all identified butterflies species and classification into forest and non-forest species). The observed butterfly species represented the total butterfly species richness in the area sufficiently as the species accumulation curves reached an asymptote (Figure A1; Chao et al., 2009). We did not observe a weather bias as precipitation and cloudiness was not related to observed butterfly species richness. In total, seven models were equally good at explaining forest butterfly species richness and these included the null-model. All models showed a trend (p-value<0.1) for a positive effect of shade level, and region on forest butterfly species richness (Figure 8b; Table 5). Fourteen models explained non-forest butterfly species richness equally well, and these included the null-model. We found a trend for a negative relation between non-forest butterfly richness and maximum canopy height, and a significant positive effect of region, specifically higher in Picota than in Alto Mayo (Table 5). Despite large variation in both distance to natural forest (0-8 km, average 2.5±2.1 km) and proportion of forested area within a one km radius (12-76%, average 41±16%), there was no relationship with forest or non-forest butterfly species richness.

3.3.4. Carbon storage

There was large variation in above-ground carbon among plantations, with an average of 31±81 Mg ha^{-1} of carbon, ranging from 0 to 537 Mg ha^{-1}. This large variation is possibly due to the presence of large trees in some of the plots. Only one model was selected and it included a strong significant positive effect of coffee shrub age and shade cover on carbon (Table 5; Figure 8c).

3.3.5. Soil fertility and yield loss due to pests and diseases

The survey data showed that coffee rust accounted for the largest share of yield loss due to pests and diseases, with an average estimated loss of 46.2±24.6%. The models for coffee yield loss due to rust showed significantly more rust damage on plantations with older coffee shrubs and situated on higher altitudes, and there was a trend towards higher rust damage with increasing shade tree density (Table A7, Table A9). Coffee yield loss due to coffee leaf rust showed a significant negative correlation with input expenses (Table A7, Table A9). Yield losses due to other pests and diseases were similar; 9.6±11.6 % due to coffee borer, 9.5±14.8% due to Ojo de Pollo and 8.5±13.1% due to Aranjero. Coffee yield losses due to coffee borer differed across regions, and we found a trend towards a negative effect of total input expenses (Table A9). Best models for both Ojo de Pollo and Aranjero explained very little variance (<1%) and were not included in final analyses (Table A8).

Soil fertility indicators showed high variability, with N varying by a factor of 16, and CEC by a factor of 25 (Table A5). In the best model sets for each soil fertility indicator, both shade management and fertilizer expenses were included. For more detailed results, see Appendix A2, Figure A3 and Table A9.

*Table 5. Averaged parameter estimates of all variables included in the models with ΔAIC <2 (Johnson and Omland, 2004) are weighed with the corresponding Akaike weight (see Table A8 for model selection procedure). Coffee shrub age, elevation and region are included as fixed variables. Levels of significance are shown as: . < 0.10; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. Units for the variables can be found in Table 4.*

		Co-variate	models containing variable	ΣWeight	Estimate		95% CI
1. Yield	a) Coffee yields (survey data; n=126)	(Intercept)			2008.155	***	879.624
		yield loss due to pests and diseases	6	0.570	-2.225	.	2.340
		chemical fertilizer expenses	5	0.430	-123.301		148.295
		total fertilizer expenses	4	0.340	-90.273		114.593
		yield loss due to coffee rust	3	0.230	-3.307		4.192
		coffee shrub density	2	0.120	-0.030		0.090

		timber shade tree density	1	0.060	-0.694		1.827
		coffee shrub age	12	1.000	-21.076	.	23.445
		elevation	12	1.000	-0.655	.	0.669
		region 2: Picota	12	1.000	-5.413		393.697
	b) Coffee yields (survey + plot data; n=39)	(Intercept)			2389.757	***	1142.500
		chemical fertilizer expenses	3	1.000	-279.001	*	231.363
		total shade tree density	2	0.630	-1.032	.	1.176
		soil OM	1	0.170	-52.015		99.843
		coffee shrub age	3	1.000	-43.976	*	37.784
		elevation	3	1.000	-0.488		1.065
		region 2: Picota	3	1.000	-322.001		419.977
2. Biodiversity	a) Forest butterfly species richness (survey + plot data; n= 53)	(Intercept)			0.203		0.576
		shade cover	2	0.320	0.003	.	0.004
		banana plant density	3	0.300	0.000		0.000
		Inga tree density	2	0.260	0.000		0.001
		total shade tree density	2	0.240	0.001		0.001
		coffee shrub age	7	1.000	0.011		0.022
		elevation	7	1.000	0.000		0.001
		region 2: Picota	7	1.000	0.487	***	0.250
	b) Non-forest butterfly species richness (survey + plot data; n=51)	(Intercept)			0.790	*	0.694
		maximum canopy height	10	0.730	-0.008	.	0.008
		timber shade tree density	5	0.330	0.000		0.000
		air temperature	5	0.320	-0.016		0.023
		shade cover	4	0.240	0.001		0.002
		coffee shrub density	3	0.160	0.000		0.000
		banana plant density	1	0.060	0.000		0.000
		coffee shrub age	14	1.000	0.006		0.012
		elevation	14	1.000	0.000		0.000
		region 2: Picota	14	1.000	0.240	***	0.119
3. Carbon	ABG carbon (survey + plot; n=53)	(Intercept)			0.436		0.772
		shade cover	1	1.000	0.017	***	0.005
		coffee shrub age	1	1.000	0.045	**	0.030
		elevation	1	1.000	0.000		0.001
		region 2: Picota	1	1.000	-0.093		0.296

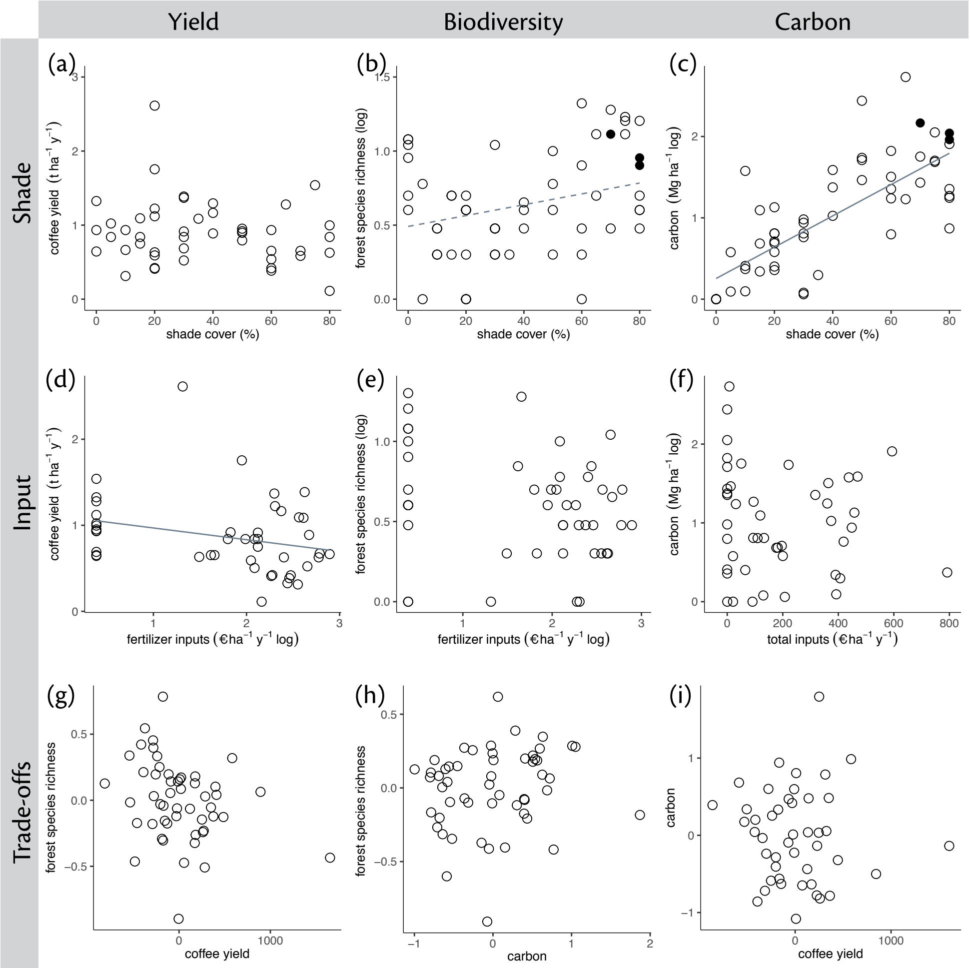

Figure 8. Effect of shade and input and exploration of trade-offs. Relation of management variables shade (first row) and input expenses (second row) are shown for: coffee yields (a, d), forest butterfly species richness (b, e) and aboveground carbon storage (c, f) with open circles. Closed circles represent observed forest butterfly species richness (b) and carbon storage (c) in natural forests as reference. Grey lines represent a significant relation (p<0.05; solid line) or a trend (p<0.1; dotted line). Exploration of trade-offs between (third-row) between (g) coffee yields and forest species richness, (h) carbon and forest species richness, (i) and coffee yields and carbon stock of linear regression analysis are presented (all $R^2<0.1$). X and Y-axis show coffee yield, biodiversity and carbon model residuals corrected for altitude, coffee shrub age and region.

3.4. Discussion

As both input and shade management can affect productivity, biodiversity and other ecosystem services, it is necessary to study their simultaneous effect (Hernández-Martínez et al., 2009), which is rarely done. Our study showed no trade-offs or synergies between coffee yields, forest butterfly species richness and above-ground carbon storage under different shade and input management regimes in smallholder coffee farms in Peru. Maintenance of higher levels of shade was associated with higher carbon storage and biodiversity, whilst amount of fertilizer and herbicide inputs showed no relation with biodiversity or carbon. Importantly, variation in levels of shade showed no negative effect on coffee yields. Contrary to expectations we found a negative conclusive relation between chemical fertilizer and coffee yields, which was possibly mediated by coffee yield losses due to a period of high incidence of coffee leaf rust. Our findings did not support other studies with regard to the negative effect of agro-chemical input on biodiversity (i.e., Gomiero et al., 2011) as higher input levels were not correlated with biodiversity, at least for the butterflies we studied. Overall, our results suggest that it is possible to manage shade to improve the conservation of biodiversity and storage of carbon, without a reduction in coffee yields.

3.4.1. Effects of shade management

While it is generally assumed that coffee yields decrease with increased levels of shade (Beer et al., 1998; Perfecto et al., 2005; Vaast et al., 2006), our results challenge this assumption by showing no relationship between coffee yields and shade cover, across a shade range of 0-80%. Although the impact of the coffee leaf rust was high for observed coffee yields, correcting for the impact of coffee leaf rust did not result in a new relation between shade and yield. These findings are in line with recent studies in Costa Rica conducted across a narrower shade range of 0-30% (Cerda et al., 2016; Meylan et al., 2017). Other studies report optimum coffee yields at intermediate shade levels of approximately 35-50% (e.g., Mora et al., 1997; Soto-Pinto et al., 2000). The majority of these studies focused on the effect of shade irrespective of applied inputs, which could explain the divergence in observed shade-yield relations. Though there is a possible bias of shade cover estimates as a result of visual estimation, this method was demonstrated to effectively characterize shade levels in the study by Bellow and Nair (2003) in particular when using trained observers as we did (Vittoz et al., 2010). Also, our results showed strong correlation between shade tree density and mean shade tree height measured in the coffee farms (Table A7, Figure A2). Consequently, we expect that the effect of a possible bias on our overall results and conclusions is limited, but nonetheless should be taken into account. On average, the levels of shade in Peru are relatively high as only 2% of the coffee farmers in Peru are estimated to cultivate coffee without shade compared to 40% worldwide (Jha et al., 2014). However, the range in shade levels observed in this study is comparable to that mentioned in other studies, such as in Mexico (Romero-Alvarado et al., 2002; Soto-Pinto et al., 2000) and India (Boreux et al., 2016).

Importantly, full-sun systems are expected to sustain a yield advantage over shaded systems only under optimal conditions (Beer et al., 1998). Therefore, although all plantations of this study were within the suitable range for Arabica coffee (500-1500 masl; Ovalle-Rivera et al., 2015), it is likely that local climate and soil conditions are sub-optimal for Arabica coffee, reducing the expected advantage sun-systems may have over shade systems (Beer et al., 1998; Vaast et al., 2006). Confirming other studies (e.g., Cerda et al., 2016; Charbonnier et al., 2017; Meylan et al., 2017) the relation between shade and input management and provisioning of ecosystem services is shown to be complex, and other characteristics such as age and elevation are of also importance - in particular if coffee is grown in suboptimal conditions. There is a need for more research spanning a wider range in altitude, shade and input management intensity to generalize the relationship between shade and input and coffee yield.

The trend that increased levels of shade maintained higher numbers of forest butterfly species richness compared to plantations with lower levels of shade is in line with the general idea that coffee plantations with higher levels of shade support higher levels of biodiversity (e.g., Bhagwat et al., 2008; Mas and Dietsch, 2003; Perfecto et al., 2005). Forest butterfly species richness observed in natural forest plots ranged between 7 and 21, values which were more closely represented in plantations with higher levels of shade (see Figure 8b). These observations are in line with the generally-supported idea that agroforestry systems can provide important refuges for forest butterfly species (Bhagwat et al., 2008), presumably as these plantations are closer in structure and diversity to natural forests than are monoculture production systems (Harvey et al., 2006). The performance of agroforestry systems might also depend on the diversity of shaded trees and associated biodiversity, suggesting its inclusion in further studies. Although butterflies do not provide direct benefits to coffee farmers, there is evidence that indicates that changes in butterfly abundance and diversity can mirror changes in other taxa, such as birds, bees and other insects (e.g., Schulze et al., 2004), some of which are known for their positive relation with coffee productivity (Kellerman et al., 2008; Perfecto et al., 2004). However, such studies may depend on the taxa and spatial scale considered (Ricketts et al., 2001), and other taxonomic groups may respond differently to shade and input management (Kessler et al., 2011).

Our results also support the idea that shaded coffee systems can significantly contribute to carbon sequestration (Jose, 2009) and the lack of relation between butterfly species richness and carbon is in line with recent findings (e.g., Di Marco et al., 2018). Above-ground carbon storage of plantations with high levels of shade was comparable to that of natural forest which ranged between 90-145 Mg ha^{-1} (n=4; Figure 8c) and was more than 15 times higher than plantations with shade levels <30%. With ~55 Mg ha^{-1}, carbon values of plantations with shade levels of >40% were comparable with shaded coffee plantations in Peru (Ehrenbergerová et al., 2016), elsewhere in Latin America (Haggar et al., 2013; Soto-Pinto et al., 2010) and other continents (van Noordwijk et al., 2002). Small plot sizes add uncertainty to the estimates of carbon values and biodiversity metrics, and in some plots individual large trees resulted in extreme carbon values when extrapolating to hectare. However, our sample size was large and we took care in avoiding such data points overly influencing the results. With more than 20 thousand ha^{-1} y^{-1}, deforestation rates of the study region San Martín are amongst the highest in Peru (Valqui et al., 2015) and it is estimated that 30% of the total primary forest area has been converted into agriculture (Rodriguez, 2010). Indeed, about 75% of the studied plantations replaced natural forest, of which a majority was established by clear-cut of natural forest trees and planting of new trees as service trees, stressing the importance of the potential of coffee plantations to maintain forest biodiversity and carbon stock values.

3.4.2. Effects of input management

Average coffee yields of this study (854±514 kg ha^{-1} y^{-1}) are comparable to average Arabica smallholder coffee plantations yields in Peru (Bean and Nolte, 2017; Nelson et al., 2016) and elsewhere in Latin America (Panhuysen and Pierrot, 2014), including Mexico (Soto-Pinto et al., 2000) and Costa Rica (ICO, 2016). Estimates of coffee yields were obtained through farmer surveys, similar to other studies (Beuchelt and Zeller, 2011; Haggar et al., 2017), as it was not possible to obtain yield-data for five consecutive years using field-measurements. Although this can be a source of error since reporting yield for consecutive years relies on memory and annotations of the farmers, we expect that even if a few reported yields are erroneous they will have little effect on average values because of our large sample size. Input use showed no relation with either biodiversity or carbon, yet coffee yields were related to inputs, in particular fertilizer and pesticide applications as yield losses due to coffee rust were lower when pesticide expenses were higher. These results come with high levels of uncertainties. Indeed, measuring pest and disease impact in an experimental setting over a representative period is costly and time consuming, so we opted for a survey rather than field-observations as this is a relatively easy way to obtain data that can be used for an integrated assessment. The negative relationship between application of fertilizer and coffee productivity may indicate that current input management seems to be reactive to the severe coffee rust incidence (Boudrot et al., 2016) and that input management can be a response to improve yields when farmers experience losses. Applying fertilizer when yields are high is recommended, as this is when many nutrients are extracted from the soil (Bornemiza, 1982). Also, the use of costs of inputs as proxy for fertilizer use, not the actual active substances found in fertilizers, may have confounded this relation. Although we found no effect of input intensity on biodiversity or carbon, some studies observed detrimental effects of the use of agrochemicals on butterfly, bee and plant diversity (e.g., Potts et al., 2010) and more research focussing on key-taxa for coffee production is recommended.

3.4.3. Implications

Shaded coffee systems supported biodiversity and carbon storage, without evidence for reduced yields. In our study area farmers can manage their plantations to maintain biodiversity and carbon, before any trade-offs with productivity start materializing, similar to what was found in Costa Rica (Cerda et al., 2016). Average yields (~850 kg ha^{-1} y^{-1}) were less than half those observed for extensive production systems in Brazil and Colombia (~1897 kg ha^{-1} y^{-1}; (Capa et al., 2015), and it is possible that clearer trade-offs are observable in such systems where other production factors are closer to optimal. However, the lack of relationship between shade cover and coffee yields is an important finding in support of adoption of agroforestry practices worldwide and in line with other studies where coffee yields were not lower for shaded systems when grown in sub-optimal conditions (e.g., Beer et al., 1998; Charbonnier et al., 2017). Application of fungicides is reported to effectively control coffee rust (Avelino et al., 2006), but at the same time this may reduce natural pest control (Vandermeer et al., 2009). Additionally, Allinne et al. (2016) recommended that pest and disease management should be adapted to physical conditions of the plantation such as climate and soil. On the short term, development and establishment of rust-resistant coffee cultivars will be an important strategy to improve and stabilize yields, particularly for farmers at lower altitudes where the disease is more severe (Ribeyre and Avelino, 2012). Adoption of sustainable coffee systems providing both economic and ecological benefits will depend on capacity building, which is currently insufficient in the area. Extension services should provide farmers with the necessary skills and information to tackle severe losses due to pest and diseases as well as support farmers with the choice of shade tree species and improved tree management, taking nutrient competition, management requirements and local markets prices of timber and fruits into consideration. In general, given that the major coffee producing regions in Peru are highly biodiverse and the majority of the coffee farms are currently managed with relatively low levels of agrochemical inputs (Bean and Nolte, 2017) and relatively high levels of shade (Jha et al., 2014), there is still large potential to safeguard biodiversity and carbon stocks while increasing income and improving livelihoods.

3.5. Conclusions

Our results provide evidence that when optimizing shade and input management for coffee production, increased carbon storage and/or biodiversity conservation in coffee plantations could be pursued simultaneously. Future research is expected to benefit from classification of coffee systems along the two dimensions of shade and input management as shade and input management independently affected yields, biodiversity and carbon. We therefore advise against using level of shade as a sole management intensity indicator. In general, more insight on the effect of environmental factors such as altitude, local climate, and specific disease problems on coffee productivity and other ecosystem services is needed to produce recommendations for a range of shade and input management across the globe.

3.6. Acknowledgements

We are grateful for the valuable support received by staff members from the local Solidaridad office in Moyobamba, Luis Sanchez Celis (CEDISA) and Ronald Mori Pezo (butterfly specialist). We thank Vincent de Leijster, Claudia Rieswijk, Steffie Rijpkema and Rutger Baar for field data collection and Martin Junginger for his critical inputs on the manuscript. We thank all coffee farmers who welcomed us to their farms and were willing to share their experiences, knowledge and views on their farming practices. The work was funded by the Business for Biodiversity project of Hivos, and Tropenbos International.

4

Effects of shade and input management on economic performance of small-scale Peruvian coffee systems

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This chapter has been published in Agricultural Systems (2018), 162, 179-190

Abstract

Tropical agroforestry systems provide a number of ecosystem services that might help sustain the production of multiple crops, improve farmers' livelihoods and conserve biodiversity. A major drawback of agroforestry coffee systems is the perceived lower economic performance compared to high-input monoculture coffee systems, which is driving worldwide intensification practices of coffee systems. However, comprehensive cost-benefit analyses of small-scale coffee plantations are scarce. Consequently, there is a need to improve our understanding of the economic performance of coffee systems under different shade and input management practices. We provide a comprehensive economic analysis of Arabica coffee farming practices where we compare productivity, costs, net income and benefit-cost ratio (BCR) of 162 small-scale, Peruvian coffee plantations under different shade and input management practices along an elevation gradient. By using a cluster analysis, three shade and three input classes (low, medium and high) were defined. We found similar economic performance for all shade classes, but reduced net income and BCR in the High-Input class. More specifically, there was no difference in net income or BCR between low, medium and high shade classes. The High-Input class had significantly lower net income and BCR, mainly due to increased costs of (hired) labour, land, and fertilizer and fungicides; costs which were not fully compensated for by higher coffee yields. Coffee yield decreased with elevation, whereas gate coffee price and quality, as well as shade levels, increased with elevation. Additional revenues from timber could increase farmers' income and overall economic performance of shaded plantations in the future. Our analysis provides evidence that for small-scale coffee production, agroforestry systems perform equally well or better than unshaded plantations with high input levels, reinforcing the theory that good economic performance can coincide with conservation of biodiversity and associated ecosystem services. Additional comprehensive and transparent economic analyses for other geographic regions are needed to be able to draw generalizable conclusions for smallholder coffee farming worldwide. We advise that future economic performance studies simultaneously address the effects of shade and input management on economic performance indicators and take biophysical variation into account.

Key words: *agroforestry systems; Arabica coffee; benefit-cost ratio; net income; smallholders*

4.1. Introduction

Millions of smallholder farmers in the humid tropics depend on tree crops such as cocoa, coffee, oil palm and rubber for their livelihoods (Schroth et al., 2014). In 2011, the annual retail value of coffee was approximately US$ 90 billion, making it the world's most valued tropical export crop (Jaramillo et al., 2011). An estimated 25 million farmers are growing coffee on over 11 million hectares in more than 60 countries (Waller et al., 2007), predominantly by smallholders who account for approximately

70% of worldwide coffee production (Bacon, 2005). In recent decades, there has been a transformation of coffee farming systems worldwide to more intensified systems by eliminating shade trees, increasing agro-chemical inputs and selecting genotypes (Bosselmann, 2012; Jha et al., 2014; Perfecto et al., 1996). Consequently, a large share of coffee production area worldwide is currently being managed without shade, and only less than a quarter of coffee plantations has multi-layered, diversified shade (Jha et al., 2014; Perfecto et al., 1996). This transformation is driven by the perceived higher economic performance of intensified systems, aiming to increase short term income (Clough et al., 2011; Siebert, 2002). Economic performance indicators such as yield, costs and profitability are important determinants for decision making of small-scale coffee farmers (Bravo-Monroy et al., 2016). This intensification trend, however, appears to come at the expense of long-term maintenance of ecosystem services relevant for agricultural production (Foley et al., 2011), as intensified farming systems are known to cause environmental problems, such as loss of biodiversity and increased soil erosion (Perfecto and Vandermeer, 2015).

Fluctuating (global) market prices and increased incidence of pest and disease are putting pressure on smallholder coffee farmers, and climate change is expected to exacerbate their vulnerability (Morton, 2007). In the face of current and future challenges, it is important to identify farming practices that meet both economic and environmental goals while being resilient to current and future changes. Tropical agroforestry systems have been proposed as farming systems which can reconcile economic and environmental goals (e.g., Schroth et al., 2004; Steffan-Dewenter et al., 2007). Ample research has shown that agroforestry systems can sustain high biodiversity levels (e.g., De Beenhouwer et al., 2013). The shade trees planted with coffee can provide other important ecosystem services such as enhanced soil fertility (Tscharntke et al., 2011) and stabilized microclimate (Lin, 2007), which are expected to reduce the vulnerability of farms to climate change (Perfecto and Vandermeer, 2015). However, because agroforestry is perceived to have lower economic performance, it is questionable whether it decreases farmers' vulnerability in face of fluctuating market prices.

In a recent review article on economic performance of shaded coffee and cocoa systems, we concluded that the general perception of lower economic performance of agroforestry systems is often based on incomplete economic analyses (Jezeer et al., 2017). Firstly, coffee yield is often used as the sole indicator of economic performance. Multiple studies have shown a negative relation between coffee yield and shade (Jaramillo-Botero et al., 2010; Vaast et al., 2006), yet this assumption is challenged by several recent studies showing that shade had no effect on coffee productivity (Cerda et al., 2016; Meylan et al., 2017). Also, despite lower coffee productivity, higher coffee prices due to improved quality or certification premiums have been linked to higher levels of shade (Muschler, 2001; Vaast et al., 2006). Secondly, the costs associated with producing coffee are not always taken into account and it is debated whether these production costs of agroforestry systems are higher than those of more intensified systems (Cerda et al., 2016) or the opposite (Lyngbæk et al., 2001). Thirdly, benefits derived from shade-tree products like fruits and firewood are frequently overlooked, underestimating potential income from agroforestry plantations. The studies that include these benefits show that shade tree products can significantly contribute to farmers' income (Cerda et al., 2014; Gobbi, 2000; Wulan et al., 2008). Overall, outcomes of previous studies suggest that it is important to not only consider coffee yield but also production costs and other revenues to evaluate economic performance because these indicators are likely to influence economic performance. To be able to compare economic performance across studies and draw generalizable lessons, more comprehensive analyses are needed that include multiple economic performance indicators.

The transformation towards more intensified coffee systems (which we define as increased use of input and lower levels of shade) has resulted in a broad spectrum of coffee plantation management practices, ranging from low-input shaded plantations to high-input full-sun plantations. For agroforestry systems, both the forestry (shade tree) and the agricultural components (e.g., input use, pruning or weeding practices) are expected to affect the productivity and economic performance of the coffee plantation and studies should reflect both simultaneously. A recent study by Cerda et al. (2016) observed an interaction between shade and input management, confirming the need to include both dimensions in comprehensive economic analyses. Additionally, it is important to take specific biophysical conditions into account, which may have a large effect on coffee productivity, bean quality and the management/productivity relation, as the coffee crop is very sensitive to changes in for example temperature, precipitation and insolation (Avelino et al., 2006; Perfecto and Vandermeer, 2015). Comparing the effect of shade and input management on performance of coffee plantations without looking into the biophysical conditions may therefore result in an incomplete or incorrect picture. In general, we expect coffee management practices to be adjusted to variation in biophysical conditions, which will in turn affect economic performance.

We aim to address the following research questions: (i) what is the economic performance of small scale coffee systems under different shade and input levels? and (ii) what are the options to enhance the economic performance of coffee agroforestry systems? We hypothesize that the benefits of high shade low input systems are at least similar to unshaded, high input coffee plantations. To this regard, we analyse the economic performance of Peruvian coffee farming practices in the department of San Martín, which is one of the major coffee producing regions of the country (Valqui et al., 2015). Here we compare productivity, costs, net income and benefit-cost ratio of small-scale coffee plantations and link this to shade and input management practices. The information compiled in this study can be useful to enhance the economic performance of smallholder coffee agroforestry systems, especially in the face of current and future challenges posed on smallholder coffee farmers worldwide.

4.2. Methods

4.2.1. Study region

The study was conducted in the department of San Martín, Peru, distributed over an area of approximately 2000 km^2 with an average altitude of 1066 m (Figure 9a; 673-1497 m). Most plantations (n=143) were situated in the provinces of Moyobamba and Rioja, which together form the 'Alto Mayo', a tropical highland with an average altitude of 1101 m (range 850-1497 m). The average rainfall is 1512 mm per year, the mean temperature 22.8°C. The remaining 19 plantations were situated in the lowland province of Picota, with an average altitude of 861 m (range 673-1001 m.). The nearest weather station lies approximately 20 km from each of these plantations at an altitude of 218 m and reports a mean temperature of 26.5 °C and a mean annual rainfall of 937 mm. The dry season occurs from May to September (Gobierno Regional de San Martín, 2008).

4.2.2. Sampling and surveying method

Household surveys were conducted with 162 coffee to characterise coffee management practices both on shade management (e.g. canopy closure, tree species richness) and on input management (e.g. application of fertilizer and pesticides), and used these to classify coffee systems in terms of shade and input. Plantations were selected to cover the range of shade and input intensity found in the study area, from full sun monoculture coffee to multi-layered shaded plantations, and from high agro-chemical input, use of organic inputs or without inputs. We chose coffee plantations older than three years and producing coffee berries with marketable beans, which were owned by smallholder farmers. Plantation elevation was measured with a GPS (Garmin GPS 62s).

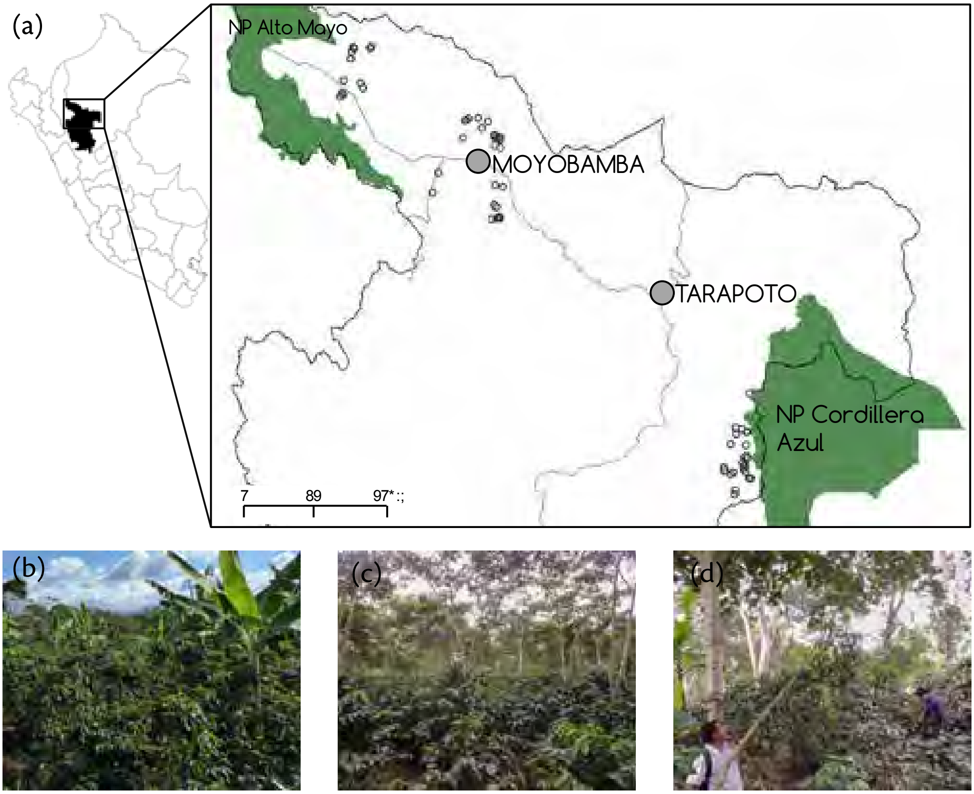

Figure 9. Study area and management regimes. (a) Study area in the region of San Martín, Peru. Open circles represent the locations of the plantations were plot measurement where made, grey-filled circles represent important cities, grey lines depict major roads and the dark green areas depict national parks. Region 1 refers to the area near Moyobamba, all north of Tarapoto, whereas region 2 refers to the area southeast of Picoa, near the national park (NP) Cordillera Azul; (b) full sun monoculture management regime, sometimes sparsely intercropped with bananas during the first years, (c) single-species shade management regime, (d) diversified shade management regime.

We performed household surveys twice; the first time in 2014 and the second time in 2016. This was necessary because the sample from 2014 did not include information on coffee bean quality and thus we collected additional information on 2016 (see below and Figure A5 for hierarchy of collected data). On both cases we performed household surveys using a semi-structured questionnaire and we collected data on (i) farm characteristics (e.g., size (ha), age (y)), (ii) shade tree species and approximate density (2014; trees ha^{-1}), (iii) harvested coffee yield (2010-2016; kg ha^{-1} y^{-1}), (iv) costs of inputs, labour and land (2014; € ha^{-1} y^{-1}), (v) coffee price (2010-2016; € kg^{-1}), (vi) coffee quality of dry green beans (2014-2016; at the farm gate, local scale from 0-100), and (vii) benefits derived from other products (firewood, fruit, livestock; 2014; € ha^{-1} y^{-1}). Data for coffee yield, price and quality for consecutive years was included for those years that the farmer could report values from 2010-2016. Coffee yield and price were obtained by both the 2014 and the 2016 surveys. Costs of input, labour, land and equipment, as well as income from other products were obtained for 2014 only. Tree species richness was assessed with the survey in 2016 by questioning the farmers about the different types of trees present at their coffee farms and by estimating the number of trees present at their coffee farm. Subsequently, the farmers were asked how difficult they thought it was to report the number and type of trees present at their coffee farm (easy, medium or difficult). If they responded that they found this 'difficult' then the answer was not included in the database. The interviewers were trained by the same person and surveys lasted between 45-60 minutes per farmer. The interviewers assessed qualitatively if the farmers responded with confidence, and outliers were double checked. In 2016, data was collected and recorded in a smartphone/tablet app developed for this study, using ODK software (ODK Collect, version 1.4.10). The app included fields for each question, which provided guidance for the surveyors to minimise interview bias.

More detailed information on plot level was obtained in 2014 using field measurements for a subset of the farms (n=62), to complement the information obtained from the household surveys (see Figure A5); it was only possible to collect such complete and detailed field data for a smaller number of farms. These were chosen to reflect the same range in shade and input management practices as that observed for all the plantations. Data collected on plot level included for example, basal area, shade level, timber tree species and timber tree values. To collect this data, we established plots of 10x10 m (n=19) or 20x20 m (n=43) in representative areas of the farm, for a subset of 62 coffee plantations. All shade trees with diameter at breast height >5 cm within the plots were identified to species level if possible and otherwise to genus level, using a field guide (Pennington et al., 2004), and knowledge from local experts and farmers. Shade tree density and tree basal area were estimated on a plot basis and extrapolated to hectare and were reported in trees ha^{-1} and m^2 ha^{-1} respectively. Tree height was measured with a Nikon Forestry Hypsometer. Level of shade (hereafter referred to as shade cover) was determined visually by estimating canopy cover on a scale of 0% to 100% (Samnegård et al., 2014). Visual estimation techniques have potential for accurately estimating shade levels (Bellow and Nair, 2003) and are recommended when it is logistically difficult to collect canopy cover data above the tall coffee canopy, using hemispheric lenses. Following Vittoz et al. (2010), who concluded that only the use of highly trained observers could improve the power for detecting changes in cover, we used at least two trained observers whom practiced until their estimated aligned before setting out to estimate shade cover for data collection. Shade trees were rarely pruned and the shade measurements were taken once per plantation from May to August in 2014 and 2015, which corresponds to the dry season. As these are predominantly tropical evergreen trees, we have no reason to expect a large variation of shade cover during the year.

4.2.3. Economic performance indicators

To compare the economic performance of coffee farms with different shade and input management practices, we evaluated a set of economic performance indicators including coffee productivity, costs, gross income, net income and benefit-cost ratio (BCR; Table 6). This set of indicators was chosen because their combination allows for a comprehensive economic performance analysis. All data was derived from farmer surveys, except for the current value of standing timber volume of shade trees that was estimated by a combination of field measurements and survey data.

4.2.3.1. Yields and revenues

Coffee yields (kg ha^{-1} y^{-1}) were reported by farmers as harvested dry coffee beans from 2010-2016. Coffee bean quality was surveyed for 2014, 2015 and 2016 and average value was used in further analysis. This measure of coffee quality is expressed on a scale from 0-100 and the rank value is given to the coffee beans by the buyer when the coffee is being purchased. This is known as 'rendimiento físico' of dry green beans and is an integrated measure of bean moisture content, size, colour, smell and percentage of defect beans (Rosero et al., 2015). We will refer to this variable as 'gate quality' from here onwards. Shade species were classified as: *Musaceae* (bananas and plantains), guavas (from the leguminous genus *Inga*), fruit trees (e.g., lemon and orange) or timber trees (all other trees). Benefits of livestock, trees and crops were estimated by taking substitution costs using the respective market prices of these products, irrespective of whether the products were sold or used for domestic consumption. The estimated prices for the most relevant agroforestry products between as reported in 2014 were €1.60 per bunch of bananas, €2.70 per bundle of firewood and €6.75 per 50 kg of cassava (*Manihot esculenta*) as reported by farmers in 2014. Standing timber value was analysed separately. Cubic volume of sawn wood (m^3 ha^{-1}) was estimated for the trees that could provide timber by first calculating the volume of round wood. In absence of local equations, we used the generic equation from the Food and Agriculture Organization (FAO), which estimates commercial wood volume per tree trunk as $v=0.42*B*H$, where B is basal area at 1.30 m above ground level, H tree height in m, and 0.42 is the generic correction factor for tapered stems. Secondly, 1 m^3 roundwood was assumed to convert to 0.52 m^3 sawn wood in Peru (Gobierno Regional de San Martín, 2012). Using local species-specific export prices for sawnwood, the monetary value of standing tree stock per plot was estimated. Third, these values were extrapolated to hectare and annuitized according to a 30 yr harvest cycle as this is the average lifespan of a coffee plantation (Wintgens, 2012). A 10% discount rate was applied which is commonly used for tropical countries and is assumed to match local conditions of the banking system (Rahman et al., 2007). As these are values estimated for currently standing trees, they represent potential rather than actual income and costs, and costs for felling, sawing and transport are not included; therefore, we chose to report all economic performance indicators without income from timber, unless specified.

4.2.3.2. Costs

Fixed costs: Land and equipment costs - Price of land and investment costs of equipment were obtained by farmer surveys. The majority of farmers own their land and we asked the purchase price to include in the analysis. There were also farmers who rent the land for periods of six or seven years. Equipment costs include the purchase of e.g., fruit pulp machines, machetes and brush cutters. All costs were annuitized assuming a 30 year's coffee cycle and applying a 10% discount rate.

Flexible costs: Labour - Labour days per management activity were recorded for establishment, pruning, weeding, fertilizing, pest and disease control, harvest and post-harvest activities. A distinction was made between hired labour and family labour. Plantation specific wages per day were used to calculate labour costs per plantation. As costs for family labour are not actually incurred costs, we hereafter refer to labour costs excluding family labour, unless specified otherwise.

Flexible costs: Input - Costs of all material used for fertilization, pest and disease control and weeding were calculated in euro per hectare per year and are referred to as inputs. Differentiation was made between (i) organic and chemical substances, and (ii) type of input in terms of herbicides, pesticides, fertilizer or fungicides.

Table 6. List of economic performance indicators and methods, formulas and assumptions used. Exchange rate of Peruvian Sol (S/.) to Euro (€) = 0.27 was applied (November 1st 2014, www.oanda.com). Values are presented on a € per hectare per year basis (€ ha^{-1} y^{-1}).

Indicators of economic performance	**Methods, formulas and assumptions**
Coffee yield (kg ha^{-1} y^{-1})	Harvested dry green coffee beans[a] from 2010-2016, average
Coffee price (€ kg^{-1})	Farm gate price from 2010-2016, average
Coffee gate quality (0-100)	Quality of coffee beans at the farm gate, from 2014-2016, average
Gross coffee income (€ ha^{-1} y^{-1})	[Yield] * [Price]
Other income (€ ha^{-1} y^{-1})	Value of firewood, other crops and livestock, estimated by the farm gate price either for sale or domestic consumption. Timber value was analysed separately
Costs (€ ha^{-1} y^{-1})	Production costs in terms of [Fixed costs] + [Flexible costs]
Net coffee income (€ ha^{-1} y^{-1})	[Gross coffee income] – [Costs]
Farm income (€ ha^{-1} y^{-1})	[Net coffee income] + [Other income]
Benefit-cost ratio (BCR)	[Net coffee income] / [Costs], with or without costs of family labour included

[a] 1 quintal (qq) of dried green coffee known as café pergamino = 56 kilogram

4.2.4. Input and shade indices

4.2.4.1. Input index

Using the survey data, an input index was calculated for each coffee plantation, similar to indices used in other coffee studies (Cerda et al., 2016; Hernández-Martínez et al., 2009; Mas and Dietsch, 2003). In this study, the input index is an aggregate of five management variables that describe fertilizing, weeding and pest and disease control activities (Table 8), which are important management practices in the region as verified based on the survey. These input management variables were transformed to range between 0 and 1. For the continuous variables (pesticide quantity and fertilizer quantity; € ha^{-1} y^{-1}), a value between 0 and 1 was obtained by $index\ value = \frac{value - minimum}{maximum - minimum}$. For the categorical variables, values of 0, 0.5 or 1 were assigned based on applied type of fertilizer, pest and disease control and weeding (Table 8). The final index value corresponds to the sum of the ranks for the five variables of each farm. These farm-specific values were subsequently re-scaled to values between 0 and 1, with zero representing the lowest input and one the highest.

4.2.4.2. Shade index

Two separate, yet complementary, shade indices were calculated, one based on field data and the other on survey data. The index based on survey data used information on shade tree density and shade tree species richness. For the farms for which we collected data in 2016, we used this data because this was considered more accurate, but if only survey 2014 data was collected, we used survey 2014 data. Consequently, there is only one shade clustering based on survey data. The index based on plot data included information on shade tree density and species richness, and also shade cover and basal area, all collected by field measurements on plot level. All variables were continuous and standardized to range between 0 and 1, as described above for input. Farm-specific totals were rescaled, with zero representing the absence of shade and one representing high shade.

4.2.4.3. Using input and shade indices for farm classification

Farm profiles were classified according to their input and shade management characteristics. To identify clusters of farms that had similar levels of shade and input management, i.e. different farm profiles, we used a Principal Component Analysis (PCA). Subsequently, we used a hierarchical cluster analysis with Euclidean distances and the Ward minimum variance method to define homogeneous groups. Analysis of variance was used to test for significant differences between farm profiles in terms of shade and input levels. For non-normally distributed data without homogeneity of variance, the non-parametric Kruskal-Wallis test was used. Data were tested for normality with Shapiro-Wilk test and for homogeneity of variances with Levene's test. More information on the cluster analysis can be found in Appendix A2 in supporting information.

4.2.5. Statistical analysis

To assess if there was a relation between input and shade management and cost and benefits, we checked for correlations between general plantations characteristics, input and shade management variables and cost and benefit indicators with Pearson correlation coefficient for normally distributed variables. Spearman's rank correlation was used for data which did not meet assumptions of normality. To assess whether economic performance differed between input classes and shade classes we used Kruskal–Wallis test and Tukey's post-hoc test with Chi-square distance. We checked for correlations between the explanatory variables with Spearman's rank correlation (Table A12), which was also used to check the robustness of the data obtained, in particular the visually estimated shade cover (Figure A9). Significance level was set at $\alpha=0.05$. Statistical analyses were performed with R (version 3.0.2, R Core Team, 2014), using the 'mclust' (Fraley et al., 2017) and 'car' (Fox et al., 2016) packages.

4.3. Results

4.3.1. plantation characteristics

Average coffee plantation area was 2.74±1.96 ha (Table 7), which is general for Peru as the largest share of coffee in San Martín is produced by smallholders (CENAGRO 2012). The majority of the farmers were migrants (90%) and farmers had on average 14±8 years of experience of cultivating coffee. Only Arabica coffee (*Coffea arabica L.*), is grown in this region, of which Costa Rica 95 from the Catimor family and Iapar 59 were recognized as more coffee rust- tolerant varieties, and Pache, Caturra, Típica, Borbón, Catuaí and Nacional as varieties more sensitive to coffee rust (Arrieta et al., 2016). In total, 533 individual shade trees and plants were observed, the majority of which was identified to species level (92.5%). A third of observed trees and plants was a mix of bananas and palm trees (32.6%) and the other third were Inga trees (33.3%). Of the remaining shade trees, 146 individual trees were identified to species level (27.4%), which consisted of a mix of 39 tree species. The remaining shade trees could not be identified to species level (6.5%). The shade index was significantly higher for plantations at higher elevations (see Table A12). For more information on plantation characteristics see Table 7).

Table 7. Descriptive statistics of general plantation characteristics and shade and input practices. Data was collected using farmer surveys, unless indicated otherwise.

	unit	*mean*	*±SD*	*min*	*max*	*n*
General farm characteristics						
Farm size	ha	6.38	8.42	0.50	80.00	154
Productive coffee area	ha	2.74	1.96	0.50	13.00	154
Elevation	m a.s.l.	1066.36	171.74	673.00	1497.00	162
Coffee shrub age	year	8.75	4.56	3.00	30.00	159
Coffee shrub density	shrubs ha^{-1}	3934.63	1139.65	1000.00	7000.00	154
Shade management						
Shade tree density	trees ha^{-1}	71.34	105.33	0.00	700.00	154
Shade tree density (plot)	trees ha^{-1}	222.22	183.75	0.00	700.00	54
Shade tree species richness	species per $farm^{-1}$	4.24	3.6	0.00	22.00	161
Shade tree species richness (plot)	species per plot	2.31	1.72	0.00	7.00	54
Shade cover (plot)	%	36.76	26.74	0.00	80.00	54
Basal area (plot)	m^2 ha^{-1}	8.84	15.91	0.00	101.42	54
Input management						
Total	€ ha^{-1} y^{-1}	149.74	196.90	0.00	1021.80	151
Fertilizer	€ ha^{-1} y^{-1}	123.93	174.29	0.00	951.60	140
Pesticide	€ ha^{-1} y^{-1}	34.07	77.25	0.00	468.00	128
Herbicides	€ ha^{-1} y^{-1}	6.67	26.21	0.00	249.60	138

4.3.2. Input and shade indices

Three shade classes were distinguished for the field and the survey data (Low-, Medium- and High-Shade) that differed significantly for all shade variables (Figure 10, Table 8). The Low-Shade class derived from the field-subset (n=8) corresponded to a mean shade cover of 1.2±2.3% and on average 13±23 shade trees ha^{-1}, on average from a single tree species. The Medium-Shade plantations (n=27) corresponded to a mean level of shade of 28±16% and an average of 157±65 shade trees ha^{-1}, on average with two species. High-Shade plantations (n=19) were characterized by a mean shade cover of 64±17% and an average of 403±181 shade trees ha^{-1}, which consisted of three different shade tree species on average. For more details on the cluster analysis see Appendix A3.

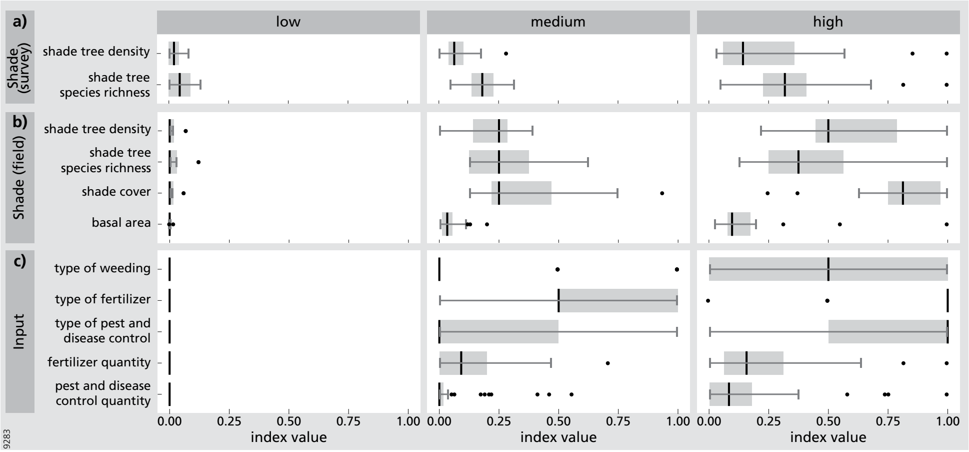

Figure 10. Representation of profiles obtained from a hierarchical cluster analysis of variables describing; a) Shade practices (survey data); b) Shade practices (field data) and c) Input practices. Shade practices variables included are: shade tree density, shade tree species richness, level of shade and basal area. Input practices variables included are: type of weeding (0= by hand, machete; 0.5= mechanical, brush cutter; 1= herbicide), fertilizer type (0=none, 0.5= organic; 1= chemical), pest control type (0=none, 0.5= organic; 1= chemical), fertilizer quantity (fertilizer costs, € ha^{-1} y^{-1}) and pest and disease control quantity (costs of e.g., pesticides and fungicides, € ha^{-1} y^{-1}). Boxplots indicate the lower quartile, median and upper quartile, with whiskers extending to the most extreme data point that is no more than 1.5 times the interquartile range from the edge of the box.

Three input classes (Low-, Medium- and High-Input) were significantly different for variables describing the fertilizing, weeding and pest and disease control management (Figure 10, Table 8). Low-Input plantations (n=23) were characterized by absence of pest and disease control activities and fertilizer application and all weeding was done manually. Medium-Input plantations corresponded to the largest group of farmers (n=50) and who spent on average € 124 ha^{-1} y^{-1} on predominantly organic fertilizers. Also, some of these farmers applied pest and disease control (40%), largely using organic inputs (72%). Although the majority of the farmers were weeding manually, some farmers were weeding mechanically by using a bush cutter. High-Input plantations (n=37) corresponded to plantations where weeding was mostly mechanical, yet some were applying herbicides. The majority of these farmers applied chemical fertilizers with a cost of € 220 ha^{-1} y^{-1} and applied chemicals (pesticides and/or fungicides) to control pests and diseases. Overall, applied fertilizer, weed and pest management intensities were higher on plantations at lower elevations, as the Input Index was negatively related to elevation (see Table A12). The values obtained by the survey and by field work shows strong correlation for species richness (R^2=0.55; p<0.001) and shade tree density (R^2=0.78; p<0.001).

*Table 8. List of selected variables to obtain Input and Shade Indices and description of coffee plantation management practices. Results are obtained from a k-means cluster analysis for Shade Index (survey), Shade Index (field) and Input Index separate. For each group, mean and standard deviation (SD) are summarized for all variables. Significant differences between groups were evaluated using an ANOVA performed on a linear model for data with a Normal distribution (a) or with a Kruskal–Wallis non-parametric test (b). Significance level of $p<0.001$ is indicated with ***.*

		low (n=45) mean		**SD**	***medium (n=56) mean***		**SD**	***high (n=51) mean***		**SD**	***Sig.***
Shade Index (survey)	shade tree density (trees ha^{-1})	19.0	±	20.0	52.0	±	35.0	153.0	±	149.0	*** (b)
	shade tree species richness (per farm)	1.0	±	1.0	3.9	±	1.4	7.5	±	4.1	*** (b)
	Shade Index	0.0	±	0.0	0.1	±	0.0	0.3	±	0.1	*** (b)

		low (n=8) mean		**SD**	***medium (n=27) mean***		**SD**	***high (n=19) mean***		**SD**	***Sig.***
Shade Index (field)	shade tree density (trees ha^{-1})	12.0	±	23.0	157.0	±	65.0	403.0	±	181.0	*** (b)
	shade tree species richness (per plot)	0.3	±	0.5	2.1	±	1.2	3.5	±	1.8	*** (b)
	shade cover (%)	1.2	±	2.3	28.3	±	16.3	63.7	±	16.9	*** (b)
	basal area (m^2 ha^{-1})	0.3	±	0.7	4.6	±	4.8	18.6	±	23.5	*** (b)
	Shade Index	0.0	±	0.0	0.2	±	0.1	0.5	±	0.1	*** (a)

		low (n=23) mean		**SD**	***medium (n=50) mean***		**SD**	***high (n=37) mean***		**SD**	***Sig.***
Input index	pesticide quantity [a] (€ ha^{-1} y^{-1})	0.0	±	0.0	25.0	±	58.0	80.0	±	114.0	*** (b)
	fertilizer quantity [a] (€ ha^{-1} y^{-1})	0.0	±	0.0	124.0	±	146.0	220.0	±	222.0	*** (b)
	type of pest and disease control (0=none, 0.5= organic; 1= chemical)	0.0	±	0.0	0.3	±	0.4	0.7	±	0.4	*** (b)
	type of fertilizer (0=none, 0.5= organic; 1= chemical)	0.0	±	0.0	0.5	±	0.4	0.9	±	0.2	*** (b)
	type of weeding (0= by hand; 0.5= mechanical; 1= chemical)	0.0	±	0.0	0.2	±	0.4	0.5	±	0.4	*** (b)
	Input Index	0.0	±	0.0	0.2	±	0.1	0.5	±	0.1	*** (b)

[a] Input such as fertilizer or pesticides are partly used as concentrates, we therefore considered the total value of the applied herbicides in the analyses, assuming a positive correlation between the concentration of active substances and price.

4.3.3. Economic performance

Here we present the results from the analysis of the effects of shade and input practices on economic performance indicators, while taking the effect of elevation into account. We first present results on the benefits derived from coffee and other products, and secondly the costs of coffee production. Finally, we present the results on net income and BCR of coffee plantations under different shade and input management practices.

4.3.3.1. Gross revenues of coffee, other farm products and timber

Gross coffee revenues averaged (±SD) 1585±917 € ha^{-1} y^{-1} and ranged between 204 and 5080 € ha^{-1} y^{-1}. Following these large differences, there was a significant difference in gross coffee revenues between shade classes, with higher gross revenues for Medium-Shade than for High-Shade (Figure 11a-b; see Table A13 for detailed numbers). Additionally, we found a trend of lower gross coffee revenues for Medium-Input compared to High-Input. The large variation in gross coffee revenues can partially be explained by the large variation in coffee yield, which ranged between 112 and 2893 kg ha^{-1} y^{-1} (854±514 kg ha^{-1} y^{-1}). Coffee yield was also highly variable over the years as average yields in 2014 were roughly half of those in 2011, respectively 1162 and 514 kg ha^{-1} y^{-1} (Figure A10). Coffee yields were significantly lower for High-Shade plantations compared to Medium-Shade and there was a negative relation between the shade index derived from the survey data (n=162) and coffee yields (Figure 12, Table A13). This relation was not found for the Shade classes based on field measurements (n=62; Table A13). Also, coffee yields were higher in plantations with higher costs (R2= 0.39; p-value<0.001), i.e., costs for the land and equipment (R^2=0.33; p-value<0.001), chemical inputs (R^2= 0.15; p-value<0.05) and hired labour (R^2=0.35; p-value <0.001). There was a large variability in the price that farmers received for their coffee beans (1.87±0.26 € kg^{-1}), which ranged between 1.21 and 2.74 € kg^{-1} (Figure A10). Coffee bean price significantly increased with gate quality (R^2=0.38) and fluctuated over the years (Figure A10). We found no relation between gate quality and shade or input practices, yet gate quality was significantly higher on plantations situated at higher elevations (Figure 12).

On top of gross coffee revenues, farmers were estimated to receive an additional 345±314 € ha^{-1} y^{-1} from firewood, livestock and other crops combined, either by selling these products or use them for their own livelihoods. Though no difference in revenue from other products was observed between input classes, there was a difference in revenues between shade classes obtained by farmer surveys. Even without including potential timber income, farmers with Medium- and High-Shade plantations gained approximately 60% more income from other products compared to Low-Shade plantations (Table A13). Timber value was highly variable (238±852 € ha^{-1} y^{-1}) and potential income from timber was significantly higher for High-Shade compared to Low-Shade plantations. When gross revenues for coffee and other products were combined (with or without potential timber income), no differences in gross revenues were observed between input classes or between shade classes. Gross coffee revenues decreased significantly with increasing elevation, reflecting the negative relation between elevation and coffee yield (Figure 12).

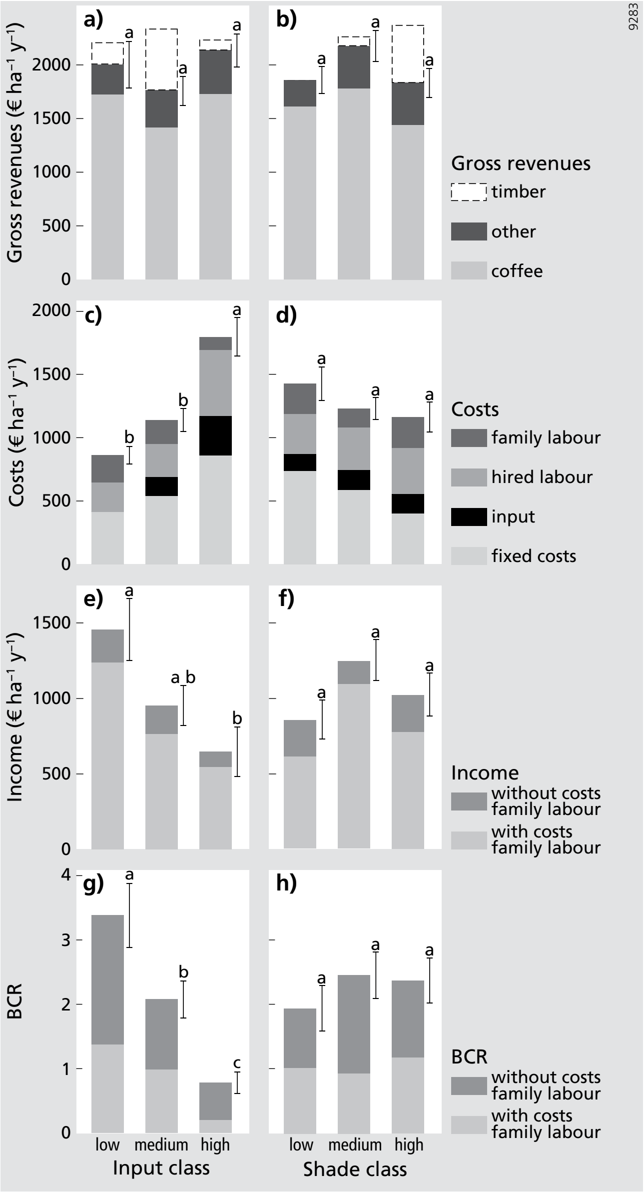

Figure 11. Revenues (a-b), costs (c-d), net income (e-f) and BCR (g-h) are presented for input (left column) and shade (right column) practices classified as low, medium and high. Bars sharing the same letter are not significantly different (p≤0.05) among mean values between classes. For more details on descriptive statistics and Kruskal-Wallis tests see Table A13.

4.3.3.2. Costs of coffee production

Total costs of coffee production were variable (1378±905 € ha^{-1} y^{-1}) and ranged between 103 and 5745 € ha^{-1} y^{-1}. The largest share of these costs were associated with land (44%), followed by labour costs (38%). Input only accounted for an average of 11% of all costs, of which fertilizer was the most important (83%; Figure 11c, d). Not surprisingly, costs of fertilizer, pesticide and herbicide input were significantly different between all input classes as these variables were used to cluster input profiles (Figure 11c, d; Table A13). Land costs were twice as high for High-Input compared to Low-Input and were higher for plantations at lower elevations. Total labour costs showed no difference between input classes, yet separate analysis of costs for hired and family labour showed contrasting results. Family labour costs showed a trend of being more than twice as high for Low-Input compared to High-Input, whereas costs of hired labour of High-Input were significantly higher and double of those of Medium-Input. Total production costs associated with High-Input plantations were approximately twice the costs associated with Medium- and Low-Input plantations (Figure 11c), both with and without costs of family labour, land costs and/or input costs. Despite a significant reduction in land costs for High-Shade plantations, no significant difference was detected in total production costs between shade groups (Figure 11d). Costs of organic input and family labour increased with elevation, while the opposite was the case for costs of chemical input and hired labour, as these were lower at higher elevations (Table A12). Costs were significantly lower for plantations at higher elevations (Figure 12).

4.3.3.3. Net income and BCR

Similar to costs and benefits, net income was highly variable with an average income of 1047±949 € ha^{-1} y^{-1}, ranging from -1480 to 4303 € ha^{-1} y^{-1}, which includes benefits from other products except timber revenues. With an average value of 345±314 € ha^{-1} y^{-1}, benefits from firewood, other crops and fruits and livestock add 49% to the average net farmer income obtained from coffee alone. Net income was significantly lower for High-Input compared to Low-Input, irrespective of whether also costs of family labour were included (Figure 11e). No difference in income was detected between shade groups (Figure 11f), nor was there a difference in net income for plantations at different elevations (Figure 12). BCR showed a high variability, with an average of 2.6±3.1 and a range of -0.85 and 13.63. BCR was highest for Low-Input, followed by Medium-Input (Figure 11g). These results suggest that the majority of the farming strategies were profitable as the break-even point of 1.0 was surpassed by 63% of the farmers. Although 14% of the farmers had five times higher returns than their investment costs, 37% of the farmers were experiencing losses, as their BCRs were <1.0. In particular, BCR of plantations with highest input levels was on average 0.78±1.05. No significant difference in net income or BCR was found between shade classes (Figure 11f, h) and for each shade class, average BCR was >1.0 (Figure 11h; Table A13). BCR was significantly higher for plantations at higher elevations (Figure 12).

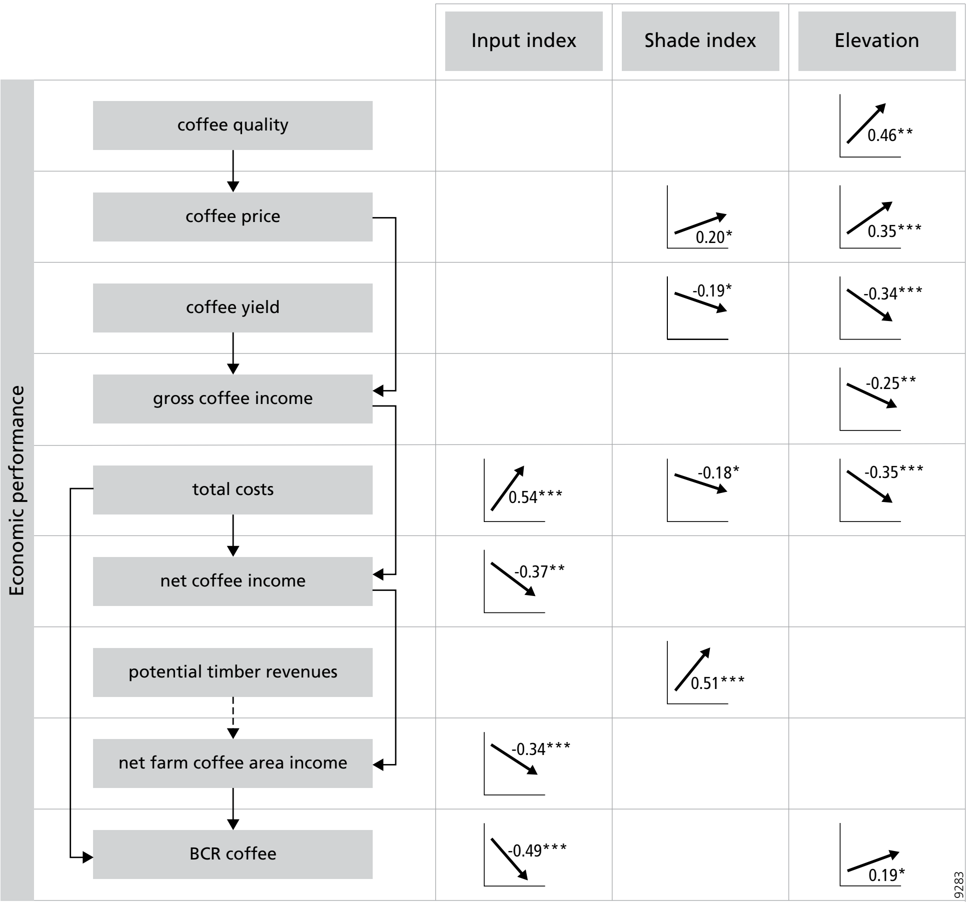

*Figure 12. Correlation matrix between economic performance indicators (y-axis) and Input Index (left column); Shade Index (middle column) and elevation (right column). Spearman rank correlation coefficients are shown. The level of significance is indicated with [empty] at p > 0.5; *p < 0.05; **p < 0.01; ***p < 0.001. For a more detailed correlation matrix see Table A12.*

4.4. Discussion

This case study provides evidence that the economic performance of coffee agroforestry systems is equally good or better than that of unshaded plantations and/or with higher input levels. The novelty of this study is that the effects of shade and input practices on net income and BCR are taken into account, as well as costs and benefits of coffee production and benefits of other products, making this a comprehensive economic performance analysis. We find that while shade showed no relation with either net income or BCR, input was negatively related to economic performance. At the same time, these relations were elevation dependent likely due to differences in biophysical conditions. In the following sections, we discuss how the economic performance in terms of net income and benefit-cost ratio was affected by shade and input management, and what the implications are for smallholder coffee farmers.

4.4.1. Net income and benefit-cost ratio

The results of this study suggest that there is no difference in economic performance between small-scale coffee plantations with different shade levels as there were no differences between net income and BCR for plantations with different shade management practices. Rather, we observed a difference in economic performance between plantations with different levels of input as net income and BCR were lower for plantations with higher input practices. With an average net coffee income of 702±961 € ha^{-1} y^{-1}, the results of this study are in line with a recent study of Nelson et al. (2016), where net income of Peruvian coffee farmers in the department of San Martín was estimated to be 836 € ha^{-1} in 2011. These observed average BCR values (2.6±3.1) are in line with findings of a recent meta-analysis, where an average BCR value of 1.9 was obtained from thirteen shaded coffee systems located in six different countries (Jezeer et al., 2017). About a third of the farmers were experiencing losses, which are likely related to recent outbreaks of coffee leaf rust (*Hemileia vastatrix*) and the high costs of production, as explained in more detail below. Including the costs of family labour further reduced the BCR of these farmers. For all shade classes, average BCR was >1.0, indicating that the average farmer was gaining income from their plantations. This is likely because of reduced average labour costs and lower average input costs across different shade levels, and (when taken into consideration) added benefits from firewood, livestock and other crops. In the next sections, we will elaborate on the benefits and costs associated with shade and input practices, as well as the effect of diversification, i.e., mixed cropping systems, on economic performance.

4.4.2. Benefits

With an average of 854±514 kg ha^{-1} y^{-1}, coffee yield was comparable to average Arabica smallholder coffee plantations yields in Peru (Bean and Nolte, 2017; Nelson et al., 2016) and elsewhere in Latin American countries (Panhuysen and Pierrot, 2014; Soto-Pinto et al., 2000). An explanation for the large variation observed in coffee yields could be found in the recent outbreak of coffee leaf rust. This outbreak peaked in 2013/2014 in Peru (Avelino et al., 2015) and has been estimated to drop yields of Peruvian farmers on average by half (Nelson et al., 2016). Estimates of coffee yields were obtained from farmer surveys, similar to other studies (Beuchert & Zeller, 2016; Haggar et al., 2017). This can be a source of error, since reporting yield for consecutive years relies on memory and annotations of the farmers. Unfortunately we do not have field data to verify these estimates, yet we expect that even if a few reportings of yield are erroneous they will have little effect on average values because of our large sample size. The general consensus is that yield decreases with increased levels of shade

(Beer et al., 1998; Perfecto et al., 2005; Vaast et al., 2006). Our results support this as we observed lower coffee yields at higher shade tree densities, resulting in a negative relationship between coffee yield and shade index obtained from farmer survey data. No negative relation was observed between the shade index obtained from plot data and coffee yields, suggesting that the relationship depends on the methods used for measurements of shade. Though there is a possible bias of shade cover estimates as a result of visual estimation, this method was reported to be accurate (Bellow and Nair, 2003) in particular when using trained observers as we did (Vittoz et al., 2010). Also, our shade cover results showed strong correlation with shade tree density and mean shade tree height measured in the coffee farms (Table A12, Figure A9) and importantly, shade cover was only used in combination with other variables (shade index) and therefore we expect that even if generally biased, its effect on our overall results and conclusions is limited.

In recent years, farmers gained stronger interest in high quality coffee as demand for specialty coffees increased rapidly; sustainable coffee sales (often certified) in terms of volume increased by more than 400% between 2004-2009 and is only expected to increase further (Vellema et al., 2015). Fluctuating coffee prices are a major issue for smallholder coffee farmers, and it has been shown that in times of low world coffee prices the prices of certified coffee did not drop as low as overall market prices in Peru (Nelson et al., 2016). Although this was not observed, we saw that coffee prices were higher if gate quality was higher. A study in Mexican coffee systems shows that the dominant shift in this country to non-coffee activities was attributed to the low and variable coffee prices (Padrón and Burger, 2015), which suggests that changes in coffee price lead to diversification. As demonstrated for coffee production in Latin America, elevation and shade were expected to improve coffee quality (Muschler, 2001; Vaast et al., 2006). The relation with elevation was confirmed in this study, but we found no relationship between shade index and gate quality. These results are in line with a study of Bosselmann et al. (2009) in Colombia, where the relation between shade and quality was more complex as it depended on elevation. Although similar, the measure we used for bean quality is different from the measure of bean quality used by Vaast et al. (2006) and Bosselmann et al. (2009), which could have affected this observation.

4.4.3. Costs

With an average 1032±783 € ha^{-1} y^{-1}, costs estimated in this study were comparable to those of a recent study which reported expenditures of approximately 1068 € ha^{-1} y^{-1} for coffee production in the department of San Martín, Peru, and between 800 and 1300 € ha^{-1} y^{-1} for coffee production in El Salvador and Colombia (Nelson et al., 2016). Costs of intensified systems were higher, both for flexible (input and labour) and fixed costs (land and equipment), while an opposite relation with shade was observed as costs were lower for plantations with higher shade levels. These dynamics are not just seen in Peru but also in other coffee producing countries. For example Gobbi (2000) demonstrated that in El Salvador, the capital requirements for shaded coffee systems were low and that these requirements increased with a reduction in shade levels. Land costs in particular were high in this study as they accounted on average for 44% of the total costs. These high land costs can be partially explained by the recommended 10% discount rate (Rahman et al., 2007). However, it was clear that High-Input plantations were associated with higher land costs in general, irrespective of this applied discount rate. This could indicate that if land costs are higher, farmers are more likely to resort to high intensity practices (high input - low shade) expecting that this will increase net benefits. More generally, our study results corroborate the understanding that intensive management is related to higher yields, as higher yields were positively correlated with amount of hired labour and costs. Importantly, increase in coffee yields was not correlated with net income for these farmers. This corroborates the findings of our recent review on the economic performance of shaded coffee and cocoa plantations where we found that in general yield alone is not a good indicator of economic performance of these production systems, and more comprehensive economic assessments are needed.

More generally, a steep increase in production costs was observed in major Latin American coffee producing countries in recent years (ICO, 2016), linked to increasing labour costs and to rising prices of agro-chemical inputs. Indeed, as a response to the coffee leaf rust outbreaks, many of the farmers in the region have invested in their plantations by switching to more coffee rust resilient varieties to minimise future coffee rust induced yield losses. It appeared that farmers with high-input practices reported lower yield losses due to coffee rust (personal observation), but this was not translated into better economic performance. It has indeed been demonstrated that a reduction and misuse of inputs such as fertilizers and fungicides were important factors in the variability of the impact of the coffee rust epidemic (Avelino et al., 2015). Training of farmers to apply fertilizers and fungicides more effectively is therefore recommended. As small-scale farmers often have limited access to resources and capital, which is no different for Peru (USDA, 2014), the lower costs associated with high shade practices may be a more attractive option for many coffee farmers.

4.4.4. Diversification

Benefits derived from other products can greatly contribute to the income of small-scale farmers (Rice, 2008). In our case, income from other products accounted for an average of 32% of total farm income, excluding potential income from timber, and was lowest for plantations with high input levels and low shade levels. If the potential income from timber would be realized, the total yearly income could increase by a third in High-Shade plantations. Similar results were also found in Costa Rica and Guatemala, where income from timber and firewood accounted for more than 70% of the income derived from shaded coffee plantations (Martínez Acosta, 2005; Mehta and Leuschner, 1997). Souza et al. (2010) found similar results, as income derived from other products (mainly fruits) added more than a third to the income of coffee farmers in Brazil. There is some uncertainty in our estimates of timber values due to small plot sizes and the occurrence of some large trees and highly valuable tree species, which resulted in high timber values when extrapolating to hectare. However, our sample size was large enough and we took care in avoiding such data points overly influencing the results. Our estimate of timber values combined sawn-mill prices with current standing stock, without including costs for e.g., felling and transport. The former two were likely overestimated as they did not reflect the price farmers could receive for the harvested round wood based in commercial tree height, while the later did not consider economic effects over a 30-year cycle. Overall, it is clear that benefits from fruit trees, timber or firewood are significant and may result in a better financial performance than would occur in plantations without shade trees or with a low amount of Inga trees (Beer et al., 1998). There are, however, important ecological and economic challenges that need to be overcome, such as market access and improving the management of shade trees. If these barriers are overcome, the benefits derived from shade trees can provide important contributions to farmers' livelihoods, especially in times of low coffee prices or productivity, thereby increasing farmers' economic resilience. Although the focus of this article is on economic performance, the assumption that environmental performance is higher with higher levels of shade or lower levels of input is important to make a case for farming systems that can reconcile economic and environmental goals.

Small-scale farmers are very sensitive to changes in coffee prices and declining coffee yields, as coffee often provides their main source of income. The farmers in San Martín are no exception, as coffee provided for more than 50% of farmers' income (excluding potential timber revenues). Due to diversification, fluctuations in coffee prices will have a lower impact on total income (Gordon et al., 2007) as income from other products can be retrieved in times of low prices or failure of the coffee production. Also, environmental benefits provided by shade trees such as erosion control or nutrient cycling are less frequently included in these calculations, further underestimating potential benefits from agroforestry plantations. Compared with other Latin American coffee producing countries, intensification of shade practices in Peru is lower and only 2% of the total production was estimated to take place under full sun conditions in 2010 (Jha et al., 2014). Although this suggests that there is great potential for small scale coffee farmers in Peru to reconcile ecological and economic needs, more insight about the economic performance of coffee plantations under different management practices is needed in order to deviate from the global trend towards intensification of coffee systems.

4.5. Conclusions

Our results suggest that intercropping coffee with shade trees shows no negative relation with economic performance of smallholder coffee systems. Rather, income from other products, including income from timber, can provide these farmers with an extra source of income which is an opportunity to increase their economic resilience. As we find that economic performance shows no relation with shade management, our results suggest that conservation of biodiversity and associated ecosystem services can coincide with local development. This article therefore provides important evidence in the support of a transition towards economically and ecologically sustainable systems, which is not only needed to provide farmers with sustainable livelihoods, but also to decrease landscape degradation.

Economic performance is expected to be an important driver of farmer decision making. The most common argument against agroforestry practices is that the economic performance is relatively low in comparison to more intensive and/or unshaded plantations, thereby driving intensification practices which consequently result in environmental degradation. Extension services should support farmers with the choice of shade tree species and improved tree management, taking local market prices of timber and fruits into consideration. Furthermore, training of farmers to apply fertilizers and fungicides more effectively is highly recommended, keeping in mind that pest and disease control should be adapted to physical conditions of the plantation such as climate and soil. Such extension services seem to be increasingly important in response to the fluctuating coffee prices, rising production costs and increased pest and disease pressure.

In order to reconcile economic and ecological goals in coffee systems, comprehensive economic analyses are needed to be able to draw generalizable conclusions and gain insight in trade-offs between economic and environmental performance. To this regard, future economic performance studies should simultaneously address the effects of shade and input management on multiple economic performance indicators and take variation in biophysical variation into account.

4.6. Acknowledgements

We are grateful for the valuable support received by staff members of the local Solidaridad office in Moyobamba and Luis Sánchez Celis. We thank Vincent de Leijster, Claudia Rieswijk, Steffie Rijpkema and Rutger Baar for field data collection. We thank all coffee farmers who welcomed us to their farms and shared experiences, knowledge and views on their farming practices. Data collection and data analysis were funded by the Business for Biodiversity project of Hivos, while Tropenbos International also supported data analysis and writing.

5

Livelihood assets, experienced shocks and perceived risks on smallholder coffee management strategies in Peru

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Abstract

Smallholder farmers can adopt different management strategies to cope with the multiple stressors they face using different livelihood assets, and such decisions might have different environmental and economic outcomes. Ongoing global change, however, is leading to stronger and different stressors likely mismatched with conventional management strategies; however, this mismatch could be resolved if the livelihood assets that drive decision making are actionable. This study assessed the influence of farmers' livelihoods assets, shocks, and risk perception on the adoption of management strategies for smallholder coffee farmers in San Martín, Peru. We operationalized the sustainable livelihoods framework for the adoption of shade and input coffee management strategies and explored farmers' motives to change shade and input management strategies. We found that higher human and social assets were associated with higher shade, while a trend of higher physical and financial assets was associated with higher input use. Despite perceptions of pest and disease pressure, coffee price volatility and climate change being high, they did not explain the current shade and input management strategies. Nonetheless, farmers adapted shade and input management over the last five years as a response to pest and disease and climate change pressures, and these adaptations were in opposite directions. These findings illustrate how the many factors that influence decision-making process of smallholder farmers may push-and-pull decisions in different directions, and that perception of risk and shocks might not be sufficient to motivate behavioural change and adaptation under uncertainty. However, the relation between human and social assets with shade management suggests that these actionable assets can be useful in dealing with global changes. The insights gained on the drivers for adoption of management strategies can support the development of management strategies that enhance resilience and sustainability of smallholder coffee producers in Peru and elsewhere.

Key words: *Decision making; sustainable livelihoods framework; Arabica coffee; Capitals; shade management; input management*

5.1. Introduction

There is a global trend towards intensification of cultivation of tree crops such as oil palm, cocoa, rubber and coffee in the tropics, which is driven by the perceived higher economic performance of intensified systems aiming to increase short term income (Clough et al., 2011; Siebert, 2002). This intensification trend, however, occurs at the expense of the long-term maintenance of ecosystem services relevant for agricultural production (Foley et al., 2011). Millions of smallholders depend heavily on these tree crops for their livelihoods (Schroth and Ruf, 2014), making them particularly vulnerable to volatile market prices and global environmental changes as soil degradation, land and climate changes (Morton, 2007). Consequently, there is a need for management systems that are both productive and resilient, where alternative approaches that align short-term gains with long-term benefits, for example aligning enhanced crop yield and farmer income with maintenance of ecosystem services. Alternative approaches based on agro-ecological principles (i.e. the application of ecological concepts and principles to the design and management of sustainable agricultural systems (Gliessman, 1992)) seek to balance the maintenance of ecosystem services, and to reconcile economic and environmental goals (Altieri, 2002). Smallholder farmers adopt a wide range of management strategies with different environmental and economic outcomes, partially in response to stressors. Therefore, a better understanding of the opportunities and constraints farmers experience and the role of stressors is needed to gain insight in drivers of the adoption of different management strategies, especially in the context of global change and uncertainty.

Coffee is one of the tropical commodity crops for which the increasing worldwide demand is motivating coffee farmers to expand cultivated land (Defries et al., 2010; Laurance, 1999) and to intensify management strategies (Jha et al., 2014). An estimated 25 million farmers are growing coffee on over 11 million ha in >60 countries (Waller et al., 2007). These are predominantly smallholders, accounting for approximately 70% of worldwide coffee production (Bacon, 2005). Coffee farmers face multiple pressures. Although coffee prices have always fluctuated, over the last two decades, processes of market liberalization and integration have increased the exposure of farmers to volatile coffee prices (Eakin et al., 2014; Tucker et al., 2010). Additionally, a recent pest outbreak (coffee leaf rust (*Hemileia vastarix*)) in Latin America reduced production by 10% to 70% during peak years '13 and '14 (Avelino et al., 2015; Jha et al., 2014). On top of that, climate models predict higher maximum temperatures and rainfall variability for many Latin American coffee producing countries (Imbach et al., 2017), with potential negative effects on coffee production and quality, increased susceptibility to pests, and changes in the most suitable locations for coffee crops (Bunn et al., 2015). To deal with these pressures, smallholder coffee farmers can adopt different management strategies. Typical intensification strategies for coffee cultivation are the removal of shade trees (Aerts et al., 2011; Perfecto and Vandermeer, 2015), increase agro-chemical inputs, planting coffee shrubs in higher densities and planting new coffee varieties (Jha et al., 2014). Alternatively, smallholders can apply more environmentally-friendly management strategies, such as agro-ecological or agroforestry management strategies. These strategies are characterized by lower dependence on external inputs, higher shade levels and diversification of income (Perfecto and Vandermeer, 2015; Ruf and Schroth, 2015), and are often promoted by certification schemes.

Although there is a generalized assumption (implicit or explicit) that smallholder farmers aim to maximise productivity and profitability (Edwards-Jones, 2006; McGregor et al., 2001) research has shown that many other criteria are involved in making decisions (Feola and Binder, 2010). Smallholder farmers can adopt management strategies to pursue objectives that can range from maximizing economic performance to minimizing risks, and from stabilizing income to maintaining food security (Schroth and Ruf, 2014). Farmer decision making can be facilitated or constrained by the assets they have, i.e., their access to social, economic, cultural and biophysical resources (Bravo-Monroy et al., 2016). Assets like farmer wealth and access to credit have facilitated the adoption of management strategies that decrease risks (Bullock et al., 2014; Rahman, 2003). Wealth and level of education also lead to adoption of integrated pest management by Colombian coffee farmers (Chaves and Riley, 2001), and lack of capital or credit constrained Côte d'Ivoire farmers to diversify their cocoa plantations (Schroth and Ruf, 2014). Farmers' skills, knowledge and experience also led to the adoption of new and more environmentally-friendly management strategies (Chaves and Riley, 2001; Quiroga et al., 2015; Wollni and Brümmer, 2012). Membership of farmers' cooperatives or associations made Colombian farmers adopt certification schemes (Bravo-Monroy et al., 2016) and also improved access to coffee specialty markets in Costa Rica (Wollni and Brümmer, 2012). Studies conducted in Mexico (Weber, 2011), Costa Rica (Wollni and Brümmer, 2012) and Colombia (Bravo-Monroy et al., 2016) showed that coffee farmers with lower natural and physical assets like smaller plantations, were less likely to adopt organic management practices, possibly because they are less likely to incur the costs of joining a cooperative or converting to organic management.

Smallholder farmers may also change management strategies in response to external stressors and shocks that are outside the control of the household. For example, farmers switch crops or diversify their income to include both on- and off-farm options, to increase or secure their income in times of decreasing and volatile commodity prices. The shock of a 70% drop in cocoa price in two years in Côte d'Ivoire in the '80s contributed to switching to oil palm and rubber cultivation (Schroth and Ruf, 2014) and low coffee prices encouraged Indonesian coffee farmers to switch to cocoa (Paul et al., 2013). More recently, a stronger emphasis has been placed on the role of perception of risks, pressures and shocks in farmers' decision making (Feola et al., 2015; Levine, 2014). Farmers apply management strategies in response to their perception of the impact of risks on their livelihoods (Frank et al., 2011; Grothmann and Patt, 2005), as whatever trends in external stressors and shocks they experience, individuals must perceive motivation and the ability to act. Moreover, not all farmers respond to shocks in the same way and in the complex context of global environmental change, individuals are rarely responding to only one shock or stressor at any one time (Eakin et al., 2009).

We therefore postulate that different combinations of livelihoods assets, experienced shocks and perception of risks drive farmer decision making. We tested this hypothesis with a case study on the adoption of and the motivations for management strategies varying in shade and input by smallholder coffee producers in San Martín, Peru. San Martín is one of the most important coffee producing regions of Peru (Vargas and Willems, 2017) and shade levels and input use in smallholder coffee farms range from plantations without shade trees to diversified shade, and from little or only organic input to use of chemical fertilizers, pesticides and herbicides (Jezeer et al., 2018). However, there is limited insight in motivations underlying the adoption of these different management strategies and how they might relate to the risks faced by farmers, making for an interesting case study to assess the drivers of the adoption of different shade and input management strategies. Similar to coffee farmers worldwide, Peruvian coffee farmers are experiencing pressure due to volatile coffee prices (Larrea et al., 2014) and increased pest and disease incidence (Avelino et al., 2015), while the country appears to be especially exposed to changing climatic conditions (Vargas, 2009). Therefore, we focus on these three pressures. Insights derived from this study are fundamental to support farmers in developing management strategies that enhance resilience and sustainability of smallholder coffee producers in Peru and elsewhere in light of ongoing global changes.

5.2. Methods

5.2.1. Study region

The study was conducted in the department of San Martín, Peru, covering an area of approximately 2000 km^2. Most plantations surveyed (n=143) were situated in the provinces of Moyobamba and Rioja, which together form the 'Alto Mayo', a tropical highland with an average altitude of 1101 m (range 850-1497 m). The average rainfall is 1512 mm per year, the mean temperature 22.8 °C. The remaining 19 plantations were situated in the lowland province of Picota, with an average altitude of 861 m (range 673 - 1001 m). The nearest weather station (~20 km from these plantations at 218 m in elevation) reports a mean temperature of 26.5 °C and a mean annual rainfall of 937 mm. The dry season occurs from May to September (Gobierno Regional de San Martín, 2008).

5.2.2. Sustainable livelihoods approach

The sustainable livelihoods approach (SLA; DFID, 1999; Scoones, 1998) is widely recognised for offering an operational approach for understanding how farmer's livelihoods are shaped (e.g., Ellis, 2000). The SLA is an alternative to the single sector focus on production, employment and income as the sole concerns for livelihoods (Scoones, 2009). According to the SLA, livelihoods include both assets and strategies used by farmers or communities with the goal of improving their livelihoods. In our case, we used SLA to seek what livelihood assets of smallholder coffee farmers influence the adoption of which combinations of shade and input management strategies, and how are these choices affected by risks and shocks (Figure 13). We chose to focus on management strategies because these are more actionable for farmers, and therefore did not include livelihood outcomes and the institutional environment. To operationalize the SLA to our case study, we collected data on farmer's livelihood assets, experienced shocks of coffee price volatility and pests and diseases, and perception of risks due to coffee price volatility, pests and diseases and climate change, as well as data on shade and input management strategies adopted by coffee farmers (Figure 13).

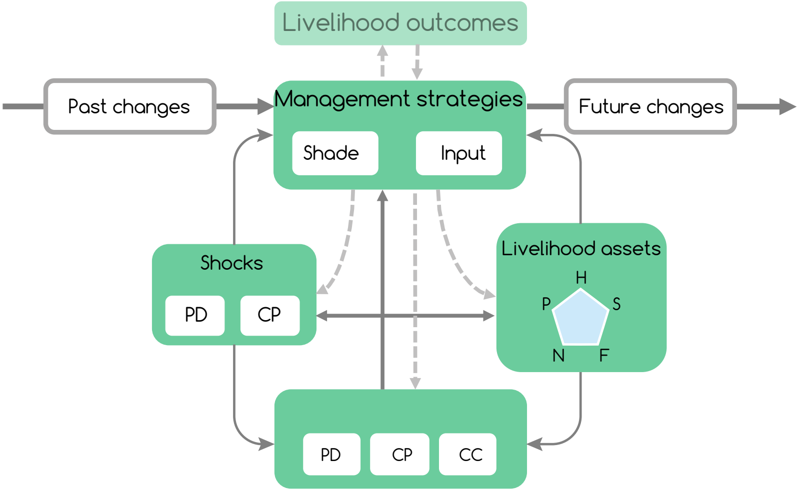


Figure 13. Conceptual framework. PD= pests and diseases; CP= coffee price volatility; and CC=climate change. Livelihood capitals: H=Human, S=Social, N=Natural, P=Physical and F=Financial. Explored relations are depicted with solid arrows, while recognizing that there might be other feedback loops at play (dashed arrows).

5.2.3. Livelihood assets

Central to the SLA are capitals that describe the farmer's assets. The following five capitals are often considered: Human, Social, Natural, Physical and Financial (Ellis, 2000). To measure each of the five capitals we chose a set of indicators based on literature (Table 9; Baca et al., 2014; Chena et al., 2013; Fang et al., 2014; Garnett et al., 2007; Rahn et al., 2014). To measure Human capital, we included indicators of the decision making process of the household (H1; Bravo-Monroy et al., 2016) and indicators that describe 'skills and knowledge' (i.e., years of experience in coffee farming (H2) and level of education (H3)). Furthermore, Human capital was also measured by the availability of family labour as described by the number of household members who work on the coffee plantation (H4). For Social capital we used indicators that reflect the farmer's embeddedness in the community and membership of association's or cooperatives (S1 and S3), in addition to indicators reflecting support received from these networks (S2 and S4) and level of engagement in these networks (S5). Natural capital refers to the natural resource stocks and environmental services that people utilize (Scoones, 1998). We therefore selected indicators that reflected the vegetation complexity (shade tree density (N1) and shade tree species richness (N2)) on the coffee plantation as this is a proxy for biodiversity and provisioning of environmental services, along with indicators coffee plantation size (N4) and perceived soil fertility (N3) which describe resources available to the farmers. Physical capital was described with indicators of household's fixed assets (material of their houses, P2), access to energy (P4) and water (P3). Further, we selected indicators that described the distance to markets (P1) and the months per year that the household experiences food scarcity (P5). For Financial capital we used indicators depicting percentage of income derived from coffee (F1), portion of income derived from off-farm activities (F2), outstanding loans (F4) and current savings (F5) of the household. In addition, we included an indicator that described the portion of work that was conducted by family labour (F3), as an increased portion of hired labour may indicate a greater wealth. Data for F1, F2 and F3 was obtained from a previous study (Jezeer et al., 2018), for which data on costs and benefits were collected (Table 9).

Table 9. Description of variables and indices used for livelihood capitals, perception of risks and shocks. All continuous variables were standardized by: value/max, unless specified otherwise. For descriptive statistics, see Table A15.

		Abbr.	***Description***	***data description***
Livelihood assets	Human	H-index	Human index	∑H1-4 (standardization =(value/ max ∑H1-4)
		H1	Family decisions made by multiple members of the family	0=one person; 1=>1 person
		H2	Years of experience of coffee farming	Continuous, year
		H3	Level of education	0=none; 0.33=primary; 0.66=secondary; 1=tertiary
		H4	Farmers members working in the plantation	Continuous; number of persons
	Social	S-index	Social index	∑S1-5 (standardization =(value/ max∑S1-5))
		S1	Family members and friends in the community	0=no; 1=yes
		S2	Support from family members and friends in community	0=no; 1=yes
		S3	Member of farmer association	0=no; 1=yes
		S4	Support from farmer association	0=no; 1=yes
		S5	Active participation in governance structure of farmer association	0=no; 1=yes
	Natural	N-index	Natural index	∑N1-4 (standardization =(value/ max∑N1-4)
		N1	Shade tree density	Continuous, # trees per farm
		N2	Shade tree species richness	Continuous , # species per farm
		N3	Soil fertility	0=not productive; 0.33=somewhat productive; 0.66=fertile; 1=highly fertile
		N4	Coffee plantation size	Continuous, hectares

		Abbr.	*Description*	*data description*
Livelihood assets	Physical	P-Index	Physical index	∑P1-5 (standardization =(value/ max∑P1-5)
		P1	Travel time to market for agricultural inputs and selling of beans	Continuous, minutes; (standardization=1-(value/max))
		P2	Material of walls and floors	Material walls: 0=non-cemented material or without corrugated tin; 0.25=timber or corrugated tin; 0.5=cement and brick casting/ concrete. Material floor: 0=dirt; 0.25=brick or wood with non-cemented material; 0.5=cement
		P3	Source of water	0=well, stream or rain; 1=tap
		P4	Source of light	0=candle or kerosene; 1=power network or solar
		P5	Food scarcity	continuous from 0-12 months (standardization=1-(value/12))
	Financial	F-index	Financial index	∑F1-5 (standardization=(value/max ∑F1-5)
		F1	Coffee farm income	Continuous, % of total farm income
		F2	Off-farm income	Continuous, % of total income
		F3	Share of hired labour	Continuous, %
		F4	Current openstanding loans	0=> S/.15.000; 0.25=S/.10.000-15.000; 0.5=S/.5.000-10.000; 0.75=S/. 0-5000; 1=S/. 0
		F5	Household savings	0=S/. 0; 0.25=S/. 0-5000; 0.5=5.000-10.000; 0.75=S/. 10.000-15.000; 1=S/.15.000
Risks	Climate change	perCC	Climate change index	∑PercCC1-7 (standardization=(value/ max∑PercCC1-7)
		perCC1	Late rains	0=absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
		perCC2	More rains	0=absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
		perCC3	Early rains	0=absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
		perCC4	More drought	0=absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
		perCC5	More cold weather	0=absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
		perCC6	Higher temperatures	0=absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
		perCC7	Lower groundwater	0=absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
	Pests and diseases	perPD	Pests and diseases index	∑PerPD1+2 (standardization=(value/ max∑PerPD1+2)
		perPD1	Impact on coffee quality	0=no/absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high

		Abbr.	*Description*	*data description*
Risks		perPD2	Impact on coffee quantity	0=no/absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
Shocks	Price fluctuations	perCP	Coffee price fluctuation	0=no/absent; 0.25=low; 0.5=medium; 0.75=high; 1=very high
	Pests and diseases	shockPD	Estimated loss due to coffee rust ('14)	Continuous, %
	Coffee price variability	shockCP	Variability in reported coffee price between '10 and '16	Continuous, € kg^{-1}

5.2.4. Experienced shocks

The SLA includes the impact of shocks, seasonality and trends on the farmers' livelihoods, which is referred to as the vulnerability context (DFID, 1999). Coffee price volatility is a major challenge for Peruvian coffee farmers as coffee prices more than tripled from 2004 to 2011, yet almost dropped again by half in 2013 (Larrea et al., 2014). Additionally, pests and diseases pose major risks as the recent coffee rust outbreak peaked in 2013 in Peru (Avelino et al., 2015) and caused a reduction of approximately 40% in national production. Therefore, we used perceived coffee yield loss due to coffee rust (%) as indicator for experienced shocks of Pests and Diseases (shockPD), while the variability in Coffee Price between '10 and '16 (shockCP) was used as indicator for experienced shocks of coffee price volatility. Due to a lack of location-specific meteorological data or high-resolution climate projections at the farm scale, it was not possible to include experienced shocks and pressures of climate change.

5.2.5. Risk perception

We also included farmers' perception of risks for their livelihoods due to (i) Pests and Diseases (perPD) impacting on both coffee productivity and quality, (ii) Coffee Price fluctuations (perCP), and (iii) impact of seven Climate Changes (perCC) the timing (early or late) and severity of rainfall patterns (more rain, more frequent periods of drought and lower groundwater level) and temperature (warmer or cooler periods; Table 9). Furthermore, farmers' greatest household concerns were also noted; farmers were asked to mark a maximum of three greatest concerns as an answer to "What worries you most when you think about possible effects on your household's wellbeing in the coming year?" (adapted from Frank et al., 2011; Tucker et al., 2010). These concerns were categorized as associated being with the farm and coffee plantation, directly or indirectly. To gain insight in the motivations for changes in management strategies over time, farmers were asked to report the changes in management strategies over the past 5 years and the motivation for this change, in particular level of shade (lower (↓), unchanged (~) or higher (↑)), and level of input (↓, ~ or ↑). Farmers were also asked if they were planning to change shade levels (↓, ~ or ↑) in the coming five years, along with their main motivation to do so.

5.2.6. Sampling and surveying methods

Household surveys were conducted with 162 coffee farmers to characterise shade and input coffee management practices. Surveys were conducted in selected plantations that cover the range of shade and input management in the study area, either between full sun monoculture coffee to multi-layered shaded plantations, or from high agro-chemical input, to only organic inputs or without inputs. Farmers were selected based on previous knowledge and databases reporting certification and organizational levels that also recorded some information on shade and input. We chose coffee plantations older than three years and producing coffee berries with marketable beans, which were owned by smallholder farmers. The interviewers were trained by the same person and surveys lasted between 45- to 60 minutes per farmer; most often plantation owners or tenants were interviewed. The interviewers assessed qualitatively if the farmers responded with confidence, and outliers were double checked. In 2016, data was collected and recorded in a smartphone/tablet app developed for this study, using ODK software (ODK Collect, version 1.4.10). The app included fields for each question, which provided guidance for the surveyors to minimise interview bias.

We performed household surveys twice; the first time in 2014 and the second time in 2016, both times using a semi-structured interview method. The second round of surveys was used to complement the data from the first survey with information on perception of risks and changes in management strategies, as well as to collect more detailed information on shade tree density and species richness. Plantation elevation was measured with a GPS (Garmin GPS 62s). The survey data was used to classify coffee systems in terms of shade and input (Jezeer et al., 2018), and to assess livelihoods assets, perception of risks and experienced shocks.

5.2.6.1. Input management

Data on input management was collected by asking farmers about fertilizing, weeding and pest and disease control activities. As fertilizer or pesticide inputs are partly used as concentrates, the total value of applied inputs was considered (€ ha^{-1} y^{-1}, excluding labour), assuming a positive correlation between the concentration of active substances and price (Table 10). Additionally, the type of fertilizer (organic or chemical) and weeding method applied (by hand using a machete, mechanically by using a brush-cutter, or by applying herbicides) were considered as indicators of intensity of input management.

5.2.6.2. Shade management

Tree species richness was assessed with the data collected in 2016 by asking farmers about the species and numbers of trees present at their coffee plantations. To assess survey data reliability, farmers were asked to rank the difficulty in estimating the number and species of trees present at their coffee farm (easy, medium or difficult).

If they found this ‘difficult’ the answer was not included in the database. Additionally, we checked for interviewer and farmer bias by comparing survey data to plot data (Figure A1 in appendix).

5.2.7. Input and shade indices

We used the input and a shade index for each coffee plantation that we calculated in a previous study (Jezeer et al., 2018); these indices are similar to those used in other coffee studies (Bisseleua Daghela et al., 2013; Hernández-Martínez et al., 2009; Mas and Dietsch, 2003). The input index is an aggregate of five management variables that describe fertilizing, weeding and pest and disease control activities, while the shade index is based on shade tree density and shade tree species richness. For both input and shade indices, Low, Medium and High classes were established using a K-mean cluster analysis (see Table A14 and Jezeer et al. 2018 for more information on index development).

5.2.8. Statistical analyses

All indicator values were standardized to range between 0 and 1 (Table 9). For continuous variables, this was done dividing the observed farm value by the maximum observed value across the sample. Categorical variables were assigned values between 0 and 1 (Table 9). Indices for each livelihood capital and perceived risks were computed by rescaling the sum of the ranks for the associated variables to values between 0 and 1. Equal weights were used in the final aggregated indicator per capital.

To assess whether farmers’ perceptions, experienced shocks or livelihood capitals differed between input and shade levels, we used an ANOVA followed by a Tukey HSD post-hoc test when data had a normal distribution, or a non-parametric Kruskal–Wallis test followed by a Dunn’s post-hoc test when data failed to meet the normality assumption. Normality of data was assessed using Shapiro-Wilk test and heteroscedasticity was tested using Levene’s test. We used a Bonferroni correction to correct for multiple comparisons and adjusted P-values are presented.

Finally, to identify farmer decision making profiles, we used a principal component analysis (PCA) in two steps. First, we run a PCA with all variables for livelihood assets, experienced shocks and risk perception so see whether farmer decision making profiles emerged. Secondly, shade and input management indices and elevation, were included as vectors in the PCA to assess whether they aligned with farmer decision making profiles. Significance level was set at $\alpha=0.05$. Statistical analyses were performed with R (version 3.0.2, R Core Team, 2014), using the ‘mclust’ (Fraley et al., 2017), ‘factoextra’ (Kassambara and Mundt, 2017) and ‘car’ (Fox et al., 2016) packages.

5.3. Results

5.3.1. Current input and shade management

Farm average size was 6.4±8.4 ha, with an average coffee cultivation area of 2.7±2.0 ha (Table 10). Majority of the farmers were migrants (90%) and farmers had on average 14±8 years of experience of cultivating coffee. Only Arabica coffee (*Coffea arabica L.*), is grown in this region, of which Costa Rica 95 from the Catimor family and Iapar 59 are coffee rust-tolerant varieties, and Pache, Caturra, Típica, Borbón, Catuaí and Nacional are varieties more sensitive to coffee rust. Nearly 60% of the farmers were a member of a farmer association, of which 86% were producing certified coffee, often carrying more than one certification label. The most common certification scheme was Organic (75%), followed by UTZ (33%), Fair Trade (29%) and Rain Forest Alliance (20%). Most shade trees in the coffee plantations were planted after land clearing, especially trees of the genus *Inga*.

Table 10. Statistics of farm and plantation characteristics and shade and input management

	unit	***mean±sd***	***min-max***	***n***
Farm characteristics				
Size	ha	6.4±8.4	0.50-80	154
Productive coffee area	ha	2.7±1.96	0.50-13	154
Elevation	m	1066±172	673-1497	162
Coffee-shrub age	year	8.75±4.6	3-30	159
Coffee-shrub density	shrubs ha^{-1}	3934±1140	1000-7000	154
Shade management				
Tree density	trees ha^{-1}	71±105	0-700	154
Tree species richness	species $farm^{-1}$	4.2±3.6	0-22	161
Input management				
Total	€ ha^{-1} y^{-1}	149.7±196.9	0-1022	151
Fertilizers	€ ha^{-1} y^{-1}	123.9±174.3	0-952	140
Pesticides	€ ha^{-1} y^{-1}	34.1±77.25	0-468	128
Herbicides	€ ha^{-1} y^{-1}	6.7±26.2	0-249.6	138

Low-Input plantations (n=23) did not have pest and disease control activities, and fertilizer application and weeding was done manually (Table A14) Medium-Input plantations corresponded to the largest group of farmers (n=50), who spent on average € 124 ha^{-1} y^{-1} on predominantly organic fertilizers. Also, 40% of these farmers applied pest and disease control, largely by using organic inputs. Within this level of input the majority of the farmers weeded manually, while others weeded mechanically using a bush cutter. High-Input plantations (n=37) corresponded to plantations where mechanical weeding and herbicides were applied. All farmers in this group applied fertilizers with an average expenditure of € 220 ha^{-1} y^{-1}, some farmers applied pesticides and/or fungicides.

The Low-Shade class (n=45) corresponded to a mean density of 13±23 trees ha^{-1}, often from a single tree species. The Medium-Shade plantations (n=27) corresponded to an average density of 57±65 trees ha^{-1}, with two species on average. High-Shade plantations (n=19) were characterized by an average of 403±181 trees ha^{-1}, which consisted of three species on average.

5.3.2. Farmers' livelihoods capitals

Human capital was significantly higher for High-Shade plantations compared to Low-Shade (z=3.2; p_{adj}=0.004; Table 3). This was predominantly due to the years of experience of farming coffee, as farmers applying Low-Shade had significantly less coffee-farming experience than those applying High-Shade (z=3.4; p_{adj}=0.002) or Medium-Shade (z=2.4; p_{adj}=0.043). Although no difference was observed for Social capital, significantly more High-Shade and Medium-Shade than Low-Shade (High-Low: z=4.2; p_{adj}=0.000; Medium-Low: z=2.8; p_{adj}=0.02) were members of a farmers' organization. Natural assets were significantly higher for High-Shade plantations compared to Medium-Shade and Low-Shade (F=26; p=0.000), coherent with the differences found for shade tree density and species richness. There was also a trend for High-Shade to have more arable coffee land than Low-Shade (z=2.4; p_{adj}=0.056). No differences in Financial assets were found for plantations with different shade levels.

Livelihood capitals for input levels were different from those for shade levels, and fewer capitals were associated with input management. We observed that High-Input plantations had more often electricity as source of light than Low-Input plantations (z=2.45; p_{adj}=0.043). Physical assets did not differ between Input groups. We found a trend for percentage of hired labour being lower for Low-Input plantations compared to High-Input plantations (z=2.23; p_{adj}=0.078).

5.3.3. Risk perception and experienced shocks

Farmers perceived pests and diseases, coffee price volatility, and climate change as major risks (Figure 14a), in particular increased temperatures. There was a significant difference between farmers with different levels of shade, (p=0.04,Table 11), and a more robust Dunn's post-hoc test with Bonferroni correction showed that there was a trend that farmers with High-Shade levels perceived lower risks due to coffee price variability than farmers with Medium-Shade (z=2.36; p_{adj}=0.055). No significant differences in perceived risks were observed between plantations with different shade levels or input levels. Farmers with Low-Input levels showed significantly higher experienced shocks due to pests and diseases than farmers with High-Input levels (z=3.2; p_{adj}=0.005). The majority of the farmers indicated that their greatest concern was coffee price fluctuations, followed by pest and disease impact (Figure

14b). Farmers were also concerned about being able to send their children to school, reoccurring food scarcity and health problems of family members.

5.3.4. Changes in management strategies

A third of the farmers increased shade levels, of whom 60% (n=14) mentioned climate change as main driver, while pest and disease pressure motivated a third of the farmers (74%; n=17) to reduce shade levels (Figure 14c). Approximately 65% (n=49) of the farmers increased inputs, while the remaining farmers kept the same input. Pest and disease pressure was the main driver mentioned by 41 farmers to increase their input levels, both to increase organic and chemical inputs.

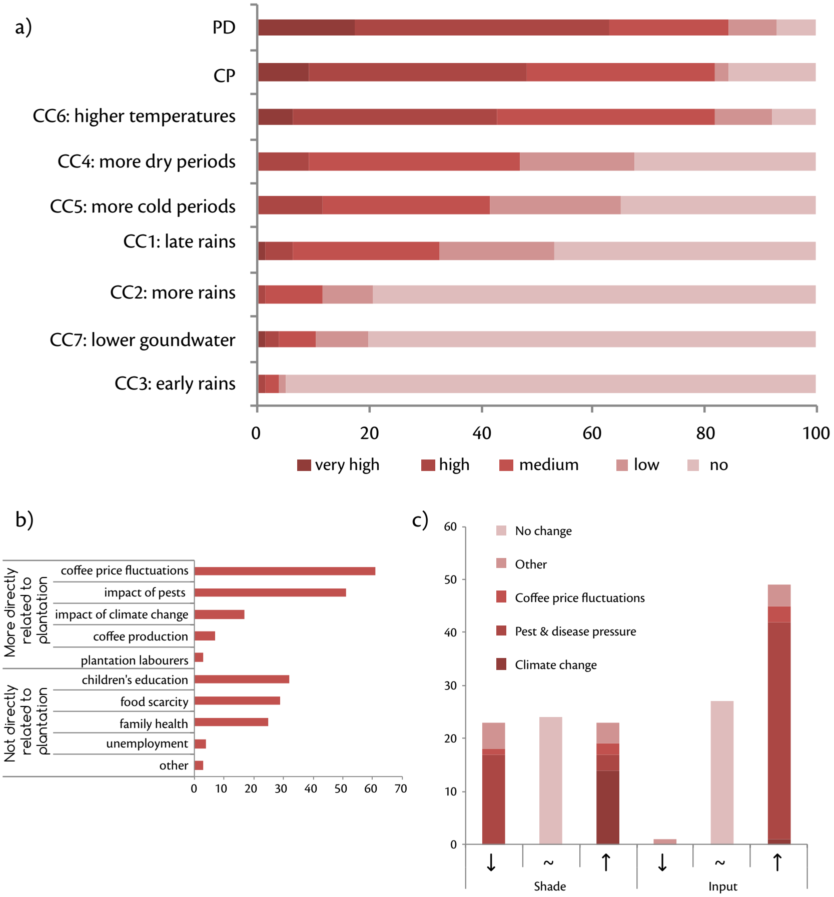


Figure 14. a) Perception of risks identified by farmers, expressed as perceived impact (none, low, medium, high, very high) of pests and diseases (PD), coffee price volatility (CP) and climate change (CC1-7) on farmers' livelihoods, x-axis = % of farmers; b) Greatest household concerns mentioned by the farmers, divided into farm-related and household-related risks; c) Most important reason stated by the farmers to decrease (↓), maintain (~) or increase (↑) their shade level in terms of shade tree density, and the amount of inputs used (organic and chemical).

*Table 11. Statistics (mean ± SD) of livelihood capitals, perception of risks and pressures for the Input and Shade classes. Significant differences between groups were evaluated using an ANOVA followed by a Tukey HSD post-hoc test with a Bonferroni correction when data conformed with normality requirements (indicated with (i)) or with a Kruskal–Wallis non-parametric test followed by a Dunn's post-hoc test with a Bonferroni correction (not indicated) when data was non-normal. The level of significance (adjusted): NS at p > 0.10; . <0.10; *p < 0.05; **p < 0.01; ***p < 0.001. Different letters indicate significant differences among shade and input classes. Standardized values are reported; see Table A15 for description of variables and formula for standardizing value.*

			Shade					**Input**				
			Low	**Medium**	**High**			**Low**	**Medium**	**High**		
			mean±sd	**mean±sd**	**mean±sd**	**sig**	**Post-hoc test**	**mean±sd**	**mean±sd**	**mean±sd**	**sig**	**Post-hoc**
Livelihood assets	**Human**	**H-index**	**0.47±0.15(a)**	**0.61±0.19**	**0.67±0.22(b)**	**	**High>Low**	**0.54±0.25**	**0.62±0.19**	**0.57±0.21**		
		H1	0.33±0.49	0.67±0.48	0.69±0.47	.	High>Low	0.50±0.53	0.71±0.46	0.48±0.51		
		H2	0.28±0.21(a)	0.36±0.20(b)	0.40±0.19(b)	**	High&Medium>Low	0.32±0.19	0.34±0.21	0.39±0.21		
		H3	0.40±0.16	0.4±0.18	0.40±0.18			0.41±0.20	0.39±0.18	0.38±0.14		
		H4	0.34±0.11	0.39±0.14	0.42±0.21			0.30±0.05	0.39±0.17	0.37±0.16		
	Social	**S-index**	**0.56±0.31**	**0.54±0.28**	**0.69±0.26**			**0.68±0.34**	**0.66±0.30**	**0.49±0.27**		
		S1	0.87±0.35	0.88±0.34	0.86±0.36			1.00±0.00	0.88±0.34	0.76±0.44		
		S2	0.60±0.51	0.50±0.51	0.46±0.51			0.62±0.52	0.54±0.51	0.38±0.50		
		S3	0.31±0.47(a)	0.61±0.49(b)	0.77±0.42(b)	***	High&Medium>Low	0.48±0.51	0.60±0.49	0.49±0.51		
		S4	0.47±0.52	0.46±0.51	0.74±0.44	.	High>Medium	0.50±0.53	0.67±0.48	0.52±0.51		
		S5	0.43±0.51	0.26±0.45	0.53±0.51			0.50±0.53	0.48±0.51	0.25±0.44		
	Natural	**N-index**	**0.28±0.11(a)**	**0.36±0.08(a)**	**0.56±0.18(b)**	***	**High>Medium&Low (i)**	**0.50±0.22**	**0.42±0.16**	**0.41±0.16**		
		N1	0.03±0.03(a)	0.07±0.05(b)	0.22±0.21(c)	***	High>Medium>Low	0.10±0.15	0.10±0.14	0.10±0.11		
		N2	0.05±0.05(a)	0.18±0.06(b)	0.34±0.18(c)	***	High>Medium>Low	0.20±0.19	0.19±0.14	0.18±0.13		
		N3	0.38±0.17	0.42±0.15	0.49±0.20			0.50±0.25	0.42±0.15	0.44±0.19		
		N4	0.58±0.21	0.63±0.19	0.65±0.23			0.48±0.36	0.62±0.18	0.58±0.22		
		N5	0.18±0.12	0.19±0.10	0.25±0.18	.	High>Low	0.18±0.10	0.21±0.14	0.20±0.11		
	Physical	**P-Index**	**0.74±0.16**	**0.66±0.19**	**0.66±0.20**	.	**ns**	**0.63±0.28**	**0.70±0.17**	**0.72±0.14**		
		P1	0.24±0.18	0.21±0.20	0.19±0.19			0.20±0.15	0.21±0.21	0.21±0.16		

		P2	0.38±0.33	0.30±0.30	0.36±0.33			0.40±0.32	0.32±0.33	0.32±0.31		
		P3	0.77±0.36	0.68±0.40	0.62±0.41			0.61±0.45	0.69±0.41	0.78±0.34		
		P4	0.78±0.41	0.79±0.41	0.75±0.43			0.61±0.49(a)	0.80±0.39	0.88±0.32(b)	*	High>Low (p=0.043)
		P5	0.65±0.16	0.68±0.15	0.71±0.17			0.66±0.19	0.71±0.16	0.68±0.14		
	Financial	**F-index**	**0.64±0.19**	**0.57±0.18**	**0.55±0.15**			**0.55±0.12**	**0.58±0.19**	**0.63±0.17**		
		F1	0.36±0.35	0.32±0.27	0.33±0.29			0.26±0.24	0.41±0.33	0.34±0.34		
		F2	0.18±0.30	0.12±0.20	0.08±0.19			0.15±0.20	0.09±0.17	0.14±0.31		
		F3	0.61±0.38	0.68±0.33	0.61±0.33			0.62±0.30	0.63±0.34	0.78±0.30	.	High>Low (p=0.078)
		F4	0.90±0.13	0.84±0.22	0.81±0.27			0.81±0.22	0.85±0.21	0.82±0.28		
		F5	0.08±0.22	0.13±0.27	0.08±0.18			0.00±0.00	0.10±0.21	0.10±0.26		
Perception of risks on livelihoods	**Climate change**	**perCC**	**0.43±0.23**	**0.52±0.24**	**0.50±0.21**			**0.59±0.07**	**0.46±0.23**	**0.40±0.21**	**.**	**Low>High (p=0.08) (i)**
		perCC1	0.17±0.20	0.25±0.22	0.26±0.30			0.31±0.26	0.24±0.29	0.19±0.22		
		perCC2	0.02±0.07	0.04±0.12	0.14±0.23	.	ns	0.16±0.23	0.07±0.17	0.02±0.08		
		perCC3	0.00±0.00	0.02±0.10	0.04±0.15			0.06±0.18	0.01±0.05	0.00±0.00		
		perCC4	0.32±0.26	0.35±0.22	0.28±0.28			0.25±0.23	0.31±0.29	0.37±0.23		
		perCC5	0.23±0.24	0.29±0.25	0.31±0.28			0.47±0.25	0.27±0.26	0.20±0.23	.	ns
		perCC6	0.57±0.24	0.56±0.30	0.54±0.23			0.59±0.13	0.53±0.26	0.51±0.28		
		perCC7	0.10±0.23	0.16±0.28	0.04±0.11			0.06±0.18	0.06±0.15	0.04±0.10		
	Pests and diseases	**perPD**	**0.62±0.14**	**0.59±0.31**	**0.69±0.23**			**0.69±0.21**	**0.67±0.24**	**0.65±0.54**		
		PerPD1	0.60±0.21	0.57±0.33	0.66±0.27			0.69±0.29	0.66±0.27	0.65±0.26		
		perPD2	0.63±0.23	0.60±0.33	0.71±0.24			0.69±0.29	0.68±0.27	0.65±0.30		
	Price fluctuations	**perM**	**0.63±0.23**	**0.66±0.28**	**0.46±0.29**	*	**Medium>High (p=0.055)**	**0.56±0.40**	**0.57±0.31**	**0.54±0.25**		
Experienced shocks	**Pests and diseases**	**shockPD**	**0.38±0.28**	**0.46±0.21**	**0.48±0.23**			**0.56±0.19(a)**	**0.48±0.21**	**0.35±0.26(b)**	**	**Low>High**
	Coffee price variability	**shockCP**	**0.40±0.16**	**0.44±0.19**	**0.38±0.18**			**0.38±0.21**	**0.40±0.18**	**0.43±0.16**		

5.3.5. Farmer decision making profile

The PCA showed that livelihood capitals and the perception of risks and experienced shocks were not clustered, thus suggesting no relation. Two farmer decision-making profiles were identified in the PCA space (Figure 15), which are in line with the differences reported above. Livelihood capitals appeared in the opposite quadrants to experienced shocks and perception of risks. Human, Natural and Social capitals were clustered and overlapped with the vector for shade index and elevation; these capitals were opposite to perceptions of climate change and perception and risk of coffee price volatility. Financial and Physical capitals were clustered and overlapped with the input index vector, and were opposite to elevation, and perception and shocks from pests and diseases. The first two axes of the PCA explained 32.9% of variability in perception of risks, livelihood capitals and experienced shocks. Loadings for the PCA are presented in Table A3.

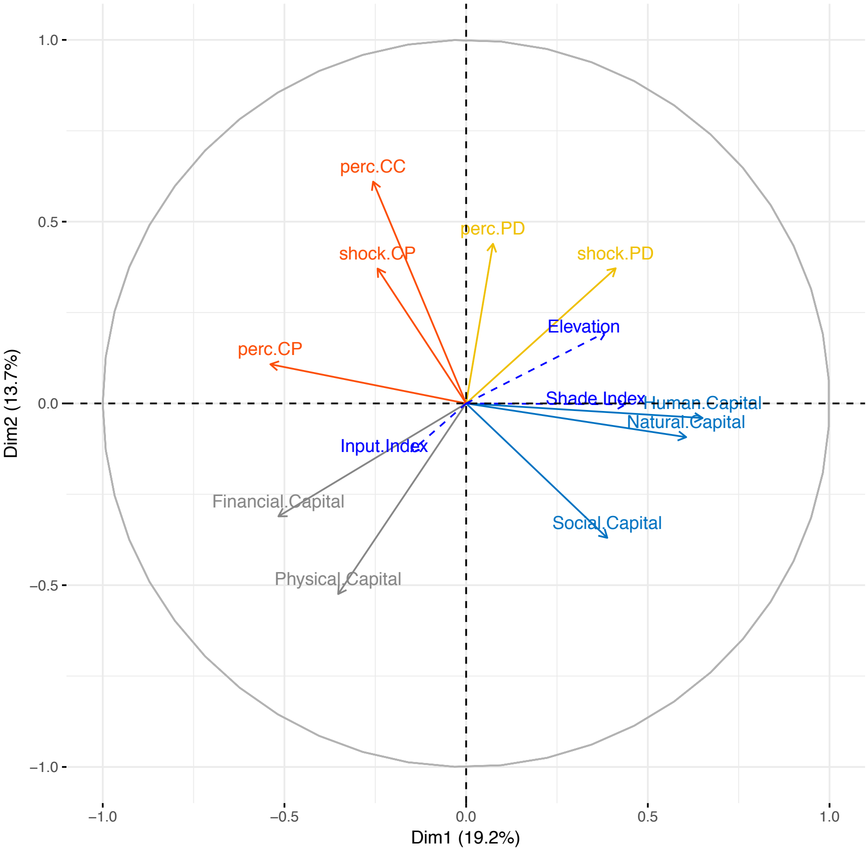


Figure 15. PCA of livelihood capitals (H, S, N, P and F), perception of risks of price variability (perc.CP), pests and diseases (perc.PD) and climate change (perc.CC); and experienced pests and diseases (shock.PD) and price volatility (shock.CP). Elevation, Shade Index and Input Index are supplementary variables (dotted arrows).

5.4. Discussion

In this study we assessed the influence of farmers' livelihoods assets, experienced shocks, and risk perception on the adoption of shade and input management strategies of small-scale Peruvian coffee farmers to better understand their decision-making process. Higher levels of human and social capitals were associated with higher shade, whilst we found a trend for higher physical and financial capitals associated with higher input use. These results provide further evidence that many livelihood factors influence farmer decision-making process and drive decisions in different directions (Bravo-Monroy et al., 2016). We found some support that livelihood capitals were inversely related to experienced shocks and perception of risks, suggesting that risk perception and experience with particular disturbances might be insufficient to motivate changes in management strategies (Frank et al., 2011). However, currently, farmers showed a high perception for risks from pest and diseases, followed by coffee price volatility and increased temperatures, suggesting that into the future this perception of volatility might trigger changes in coffee management strategies. Together these findings illustrate how the decision-making process of smallholder farmers is influenced by many factors that may push-and-pull decisions in different directions, and that livelihood assets are more important in determining management strategies than perception of risks and shocks.

5.4.1. Livelihood capitals

Human and social capitals were associated with higher shade levels, along with natural capital. In our study, farmers with more years of experience in coffee cultivation had higher shade levels in their plantations, and this finding is in line with other studies that have shown that adoption of environmentally friendly management strategies are positively influenced by farmers' skills, knowledge and experience (Chaves and Riley, 2001; Quiroga et al., 2015). This finding suggests that traditional coffee cultivation systems have higher shade. A large share of these Peruvian coffee farmers with high shade was member of a farmers' organisation often providing coffee certification. This is similar to coffee farmers from Costa Rica (Wollni and Brümmer, 2012) and Colombia (Bravo-Monroy et al., 2016), where memberships of farmers' cooperatives promoted the adoption of environmentally-friendly management strategies and certification schemes. This could be because farmers who are member of an organisation might gain access to more information, updated practices and knowledge (Frank et al., 2011), and specialty markets (Wollni and Brümmer, 2012), and might receive higher coffee prices with certification premiums (Muschler, 2001). As natural capital included shade tree species richness and density, logically, it was linked to high shade levels. Similar to other studies (Bravo-Monroy et al., 2016; Weber, 2011; Wollni and Brümmer, 2012), there was a trend that plantations with higher levels of shade were bigger and might provide an added benefit by their potential to conserve biodiversity, carbon storage and other ecosystem services (Bhagwat et al., 2008; De Beenhouwer et al., 2013).

On the other hand, decision-making over input strategies was influenced by financial and physical capitals. We found that financial capital was associated with input use, which is in line with other studies that found that wealthier farmers could invest more in inputs to enhance farm output (Bullock et al., 2014; Rahman, 2003). Other studies have shown that the lack of financial assets limits access to inputs (Chaves and Riley, 2001). This is also the case in our study, where a few farmers who decreased or did not change their input levels mentioned that this was due to lack of financial means. Bean and Nolte (2017) reported that a significant portion of Peruvian coffee exports are organic, and explained this high proportion of organic coffee producers by the smallholder's inability to pay for chemical fertilizers and pesticide. Financial and physical capitals are possibly negatively related with elevation because farmers who live at higher elevations have lower access to markets to sell their coffee and have to travel longer distances to purchase fertilizer and pesticide.

5.4.2. Experienced shocks and perceived risks

Perceived risks of pest and disease pressure, coffee price volatility and increased temperatures were high, but did not explain farmers' current shade and input management strategies. This could be because farmers might not always have the capacity or means to respond to their perceptions. For example, Tucker et al. (2010) found that farmers who perceived high risk were not more likely to engage in specific adaptations, and adopted management strategies more clearly associated with livelihood assets such as access to land and membership of farmer organisation. Perceived risks showed strong coherence with experienced shocks in the past and this might be explained by farmers having learned from previous experiences. This finding highlights again the importance of farmer's experience rather than knowledge of projected risks into the future. However, there was a trend that farmers using low inputs perceived higher risks of climate change compared to farmers with high input use. This could be because the farmers using low inputs were members of an organisation that provides certification and as well as informs farmers about projections of future climate for the region. Moreover, these results suggest that adoption of management strategies was more strongly influenced by livelihoods than perception of risks.

5.4.3. Farmers strategies for enhanced resilience

The greatest concern of farmers was related to the low prices rather than extreme climate or pest and disease events. This finding is consistent with evidence from other studies of farm communities and climate risk (Eakin, 2005; Tucker et al., 2010). This seems to underline the role of economic factors on decision making. However, there appears to be a disconnect between the perceived risks and the changes made; rather than fluctuating coffee prices, pest and disease impact and climate change were driving changes in shade and input management over the past five years.

These pressures lead to opposing management decisions: climate change perception motivated farmers to increase shade levels, while pressure from pests and disease led to a reduction in shade. Reconciling these opposing management strategies is fundamental as shade trees are expected to improve farmer's resilience to climate change, amongst other by buffering micro-climate (Lin, 2007 Farmers thus seem to be aware of the long-term risks of climate change, and appear willing to adapt their management accordingly. This is not surprising, as coffee is very sensitive to changes in climate (Bunn et al., 2015; DaMatta, 2004) and consequently farmer's livelihoods. In comparison to climate change, pest and disease pressure is more immediate and motivated farmers to intensify their management strategies by reducing shade levels and increasing inputs. Further, there is a potential interaction effect between shade and input management, as studies reported that shade can have either negative or beneficial effects on pests and diseases, including coffee leaf rust (Jackson et al., 2012; Jonsson et al., 2015). There appears to be an interest to move towards more shaded systems as about 60% of the farmers considered increasing shade levels in the future (Figure A12). This seems predominantly motivated by future timber revenues, but also by indirect benefits of shade trees such as buffering climate change effects, soil erosion control, enhanced soil fertility and improved bean quality (Figure A12a). But concerns like lack of land ownership (Mercer, 2004), lack of knowledge and limited access to seedlings and timber market (Cerda et al., 2014; Schroth and Ruf, 2014; Figure A12b) may be barriers to increase in shade levels. Generally, shade and input management decisions aim at reducing pest and disease and climate pressures, as to maintain coffee productivity or increase overall income, rather than maintaining overall ecosystem services.

5.4.4. Recommendations for practitioners and policy makers

To support adoption of management strategies, we recommend considering variation in livelihood assets to enable tailored support to farmer or farmer groups. When the aim is to move towards more environmentally-friendly management strategies, it is of particular importance to assess farmers' embeddedness in the community, membership of a farmers organisation and experience with cultivating coffee, as these have been identified as important assets. Since these assets are actionable, i.e., can be relatively easily changed they provide a promising avenue for the adoption of more-environmentally friendly management strategies. Supporting farmer organizations also improves access to information and provides technical assistance to coffee farmers, and might also improve market access and thus reduce risks due to coffee price fluctuations. Farmer's organisations may also provide information on the advantages and disadvantages of diversification, and might play a role in improving market access for shade tree products. Nonetheless, while actionable and promising, further research is needed to assess the outcomes of such associative activities. Also, it is important to understand the opportunities and barriers faced by farmers for the use of shade trees on their coffee plantations, in particular when promoting the adoption of agroforestry systems as part of some certification schemes. Lastly, we recommend that farmer's financial and physical assets are assessed, as we found some support that these pose important constraints to the adoption of the use of inputs use. Credit facilities for smallholder farmers could help overcome such financial constraints.

5.4.5. Data limitations and future research

Though we included multiple factors in this analysis using SLA, this study has some caveats that need to be taken into consideration. We chose not to include the institutional environment, although this links livelihood assets and farming strategies in SLA (Scoones, 1998) as other institutions may promote or impose decisions beyond farmer decision power and association norms and rules, and it would be important to study to which extent our results hold when other institutions are considered, or if indirectly their effect is already embedded. Secondly, while joining an organisation or certification scheme can be an important way for farmers to reduce their vulnerability to pressures, changes in membership of farmer organisations and/or certification were not considered. Third, we were unable to include experienced changes in climate over the past years, though farmers reported to perceive high risks related to climate change suggesting that actual experienced climate change might also play a role in decision making.

5.5. Conclusions

The sustainable livelihood approach allowed for more comprehensive insight into decision making of smallholders, moving beyond a focus on merely economic factors as productivity and income. Generally, this study contributes to the body of literature that suggests that livelihood factors beyond financial assets are important for the adoption of management strategies for smallholder coffee farmers, and that risk perception and experience with disturbances remain insufficient to motivate adoption of management strategies. These results suggest that improving livelihood assets is important for decision making, and these set of actionable assets differ for shade and input management; whilst human, social and natural assets may limit or enhance adoption of environmentally-friendly management systems, financial and physical assets may affect adoption of input management strategies. To maintain coffee productivity or increase overall income, adaptations in shade and input management appeared to be responsive to pest and disease and climate change pressure, in opposite directions. More insight is needed in the benefits and detrimental effects of shade to pests and disease pressure, as well as opportunities to adapt to climate change, to reconcile these opposing management strategies. The different timescales at which these pressures may interfere with farmers' livelihoods are important to take into account. Still, these are dynamic systems, so further research is expected to benefit from looking into the directionality of the relationships between management strategies, experienced shocks, perceived risks and livelihoods assets, as well as from including the effect of the institutional environment and the livelihood outcomes in the framework. Extending the livelihood framework can help identify management strategies that are able to reconcile livelihoods assets, so that economic and environmental performance can coincide. This study provides more insight in the type of support that can promote agroforestry systems as a solution to some major global environmental challenges since they can contribute to conservation of biodiversity, mitigate climate change, buffer climate effects and enhance soil fertility.

5.6. Acknowledgements

We are grateful for the valuable support received by staff members of the local Solidaridad office in Moyobamba and Luis Sánchez Celis. We thank Vincent de Leijster, Claudia Rieswijk, Steffie Rijpkema and Rutger Baar who participated in field data collection. We thank all coffee farmers who welcomed us to their farms and shared experiences, knowledge and views on their farming practices. Data collection and data analysis were funded by the Business for Biodiversity project of Hivos, while Tropenbos International also supported data collection, analysis and writing

6

Synthesis and discussion

One of the main challenges of the coming decades is to develop agricultural systems that produce food and income to sustain smallholder livelihoods in the tropics, without further compromising ecosystem functioning, including biodiversity conservation. Agroforestry systems have been put forward as a promising approach to deal with the twin challenges of local development and conservation of biodiversity and other ecosystem services. There is ample evidence supporting the ecological importance of agroforestry systems for biodiversity conservation (Bhagwat et al., 2008; De Beenhouwer et al., 2013). However, agroforestry systems are still perceived to have lower economic performance compared to intensified conventional systems, which is driving further intensification throughout the tropics. More insight in the relations between crop productivity, biodiversity conservation and smallholder livelihoods is needed to identify systems that can minimise trade-offs between economic and environmental performance or even provide double dividends. The objectives of this thesis were therefore to assess the economic and environmental outcomes of smallholder management systems to identify trade-offs and seek opportunities for double dividends, as well as to identify opportunities and constraints faced by smallholder farmers for the adoption of management strategies. Given the economic and ecological importance of coffee and cocoa worldwide, this thesis focuses on coffee and cocoa smallholder systems. Subsequently, there is a focus on coffee systems, since empirical data from a case study on smallholder coffee systems in San Martín, Peru, was used.

In this chapter, first a summary of each chapter and its main findings is presented, followed by answers to each of the four research questions, including recommendations for further research. Lastly, recommendations for policy makers and practitioners are presented.

6.1. Synthesis

Chapter 2 compared economic performance (i.e., profitability in terms of net revenue and cost-efficiency in terms of benefit cost ratio, BCR) and biodiversity performance (i.e., species richness and abundance) of small-scale shaded and intensified conventional coffee and cocoa plantations. To this regard, a meta-analysis was conducted including 23 studies on coffee and cocoa plantations over a 26 year period. Despite lower yields (-26%), shaded systems showed a better economic performance as average net revenues were significantly higher (+23%) and there was a trend that BCR was 24% higher for cocoa and coffee systems intercropped with shade trees. It was therefore interesting to consider the separate components of net revenue and BCR. Indeed, on the one hand the shaded systems had lower average costs (-13%), while on the other hand they received higher average gross benefits per hectare (+17%), which was partly a reflection of the significantly higher average price per kilogram of coffee or cocoa (+17%). A few studies included in this meta-analysis specifically reported on the relationship between biodiversity and financial performance, providing divergent results, yet various papers showed a promising optimum relationship for intermediate levels of shade. Altogether, this chapter provided evidence that shaded coffee and cocoa systems can offer competitive business opportunities for small-scale farmers in comparison to the expanding sun-grown conventional plantations, while also contributing to biodiversity conservation. Additionally, this chapter showed that the traditional indicator ‘yield’ was an inaccurate measure of financial performance when studying these diversified systems, and that the more detailed indicators of net revenue or benefit-cost ratio should be used instead.

To better understand the relationships between the three important ecosystem services, in **Chapter 3** the relationships between coffee yields, butterfly species richness and above-ground carbon storage were examined, while accounting for soil fertility and yield losses due to pests and diseases. Data were collected on smallholder coffee plantations in the department of San Martín, Peru, along a gradient of shade and input management, by survey (in 162 farms) and by plot measurements (in a subsample of 62 farms). It was shown that coffee yields, forest butterfly species richness and aboveground carbon responded differently to shade and input management. There was a trend that increased levels of shade maintained higher numbers of forest butterfly species richness and significantly higher above-ground carbon stocks compared to plantations with lower levels of shade. Forest butterfly species richness observed in natural forest plots ranged between 7 and 21 species per plot (Chapter 3), values which were more closely represented in plantations with higher levels of shade. Plantations with high shade levels had comparable above-ground carbon storage to that of the natural forest plots which ranged between 90-145 Mg ha^{-1} and was more than 15 times higher than plantations with shade levels <30%. Importantly, there was no evidence for a negative relation between coffee yields and shade cover, across a shade range of 0-80% in this case study on smallholder farmers in Peru. Further, input use showed no relation with either biodiversity or carbon, yet coffee yields were related to inputs. Input use, especially of fertilizers, was highest in low yielding sites. Yield loss due to pests and diseases, in particular due to coffee leaf rust, was an important constraint on coffee yield, but yield losses due to pests and diseases were less pronounced when more inputs were applied. No trade-offs between coffee yields, biodiversity and carbon storage were found. This implies that it is possible to maintain and enhance the provision of multiple ecosystem services without a reduction in coffee yields, yet the importance of managing soil fertility pro-actively, prioritizing pest management, and planting rust-resilient Arabica varieties was stressed. Moreover, it was concluded that when optimizing shade and input management for coffee production, increased carbon storage and/or biodiversity conservation could be pursued simultaneously in coffee plantations.

A comprehensive economic analysis of Arabica coffee farming systems in **Chapter 4** compared productivity, costs, net income and benefit-cost ratio (BCR) of 162 small-scale, Peruvian coffee plantations under different shade and input management practices along an elevation gradient. Using a cluster analysis, three shade and three input classes (low, medium and high) were defined. With an average net coffee income of 702±961 € ha^{-1} y^{-1}, economic performance was similar across different shade classes. Rather, input was negatively related to economic performance. The High-Input class had significantly lower net income and BCR, mainly due to increased costs of (hired) labour, land, and fertilizer and fungicides; costs which were not fully compensated for by higher coffee yields. The opposite relation was observed for shade, as costs were lower for plantations with higher shade levels. At the same time, these relations were elevation dependent, likely due to differences in biophysical conditions. Coffee yields decreased with elevation, whereas gate coffee price and quality, as well as shade levels, increased with elevation. In line with expectations, benefits derived from other products were important as income from other products contributed 32% on average to total farm income, excluding potential income from timber. These benefits were lowest for plantations with high input levels and low shade levels. If the potential income from timber would be realized, the total yearly income could increase by another third for plantations with high shade levels, thus improving the overall economic performance of shaded plantations. Moreover, the analysis of this chapter provides evidence that for small-scale coffee production, shaded plantations perform equally well or better than unshaded plantations with high input levels, reinforcing the theory of agroforestry systems that good economic performance can coincide with conservation of biodiversity and associated ecosystem services.

In **Chapter 5** we assessed the influence of farmers' livelihoods assets, shocks, and risk perception on the adoption of management strategies for the case study of smallholder coffee farmers in San Martín, Peru. We operationalized the sustainable livelihoods framework for the adoption of shade and input coffee management strategies and explored farmers' motives to change shade and input management strategies. Higher levels of human and social capitals were associated with higher levels of shade, while a trend of higher physical and financial assets was associated with higher input use. Perceived risks of pest and disease pressure, coffee price volatility and climate change were high, but did not explain their current shade and input management strategies. Nonetheless adaptations in shade and input management over the last five years were responsive to pest and disease and climate change pressure, in opposite directions: climate change perception motivated farmers to increase shade levels, while pressure from pests and diseases led to a reduction in shade. About 60% of the farmers considered increasing shade levels in the future, suggesting that there is an interest to move towards more shaded systems rather than towards full sun coffee systems. Generally, shade and input management decisions aim at reducing pest and disease and climate pressures, as to maintain coffee productivity or increase overall income, rather than maintaining overall ecosystem services. This study contributes to the body of literature that suggests that many livelihood factors beyond financial assets are important for the adoption of management strategies for smallholder coffee farmers and that risk perception and experience with disturbances remain insufficient to motivate adoption of management strategies. However, the relation between human and social assets with shade management suggests that these actionable assets can be useful in dealing with global changes. The insights gained on the drivers for adoption of management strategies can support the development of management strategies that enhance resilience and sustainability of smallholder coffee producers in Peru and elsewhere. Extending the livelihood framework can help identify management strategies that are able to reconcile livelihoods assets, so that economic and environmental performance can coincide.

6.2. Discussion

Based on the findings in chapters 2-5, the answers to the research questions are presented in the following sections, including recommendations for further research. In the final section, recommendations for policy makers and practitioners are given.

I - What is the *environmental performance* of coffee and cocoa systems with different shade and input management?

Here, the effects of shade and input management on ecosystem services related to biodiversity and carbon storage are discussed, as well as on the provisioning service crop production. Regarding biodiversity and carbon storage, the results of this thesis showed a trend that increased levels of shade were related to higher numbers of forest butterfly species richness and higher above-ground carbon sequestration compared to plantations with lower levels of shade, whilst amount of fertilizer and herbicide inputs showed no relation with biodiversity or carbon. These findings support the general idea that agroforestry systems can support higher levels of biodiversity than conventionally intensified systems (Bhagwat et al., 2008; Mas and Dietsch, 2003; Perfecto et al., 2005) and can significantly contribute to carbon sequestration (Jose, 2009), presumably as these plantations are closer in structure and diversity to natural forests than are monoculture production systems (Harvey et al., 2006). The findings did not support other studies with regard to the negative effect of agro-chemical input on biodiversity (e.g., Gomiero et al., 2011) as input levels were not related to biodiversity, at least for the butterflies studied. Although butterflies do not provide direct benefits to coffee farmers, some studies indicate that changes in butterfly abundance and diversity can mirror changes in other taxa, such as birds, bees and other insects (e.g., Schulze et al., 2004), some of which are known for their positive relation with coffee productivity (Kellerman et al., 2008; Perfecto et al., 2004). However, such studies may depend on the taxa and spatial scale considered (Ricketts et al., 2001), while other taxonomic groups may respond differently to shade and input management (Kessler et al., 2011). It is therefore recommended that future studies include different taxa and look at the ecological mechanisms between biodiversity and associated ecosystem services such as pollination and pest and disease control. With ~55 Mg ha^{-1}, carbon values of plantations with shade levels of >40% were comparable with shaded coffee plantations in Peru (Ehrenbergerová et al., 2016), elsewhere in Latin America (Haggar et al., 2013; Soto-Pinto et al., 2010) and other continents (van Noordwijk et al., 2002). Deforestation rates of the study region San Martín are amongst the highest in Peru (>20 thousand ha^{-1} y^{-1}; Valqui et al., 2015). Not surprisingly, about 75% of the studied plantations replaced natural forest, of which a majority was established by clear-cut of natural forest trees and planting of new trees as service trees. This emphasises the potential role coffee agroforestry plantations can play to maintain forest biodiversity and carbon stock values in this region when deforestation is minimized, as well as for other coffee regions with similar land use dynamics.

Input and shade management showed different relations to coffee yields. Importantly, there was no empirical evidence for a negative relation between coffee yields and shade across a shade cover range of 0-80% (Chapter 3, Figure 16a). Consequently, this thesis supports the growing body of literature that suggest that yields can remain stable under increasing levels of shade, especially when grown in sub-optimal conditions (Boreux et al., 2016; Cerda et al., 2016; Charbonnier et al., 2017; Meylan et al., 2017; Rajab et al., 2016). The range in shade levels observed in Chapter 3 is comparable to that mentioned in other studies, such as in Mexico (Romero-Alvarado et al., 2002; Soto-Pinto et al., 2000) and India (Boreux et al., 2016). However, results from the meta-analysis (Chapter 2) showed that coffee and cocoa yields were lower when shade tree density increased (-26%) and in Chapter 4, lower coffee yields were observed at higher shade tree densities obtained from farmer surveys. Notably, this concerned relations between crop yields and shade tree densities rather than shade cover. These different observations suggest, first of all, that the relationship between shade and crop yields depends on the methods used for measurements, as well as on the indicator chosen (shade cover versus shade tree density). In the case study, the use of shade cover by visual estimation might have resulted in possible bias of shade cover estimates, but this method was reported to be accurate (Bellow and Nair, 2003) in particular when using trained observers as was done for this case study in Peru (Vittoz et al., 2010). Nonetheless, it is recommended that future studies use more robust shade cover estimates, for example by using a densiometer. Secondly, studies often do not take intensity of input management into account, making it difficult to draw generalizable conclusions on the relation between yield and shade. Indeed, the majority of studies in the meta-analysis focused on the effect of shade irrespective of applied inputs, which might explain some of the divergence between reported shade-yield relations. For the Peruvian coffee farmers, both fertilizer and pesticide applications were related to yields in the case study, as yield losses due to coffee rust were lower when pesticide expenses were higher and fertilizer use was highest in low yielding sites (Chapter 3). These results, however, come with high levels of uncertainty. Costs of fertilizers, pesticides and herbicides were used as a proxy for input use rather than the actual amount of active substances, which may have confounded this relation. Also, the recent coffee rust outbreak peaked in 2013 in Peru (Avelino et al., 2015) and caused a reduction of approximately 40% in national production which was reflected in the collected yield data and may have confounded the results. Indeed, yield loss due to pests and diseases, in particular due to coffee leaf rust, were important constraints on coffee yield (Chapter 3).

Furthermore, there was no relation between input and shade management for the sampled plantations, and clustering farming strategies according to these two axes was not appropriate (Figure 16b). Future studies are thus expected to benefit from considering shade and input management separately. Moreover, although there is a clear continuum of coffee and cocoa management practices, researchers often develop their own characterizations of management practices. For example, the most-cited coffee biodiversity studies include more than 25 names to describe coffee-management systems (Philpott et al., 2008). This limits the comparability across case studies, thus preventing robust conclusions. A framework with a consistent terminology would allow for better comparability across studies, leading to more robust, precise and conclusive findings. To start with, future research is expected to benefit from classification of coffee systems along the two dimensions of shade and input management, rather than using level of shade as a single management intensity indicator.

Similar to other recent studies (e.g., Cerda et al., 2016; Charbonnier et al., 2017; Meylan et al., 2017; Rahn et al., 2018), the relations between shade and input management and coffee yields are complex and location specific. Growing coffee under shade might be the favoured or required system in some coffee areas, whilst in other areas lower shade levels or full sun systems may be favourable. For example in areas with high annual cloud cover, higher shade levels further reduce incoming sunlight, which leads to a decrease in coffee yields (Farfán-Valencia and Sánchez Arciniégas, 2007). As a first step, it is important to acknowledge this complexity. Secondly, there is a need for more research spanning a wider range in elevation, climatic and soil conditions, while simultaneously addressing both shade and input management, in order to be able to generalize the findings of this study with regards to the relationships between management strategies and coffee yields.

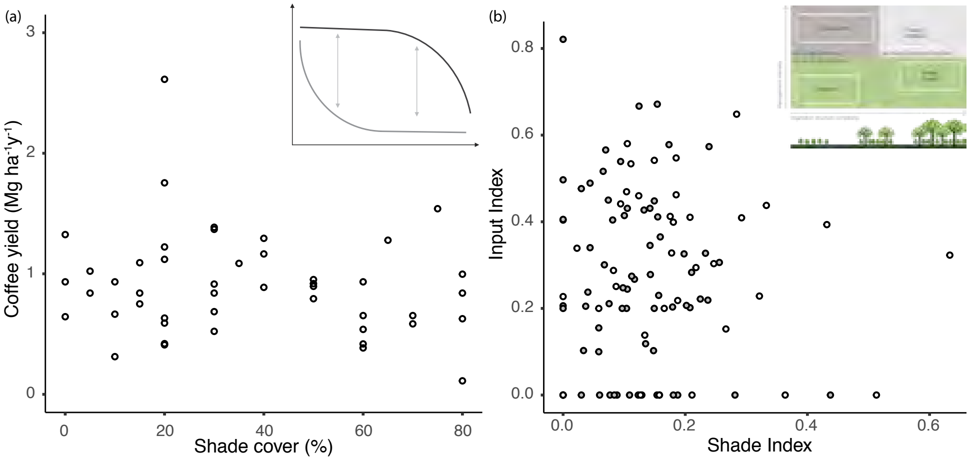


Figure 16. a) Relation between shade cover (x-axis) and coffee yields (y-axis) observed for 57 Peruvian coffee systems for which field data was collected, reflecting on Figure 1. b) Spread in Shade Index (x-axis) and Input Index (y-axis) is presented for the 162 plantations included in the Peruvian case study for both the survey dataset (open circles) and the sub dataset for which plot data was collected (grey circles), reflecting on Figure 2.

II - What is the *economic performance* of coffee and cocoa systems with different shade and input management?

This thesis provides evidence that agroforestry systems can perform equally well or better compared to plantations with lower shade levels (Chapter 2 and 4) and/or with higher input levels (Chapter 4). Importantly, this was irrespective of lower yields that were associated with higher shade levels as indicated by shade tree density in Chapters 2 and 4. There were no differences between net income and BCR for plantations with different shade management practices. With an average net coffee income of 702±961 € ha^{-1} y^{-1}, the results of the case study in Chapter 4 are in line with a recent study of Nelson et al. (2016), where net income of Peruvian coffee farmers in the department of San Martín was estimated at 836 € ha^{-1} in 2011. Average BCR values of 2.6 from the case study (Chapter 4) were in line with the average BCR of 1.9 for shaded coffee systems observed in the meta-analysis (Chapter 2). However, acquired insights on shade levels under different certification schemes may challenge the assumption made in chapter 2 that coffee plantations under certification schemes have higher shade levels. Although farmers with high-input practices reported lower yield losses due to coffee rust (Chapter 3), this was not translated into better economic performance. Rather, there was a difference in economic performance between plantations with different levels of input as net income and BCR were lower for plantations with higher input practices.

To some extent, the difference in economic performance was explained by higher costs of intensified systems, both for flexible (inputs and labour) and fixed costs (land and equipment), while economic performance of shaded systems was better as costs were lower for plantations with higher shade levels. These dynamics are not just seen in Peru but also in other coffee producing countries. For example Gobbi (2000) demonstrated that in El Salvador, the capital requirements for shaded coffee systems were low and that these requirements increased with a reduction in shade levels. Costs in this study (~1032 € ha^{-1} y^{-1}) were comparable to those of a recent study which reported expenditures of approximately 1068 € ha^{-1} y^{-1} for coffee production in the department of San Martín, Peru, and between 800 and 1300 € ha^{-1} y^{-1} for coffee production in El Salvador and Colombia (Nelson et al., 2016). As small-scale farmers often have limited access to resources and capital, which is no different for Peru (USDA, 2014), these lower costs associated with high shade practices may be a more attractive option for many coffee farmers.

Benefits derived from other products greatly contributed to the income of small-scale farmers in Peru. Income from other products - in this case firewood, other crops, fruits and livestock- accounted for an average of 32% of total farm income. These benefits were lowest for plantations with high input levels and low shade levels, which are associated with intensively management coffee systems. If the potential income from timber would be realized, the total yearly income could increase by a third for plantations with high shade levels. Although the estimated timber values come with a high level of uncertainty related to plot size, data extrapolation and timber prices (Chapter 4), similar results were found in Costa Rica and Guatemala, where income from timber and firewood accounted for more than 70% of the income derived from shaded coffee plantations (Martínez Acosta, 2005; Mehta and Leuschner, 1997). There are, however, important economic and ecological challenges that need to be overcome, such as market access and improving the choice and management of shade trees. If these barriers would be overcome, the benefits derived from shade trees can provide important contributions to farmers' livelihoods, especially in times of low coffee prices or productivity, thereby increasing farmers' economic resilience.

There was no direct relationship between coffee and cocoa productivity, and economic performance expressed as BCR and net revenue. Although the relationship between crop yields and economic performance may be straightforward for intensified monoculture land-use systems (Steffan-Dewenter et al., 2007), these results illustrate that this relationship is more complicated for diversified systems such as shaded coffee and cocoa plantations. This questions the use of yield as a direct indicator of economic performance of these systems. More comprehensive economic assessments are needed, including more detailed indicators such as net revenue or benefit-cost ratio. Nonetheless, the relationship between yield and management characteristics such as shade and input, provides important insight into the trade-offs and opportunities for double dividends in coffee and cocoa systems. So even though yield data are part of economic performance, results should be interpreted with due caution and in the right context.

III - Can *trade-offs or double dividends* be identified between environmental and economic performance of coffee and cocoa systems with different shade and input management

This thesis provides evidence that agroforestry systems can provide double dividends for smallholders and conservation of biodiversity and other ecosystem services. First of all, no trade trade-offs were found between coffee yields, forest butterfly species richness and above-ground carbon storage (Chapter 3) and shaded coffee systems supported biodiversity and carbon storage, without evidence for reduced yields. Moreover, this implies that for this study area, farmers can manage their plantations to maintain biodiversity and carbon, before any trade-offs with coffee yields start materializing, similar to what was found in Costa Rica (Cerda et al., 2016). Average coffee yields of this study (~850 kg ha^{-1} y^{-1}) are comparable to the average Arabica yields of smallholder coffee plantations in Peru (Bean and Nolte, 2017; Nelson et al., 2016) and elsewhere in Latin America (Panhuysen and Pierrot, 2014), including Mexico (Soto-Pinto et al., 2000) and Costa Rica (ICO, 2016). Nonetheless, yields are less than half those observed for extensive production systems in Brazil and Colombia (~1800 kg ha^{-1} y^{-1}; Campanha et al., 2004; Capa et al., 2015), and it is possible that clearer trade-offs can be observed in systems where other production factors are closer to optimal. Secondly, on occasions when yield is lower, this can be compensated by lower costs, higher product prices and increased revenues from other products, as illustrated in Chapter 2 and 4. Consequently, net income and BCR were equal or higher for plantations with lower input and higher shade levels.

The potential double dividend for environment and economic performance is an important argument used to advocate a land-sharing approach and confirms other studies that propose that wildlife friendly farming may be the best species conservation option in a coffee and cacao cultivation context (Clough et al., 2011; De Beenhouwer et al., 2013; Perfecto et al., 2005). In general, given that the major coffee producing regions in Peru are highly biodiverse and the majority of the coffee farms are currently managed with relatively low levels of agrochemical inputs (Bean and Nolte, 2017) and relatively high levels of shade (Jha et al., 2014), there is still large potential to safeguard biodiversity and carbon stocks while increasing income and improving livelihoods. Although coffee agroforestry systems can play an important role in biodiversity conservation, a meta-analysis of De Beenhouwer et al. (2013) showed a decline of 11% of the total species richness and a loss of 37% of ecosystem services in coffee and cocoa agroforestry systems as compared to natural forests. This stresses the importance of maintaining natural forests areas as these are irreplaceable regarding biodiversity conservation (Gibson et al., 2011) as well as ecosystem services provisioning (Cardinale et al., 2012; Naeem, 2012).

Taking it one step further and reflecting on Figure 1; there were no trade-offs between butterfly diversity and above-ground carbon storage with net income for this case study of Peruvian coffee farmers (Figure 17). Moreover, the broad spread of the relation observed between biodiversity and carbon on one hand and farmer income on the other, suggests that many options are possible, including plantations that provide double dividends for biodiversity and carbon storage, and for farmer income. In further research, it would be interesting to look into strategies that can optimise these double dividends. While recognizing that there are many factors at play, input and shade management can play an important role in optimising this relation. To this regard, it would be interesting to look in more detail at the systems located in the grey squares in Figure 17. Studying these systems in more detail may help to identify the specific set of shade and input management strategies which allow for double dividends for biodiversity and livelihoods (Cerda et al., 2016; Rapidel et al., 2015).

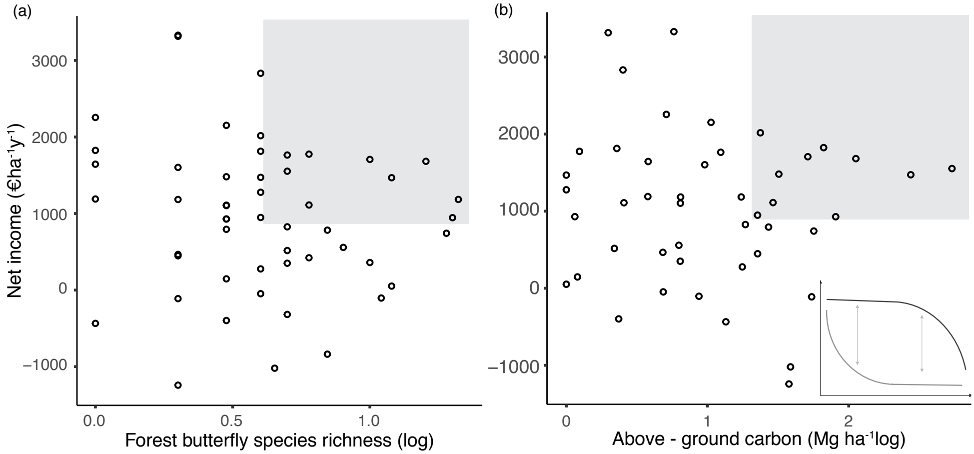


Figure 17. Relation between environmental and economic performance, depicted for empirical data from the case study in Peru, reflecting on Figure 1. Environmental performance indicators (a) Forest butterfly species richness and (b) Above-ground carbon storage (x-axis; see Chapter 3) and net income (y-axis; includes income derived from coffee as well as from firewood, livestock and other crops and fruits, but excludes potential timber revenues, see Chapter 4). No significant relations were detected. The grey squares represent 'the desirable area', where both environmental and economic performance are relatively high.

Further research is needed on options that deviate from the global trend towards conventional intensification of coffee systems. Although this thesis suggests that there is great potential for Peruvian smallholder coffee farmers to reconcile ecological and economic needs, more insight in the economic performance of coffee plantations under different management practices and in different context is needed. Additionally, research focusing on the trade-offs between economic and environmental performance is needed, taking both direct and indirect benefits into account. Also, economic and environmental performance indicators responded differently to shade and input management, which highlights the importance of including shade and input highlights the importance of including shade and input as separate variables in future studies. Moreover, there are only a limited number of multidisciplinary studies that include both economic and environmental data. To this regard, future studies should simultaneously address the effects of shade and input management on multiple economic and environmental performance indicators and take variation in biophysical variation into account.

IV - What is driving smallholder decision-making regarding the adoption of different shade and input management of coffee systems?

The sustainable livelihoods framework was used to assess how livelihood assets of smallholders influence the adoption of shade and input management strategies, and how this is affected by risks and shocks, for smallholder coffee producers in San Martín, Peru. On the one hand, higher shade levels were associated with higher levels of human and social capital, more specifically farmer experience and membership to a farmer organization which is in line with other studies (Chaves and Riley, 2001; Quiroga et al., 2015). On the other hand, there was a trend that higher physical and financial capitals were associated with higher input use, which is in line with other studies that found that wealthier farmers could invest more in inputs to enhance farm output (Bullock et al., 2014; Rahman, 2003).

These results suggest that improving livelihood assets is important for decision making, and these set of actionable assets differ for shade and input management; whilst human, social and natural assets may limit or enhance adoption of environmentally-friendly management systems, financial and physical assets may affect adoption of input management strategies. Moreover, adoption of agroforestry systems providing both economic and environmental benefits will depend on capacity building, and farmer organisations can play a crucial role to that regard. Together these findings illustrate how the decision-making process of smallholder farmers is influenced by many factors that may push-and-pull decisions in different directions, and that livelihood assets are more important in determining management strategies than perception of risks and shocks. Nonetheless, adaptations in shade and input management over the last five years were responsive to pest and disease and climate change pressure, in opposite directions: climate change perception motivated farmers to increase shade levels, while pressure from pests and disease led to a reduction in shade. Reconciling these opposing management strategies is fundamental as shade trees are expected to improve farmer's resilience to climate change (Lin, 2007; Rahn et al., 2014).

The institutional environment was not systematically included in the analysis. As this links livelihood assets and farming strategies in the sustainable livelihoods framework (Scoones, 1998), it is recommended to extend the framework to include this component in a future study. Also, as these are dynamic systems, further research is expected to benefit from including livelihood outcomes and looking into the directionality of the relationships between management strategies, experienced pressures, perceived risks and livelihoods assets. Extending the livelihood framework can help identify management strategies that are able to reconcile livelihoods assets, so that economic and environmental performance can coincide.

6.3. Recommendations for practitioners and policy makers

Besides more insight in relations between environmental and economic performance, importantly, it became clear that the benefits of agroforestry systems are very diverse and location-specific and that there is no blueprint for management systems that will provide double dividends under all circumstances. Nonetheless, there are a few important opportunities which are thought to be generally applicable for the use of agroforestry management systems. The most important economic arguments for shaded systems are lower costs, higher product price and diversification of income, including income from timber. At the same time, environmental opportunities are found in higher sustained biodiversity and carbon storage, which can contribute to both climate change mitigation and adaptation. Although reconciling the goals of livelihoods and conservation of biodiversity and other ecosystem services seems promising, there are obstacles that need to be overcome as well as opportunities that can be seized in order to reconcile these goals. In this section, recommendations for different actors involved in the coffee and cocoa value chain are presented, including practitioners who provide technical assistance to the coffee farmers, extension services, local and national policy makers, certification bodies and the international community.

6.3.1. Management of agroforestry systems and extension services

Diversification is an important strategy to increase economic resilience and as illustrated, the products from shade trees can provide substantial income for the farmers, either in kind or in cash. Training and technical assistance are needed to help farmers achieve the desired level of productivity, both for coffee as well as for other (tree) products.

Income from timber has the potential to contribute to farmer income, yet as mentioned, there are important ecological and economic challenges that need to be overcome. First of all, more knowledge on suitability of shade trees to be intercropped with coffee and cocoa is needed, taking nutrient competition, management requirements and local market prices of timber and fruits, and site-specific conditions into consideration (Chapter 3). Importantly, it is recommended that technical interventions not only take scientific information on agroforestry practices into account, but also the knowledge of the local farmers (Cerdán et al., 2012). Thus, extension services (public or local farmer organisations) and researchers should gather information on suitability of shade tree species in close collaboration with the farmers. This is expected to enhance the success of development programs and projects aimed at enhancing productivity or other ecosystem services. Secondly, improved management of shade trees is needed, in particular pruning of shade trees. This is expected to improve timber quality, as well as to control shade cover to enhance coffee and cocoa production. Third, extension services should provide farmers with information on expected benefits and disadvantages of shade trees, in particular in relation to effects of climate change and the possible role of shade trees in climate adaptation. As both shade trees and coffee shrubs take years to establish and the average lifespan of a coffee plantation is about 30 years (Wintgens, 2012), decisions should take into account the long-term scenarios of climate change.

In addition to choice and management of shade trees, it is important that farmers improve the management of their coffee shrubs to optimise yields. To this regard, training of farmers to apply fertilizers and fungicides more effectively is highly recommended, keeping in mind that pest and disease control should be adapted to physical conditions of the plantation such as climate and soil (Chapter 3). Furthermore, the higher expected bean quality with increased shade levels (Muschler, 2001; Vaast et al., 2006) provides an important opportunity to reconcile environmental and economic goals, since coffee quality is an important determinant for coffee price (Chapter 4). Although this partially depends on the access to specialty markets, extension services can play an important role to aid the farmers in improving coffee bean quality. Additionally, access to finance is important to optimise input management practices (Chapter 5), especially in response to the rising production costs (Chapter 4). Thus, credit schemes that can provide small loans with reasonable conditions (i.e. no exorbitant interest rates) to local farmers are recommended. Moreover, extension services seem to be increasingly important in response to the fluctuating coffee prices, rising production costs and increased pest and disease pressure. Uniting farmers in farmer organisations is important while support from public extension services or development organisations is recommended.

6.3.2. Marketing of coffee, agroforestry products and services and enabling environment

Marketing of coffee and other agroforestry products (including timber) provides serious challenges to smallholder farmers, as well as marketing of indirect benefits provided by shade trees that are captured in ecosystem services. In recent years, demand for specialty coffees increased rapidly as sustainable coffee sales in terms of volume increased by more than 400% from 2004-2009 and is also expected to increase further (Jha et al., 2014; Vellema et al., 2015). Access to specialty markets is often obtained through certification schemes, which was also confirmed in this study (Chapter 5). To this regard, environmental certification schemes such as UTZ, Bird-friendly and Rainforest Alliance provide potential to steer the production of coffee and cocoa towards more sustainable directions while the price premiums that smallholders receive can increase their net income (Lyngbæk et al., 2001). However, certification schemes come with significant transaction costs which are commonly carried by the producers, reducing the added price premium for the coffee and cocoa farmers. These transaction costs should be more equally carried by the value chain, emphasizing the responsibility of different parties such as buyers and roasters, as well as consumers. Generally, if farmers are to consider switching from a conventional to a shaded system, the presumed decrease in coffee or cocoa yield needs to be compensated by a price premium, irrespective of the difference in quality of the product (Chapter 2 and 4). Thus, goals of farmers and certification schemes need to be aligned in order for certification schemes to improve farmers' livelihoods. In conclusion, there are no blueprints for management systems that will provide double dividends. This has implications for the effectiveness of certification schemes that promote shaded systems using a set of fixed requirements. Effectiveness of certifications schemes may therefore benefit from more locally-specific requirements as well as using multiple key variables for the requirements of shade management, including the number of strata and shade cover.

Incentives need to be developed to stimulate adoption of systems which maintain conservation of biodiversity and other ecosystem services, especially if this is expected to reduce coffee and cocoa yields. An opportunity to improve benefits derived from shaded coffee and cocoa plantations are payments for environmental services, through markets for environmental services. Payment schemes linked to carbon storage are well known such as Reduced Emissions from Deforestation and Degradation (REDD)+ and other payment for ecosystem services (PES) schemes. However, functional markets for services produced by agroforests in developing countries are lacking. Some of this is due to lack of buyers, while for some environmental services there are potential buyers, but many challenges remain in connecting these buyers to agroforestry suppliers, and legislation needs to be adapted accordingly. Also, even if markets are functioning properly, the benefits of these schemes are a mere addition to farmers' income. So, even though certification and ecosystem payment schemes can potentially increase economic resilience of smallholders, it is important to ultimately seek systems that reconcile economic and environmental performance without dependency on certification schemes or other external mechanisms. Therefore, in the first place, it is important to recognise and promote the ecological benefits of shade trees for smallholders such as enhanced soil fertility and buffering of microclimate, as well as promote further research on these ecological mechanisms.

Importantly, local and national governance should favour and promote biodiversity-friendly management; i.e., intercropping of coffee and cocoa with shade trees (taking local conditions into account) while sustainably intensifying management practices such as fertilizing and weeding. Local and national regulations need to be adapted. More specifically, it is important that the close link between agriculture and forestry is recognised in order to use a more integrated perspective on land use. Legislation for forestry and agriculture is contradictory in many countries, so it is recommended to integrate these policy measures. Also, lack of land tenure is a major barrier for smallholders to engage in agroforestry practices, so national and local policies should emphasize the promotion of tenure rights. However, the expansion of coffee and cocoa areas should be carefully managed via land tenure and property rights, and new areas should avoid biodiversity hotspots and national parks.

Altogether, this thesis supports the theory that agroforestry systems can offer competitive business opportunities in comparison to the expanding conventionally intensified systems and can reconcile farmer livelihoods and conservation of biodiversity and other ecosystem services. This potential of agroforestry systems to provide double dividends is especially important in the light of increasing pest and disease pressure, global price fluctuations, land degradation and climate change. In order to reconcile economic and ecological goals in coffee and cocoa systems, comprehensive multidisciplinary analyses are needed, including for other regions, to be able to draw generalizable conclusions and deepen our insight in trade-offs between economic and environmental performance. To this regard, future economic performance studies should simultaneously address the effects of shade and input management on multiple economic and environmental performance indicators and take variation in biophysical factors into account. Furthermore, extension services and training of farmers, as well as adequate certification schemes, access to finance and markets, and appropriate legislation are needed to promote the adoption agroforestry systems that provide double dividends for livelihoods and conservation of biodiversity and other ecosystems services.

7

Appendices

Table A1. Overview of articles included in the analysis and their respective data of shaded plantations (part 1). BCR = Benefit-Cost Ratio.

				Shaded system										
					Plantation Structure			Costs and Benefits						
Reference	Commodity	Country	ID	System description in article	Coffee shrub/ cocoa tree density (# ha^{-1})	Shade tree density (# ha^{-1})	Shade tree density category	Costs (US$ ha^{-1})	Yield (kg ha^{-1})	Yield/tree (kg tree$^{-1)}$	Product price (US$ kg^{-1})	Gross income (US$ ha^{-1})	Net income (US$ ha^{-1})	BCR
Bagua (2007)	Coffee	Peru	1	Medium-shade		25-100	Medium		602.56					
			2	Shaded		>101	High		758.80					
Campanha et al., (2004)	Coffee	Brazil	3	Agroforestry system		300	High		514.80	1.60				
Detlefsen (1988)	Coffee	Costa Rica	4	Shaded	4790	400	High		577.51	0.55				
Gobbi (2000)	Coffee	El Salvador	5	Traditional polyculture	1700	200	High		575.00	0.34			$ 369.00	
			6	Commercial polyculture	2200	214	High		895.00	0.41			$ 15.00	
			7	Technified shade (low+m. altitude)	4050	58.5	Medium		1865.00	0.46			$ 241.00	
Gockowski et al. (2013)	Cocoa	Ghana	8	Extensive shade non-fertilized	1086	55	Medium		240.00	0.22			$ 47.73	0.99
			9	Certified, medium shaded, fertilized	1086	12	Low		950.00	0.87			$ 217.62	1.20
Gordon et al. (2007)	Coffee	Mexico	10	Bajo Monte			High	$ 151.70	1161.90		$ 0.17		$ 813.58	5.36
			11	Commercial Polyculture			Medium	$ 279.06	788.86		$ 0.17		$ 340.86	1.22
			12	Specialised Shade			Low	$ 394.86	1390.83		$ 0.17		$ 875.06	2.22
Haggar et al. (2012)	Coffee	Nicaragua	13	Organic		200	High	$ 529.00	499.00		$ 0.74	$ 1,745.00	$ 1,216.00	2.30
			14	Fairtrade				$ 1,336.00	1023.00		$ 0.54	$ 2,689.00	$ 1,351.00	1.01
			15	UTZ certified				$ 676.00	661.00		$ 0.44	$ 1,426.00	$ 748.00	1.11
			16	C.A.F.E. practices				$ 1,734.00	1335.00		$ 0.53	$ 3,530.00	$ 1,795.00	1.04
Harold (2013)	Coffee	Tanzania	17	Shaded organic	1168			$ 168.21			$ 2.80	$ 526.83	$ 296.42	1.76
Hernandez (1995)	Coffee	Costa Rica	18	Average: 200 Laurel/ha	4780	200	High		1714.17	0.40				2.10

				Shaded system										
					Plantation Structure			Costs and Benefits						
Reference	Commodity	Country	ID	System description in article	Coffee shrub/ cocoa tree density (# ha^{-1})	Shade tree density (# ha^{-1})	Shade tree density category	Costs (US$ ha^{-1})	Yield (kg ha^{-1})	Yield/tree (kg tree^{-1})	Product price (US$ kg^{-1})	Gross income (US$ ha^{-1})	Net income (US$ ha^{-1})	BCR
Lyngbæk et al. (2001)	Coffee	Costa Rica	19	Multistrata organic	5280			$ 1,470.00	600.00		$ 0.44		$ 1,448.00	0.99
Martínez Acosta (2005)	Coffee	Guatemala	20	Traditional s/m (Tpm-bx)			High	$ 165.38	368.00					1.50
			21	Traditional s/m (organic (Top-hx)			High	$ 60.63	308.20					1.70
Metha & Leuschner (1997)	Coffee	Costa Rica	22	Agroforestry coffee	5000	324	High						$ 6,778.24	
Obiri et al. (2007)	Cocoa	Ghana	23	Shaded Hybrid		70	Medium	$ 390.48				$ 1,509.03	$ 1,118.56	1.71
			24	Traditional				$ 399.39				$ 1,424.39	$ 1,025.00	1.57
Pinard et al. (2014)	Coffee	Rwanda	25	Shade					352.00					
Ramírez et al. (2001)	Cocoa	Panama	26	Cocoa with plantain (average S1,2,3)	710	69	Medium	$ 1,046.72	744.03	1.05			$ 1,197.56	1.14
Sánchez-de León et al. (2006)	Coffee	Costa Rica	27	Organic Shaded Erythrina		49	Medium		950.00					
			28	Organic shaded Terminalia		63	Medium		1141.67					
Souza et al. (2010)	Coffee	Brazil	29	Agroforestry	2050	100	Medium	$ 345.00	1271.00	0.62	$ 0.90	$ 1,143.90	$ 806.40	2.34
Victor et al. (2010)	Cocoa	Ghana	30	High Input medium shade, certified	1100	12	Low							1.00
			31	Low input Landrace	1100		Medium							0.97
			Average		2579	145.4	-	$ 609.76	851.5	0.65	$ 0.82	$ 1,749.27	$ 1,089.47	1.66

Table A1. Overview of articles included in the analysis and their respective data of conventional plantations (part 2). BCR = Benefit-Cost Ratio.

			Plantation Structure	Costs and Benefits						
Reference	ID	System description in article	Coffee shrub/ cocoa tree density (# ha^{-1})	Costs (US$ ha^{-1})	Yield (kg ha^{-1})	Yield per tree (kg tree -1)	Product price (US$ kg-1)	Gross income (US$ ha^{-1})	Net income (US$ ha^{-1})	BCR
Bagua (2007)	1	Monoculture			597.52					
	2									
Campanha et al., (2004)	3	Monoculture			2442.80	4.53				
Detlefsen (1988)	4	Monoculture	7215		3401.00	0.47				
Gobbi (2000)	5	Monoculture	5500		2520.00	0.46			$ 526.00	
	6									
	7									
Gockowski et al. (2013)	8	Monoculture, fertilized (high-tech)	1086		1220.00	1.12			$ 261.01	1.31
	9									
Gordon et al. (2007)	10	Monoculture		$ 744.57	1604.80		$ 0.17		$ 484.35	0.65
	11									
	12									
Haggar et al. (2012)	13	Conventional		$ 1084.00	840.00		$ 0.45	$ 1,921.00	$ 836.00	0.77
	14									
	15									
	16									
Harold (2013)	17	Conventional	1084	$ 226.04			$ 2.09	$771.78	$ 489.44	2.17
Hernandez (1995)	18	Monoculture	7215		3060.00	0.42				1.80
Lyngbæk et al. (2001)	19	Conventional	5730	$ 1,403.00	770.00		$ 0.36		$ 1,483.00	1.06
Martínez Acosta (2005)	20	Semi-intensive		$ 173.71	563.50					2.05
	21									
Metha & Leuschner (1997)	22	Monoculture	5000						$ 5,604.83	

			Plantation Structure	Costs and Benefits						
Reference	ID	System description in article	Coffee shrub/ cocoa tree density (# ha^{-1})	Costs (US$ ha^{-1})	Yield (kg ha^{-1})	Yield per tree (kg tree -1)	Product price (US$ kg-1)	Gross income (US$ ha^{-1})	Net income (US$ ha^{-1})	BCR
Obiri et al. (2007)	23	Monoculture	$ 290.58			$ 972.55	$ 681.97	1.74		
	24									
Pinard et al. (2014)	25	Monoculture			228.67					
Ramírez et al. (2001)	26	Monoculture	1111	$ 575.00	880.20				$ 792.42	1.38
Sánchez-de León et al. (2006)	27	Monoculture (high-conventional)			1891.67					
	28									
Souza et al. (2010)	29	Monoculture	2650	$ 1,035.00	2093.50	0.79	$ 0.90	$ 1,884.15	$ 849.15	0.82
Victor et al. (2010)	30	Monoculture, high input	1100							1.05
	31									
	Average		3769	$ 691.49	1579.55	1.30	$ 0.79	$ 1,295.74	$ 1,200.82	1.44

Table A2. Overview of articles and their respective biodiversity performance data in terms of species diversity and abundance. BCR = Benefit-Cost Ratio.

				Shade quality				Species diversity			Species abundance			BCR	
Reference	Commodity	Country	ID	Shade tree density	Shade tree density category	Shaded vs Conventional	Species group	Shaded	Conventional	Difference (%)	Shaded	Conventional	Difference (%)	Shaded	Conventional
Gordon et al. (2007)	Coffee	Mexico	10		High	↑	Birds	46	15	306%				5.36	0.65
			11		Medium	↑		30		200%				1.22	
			12		Low	↑		18		120%				2.22	
Haggar et al. (2012)	Coffee	Nicaragua	13	200	High	↑	Tree species	4.6	2.7	170%				2.3	0.77
Sánchez-de León et al. (2006)	Coffee	Costa Rica	27	49	Medium	↑	Earthworms	265 ind m^{-2}	63 ind m^{-2}	420%	99 gr m^{-2}	20 gr m^{-2}	495%		
			28	63	Medium	↑		334 ind m^{-2}	64 ind m^{-2}	530%	118 gr m^{-2}	20 gr m^{-2}	590%		

Table A3. Identified plant and tree species if possible to species level (third column), otherwise to genus level (second column) based on known local names (fourth column). Fifth column describes assigned class: i) banana/palm; ii) leguminous and; iii) other. The sixth column (n) reports total observed individuals amongst all plantations and forest sites (n=60)

Family	Genus	Species	Local name(s)	Classification	n
Anacardioideae	*Mangifera*	*indica*	Mango	Other	2
Apocynaceae	*Aspidosperma*	*macrocarpon*	Pumaquiro	Other	1
Arecaceae	*Socratea*	*exorrhiza*	Cashapona	Banana/palm	1
	Ceroxylon	*peruvianum*	Pona	Banana/palm	3
Betulaceae	*Alnus*	*acuminata*	Mentol	Other	4
Calophyllaceae	*Calophyllum*	*brasiliense*	Alfaro	Other	2
Caricacea	*Carica*	*papaya*	Carica papaya	Banana/palm	2
Euphorbiaceae	*Hevea*	*brasiliensis*	Shiringa	Other	2
	Alchornea	*iricurana*	Tapia	Other	2
Fabaceae	*Inga*	*spp.*	Guaba, Guaba sherimba, Rufindi, Umpacay	Leguminous	150
	Inga	*feuilleei*	Pacay	Leguminous	28
	Amburana	*cearensis*	Ishpingo	Other	2
	Mariosousa	*willardiana*	Palo blanco	Other	7
	Mariosousa	*spp.*	Palo sp.	Other	1
	Cedrelinga	*cateaeformis*	Tornillo	Other	5
Lauraceae	*Persea*	*americana*	Palta (avocado)	Other	10
	Cinnamomum	*verum*	Canella	Other	1
	Nectandra	*spp.*	Moena	Other	20
	Clorocardium	*venenosum*	Palta Moena	Other	2
Malvaceae	*Theobroma*	*cacao*	cocoa	Other	2
	Ochroma	*pyramidale*	Balsa	Other	1
Meliaceae	*Cedrela*	*odorata*	Cedrillo,cedro blanco	Other	7
	Cedrela	*NA*	Cedro	Other	2
	Cabralea	*canjerana*	Cedro Mullaca	Other	10
Moraceae	*Poulsenia*	*armata*	Lanche	Other	2
	Brosimum	*alicastrum*	Lechero	Other	2
	Ficus	*insipida*	Oje	Other	7
	Ficus	*spp.*	Renaco	Other	1
Musaceae	*Musa*	*NA*	Platano (artan, de la isla, dulce, seda, verde)	Banana/palm	174
Myrtaceae	*Eucalyptus*	*torreliana*	Eucalipto relleno	Other	3
	Eucalyptus	*saligna*	Eucalypto saligna	Other	17
	Corymbia	*calophylla*	Goma roja	Other	1

Rosaceae	*Prunus*	*amygdalus*	Almendra	Other	1
Rubiaceae	*Calycophylleae*	*spruceanum*	Capirona	Other	9
	Genipa	*americana*	Jagua	Other	2
Rutaceae	*Citrus*	*spp.*	Limon dulce	Other	6
Urticaceae	*Cecropia*	*spp.*	Setico	Other	3
	Pourouma	*cecropiifolia*	Uvilla	Other	2
NI			Cedrico (naranja)	Other	1
			Copazra	Other	1
			Estorace	Other	1
			Huarunsetico	Other	1
			Jetico	Other	1
			Mandarina	Other	7
			Oquera	Other	1
			Rijndi	Other	1
			Unshakiro	Other	1
			Palmera	Banana/palm	4
			NA	Other	61

Appendix A2. Soil fertility measurements

Soil nitrogen content (N), soil organic matter (OM), soil pH, soil cation exchange capacity (CEC) and soil C:N ratio are important indicators for soil quality (e.g., Beer et al., 1998; Robertson and Swinton, 2005) and therefore used as indicators for maintenance of soil fertility. In each plantation site five samples of soil from the top layer (0-15 cm) weighing approximately 500 gr each, were collected randomly throughout the plot. After mixing thoroughly, a sub-sample of approximately one kilogram was sent to a laboratory for analysis. Soil samples taken in Alto Mayo were sent to Laboratory for Analysis of Agricultural Soil of a regional governmental institute, Proyecto Especial Alto Mayo (PEAM) in Nueva Cajamarca. Soil samples taken from the Picota region were analyzed at the Instituto de Cultivos Tropicales (ICT) in Tarapoto. Lab procedures were the same (Table A5) and measurements are therefore comparable and consistent. Soil carbon content (Cc%) was calculated as being 58% of soil OM (%; Mann, 1986). Soil Cc was used to calculate soil C: N ratio.

Appendix A3. Yield loss due to pests and diseases and soil fertility

Yield loss due to pests and diseases - The survey data showed that coffee rust was the most important factor in yield loss due to pests and diseases, with an average estimated loss of 46.2±24.6%. The range of reported losses was large (0-100%) implies that some farmers perceived to have lost the majority of their coffee harvest due to coffee rust, while others experience limited to no loss. Rust damage was significantly negatively related to total input expenses (Table A9) as well as to plague input expenses separately. Besides input management, there was a trend towards higher rust damage with increasing shade tree density, and significantly more rust damage on plantations with older coffee shrubs and plantations situated on higher altitudes. We found no relation between coffee variety and coffee rust damage. With an average loss of 9.6±11.6%, the pest coffee berry borer was associated with lower average yield loss than the coffee rust, yet losses up to 50% on single plantations were reported. Four models were equally good in explaining berry borer damage, and included the null-model. Berry borer associated loss was affected by input management and by timber trees. There was a trend that higher input expenses were related to decreased berry borer damage (Table A9). We found no difference for rust damage between regions, yet berry borer associated loss was significantly higher in the region of Picota. The remaining diseases showed similar losses of 9.5±14.8% due to Ojo de Pollo and 8.5±13.09% due to Aranjero. Best models for both Ojo de Pollo and Aranjero explained very little variance (<1%) and no best model set was derived for these diseases (Table A8).

Soil fertility - Soil samples showed large variation in values of all soil fertility indicators, with soil N varying by a factor of 16, and soil CEC even by a factor of 25 (Table A8). In the best model sets for each soil fertility indicator, both shade management and fertilizer expense variables were included (Table A9). Best model sets identified that fertilizer input was negatively related to soil N (organic: 3 out of 4), soil OM (total: 2 out of 3, organic: 1 out of 3 and chemical: 1 out of 3) and soil C:N (chemical: 3 out of 3). Regarding shade management, best model sets identified that shading practices positively affected soil OM (total shade tree density: 3 out of 3) and soil pH (shade cover: 2 out of 2). In case of soil pH, shade provided by banana plants appeared to be important in that regard (2 out of 2) with significantly higher pH values in plantations with more banana plants. Besides input and shade management, plantations at higher altitudes had significantly higher soil OM values, and showed a trend towards higher soil N and pH values. Contrary to expectations, coffee shrub age showed no relation with any of the soil fertility indicators.

Table A4. Identified butterfly species and categorization in forest and non-forest habitat species

Genus	**Species**	**Habitat preference**	**Reference**
Adelpha	*capucinus*	forest	F
	cytherea	non-forest	F
	iphiclus	non-forest	B
	spp.	forest	F
	thessalia	forest	F
Altinote	*negra*	forest	D, O
Amarynthis	*meneria*	forest	D
Anartia	*amathea*	non-forest	A,D
	jatrophae	non-forest	A, D
Anthanassa	*drusilla alceta*	non-forest	A, D, G
Antigonus	*mutilatus*	forest	D
Apaustus	*menes*	non-forest	D
Arawacus	*separata*	non-forest	D,E,G
Ascia	*spp.*	non-forest	A
Astraptes	*anaphus*	forest	D,E
	spp.	forest	D,E
Autochton	*neis*	non-forest	O
	spp.	non-forest	O
	zarex	non-forest	O
Battus	*polydamas*	non-forest	D,I
Bia	*spp.*	forest	D
Bungalotis	*spp.*	forest	D,P
Callicore	*aegina*	forest	D
Calycopis	*atnius*	forest	D,P, R
	malta	forest	D,P, R
	spp.	forest	D,P, R

Genus	**Species**	**Habitat preference**	**Reference**
Catanophele	*acontius*	forest	D
Ceratinia	*tutia*	forest	
Chalodeta	*spp.*	forest	Q
Chloreuptychia	*arnaca*	forest	D, G
	spp.	forest	D, G
Cissia	*labe*	non-forest	E
	NA	non-forest	E
	penelope	non-forest	E
	proba	non-forest	E
	spp.	non-forest	E
	terrestris	non-forest	C,D
Cithaerias	*spp.*	forest	G
Colobura	*dirce*	forest	D, F
Consul	*fabius*	forest	D
Crocozona	*coecias*	non-forest	D
Danaus	*plexippus erippus*	non-forest	D
Diaethria	*clymena*	forest	D,E, S
Dione	*juno*	non-forest	D
Dircenna	*adina xanthophane*	forest	D
	dero	forest	A
Dryas	*iulia*	non-forest	A, G
Episcada	*sulphurea*	forest	A
Eueides	*isabella*	forest	T
	libitina	forest	D
	vibilia	forest	D
Eunica	*spp.*	forest	A
Eurema	*albula*	non-forest	G
Eurybia	*dardus*	forest	D, G
	spp.	forest	D, G
Euselasia	*orfita*	forest	D
Fountainea	*ryphea*	forest	H,T
Glutophrissa	*spp.*	forest	G, P
Godyris	*zabaleta*	forest	D
Hamadryas	*feronia*	forest	A, D
Heliconius	*arcuella*	forest	A,G
	burneyi	forest	G
	erato	forest	A
	ethila	forest	A,G

Genus	Species	Habitat preference	Reference
	hecale	forest	A
	melpomene	forest	G
	numata	forest	D
	numata bicoloratus	forest	D
	pardalinus	forest	A
	sara	forest	A
	spp.	forest	A
Heliopetes	*arsalte*	non-forest	D
Hermeuptychia	*hermes*	non-forest	G
Hyparnatia	*lethe*	forest	D
Hypothyris	*cantobrica*	forest	P
	euclea	forest	P
	fluonia	forest	P
	mansuetus	forest	P
	ninonia	forest	P
	spp.	forest	P
Ithomia	*agnosia*	forest	N
	arduinna	forest	D
	derasa	forest	D
	terra	forest	D
Ithomiini	*spp.*	forest	N
Magneuptychia	*ocnus*	forest	D
Mechanitis	*lysimnia*	forest	A
	polymnia	forest	A,D,G
	spp.	forest	A
Melinaea	*marsaeus*	forest	V
	tarapotensis	forest	V
Morpho	*achilles*	forest	G
	helenor	forest	G
	menelaus	forest	G
	spp.	forest	G
Napeogenes	*glycera*	forest	J
	spp.	forest	J
Nessaea	*obrinus*	forest	M,Q
	spp.	forest	M,Q
Nisoniades	*rubescens*	forest	D
Nymphidium	*ascolia*	forest	G
	spp.	forest	G

Genus	**Species**	**Habitat preference**	**Reference**
Oleria	*onega*	forest	N
Ortilia	*liriope*	non-forest	X
Pachyneuria	*duidae*	forest	D
Pareuptychia	*metaleuca*	non-forest	D
	ocirrhoe	non-forest	D
Parides	*neophilus*	forest	D,I
	vetumnus	forest	D
Philaethria	*dido*	forest	D
Phoebis	*philea*	non-forest	D,G
	sennae	non-forest	D,G
	spp.	non-forest	D,G
Pierella	*astyoche*	forest	A, G
	hyceta	forest	A, G
	lena	forest	A, G
	luna	forest	A, G
Prepona	*leartes*	forest	J
Pteronymia	*primula*	forest	J
	tucuna	forest	J
Pyrgus	*orcus*	non-forest	D
Pyrisitia	*venusta*	non-forest	D,G
Pyrrhogyra	*crameri*	forest	A,D
	otalais	forest	A,D
Quadrus	*cerialis*	forest	D
Rhetus	*periander*	forest	D
Semomesia	*croesus*	forest	D
Siproeta	*stelenes*	non-forest	D,G
Smyrna	*blomfildia*	forest	D
Staphylus	*minor*	non-forest	D
	oeta	non-forest	D
Symbiopsis	*tanais*	forest	D
Taygetis	*spp.*	forest	M
Tegosa	*claudina*	forest	D
Temenis	*laothoe*	forest	D
Theclinae	*spp.*	forest	K,M
Thyridia	*psidii*	forest	D
	spp.	forest	D
Tigridia	*acesta*	forest	M

Genus	Species	Habitat preference	Reference
Tithorea	*harmonia*	forest	D, J
Typhedanus	*crameri*	non-forest	W
Urbanus	*dorantes*	non-forest	D
	proteus	non-forest	D
	spp.	non-forest	D
Vila	*emilia*	forest	D, S
Zelotaea	*nivosa*	forest	D
	spp.	forest	D

References

A: Raguso, R. a & Llorente-bousquets, J., 1990. The Butterflies (*Lepidoptera*) of the Tuxtlas Mts., Veracruz, Mexico, Revisited: Species-Richness and Habitat Disturbance. *Journal of Research on the Lepidoptera*, 29(1–2), *pp.105–133.*

B: Brower, A.V.Z., 2006. The Genus Adelpha: Its Systematics, Biology and Biogeography (*Lepidoptera: Nymphalidae: Limenitidini*). *Annals of the Entomological Society of America*, 99(1), *pp.184–185.*

C: Montero-Ramírez, J.J. & González-Maya, J.F., 2009. *Lepidoptera, Nymphalidae, Satyrinae, Cissia terrestris*: First record from Costa Rica. *Check List*, 5(1), pp.83–85.

D: Hoskins, A., learn about butterflies; the complete guide to the world of butterflies and moths. www.learnaboutbutterflies.com.

E: Pozo, C. et al., 2003. Butterflies (*Papilionoidea and Hesperioidea*) of Calakmul, Campeche, México. *The Southwestern Naturalist*, 48(4), pp.505–525.

F: Willmott, K., Constantino, L.M. & Hall, J.P.W., 2001. Post-cocooning temperatures and diapause in the alfalfa pollinator *Megachile rotundata (Hymenoptera: Megachilidae*). *Annals of the Entomological Society of America*, 94(2), pp.244–250.

G: Wiemers, M. & Fiedler, K., 2008. Butterfly diversity of the Piedras Blancas National Park and its vicinity - a preliminary assessment (*Lepidoptera: Papilionoidea & Hesperioidea*). Natural and Cultural History of the Golfo Dulce Region, Costa Rica, (June 2016), pp.257–266.

H: Vester, H.F.M. et al., 2007. Land chenge in the sourthern Yucatán and Calakmul Biosfera Reserve: effects on habitat and biodiversity. *Ecological Applications*, 17(4), pp.989–1003.

I: Herkenhoff, E.V., Monteiro, R.F. & Esperanco, A.P., 2013. Population Biology of the Endangered Fluminense Swallowtail Butterfly. *Journal of Lepidopterists' Society*, 67(1), pp.29–34.

J: Hill, R.I., 2010. Habitat segregation among mimetic ithomiine butterflies (*Nymphalidae*). *Evolutionary Ecology*, 24(2), pp.273–285.

K: Robbins, R., Duarte, M., 2005. Two phylogenetically significant new *Calycopis* species (*Lycaenidae: Theclinae: Eumaeini*). *Journal of Research on the Lepidoptera*, 38, pp.27–34.

M: Pardonnet, S. et al., 2013. Effect of tree-fall gaps on fruit-feeding nymphalid butterfly assemblages in a Peruvian rain forest. *Biotropica*, 45(5), pp.612–619.

N: Gallusser, S., 2002. Biology, Behaviour and Taxonomy of two *Oleria onega* subspecies (*Ithomiinae, Nymphalidae, Lepidoptera)* in north-eastern Peru. Theses Ph. D, Université of Neuchâtel. France.

O: Nic Funet, website. ftp.funet.fi/index/Tree_of_life/insecta/lepidoptera/

P: Gaviria-Ortiz, F.G. & Henao Bañol, E.R., 2011. Diversidad de mariposas diurnas (*Hesperioidea-Papilionoidea*) del Parque Natural Regional el Vínculo (Buga-Valle del Cauca). Boletín Científico. Centro de Museos. *Museo de Historia Natural*, 15(1), pp.115–133.

Q: Emmel, T.C. & Austin, G.T., 1990. the Tropical Rain Forest Butterfly Fauna of Rondonia, Brazil Species Diversity and Conservation. *Tropical Lepidotera*, 1(1), pp.1–12.

R: Duarte, M.; Robbins, R., 2010. Description and phylogenetic analysis of the *Calycopidina* (*Lepidoptera, Lycaenidae, Theclinae, Eumaeini*): a subtribe of detritivores. *Revista Brasilera de Entomología*, 54(1), pp.45–65.

S: Checa, M.F. et al., 2009. Temporal abundance patterns of butterfly communities (*Lepidoptera: Nymphalidae*) in the Ecuadorian Amazonia and their relationship with climate. *Annales de la Sociéte*, 45(4), pp.470–486.

T: Núñez-Bustos, E. & Volkmann, L., 2011. Mariposas diurnas escasas y asociadas a determinados ambientes de montaña de Argentina central con nuevos registros para el área de estudio (*Lepidoptera: Papilionoidea y hesperioidea*). SHILAP *Revista de lepidopterologia*, 39(155), pp.245–262.

U: Joron, M. et al., 1999. Variable selection and the coexistence of multiple mimetic forms of the butterfly *heliconius numata*. *Evolutionary Ecology*, 13(7–8), pp.721–754.

V: McClure, M. & Elias, M., 2016. Ecology, life history, and genetic differentiation in Neotropical *Melinaea* (*Nymphalidae: Ithomiini*) butterflies from north-eastern Peru. *Zoological Journal of the Linnean Society*.

W: Paluch, M. et al., 2016. Butterflies (*Lepidoptera: Papilionoidea and Hesperioidea*) of the Private Reserve of Natural Heritage Fazenda Lontra/Saudade, Itanagra, Northern Coast of Bahia, Brazil. *Biota Neotropica*, 16(1), pp.1–7.

X: Silva, P.L. et al., 2008. Immature stages of the Brazilian crescent butterfly *Ortilia liriope* (Cramer) (*Lepidoptera: Nymphalidae*). *Neotropical entomology*, 40, pp.322–327.

Table A5. References to analytical methods for soil samples as executed by PEAM and ICT, Peru and comparison of soil property levels of this study with recommendations for Coffea arabica.

			Snoeck & Lambot (2004)	**Méndez et al. (2009)**	**Olsson (2008)**	**This study**		
	Unit	**Method**			**median**	**mean ±sd**	**min**	**max**
N	%	Kjeldahl (1883)	1.25-5.14	0.32 ±0.10	0.2	0.16 ±0.07	0.02	0.36
OM	%	Walkley & Black (1934)	1.6-9.8	4.6 ±1.5	4.5	4.80 ±2.20	1.38	12.52
pH		Solution into water (1:1), using a pH meter	4.5-6.5	4.95 ±0.4	5.9	5.80 ±1.01	4.28	7.8
CEC	Meq/100g	Snoeck & Lambot (2004)	5-25	20.3 ±6.2	16.5	15.00 ±12.04	2.34	60.67
C:N	Ratio	Mann (1986)	0.74 - 1.10	8.34 ±8.7	13.05	25.4 ±22.3	11.89	127.24

Table A6. Model description and hypotheses.

Explanatory variables	**Model 1: coffee yields** **a) survey: average '10-'14**	**b) survey +plot : average '10-'14**	**Model 2: Biodiversity** **a) Forest species richness (log)**	**b) non-forest species richness (log)**	**Model 3: Carbon** **AGB carbon (log)**	**Model 4: Pests & diseases** **Estimated loss due to CLF; CBB; Ara; OdP**	**Model 5: Soil fertility** **N; OM; pH; CEC ; C:N**
General plantation characteristics							
Farm size (survey)							
Productive coffee area (survey)							
Elevation (survey or plot)	±	±	±		±	±	±
Coffee shrub age (survey)	-	-	+		+	±	-
Region	±	±	±		±	±	±
Vegetation structure							
Coffee shrub density (survey)	+	+	-	+	-	±	-
Banana plant density (plot)	+	+	-	+	-		
Inga tree density (survey)	±					±	
Inga tree density (plot)		±	+		+		+
Timber-species tree density (survey)	±					±	
Timber-species tree density (plot)		±	+		+		+
Total tree density (survey)							
Total tree density (plot)		±					
Shade cover (plot)		±	+	-	+		+
Maximum canopy height (plot)		±	+	-	+		
Coffee variety (survey)	±					±	
Microclimate							
Air temperature (plot)		±	-			±	
Air humidity (plot)		±	+			±	
Input management							
Total (survey)			-			-	
Fertilizer (survey)	+	+				-	+
Pesticide (survey)						-	
Herbicides (survey)							
Landscape configuration							
Distance to natural forest (plot)			-				
Forested area in 1km radius (plot)			+				

Explanatory variables	Model 1: coffee yields a) survey: average '10-'14	b) survey +plot : average '10-'14	Model 2: Biodiversity a) Forest species richness (log)	b) non-forest species richness (log)	Model 3: Carbon AGB carbon (log)	Model 4: Pests & diseases Estimated loss due to CLF; CBB; Ara; OdP	Model 5: Soil fertility N; OM; pH; CEC ; C:N
Confounding variables							
Pests & Diseases- Estimated loss							
Total loss (survey)	-	-					
Coffee leaf rust (Hemileia vastatrix, CLR; survey)	-	-					
Berry borer (Hypothenemus hampei, CBB; survey)	-	-					
Ojo de pollo (Mycena citricolor, OdP; survey)	-	-					
Aranjero (Pellicularia koleroga, Ara; survey)	-	-					
Soil Quality							
Nitrogen (N; plot)		+			+		
Organic matter (OM; plot)		+			+		
pH (plot)		±			±		
Cation exchange capacity (CEC; plot)		+			+		
C:N (plot)							

*Table A7. Correlation matrix showing Spearman correlations between all dependent variables. Levels of significance are shown as: *p < 0.05; **p < 0.01; ***p < 0.001.*

		General plantatation characteristics				Shade management							
		Farm size	Coffee plantation size	Altitude	Coffee shrub age	Coffee shrub density	Banana plant density (plot)	Inga tree density (survey)	Inga tree density (plot)	Timber-species tree density (survey)	Timber-species tree density (plot)	Total tree density (survey)	Total tree density (plot)
General plantatation characteristics	Farm size		0.68***				-0.32*	0.20*		0.30***	0.35*	0.35***	0.37*
	Coffee plantation size							0.22**				0.24**	0.38**
	Altitude				0.49***	0.25*							
	Coffee shrub age									0.18*	0.33*	0.19*	0.22
Shade management	Coffee shrub density												
	Banana plant density (plot)										-0.27*		
	Inga tree density (survey)								0.66***			0.64***	0.44***
	Inga tree density (plot)											0.45***	0.53***
	Timber-species tree density (survey)										0.67***	0.57***	0.5***
	Timber-species tree density (plot)											0.32*	0.56***
	Total tree density (survey)												0.66***
	Total tree density (plot)												
	Shade cover (plot)												
Micro-climate	Air temperature												
	Air humidity												
Input management	Total												
	Fertilizer												
	Pesticide												
	Herbicides												
Landscape configuration	Distance to natural forest												
	Forested area in 1km radius												
Pests & diseases impact	Total loss												
	Coffee leaf rust												
	Coffee berry borer												
	Ojo de pollo												
	Aranjero												
Soil quality	Nitrogen(N)												
	Organic matter (OM)												
	pH												
	Cation exchange capacity (CEC)												
	C:N												

	Microclimate		Input management				Landscape configuration		Pests & diseases impact					Soil quality				
Shade cover (plot)	Air temperature	Air humidity	Total	Fertilizer	Pesticide	Herbicides	Distance to natural forest	Forested area in 1km radius	Total loss	Coffee leaf rust	Coffee berry borer	Ojo de pollo	Aranjero	Nitrogen(N)	Organic matter (OM)	pH	Cation exchange capacity (CEC)	C:N
									0.20*		0.27***				-0.26*			
									0.20*		0.19*	0.22**						
	-0.57***			0.3*		-0.32*	-0.44***					0.28***						0.51***
0.33*	-0.38**					-0.20*			0.24**	0.37***								0.37**
			0.28***	0.35***										-0.33*				0.35*
																0.29*		
0.56***																		
0.52***																		
0.43***	-0.5***	0.5***				-0.2*								-0.27*				
0.41**	-0.35**											0.32*						
0.58***	-0.33*	0.44**																
0.66***	-0.39**										-0.31*	0.38**						
		-0.70***				0.38*	0.39**	-0.34*				-0.34*						-0.46***
								0.28*						-0.33*				0.37**
				0.92***	0.56***				-0.28***	-0.29***	-0.24**			-0.37*				
					0.32***				-0.23**	-0.19*	-0.25**			-0.38*				
							0.36*			-0.21*								
									-0.21*	-0.23**							-0.34*	
														0.27*				
										0.71***	0.58***	0.58***	0.47***					
												0.20*						
												0.33***	0.5***					
													0.46***				0.32*	
															0.45***		0.35**	
																	0.42**	0.49***
																	0.53***	

Table A8. Model results. For all models, plantation age (y), elevation (m) and region (1=Alto Mayo, 2= Picota) are included as fixed covariates, except for the soil C: N model, were only data from region 1 is included. Models are fitted with the R function lme with the maximum likelihood option.

	Analysis	Model	Candidate regression models	df	AICc	ΔAIC	Weight	r^2
1. Coffee yields	*a) survey (n=126)*	21	loss total pests + total fertilizer expenses	7	1939.60	0.00	0.15	0.13
		18	loss total pests + chemical fertilizer expenses	7	1939.70	0.04	0.14	0.13
		17	loss total pests	6	1940.50	0.86	0.10	0.11
		10	loss coffee leaf rust + chemical fertilizer expenses	7	1940.70	1.04	0.09	0.12
		13	loss coffee leaf rust + total fertilizer expenses	7	1940.90	1.25	0.08	0.12
		1	empty- besides fixed variables	5	1941.00	1.42	0.07	0.09
		2	chemical fertilizer expenses	6	1941.10	1.45	0.07	0.10
		9	loss coffee leaf rust	6	1941.20	1.62	0.07	0.10
		274	loss total pests + chemical fertilizer expenses + coffee tree density	8	1941.30	1.68	0.06	0.13
		82	loss total pests + chemical fertilizer expenses + Inga tree density	8	1941.30	1.73	0.06	0.13
		277	loss total pests + total fertilizer expenses + coffee tree density	8	1941.60	1.96	0.06	0.13
		5	total fertilizer expenses	6	1941.60	2.00	0.05	0.10
		full	*all, except [total fertilizer expenses]; [loss CLR]; [total shade tree density]*	*13*	*1950.80*	*11.16*	*0.00*	*0.15*
	b) survey + plot (n=39)	49	chemical fertilizer expenses + total shade tree density	7	561.00	0.00	0.45	0.32
		33	chemical fertilizer expenses	6	561.30	0.39	0.37	0.25
		8265	chemical fertilizer expenses + total shade tree density+ soil OM	8	562.90	1.91	0.17	0.34
		full	*all, except [total fertilizer expenses]; [loss CLR]; [total shade tree density]*	*12*				
2. Biodiversity	*Forest butterfly species richness (survey + plot)*	3	shade cover	6	21.20	0.00	0.23	0.39
		1	*empty- besides fixed variables*	*5*	*21.70*	*0.55*	*0.18*	*0.34*
		17	Inga tree density	6	21.80	0.60	0.17	0.38
		65	total shade tree density	6	22.40	1.24	0.12	0.37
		73	total shade tree density+ banana plant density	7	22.50	1.30	0.12	0.41
		11	shade cover + banana plant density	7	23.00	1.82	0.09	0.40

	Analysis	Model	Candidate regression models	df	AICc	ΔAIC	Weight	r^2
2. Biodiversity		25	Inga tree density+ banana plant density	7	23.10	1.94	0.09	0.40
		full	*all, except [total input expenses]*	*11*	*36.60*	*15.42*	*0.00*	*0.41*
	Non-forest butterfly species richness	513	maximum canopy height	6	-38.50	0.00	0.12	0.39
		545	timber shade tree density + maximum canopy height	7	-38.30	0.17	0.11	0.43
		1	empty- besides fixed variables	5	-38.20	0.28	0.11	0.35
		1537	maximum canopy height + air temperature	7	-37.90	0.64	0.09	0.42
		1539	shade cover + maximum canopy height + air temperature	8	-37.30	1.16	0.07	0.45
		547	shade cover + timber shade tree density + maximum canopy height	8	-37.30	1.22	0.07	0.45
		9	banana plant density	6	-37.10	1.36	0.06	0.37
		515	shade cover+ maximum canopy height	7	-37.10	1.40	0.06	0.41
		2561	maximum canopy height + coffee shrub density	7	-37.00	1.49	0.06	0.41
		1569	maximum canopy height + air temperature+ timber tree density	8	-37.00	1.51	0.06	0.45
		1025	air temperature	6	-36.80	1.69	0.05	0.37
		2049	coffee shrub density	6	-36.80	1.71	0.05	0.37
		1571	shade cover + timber shade tree density + maximum canopy height + air temperature	9	-36.80	1.75	0.05	0.48
		2593	maximum canopy height + timber shade tree density + coffee shrub density	8	-36.70	1.79	0.05	0.44
		full	*all, except [total input expenses]*	*11*	*-19.60*	*16.59*	*0.00*	*0.38*
3. Carbon	ABG carbon stock	2	shade cover	6	69.40	0.00	1.00	0.63
		full	*all, except [shade cover]; [pH]; [soil OM]*	*9*	*86.20*	*16.81*	*0.00*	*0.57*
4. Pests and diseases	Loss CLR	34	total input expenses + total shade tree density	7	964.10	0.00	0.24	0.21
		35	total pesticides expenses + total shade tree density	7	964.90	0.71	0.16	0.20
		39	total pesticides expenses + total shade tree density + total fertilizer expenses	8	965.10	0.96	0.15	0.22
		18	total input expenses + timber shade tree density	7	965.10	1.01	0.14	0.20

	Analysis	Model	Candidate regression models	df	AICc	ΔAIC	Weight	r^2
4. Pests and diseases		2	total input expenses	6	965.30	1.11	0.14	0.18
		26	total input expenses + timber shade tree density + Inga tree density	8	966.00	1.88	0.09	0.21
		10	total input expenses + Inga tree density	7	966.10	1.97	0.09	0.19
		full	*all, except [total input expenses]; [total shade tree density]*	*12*	*973.10*	*8.91*	*0.00*	*0.23*
	Loss CBB	2	total input expenses	6	829.50	0.00	0.37	0.12
		5	total fertilizer expenses	6	830.30	0.80	0.25	0.11
		1	empty	5	830.30	0.84	0.24	0.09
		18	total input expenses + timber tree density	7	831.40	1.93	0.14	0.12
		full	*all, except [total input expenses]; [total shade tree density]*	*12*	*843.90*	*14.41*	*0.00*	*0.12*
	Loss Ara	NA						<0.01
	Loss OdP	NA						<0.01
5. Soil Fertility	soil N	65	organic fertilizer expenses	6	-108.90	0.00	0.40	0.24
		69	organic fertilizer expenses + Inga tree density	7	-107.90	1.03	0.24	0.28
		1	empty	5	107.60	1.30	0.21	0.16
		67	organic fertilizer expenses + banana plant density	7	107.10	1.86	0.16	0.26
		full	*all, except [shade cover]; [total shade tree density]; [total fertilizer expenses]*	*11*	*-95.50*	*13.39*	*0.00*	*0.31*
	soil OM	145	total fertilizer expenses + total shade tree density	7	152.00	0.00	0.56	0.41
		113	organic fertilizer expenses + chemical fertilizer expenses + total shade tree density	8	153.60	1.68	0.24	0.43
		147	total fertilizer expenses + total shade tree density + banana plant density	8	153.90	1.98	0.21	0.43
		full	*all, except [shade cover]; [total shade tree density]; [total fertilizer expenses]*	*11*	*162.30*	*10.37*	*0.00*	*0.47*
	soil CEC	19	total shade tree density + banana plant density	7	303.70	0.00	0.12	0.17
		1	empty	5	303.90	0.13	0.11	0.03

	Analysis	Model	Candidate regression models	df	AICc	ΔAIC	Weight	r^2
5. Soil Fertility		2	shade cover	6	303.90	0.17	0.11	0.10
		15	timber shade tree density + Inga tree density + banana plant density	8	304.40	0.63	0.08	0.22
		5	Inga tree density	6	304.70	0.98	0.07	0.08
		4	shade cover+ banana plant density	7	304.90	1.15	0.07	0.14
		66	shade cover + organic fertilizer expenses	7	304.90	1.21	0.06	0.14
		3	banana plant density	6	305.00	1.26	0.06	0.07
		7	Inga tree density + banana plant density	7	305.00	1.31	0.06	0.14
		9	timber shade tree density	6	305.20	1.43	0.06	0.07
		11	timber shade tree density + banana plant density	7	305.20	1.45	0.06	0.14
		17	total shade tree density	6	305.20	1.48	0.06	0.07
		65	organic fertilizer expenses	6	305.40	1.69	0.05	0.06
		34	shade cover + chemical fertilizer expenses	7	305.60	1.86	0.05	0.13
		full	*all, except [shade cover]; [total shade tree density]; [total fertilizer expenses]*	*11*	*314.10*	*10.33*	*0.00*	*0.20*
	soil pH	68	shade cover + banana plant density + organic fertilizer expenses	8	98.50	0.00	0.66	0.52
		4	shade cover + banana plant density	7	99.80	1.29	0.34	0.47
		full	*all, except [shade cover]; [total shade tree density]; [total fertilizer expenses]*	*10*	*118.30*	*13.10*	*0.00*	*0.32*
	soil C:N	49	chemical fertilizer expenses + total shade tree density	6	272.80	0.00	0.51	0.28
		33	chemical fertilizer expenses	5	274.00	1.27	0.27	0.16
		34	chemical fertilizer expenses + shade cover	6	274.50	1.72	0.22	0.24
		full	*all, except [shade cover]; [total shade tree density]; [total fertilizer expenses]*	*10*	*288.20*	*15.47*	*0.00*	*0.31*

Table A9. Averaged parameter estimates of variables for yield loss due to pest and disease and soil fertility models with ΔAIC <2 are weighed with the corresponding Akaike weight. Coffee shrub age, elevation and region are included as fixed variables.

		Co-variate	Σ Weight (relative variable importance subset ΔAIC <2)	models containing variable	Estimate	sig.	CI 2.5%	CI 97.5%	z-value	SD	P-value
4. Pests and diseases	*Loss CLR*	(Intercept)			-6.06		-42.14	30.02	0.33	18.20	0.74
		total input expenses	0.69	5	-0.03	*	-0.05	0.00	2.28	0.01	0.02
		total shade tree density	0.54	3	0.05	.	0.00	0.10	1.94	0.03	0.05
		total pesticide expenses	0.31	2	-0.06	*	-0.12	0.00	2.02	0.03	0.04
		timber shade tree density	0.23	2	0.06		-0.02	0.15	1.50	0.04	0.13
		Inga tree density	0.18	2	0.04		-0.02	0.10	1.16	0.03	0.25
		total fertilizer expenses	0.15	1	-3.67		-8.85	1.51	1.39	2.61	0.17
		plantation age	1.00	7	1.37	*	0.30	2.45	2.50	0.54	0.01
		elevation	1.00	7	0.04	*	0.01	0.07	2.36	0.02	0.02
		region 2: Picota	1.00	7	4.36		-12.91	21.63	0.50	8.71	0.62
	Loss CBB	(Intercept)			11.97		-7.22	31.15	1.22	9.68	0.22
		total input expenses	0.51	2	-0.01	.	-0.02	0.00	1.71	0.01	0.09
		total fertilizer expenses	0.25	1	-2.04		-4.77	0.69	1.47	1.37	0.14
		timber shade tree density	0.14	1	-0.01		-0.06	0.03	0.58	0.02	0.56
		plantation age	1.00	4	-0.14		-0.71	0.43	0.49	0.29	0.63
		elevation	1.00	4	0.00		-0.02	0.02	0.05	0.01	0.96
		region 2: Picota	1.00	4	11.07	*	1.84	20.29	2.35	4.65	0.02
	Loss Ara	NA									
	Loss OdP	NA									

		Co-variate	Σ Weight (relative variable importance subset ΔAIC <2)	models containing variable	Estimate	sig.	CI 2.5%	CI 97.5%	z-value	SD	P-value
5. Soil Fertility	*soil N*	(Intercept)			0.03		-0.10	0.16	0.41	0.07	0.68
		organic fertilizer expenses	0.79	3	-0.02	.	-0.04	0.00	1.88	0.01	0.06
		Inga tree density	0.24	1	0.00		0.00	0.00	1.26	0.00	0.21
		banana plant density	0.16	1	0.00		0.00	0.00	0.95	0.00	0.34
		plantation age	1.00	4	0.00		-0.01	0.00	0.15	0.00	0.88
		elevation	1.00	4	0.00	.	0.00	0.00	1.87	0.00	0.06
		region 2: Picota	1.00	4	0.05	.	0.00	0.10	1.88	0.02	0.06
	soil OM	(Intercept)			2.29		-1.80	6.37	1.10	2.01	0.27
		total shade tree density	1.00	3	0.00	*	-0.01	0.00	2.31	0.00	0.02
		total fertilizer expenses	0.76	2	-0.86	*	-1.65	-0.07	2.12	0.39	0.03
		chemical fertilizer expenses	0.24	1	-0.85	.	-1.76	0.05	1.85	0.44	0.06
		organic fertilizer expenses	0.24	1	-0.68	*	-1.31	-0.06	2.15	0.31	0.03
		banana plant density	0.21	1	0.00		0.00	0.00	0.96	0.00	0.34
		plantation age	1.00	3	-0.01		-0.14	0.11	0.20	0.06	0.84
		elevation	1.00	3	0.01	**	0.00	0.01	2.96	0.00	0.00
		region 2: Picota	1.00	3	-1.70	.	-3.50	0.09	1.86	0.88	0.06
	soil CEC	(Intercept)			4.11		-24.87	33.10	0.28	14.34	0.78
		banana plant density	0.44	6	0.01		0.00	0.03	1.54	0.01	0.12
		shade cover	0.28	4	0.11		-0.03	0.25	1.59	0.07	0.11
		Inga tree density	0.22	3	0.02		-0.01	0.05	1.52	0.01	0.13
		timber shade tree density	0.20	3	0.03		-0.01	0.06	1.45	0.02	0.15
		total shade tree density	0.17	2	0.03		-0.01	0.06	1.52	0.02	0.13

		Co-variate	Σ Weight (relative variable importance subset ΔAIC <2)	models containing variable	Estimate	sig.	CI 2.5%	CI 97.5%	z-value	SD	P-value
5. Soil Fertility		organic fertilizer expenses	0.11	2	2.37		-1.70	6.43	1.14	2.00	0.25
		chemical fertilizer expenses	0.05	1	-3.03		-8.86	2.80	1.02	2.86	0.31
		plantation age	1.00	14	-0.18		-1.14	0.79	0.36	0.48	0.72
		elevation	1.00	14	0.01		-0.02	0.03	0.51	0.01	0.61
		region 2: Picota	1.00	14	5.69		-4.96	16.34	1.05	5.27	0.30
	soil pH	(Intercept)			7.16	***	5.22	9.10	7.23	0.95	0.00
		shade cover	1.00	2	0.01	*	0.00	0.02	2.15	0.00	0.03
		banana plant density	1.00	2	0.00	**	0.00	0.00	3.23	0.00	0.00
		organic fertilizer expenses	0.66	1	0.27	.	-0.01	0.55	1.90	0.14	0.06
		plantation age	1.00	2	-0.05		-0.12	0.02	1.48	0.03	0.14
		elevation	1.00	2	0.00	.	0.00	0.00	1.73	0.00	0.08
		region 2: Picota	1.00	2	-0.40		-1.11	0.32	1.09	0.35	0.27
	soil C/N	(Intercept)			67.00	*	0.11	133.89	1.96	32.44	0.05
		chemical fertilizer expenses	1.00	3	-14.87	*	-28.18	-1.57	2.19	6.45	0.03
		total shade tree density	0.51	1	-0.07	.	-0.14	0.00	1.90	0.04	0.06
		shade cover	0.22	1	-0.31		-0.72	0.10	1.47	0.20	0.14
		plantation age	1.00	3	-1.17		-3.48	1.13	1.00	1.12	0.32
		elevation	1.00	3	0.00		-0.06	0.07	0.09	0.03	0.93
		region 2: Picota	NA								

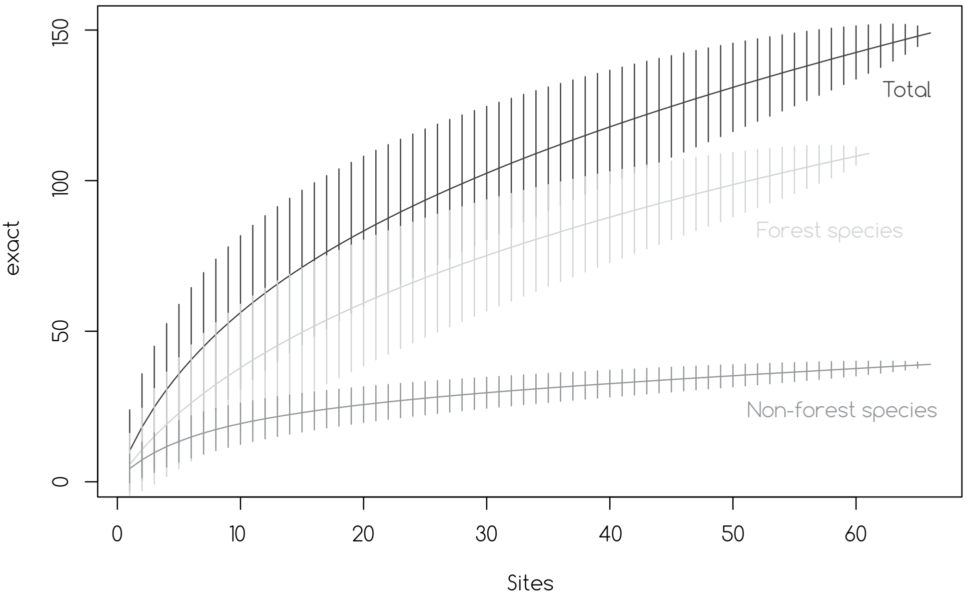


Figure A1. Species accumulation curves presented for total, forest and non-forest butterfly species richness. These curves show the cumulative number of species collected (exact, y-axis) as a function of sampling effort (n sites, x-axis).

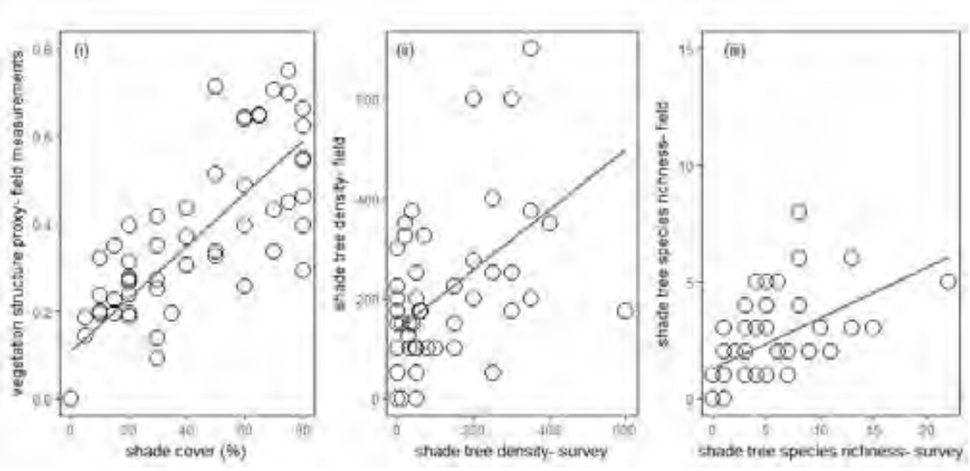


Figure A2. Comparison of shade variables between survey and plot level for (i) visually estimated shade cover on plot level (x-axis) and a proxy for vegetation structure obtained by combining shade tree density and mean shade tree height as measured on plot level (y-axis); (ii) shade tree density obtained by farmer surveys (x-axis) and plot measurements (y-axis); and (iii) shade tree species richness values obtained by farmer surveys (x-axis) and plot measurements (y-axis). We checked for correlations between the explanatory variables with Spearman's rank correlation. For correlation coefficients between all variables see Table A7.

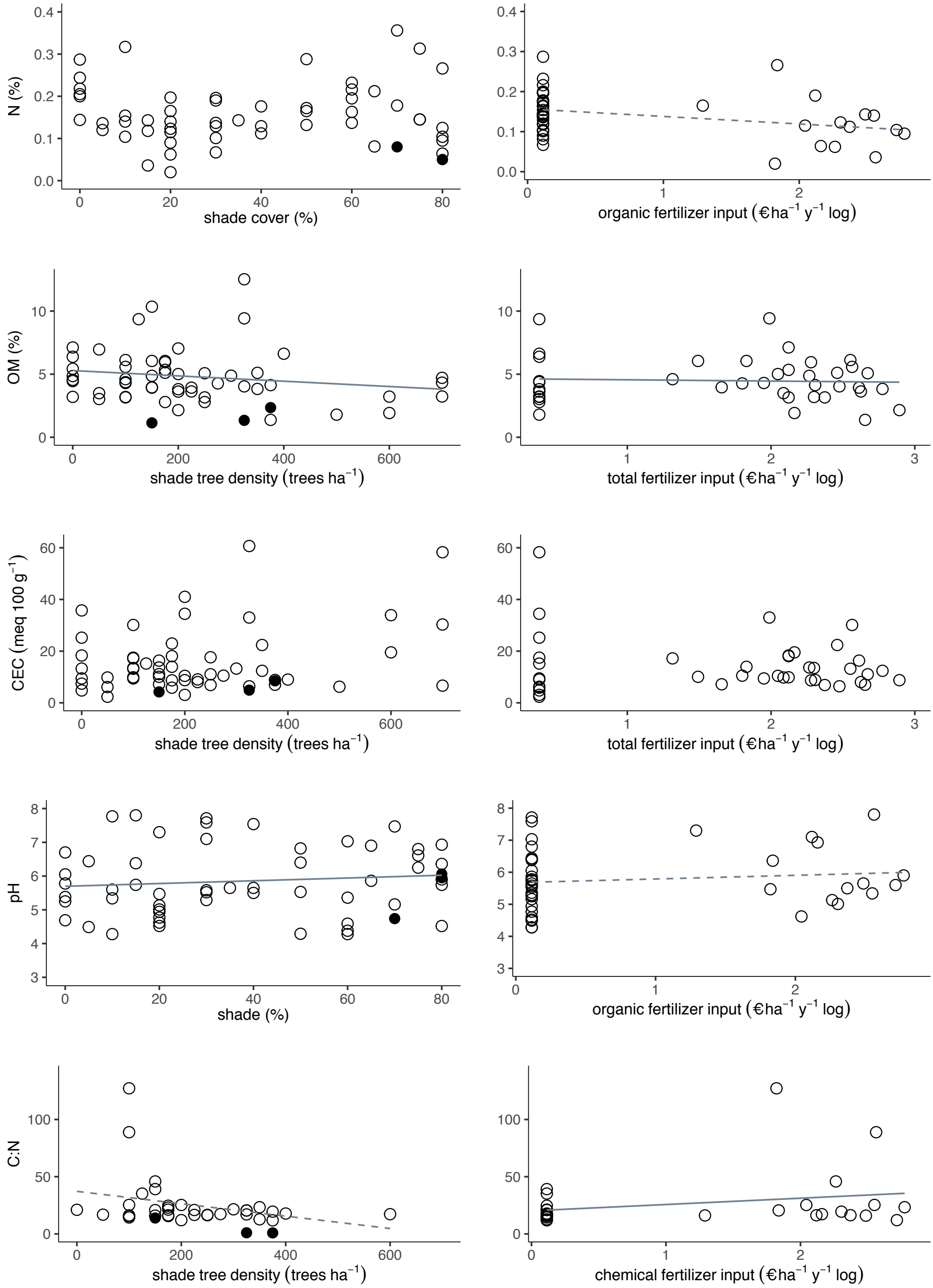


Figure A3. Relation of management variables shade (left graphs) and input expenses (€ ha-1 y-1; right graphs) with soil fertility indicators soil N (a, b), soil OM (c, d), soil CEC (e, f), soil pH (g, h) and soil C:N (i, j) for coffee plantations (open circles). Closed circles represent observed values in natural forests as reference. Grey lines indicate a significant linear relation (p<0.05; solid line) or a trend (p<0.1; dotted line).

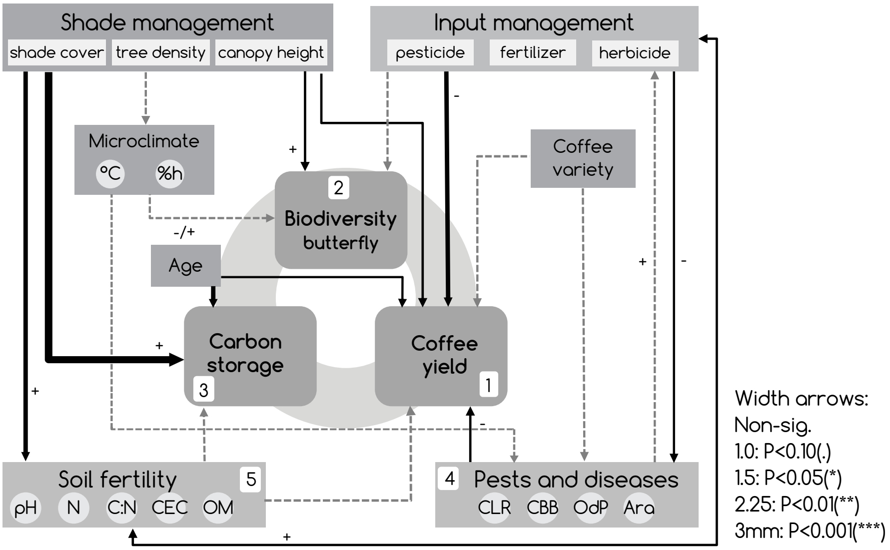


Figure A4. Conceptual diagram depicting observed relations. Width of arrows indicates significance level

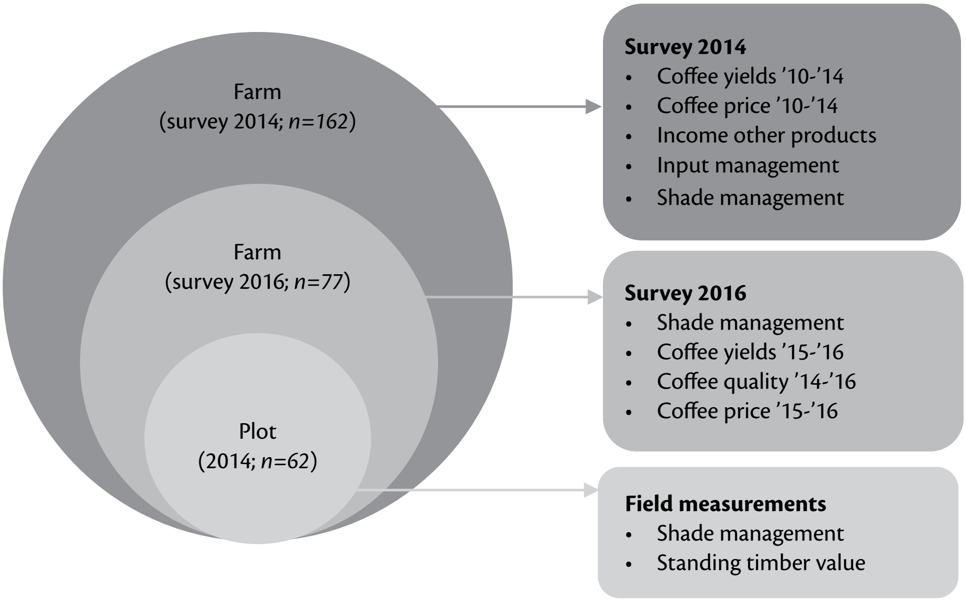


Figure A5. Hierarchy of collected data and number of samples at each level, along with key variables collected per level.

Appendix A3: Standardizing and classifying coffee plantations by shade and input practices

Based on readily available data, we identified different management practices on based on shade and input management. To represent management regimes and quantitatively classify farming practices, we created a coffee plantation Shade Index and a coffee plantation Input Index (Bisseleua Daghela et al., 2013; Hernández-Martínez et al., 2009; Mas and Dietsch, 2003).

Shade Index: Two Shade indices were created; one based on the data obtained from farmer surveys (n=162) and included shade tree density and shade tree species richness. The other shade index is based on plot data collected for a subset of the farms (n=62) and includes addition information on level of shade (shade cover, %) and basal area. Variables were standardized using a common scale, ranging from 0.0 to 1.0. Here the highest index values were assigned to the maximum values of shade variables that were encountered in the dataset. The resulting index values for the shade variables were added together for each farm studied. Farm-specific totals were subsequently re-standardized, such that a value of zero represents the absence of shade vegetation and a value of one represents the most complex shade system possible in this study (Hernández-Martínez et al., 2009; Mas and Dietsch, 2003).

Input Index: One Input Index was created from the survey data. This index is based on five management variables: means of weeding (0= by hand, machete; 0.5= mechanical, brush cutter; 1= herbicide); fertilizer type (0=none, 0.5= organic; 1= chemical); fertilizer quantity (fertilizer costs, euro ha^{-1} y^{-1}); pest control type (0=none, 0.5= organic; 1= chemical); pest control quantity (pesticides costs, euro ha^{-1} y^{-1}). The Input Index was calculated just as the Shade Index, by standardizing variables using a common scale from 0.0 to 1.0. Farm specific totals were subsequently re-standardized so that a value of zero represented lowest management intensity and a value of one represented the greatest degree of management intensity to be found in this study.

Statistical analyses

To justify the use of the shade and input indices, the data matrix for both Shade Index and Input Index were analyzed using a Principal Components Analysis (PCA). The factor scores from the first principal component, describing variation in shade and management variables were then compared with created Shade Index and Input Index values respectively using a simple linear regression analysis, in order to verify the explanatory power of these indices. The relationships between the original farm-specific structural and management variables were also compared with Shade Index and Input Index values, as well as the factor scores from their respective PCAs, using Pearson correlation coefficients. Standard alpha levels of 0.05 were used in all tests.

In order to define the classes produced by the PCA, we then carried out a k-means cluster analysis using the Euclidian distance method and the Ward link option.

Verification of Shade and Input Indices using PCAs

Shade Index: The PCA of factors describing the shade structure of coffee farms shows that the first three factors explain 73% of the total variance (Table 1). The first factor (explaining 56% of total variance) was positively correlated with all variables (Figure A6). Based on the significant correlation between the first PCA factor and the created Shade Index (plot), use of this aggregated value as a measure for plantation shade complexity is justified.

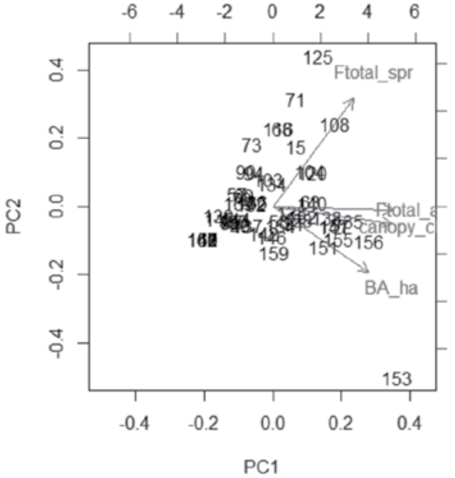


Figure A6: Shade Index (plot): Distribution of coffee plantations in a two-dimensional space defined by factor scores of the first two principal components of a PCA incorporating variables describing the plantation structure.

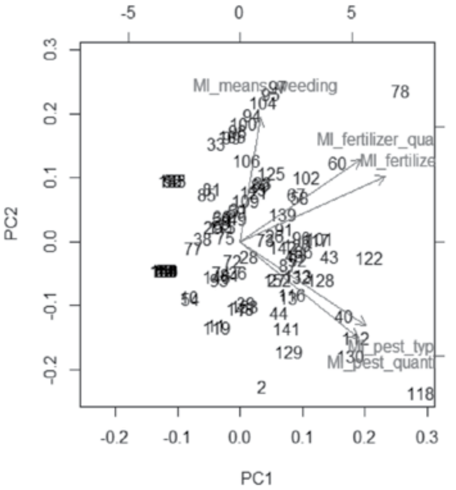


Figure A7: Input Index: Distribution of coffee plantations in a two-dimensional space defined by factor scores of the first two principal components of a PCA incorporating variables describing the plantation management intensity.

Input Index: The PCA of factors describing the management intensity of the fieldwork subset of coffee farms shows that the first three factors explain 82% of the total variance. The first factor (explaining 39% of total variance) was positively correlated with all variables, except for means of weeding which was not significant (Figure A7) The orientation of study sites in the two-dimensional space, described by these factor scores as the x- and y-axis respectively suggests that coffee plantations in San Martín exhibit a circular distribution, when characterized by their management alone, indicating large differences in Input management. Based on the significant correlation between the first PCA factor and the created Input Index, use of this aggregated values as a measure for management intensity is justified (Figure A7, Table A10).

Table A10. Principal component analysis (PCA) results for the Shade Index and Input Index, both for the subset of data (n=62) and the survey dataset (n=162).

Plot (n=62)		PCA		PCA first component regression		Shade Index regression	
Shade Index (plot)	1st factor	2nd factor	3rd factor	r²		r²	
Shade tree density	0.57	-0.03	-0.4	0.86	***	0.85	***
Shade tree species richness	0.38	0.85	0.36	0.58	***	0.61	***
Level of shade	0.56	-0.13	-0.43	0.85	***	0.87	***
Basal area	0.46	-0.52	0.73	0.68	***	0.62	***
variance explained	0.56	0.21	0.15				
sum of variance explained	0.56	0.77	0.92				

Survey dataset (n=162)		PCA		PCA first component regression		Shade Index regression	
Shade Index (Survey)	1st factor	2nd factor	3rd factor	r²		r²	
Shade tree density	0.71	0.71	-	0.76	***	0.74	***
Shade tree species richness	0.71	-0.71	-	0.76	***	0.78	***
variance explained	0.58	0.42	-				
sum of variance explained	0.58	1.00	-				

		PCA		PCA first component regression		Shade Index regression	
Input Index	1st factor	2nd factor	3rd factor	r²		r²	
means of weeding	0.08	0.60	-0.77	0.11		0.45	***
fertilizer type	0.57	0.32	0.14	0.78	***	0.77	***
fertilizer quantity	0.47	0.40	0.49	0.64	***	0.52	***
pest control type	0.49	-0.40	-0.30	0.67	***	0.67	***
pest control quantity	0.46	-0.47	-0.23	0.63	***	0.48	***
variance explained	0.38	0.23	0.18				
sum of variance explained	0.38	0.61	0.79				

Shade and Input classification

PCA results confirm that index values provide a good representation of the variation within the original dataset. The high correlation with the PCA first component suggests that both the Shade Index and Input Index capture the variation in the variables (Table A10, Figure A6, Figure A7). This justifies the use of the indices for classification of Input and Shade of the coffee plantations. As both Shade and Input are important to determine economic performance of a plantation, plantations are classified according to Input and Shade separately, in order to use this classification in further analysis. Number of clusters for both Input and Shade classification was determined using the “elbow criterion” in the sum of squared error scree plot. For all three indices this was set at three (Figure A8a). Classification of individual plantations was based on Euclidian distance, Ward link option (Figure A8b-d).

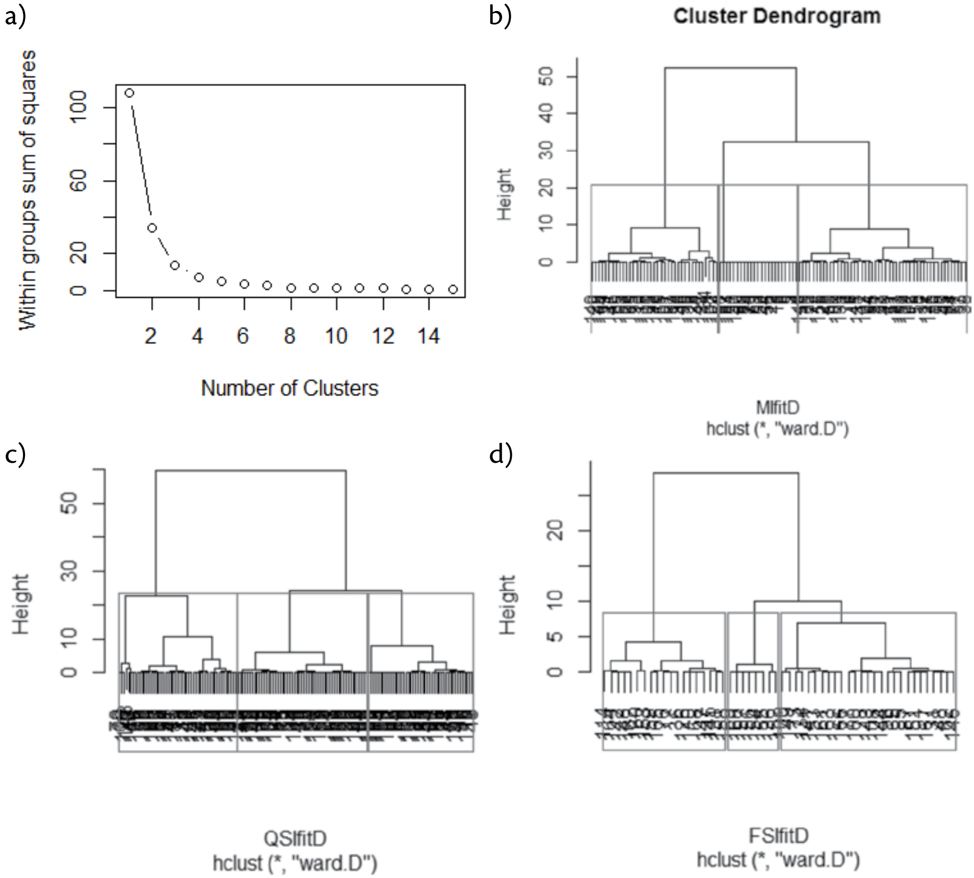


Figure A8. Different steps of the cluster analysis for the subset (n=62) are shown. a) Scree plot for determining number of clusters, similar for Input, Shade (field) and Shade (survey); clustering based on a dendrogram providing classification for b) Input; c) Shade (survey) and; d) Shade (plot).

Log transformation

Classification based on log-transformation of basal area and shade tree density was tried. However, by log transforming these variables, some plantations with very low values for tree density were in this way categorised as Medium-Shade, which is not correct in comparison to other plantations. Therefore, all data was used un-transformed.

Plantation Shade and Input classes

Based on this cluster analysis, three groups were identified for each of the indices. This resulted in the classification and descriptive statistics of the different identified groups as described in Table A11.

Table A11. Descriptives of different shade and input classes indentified

		mean	±SD	min	max	n
Input	Low	0.00	0.00	0.00	0.00	23
	Medium	0.24	0.07	0.10	0.37	50
	High	0.49	0.10	0.39	0.82	37
Shade (survey)	Low	0.04	0.03	0.0	0.01	45
	Medium	0.13	0.02	0.09	0.17	56
	High	0.28	0.11	0.17	0.63	51
Shade (plot)	Low	0.02	0.03	0.00	0.07	8
	Medium	0.22	0.08	0.13	0.36	27
	High	0.50	0.09	0.39	0.69	19

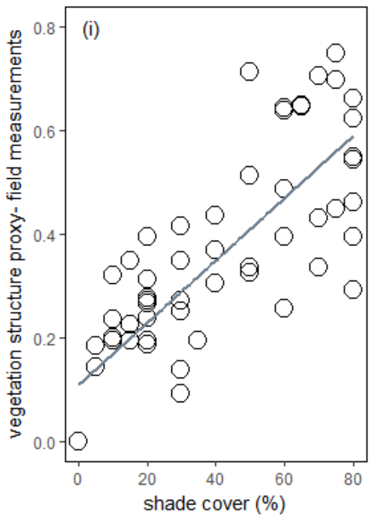


Figure A9. Comparison of shade variables for visually estimated shade cover on plot level (x-axis) and a proxy for vegetation structure obtained by combining shade tree density and mean shade tree height as measured on plot level (y-axis). The relation was significant (Spearman's rank correlation R2=0.81; p<0.001). For correlation coefficients between all variables see Table A12.

*Table A12. Correlation matrix showing Spearman rank correlation coefficients. Levels of significance are shown as:[empty]at p>0.10; . at p<0.10; *p < 0.05; **p < 0.01; ***p < 0.001.*

		General plantatation characteristics				Shade Index						Input Index			
		Farm size	Coffee plantation size	Plantation age	Elevation	Shade tree density (plot)	Shade tree density (Survey)	Shade tree species richness (plot)	Shade tree species richness	Shade cover (plot)	Basal area (plot)	Fertilizer quantity	Pest and disease control quantity	Type of weeding (0-1)	Type of pest and disease control (0-1)
General plantatation characteristics	Farm size		0.68***	0.14.	0.18*	0.39**	0.28***		0.15.	0.26.	0.37*				
	Coffee plantation size					0.38**	0.25**	0.31*							
	Plantation age				0.33***		0.20*	0.29*	0.28***	0.33*	0.43**				
	Elevation							0.40**	0.46***					-0.28***	
Shade Index	Shade tree density (plot)						0.68***	0.57***	0.51***	0.70***	0.71***				
	Shade tree density							0.39**	0.35***	0.60***	0.61***				
	Shade tree species richness (plot)								0.65***	0.45***	0.58***	0.38*			
	Shade tree species richness									0.40**	0.52***		0.16.	-0.20*	
	Shade cover (plot)										0.81***				
	Basal area (plot)														
Input Index	Fertilizer quantity												0.32***		0.23**
	Pest and disease control quantity														0.87***
	Type of weeding (0-1)														
	Type of pest and disease control (0-1)														
	Type of fertilizer (0-1)														
Indices	Input Index														
	Shade index														
	Shade index (plot)														
Coffee revenues	Coffee quality														
	Coffee price														
	Coffee yield														
	Gross coffee income														
Costs	Fixed costs														
	Input organic														
	Input chemical														
	Family labour														
	Hired labour														
	Total costs														
Other benefits	Other farm products														
	Timber value (plot)														
Net income and BCR	Net coffee income														
	Net coffee area income														
	BCR coffee														
	BCR farm income														

	Indices			Coffee revenues				Costs						Other benefits		Net income and BCR			
Type of fertilizer (0-1)	Input Index	Shade index	Shade index (plot)	Coffee quality	Coffee price	Coffee yield	Gross coffee income	Fixed costs	Input organic	Input chemical	Family labour	Hired labour	Total costs	Other farm products	Timber value (plot)	Net coffee income	Net coffee area income	BCR coffee	BCR farm income
		0.28***	0.39**					-0.36***		-0.26**		0.21**	-0.20*						
		0.21*	0.32*		0.13.						-0.15.	0.25**							
	-0.17.	0.26**	0.30*			-0.28***	-0.28***	-0.25**		-0.31***		-0.22**	-0.31***		0.32*			0.16*	0.19*
-0.19*	-0.23*	0.25**		0.46***	0.35***	-0.34***	-0.25**	-0.31***	0.21**	-0.38***	0.14.	-0.17*	-0.35***					0.19*	0.22**
		0.78***	0.88***		0.25.			-0.38**					-0.30*	0.18	0.49***				
		0.70***	0.68***						0.15.					0.28***	0.33*		0.17*		
0.41**		0.58***	0.70***		0.30*										0.68***				
		0.84***	0.51***	0.24.	0.27***	-0.27***	-0.19*	-0.20*	0.22**	-0.16*					0.54***				
		0.64***	0.88***					-0.26.						0.25.	0.36**				
		0.70***	0.87***												0.66***				
0.76***	0.65***							0.17*	0.52***	0.57***	-0.28***	0.25**	0.46***			-0.42***	-0.37***	-0.53***	-0.53***
0.33***	0.65***							0.16.	0.38***	0.33***		0.16.	0.33***			-0.17.	-0.16.	-0.30***	-0.32***
	0.44***	-0.15.		-0.26*	-0.15.			0.32***	-0.17*	0.32***			0.29***					-0.18*	-0.22*
0.33***	0.66***							0.15.	0.18*	0.38***		0.15.	0.29***			-0.15.		-0.26**	-0.27**
	0.79***							0.16.	0.18*	0.74***	-0.19*		0.35***			-0.25**	-0.20*	-0.35***	-0.35***
								0.34***	0.17.	0.75***	-0.25**	0.2*	0.54***			-0.37***	-0.33***	-0.49***	-0.52***
			0.77***		0.20*	-0.19*		-0.27***	0.20*	-0.16.			-0.18*		0.51***				
								-0.27.							0.59***				
					0.38**			-0.35**	0.23.				-0.23.					0.22.	0.21.
							0.20*		0.16*							0.18*	0.18*	0.14.	
							0.96***	0.33***		0.16*		0.35***	0.39***			0.63***	0.63***	0.21*	
								0.29***		0.14.		0.36***	0.37***			0.67***	0.67***	0.24**	
										0.29***	-0.25**		0.80***			-0.19*	-0.16.	-0.50***	-0.54***
												0.21*	0.20*			-0.23**	-0.19*	-0.28***	-0.26**
											-0.28***	0.16.	0.46***			-0.20*	-0.16*	-0.37***	-0.39***
												-0.15.	-0.37***		-0.25.	0.18*	0.17*	0.28***	0.30***
													0.55***			-0.14.		-0.46***	-0.51***
																-0.32***	-0.28***	-0.73***	-0.79***
																	0.29***		0.18*
																-0.25.			
																	0.96***	0.80***	0.73***
																		0.76***	0.73***
																			0.97***

Table A13. General statistic measures (mean ± SD) of economic performance indicators for the defined Input and Shade classes. For each class, mean and standard deviation (SD) are summarized for all variables. Significant differences between groups were evaluated using a Kruskal–Wallis non-parametric test (df=2 for all test). The level of significance: NS at $p > 0.10$*; . <0.10; **$p < 0.05$*; ***$p < 0.01$*; ****$p < 0.001$*.*

		Input classes										Shade Classes (survey)								
		Low			Medium			High				Low			Medium			High		
		mean	±	SD	mean	±	SD	mean	±	SDw	*Sig.*	mean	±	SD	mean	±	SD	mean	±	SD
Coffee revenues	Coffee quality	64.0	±	8.7	68.0	±	4.9	67.0	±	5.6	*NS*	66.0	±	5.4	68.0	±	4.4	68.0	±	5.9
	Coffee price (a)	1.8	±	0.4	1.9	±	0.3	1.8	±	0.3	*NS*	1.8	±	0.3	1.9	±	0.2	1.9	±	0.3
	Coffee yield	993.0	±	584.0	751.0	±	455.0	967.0	±	561.0	*NS*	905.0	±	488.0	959.0	±	602.0	736.0	±	429.0
	Gross coffee income	1728.0	±	975.0	1417.0	±	923.0	1729.0	±	920.0	*NS*	1616.0	±	872.0	1783.0	±	1011.0	1441.0	±	901.0
Costs	Land costs	359.0	±	298.0	462.0	±	540.0	737.0	±	538.0	**	661.0	±	596.0	507.0	±	462.0	326.0	±	406.0
	Equipment costs	56.0	±	45.0	77.0	±	114.0	120.0	±	182.0	*NS*	76.0	±	120.0	81.0	±	123.0	74.0	±	64.0
	Organic inputs	0.0	±	0.0	84.0	±	136.0	81.0	±	187.0	***	47.0	±	111.0	48.0	±	127.0	76.0	±	138.0
	Chemical inputs	0.0	±	0.0	64.0	±	105.0	233.0	±	229.0	***	87.0	±	186.0	106.0	±	149.0	77.0	±	159.0
	Family labour	216.0	±	228.0	188.0	±	263.0	101.0	±	144.0	.	240.0	±	377.0	149.0	±	199.0	245.0	±	329.0
	Hired labour	233.0	±	189.0	259.0	±	242.0	522.0	±	635.0	.	317.0	±	334.0	339.0	±	372.0	365.0	±	510.0
	Total costs	864.0	±	411.0	1287.0	±	809.0	2032.0	±	1056.0	***	1639.0	±	1019.0	1411.0	±	765.0	1273.0	±	910.0
Other benefits	Other farm products	277.0	±	193.0	346.0	±	194.0	406.0	±	460.0	*NS*	243.0	±	164.0	393.0	±	307.0	391.0	±	413.0
	Timber value (plot)	206.0	±	332.0	575.0	±	1764.0	101.0	±	201.0	*NS*									
Net income and BCR	Net coffee income (all labour)	965.0	±	988.0	417.0	±	907.0	142.0	±	1163.0	**	367.0	±	862.0	699.0	±	946.0	380.0	±	1138.0
	Net coffee income (only hired labour)	1180.0	±	950.0	606.0	±	906.0	242.0	±	1178.0	**	608.0	±	850.0	848.0	±	932.0	625.0	±	1144.0
	Net farm income (only hired labour)	1457.0	±	995.0	952.0	±	949.0	648.0	±	1005.0	**	851.0	±	827.0	1242.0	±	1032.0	1016.0	±	992.0
	BCR coffee	2.8	±	2.4	1.3	±	1.4	0.5	±	1.0	***	1.4	±	1.9	1.8	±	2.2	1.6	±	2.0
	BCR farm income	3.4	±	2.4	2.1	±	2.1	0.8	±	1.1	***	1.9	±	2.3	2.5	±	2.7	2.4	±	2.5

		Shade Classes (plot)									
		Low			Medium			High			
		mean	±	SD	mean	±	SD	mean	±	SDw	*Sig.*
Coffee revenues	Coffee quality	68.0	±	x	69.0	±	4.9	68.0	±	7.8	*NS*
	Coffee price (a)	1.8	±	0.1	1.9	±	0.3	1.9	±	0.3	*NS*
	Coffee yield	1121.0	±	396.0	963.0	±	518.0	774.0	±	330.0	*NS*
	Gross coffee income	2051.0	±	838.0	1828.0	±	959.0	1479.0	±	578.0	*NS*
Costs	Land costs	389.0	±	280.0	691.0	±	713.0	331.0	±	297.0	*NS*
	Equipment costs	129.0	±	139.0	95.0	±	141.0	56.0	±	42.0	*NS*
	Organic inputs	0.0	±	0.0	102.0	±	167.0	82.0	±	168.0	*NS*
	Chemical inputs	105.0	±	164.0	113.0	±	152.0	73.0	±	142.0	*NS*
	Family labour	318.0	±	324.0	216.0	±	266.0	298.0	±	431.0	*NS*
	Hired labour	566.0	±	447.0	552.0	±	684.0	388.0	±	295.0	*NS*
	Total costs	1548.0	±	353.0	1799.0	±	1156.0	1245.0	±	451.0	*NS*
Other benefits	Other farm products	125.0	±	142.0	466.0	±	652.0	360.0	±	228.0	.
	Timber value (plot)	0.0	±	0.0	91.0	±	223.0	541.0	±	1368.0	***
Net income and BCR	Net coffee income (all labour)	710.0	±	650.0	354.0	±	1297.0	393.0	±	698.0	*NS*
	Net coffee income (only hired labour)	1028.0	±	616.0	570.0	±	1394.0	691.0	±	556.0	*NS*
	Net farm income (only hired labour)	1153.0	±	655.0	1036.0	±	1251.0	1051.0	±	549.0	*NS*
	BCR coffee	2.0	±	2.7	1.4	±	2.1	1.5	±	2.0	*NS*
	BCR farm income	2.1	±	2.7	1.9	±	2.5	2.1	±	2.6	*NS*

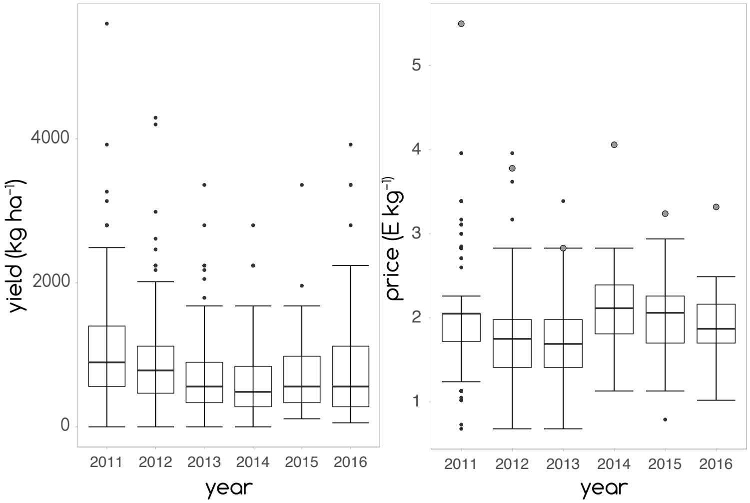


Figure A10. Boxplot depicting variation in a) yield and b) coffee price from 2011-2016. Grey circles in b) represent world coffee price for Mild-Arabicas (ICO. www.ico.org/new_historical.asp; 03/04/2017 last visited)

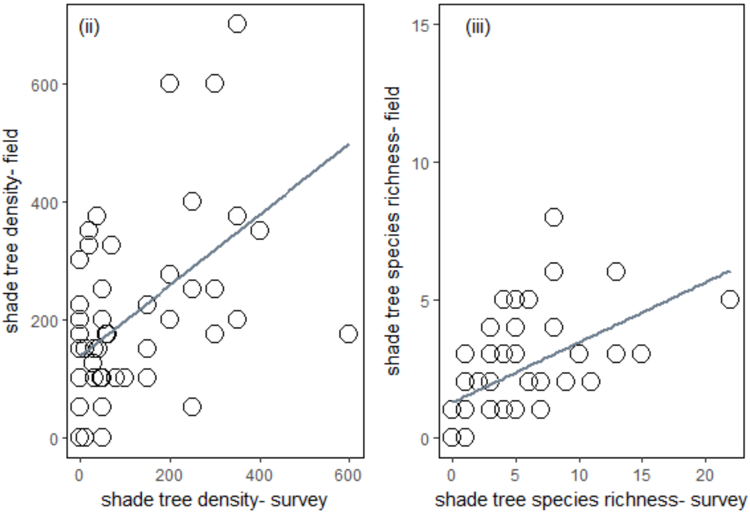


Figure A11. To check for interviewer and farmer bias. survey data was compared to plot data. Field plot data on shade management was collected in 2014 for a subset of plantations (n=62). We established plots of 10x10 m (n=19) or 20x20 m (n=43) in representative areas of the farm. and identified all shade trees with diameter at breast height >5 cm within the plots. Trees were identified to species level if possible and otherwise to genus level. using a field guide Pennington et al., 2004) and knowledge from local experts and farmers. Shade tree density was estimated for the plot and extrapolated to hectare and reported in trees ha-1. Comparison of shade variables between survey and plot level for a) shade tree density obtained by farmer surveys (x-axis) and plot measurements (y-axis); and b) shade tree species richness values obtained by farmer surveys (x-axis) and plot measurements (y-axis). We checked for correlations between the explanatory variables with Spearman's rank correlation.

Table A14. List of variables used in the Input and Shade Indices. Results are obtained from a k-means cluster analysis for Shade Index and Input Index separate. For each group, mean and standard deviation (sd) are summarized for all variables.

		low (n=45) mean±sd	medium (n=56) mean±sd	high (n=51) mean±sd
Shade	shade tree density (trees ha^{-1})	19.0±20.0	52.0±35.0	153.0±149.0
	shade tree species richness (per farm)	1.0±1.0	3.9±1.4	7.5±4.1
	Shade Index	**0.0±0.0**	**0.1±0.0**	**0.3±0.1**

		low (n=23) mean±sd	medium (n=50) mean±sd	high (n=37) mean±sd
Input	pesticide quantity a (€ ha^{-1} y^{-1})	0.0±0.0	25.0±58.0	80.0±114.0
	fertilizer quantity a (€ ha^{-1} y-^{1})	0.0±0.0	124.0±146.0	220.0±222.0
	type of pest and disease control (0=none. 0.5=organic; 1=chemical)	0.0±0.0	0.3±0.4	0.7±0.4
	type of fertilizer (0=none. 0.5=organic; 1=chemical)	0.0±0.0	0.5±0.4	0.9±0.2
	type of weeding (0=by hand; 0.5=mechanical; 1=chemical)	0.0±0.0	0.2±0.4	0.5±0.4
	Input Index	**0.0±0.0**	**0.2±0.1**	**0.5±0.1**

Table A15. Descriptive statistics of variables used for livelihood capitals. perception of risks and shocks

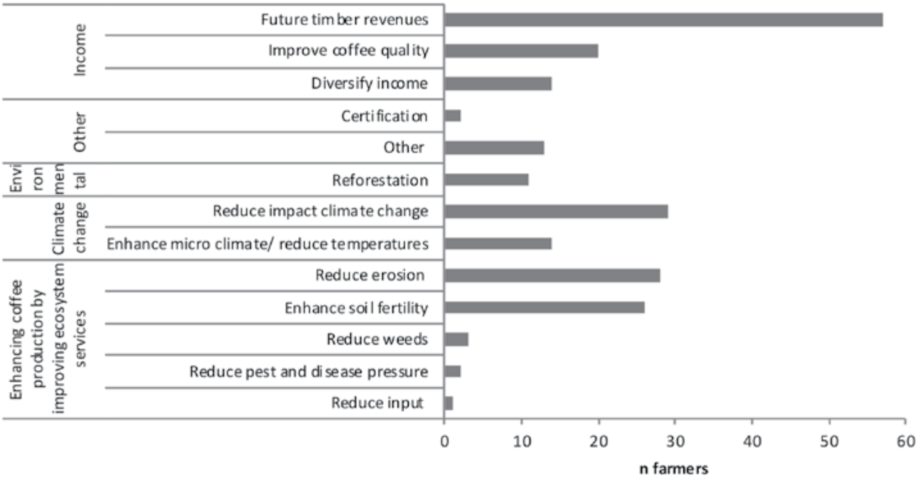
		abbr.	description	mean±sd	min-max	n
Livelihood assets	**Human**	**H-index**	**Human index**	**0.61±0.21**	**0.23-1**	**77**
		H1	family decisions made by multiple members of the family	0.62±0.49	0-1	77
		H2	years of experience of coffee farming	14.11±08.16	2-40	156
		H3	level of education	0.40±0.17	0-1	155
		H4	farmers members working in the plantation	2.74±1.19	1--7	155
	Social	**S-index**	**Social index**	**0.62±0.28**	**0-1**	**74**
		S1	Family members and friends in the community	0.87±0.34	0-1	77
		S2	Support from family members and friends in community	0.52±0.50	0-1	77
		S3	Member of farmer association	0.59±0.49	0-1	154
		S4	Support from farmer association	0.60±0.49	0-1	77
		S5	Active participation in governance structure of farmer association	0.42±0.50	0-1	74
	Natural	**N-index**	**Natural index**	**0.44±0.19**	**0.05-1**	**74**
		N1	Shade tree density	75.76±105.34	0-700	153
		N2	Shade tree species richness	4.25±3.60	0-22	161
		N3	Soil fertility	0.44±0.18	0-1	77
		N4	Coffee plantation size	2.74±1.96	0.5-13	154
	Physical	**P-Index**	**Physical index**	**0.68±0.19**	**0.12-1**	**125**
		P1	Travel time to market for agricultural inputs and selling of beans	25.67±23.60	0-120	129
		P2	Material of walls and floors	0.34±0.32	0-1	152
		P3	Source of water	0.67±0.41	0-1	153
		P4	Source of light	0.77±0.41	0-1	152
		P5	Food scarcity	3.84±1.91	0-9	150
	Financial	**F-index**	**Financial index**	**0.58±0.17**	**0.24-1**	**75**
		F1	Coffee farm income	33±29	0-100	140
		F2	Off-farm income	12±22	0-100	140
		F3	Share of hired labour	63±34	0-100	154
		F4	Current openstanding loans	0.84±0.23	0-1	77
		F5	Household savings	0.10±0.21	0-1	77
Risks	**Climate change**	**perCC**	**Impact of climate change index**	**0.49±0.22**	**0-1**	**76**
		perCC1	Late rains	0.23±0.26	0-1	77
		perCC2	More rains	0.08±0.18	0-0.75	77
		perCC3	Early rains	0.03±0.12	0-0.75	77

		abbr.	description	mean±sd	min-max	n
Risks		perCC4	More drought	0.31±0.25	0-0.75	77
		perCC5	More cold weather	0.30±0.26	0-0.75	77
		perCC6	Higher temperatures	0.56±0.25	0-1	77
		perCC7	Lower groundwater	0.09±0.21	0-1	76
	Pests and diseases	**perPD**	**Impact of pests and diseases index**	**0.64±0.24**	**0-1**	**77**
		perPD1	Impact on coffee quality	0.63±0.28	0-1	77
		perPD2	Impact on coffee quantity	0.66±0.27	0-1	77
	Price fluctuations	**perCP**	**Impact of fluctuating coffee price on livelihood**	**0.56±0.29**	**0-1**	**77**
Shockss	**Pests and diseases**	**shockPD**	**Estimated loss due to coffee rust ('14)**	**46.20±24.60**	**0-100**	**152**
	Coffee price variability	**shockCP**	**Variability in reported coffee price from between '10 and '16**	**1.04±0.47**	**0.28-2.54**	**154**

Table A16. Principal component analysis (PCA) loadings.

Variable		PCA 1	PCA 2	PCA 3	PCA 4	PCA 5
Capitals	Human.Capital	0.65	-0.04	0.26	-0.35	-0.12
	Social.Capital	0.39	-0.37	0.52	0.29	0.28
	Natural.Capital	0.61	-0.09	0.28	0.46	-0.28
	Physical.Capital	-0.35	-0.52	0.03	-0.03	-0.24
	Financial.Capital	-0.52	-0.31	0.09	0.52	0.38
Risks	perc.CC	-0.26	0.61	0.32	0.23	-0.35
	perc.PD	0.07	0.44	-0.40	0.49	0.03
	perc.CP	-0.54	0.11	0.39	-0.30	0.19
Shocks	shock.PD	0.41	0.37	-0.05	-0.12	0.65
	shock.CP	-0.24	0.37	0.62	0.00	0.03
	Variance explained	19.2	13.7	12.2	10.9	9.7
	Σ variance explained	**19.2**	**32.9**	**45.1**	**56.0**	**65.7**

a)



b)

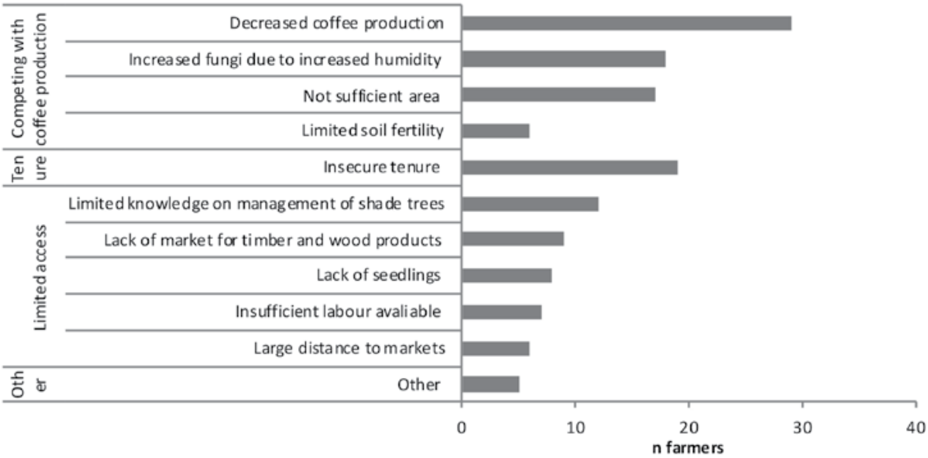


Figure A12. Barplot depicting most important reasons to a) increase shade level or maintain medium or high levels of shade; b) reduce shade level or maintain low shade levels. Each farmer gave a maximum of three reasons.

8

References

Aerts, R., Hundera, K., Berecha, G., Gijbels, P., Baeten, M., Van Mechelen, M., Hermy, M., Muys, B., Honnay, O., 2011. Semi-forest coffee cultivation and the conservation of Ethiopian Afromontane rainforest fragments. For. Ecol. Manage. 261, 1034–1041. https://doi.org/10.1016/j.foreco.2010.12.025

Allinne, C., Savary, S., Avelino, J., 2016. Delicate balance between pest and disease injuries, yield performance, and other ecosystem services in the complex coffee-based systems of Costa Rica. Agric. Ecosyst. Environ. 222, 1–12. https://doi.org/10.1016/j.agee.2016.02.001

Altieri, M. A, 2002. Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric. Ecosyst. Environ. 93, 1–24. https://doi.org/10.1016/S0167-8809(02)00085-3

Arrieta, N., Anzueto, F., Echeverria, F., McCook, G., Schuller Petzold, S., Obin, D., Pineda, J.A., Ramos, O., Rodríguez, C.M., Zamarripa, A., 2016. Las variedades de café de Mesoamérica y el Caribe. College Station, US.

Asner, G.P., Knapp, D.E., Roberta, M.E., Tupayachi, R., Anderson, C.B., Mascaro, J., Sinca, F., Chadwick, D.K., Sousan, S., Higgins, M., Farfan, W., Silman, M.R., Augusto, W., León, L., Palomino, A.F.N., 2014. The High-Resolution Carbon Geography of Perú. Lima, Perú.

Atangana, A., Khasa, D., Chang, S., Degrande, A., 2014a. Chapter 10. Carbon sequestration in Agroforestry Systems, in: Tropical Agroforestry. Springer, Dordrecht, pp. 217–225. https://doi.org/10.1007/978-94-007-7723-1_10

Atangana, A., Khasa, D., Chang, S., Degrande, A., 2014b. Chapter 3. Definitions and Classification of Agroforestry Systems, in: Tropical Agroforestry. Springer Netherlands, Dordrecht, pp. 35–47. https://doi.org/10.1007/978-94-007-7723-1

Avelino, J., Cristancho, M., Georgiou, S., Imbach, P., Aguilar, L., Bornemann, G., Läderach, P., Anzueto, F., Hruska, A.J., Morales, C., 2015. The coffee rust crises in Colombia and Central America (2008–2013): impacts, plausible causes and proposed solutions. Food Secur. 7, 303–321. https://doi.org/10.1007/s12571-015-0446-9

Avelino, J., Romero-Gurdián, A., Cruz-Cuellar, H., A., D.F., 2012. Landscape context and scale differentially impact coffee leaf rust, coffee berry bore , and coffee root-knot nematodes. Ecol. Appl. 22, 584–596.

Avelino, J., Zelaya, H., Merlo, A., Pineda, a., Ordoñez, M., Savary, S., 2006. The intensity of a coffee rust epidemic is dependent on production situations. Ecol. Modell. 197, 431–447. https://doi.org/10.1016/j.ecolmodel.2006.03.013

Baca, M., Laderach, P., Haggar, J., Schroth, G., Ovalle, O., 2014. An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee growing families in mesoamerica. PLoS One 9. https://doi.org/10.1371/journal.pone.0088463

Bacon, C., 2005. Confronting the coffee crisis: can fair trade, organic, and specialty coffees reduce small-scale farmer vulnerability in northern Nicaragua? World Dev. 33, 497–511. https://doi.org/10.1016/j.worlddev.2004.10.002

Bagua, J.S.I., 2007. Evaluación comparativa de la producción del cultivo de café bajo diferentes tipos de sombra en la microcuenca Amojú, Jaén -Perú.

Balvanera, P., Pfisterer, A.B., Buchmann, N., He, J.S., Nakashizuka, T., Raffaelli, D., Schmid, B., 2006. Quantifying the evidence for biodiversity effects on ecosystem functioning and services. Ecol. Lett. 9, 1146–1156. https://doi.org/10.1111/j.1461-0248.2006.00963.x

Barham, B.L., Weber, J.G., 2012. The Economic Sustainability of Certified Coffee: Recent Evidence from Mexico and Peru. World Dev. 40, 1269–1279. https://doi.org/10.1016/j.worlddev.2011.11.005

Barton, K., Anderson, D.R., 2015. Package 'MuMIn'- Multi-model Inference; Model selection and model averaging based on information criteria (AICc and alike).

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting Linear Mixed-Effects Models Using lme4. https://doi.org/10.18637/jss.v067.i01

Bean, C., Nolte, G.E., 2017. Peru- Coffee Annual- Peruvian Coffee Production Bouncing Back. USDA Foreign Agricultural Services; Global Agricultural Information Network.

Beer, J., Muschler, R., Kass, D., Somarriba, E., 1998. Shade management in coffee and cacao plantations. Agrofor. Syst. 38, 139–164. https://doi.org/10.1023/A:100595652

Bellow, J.G., Nair, P.K.R., 2003. Comparing common methods for assessing understorey light availability in shaded-perennial agroforestry systems. Agric. For. Meteorol. 114, 197–211. https://doi.org/10.1016/S0168-1923(02)00173-9

Belsky, J.M., Siebert, S.F., 2003. Cultivating cacao: Implications of sun-grown cacao on local food security and environmental sustainability. Agric. Human Values 20, 277–285. https://doi.org/10.1023/A:1026100714149

Beuchelt, T.D., Zeller, M., 2011. Profits and poverty: Certification's troubled link for Nicaragua's organic and fairtrade coffee producers. Ecol. Econ. 70, 1316–1324. https://doi.org/10.1016/j.ecolecon.2011.01.005

Beukema, H., Danielsen, F., Vincent, G., Hardiwinoto, S., Andel, J., 2007. Plant and bird diversity in rubber agroforests in the lowlands of Sumatra, Indonesia. Agrofor. Syst. 70, 217–242. https://doi.org/10.1007/s10457-007-9037-x

Bhagwat, S.A., Willis, K.J., Birks, H.J.B., Whittaker, R.J., 2008. Agroforestry: a refuge for tropical biodiversity? Trends Ecol. Evol. 23, 261–267. https://doi.org/10.1016/j.tree.2008.01.005

Bisseleua, D.H.B., Missoup, A.D., Vidal, S., 2009. Biodiversity conservation, ecosystem functioning, and economic incentives under cocoa agroforestry intensification. Conserv. Biol. 23, 1176–84. https://doi.org/10.1111/j.1523-1739.2009.01220.x

Bisseleua Daghela, H.B., Fotio, D., Yede, Missoup, A.D., Vidal, S., 2013. Shade tree diversity, cocoa pest damage, yield compensating inputs and farmers' net returns in West Africa. PLoS One 8, e56115. https://doi.org/10.1371/journal.pone.0056115

Bobo, K.S., Waltert, M., Fermon, H., Njokagbor, J., Mühlenberg, M., 2006. From forest to farmland: butterfly diversity and habitat associations along a gradient of forest conversion in Southwestern Cameroon. J. Insect Conserv. 10, 29–42. https://doi.org/10.1007/s10841-005-8564-x

Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: Harnessing ecosystem services for food security. Trends Ecol. Evol. 28, 230–238. https://doi.org/10.1016/j.tree.2012.10.012

Boreux, V., Vaast, P., Madappa, L.P., Cheppudira, K.G., Garcia, C., Ghazoul, J., 2016. Agroforestry coffee production increased by native shade trees, irrigation, and liming. Agron. Sustain. Dev. 36, 42. https://doi.org/10.1007/s13593-016-0377-7

Bornemiza, E., 1982. Nitrogen cycling in coffee plantations. Plant Soil 246, 241–246. https://doi.org/10.1007/BF02182771

Bosselmann, A.S., 2012. Mediating factors of land use change among coffee farmers in a biological corridor. Ecol. Econ. 80, 79–88. https://doi.org/10.1016/j.ecolecon.2012.05.007

Bosselmann, A.S., Dons, K., Oberthur, T., Olsen, C.S., Ræbild, A., Usma, H., 2009. The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia. Agric. Ecosyst. Environ. 129, 253–260. https://doi.org/10.1016/j.agee.2008.09.004

Boudrot, A., Pico, J., Merle, I., Granados, E., Vílchez, S., Tixier, P., Filho, E. de M.V., Casanoves, F., Tapia, A., Allinne, C., Rice, R.A., Avelino, J., 2016. Shade effects on the dispersal of airborne Hemileia vastatrix uredospores. Phytopathology 106, 572–580. https://doi.org/10.1094/PHYTO-02-15-0058-R

Bravo-Monroy, L., Potts, S.G., Tzanopoulos, J., 2016. Drivers influencing farmer decisions for adopting organic or conventional coffee management practices. Food Policy 58, 49–61. https://doi.org/10.1016/j.foodpol.2015.11.003

Bullock, R., Mithöfer, D., Vihemäki, H., 2014. Sustainable agricultural intensification: The role of cardamom agroforestry in the East Usambaras, Tanzania. Int. J. Agric. Sustain. 12, 109–129. https://doi.org/10.1080/14735903.2013.840436

Bunn, C., Laderach, P., Ovalle Rivera, O., Kirschke, D., 2015. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. Clim. Change 129, 89–101. https://doi.org/10.1007/s10584-014-1306-x

Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodal inference: a practical information-theoretic approach. Springer, New York.

Campanha, M.M., Henrique, R., Santos, S., De, G.B., Emília, H., Martinez, P., Lages, S., Garcia, R., Santos, R.H.S., De Freitas, G.B., Martinez, H.E.P., Garcia, S.L.R., Finger, F.L., 2004b. Growth and yield of coffee plants in agroforestry and monoculture systems in Minas Gerais , Brazil. Agrofor. Syst. 63, 75–82. https://doi.org/10.1023/B:AGFO.0000049435.22512.2d

Cannell, M.G.R., 1975. Crop physiological aspects of coffee bean yield: a review. J. coffee Res. 5, 7–20.

Capa, D., Pérez-Esteban, J., Masaguer, A., 2015. Unsustainability of recommended fertilization rates for coffee monoculture due to high N2O emissions. Agron. Sustain. Dev. 35, 1551–1559. https://doi.org/10.1007/s13593-015-0316-z

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., MacE, G.M., Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S., Naeem, S., 2012. Biodiversity loss and its impact on humanity. Nature 486, 59–67. https://doi.org/10.1038/nature11148

Castro-Tanzi, S., Dietsch, T., Urena, N., Vindas, L., Chandler, M., 2012. Analysis of management and site factors to improve the sustainability of smallholder coffee production in Tarrazú, Costa Rica. Agric. Ecosyst. Environ. 155, 172–181. https://doi.org/10.1016/j.agee.2012.04.013

Caudill, S.A., Rice, R.A., 2016. Do Bird Friendly ® Coffee Criteria Benefit Mammals ? Assessment of Mammal Diversity in Chiapas, Mexico 1–12. https://doi.org/10.5061/dryad.q5gh6. Funding

CENAGRO, 2012. Censo Nacional Agropecuario 2012. Lima.

Cerda, R., Allinne, C., Gary, C., Tixier, P., Harvey, C.A., Krolczyk, L., Mathiot, C., Clément, E., Aubertot, J.-N., Avelino, J., 2016. Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. Eur. J. Agron. 82, 308–319. https://doi.org/10.1016/j.eja.2016.09.019

Cerda, R., Deheuvels, O., Calvache, D., Niehaus, L., Saenz, Y., Kent, J., Vilchez, S., Villota, A., Martinez, C., Somarriba, E., 2014. Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. Agrofor. Syst. 88, 957–981. https://doi.org/10.1007/s10457-014-9691-8

Cerdán, C.R.R., Rebolledo, M.C.C., Soto, G., Rapidel, B., Sinclair, F.L.L., 2012. Local knowledge of impacts of tree cover on ecosystem services in smallholder coffee production systems. Agric. Syst. 110, 119–130. https://doi.org/10.1016/j.agsy.2012.03.014

Chandler, R.B., King, D.I., Raudales, R., Trubey, R., Chandler, C., Chávez, V.J.A., 2013. A small-scale land-sparing approach to conserving biological diversity in tropical agricultural landscapes. Conserv. Biol. 27, 785–95. https://doi.org/10.1111/cobi.12046

Chao, A., Colwell, R.K., Lin, C.W., Gotelli, N.J., 2009. Sufficient sampling for asymptotic minimum species richness estimators. Ecology 90, 1125–1133. https://doi.org/10.1890/07-2147.1

Charbonnier, F., Roupsard, O., le Maire, G., Guillemot, J., Casanoves, F., Lacointe, A., Vaast, P., Allinne, C., Audebert, L., Cambou, A., Clément-Vidal, A., Defrenet, E., Duursma, R.A., Jarri, L., Jourdan, C., Khac, E., Leandro, P., Medlyn, B.E., Saint-André, L., Thaler, P., Van Den Meersche, K., Barquero Aguilar, A., Lehner, P., Dreyer, E., 2017. Increased light-use efficiency sustains net primary productivity of shaded coffee plants in agroforestry system. Plant Cell Environ. 40, 1592–1608. https://doi.org/10.1111/pce.12964

Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G., Zanne, A.E., 2009. Towards a worldwide wood economics spectrum. Ecol. Lett. 12, 351–366. https://doi.org/10.1111/j.1461-0248.2009.01285.x

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob. Chang. Biol. 20, 3177–3190. https://doi.org/10.1111/gcb.12629

Chaves, B., Riley, J., 2001. Determination of factors influencing integrated pest management adoption in coffee berry borer in Colombian farms. Agric. Ecosyst. Environ. 87, 159–177. https://doi.org/10.1016/S0167-8809(01)00276-6

Chena, H., Zhu, T., Krotta, M., Calvo, J.F., Ganesh, S.P., Makot, I., 2013. Measurement and evaluation of livelihood assets in sustainable forest commons governance. Land use policy 30, 908–914. https://doi.org/10.1016/j.landusepol.2012.06.009

Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T.C., Anshary, A., Buchori, D., Cicuzza, D., Darras, K., Putra, D.D., Erasmi, S., Pitopang, R., Schmidt, C., Schulze, C.H., Seidel, D., Steffan-Dewenter, I., Stenchly, K., Vidal, S., Weist, M., Wielgoss, A.C., Tscharntke, T., 2011. Combining high biodiversity with high yields in tropical agroforests. Proc. Natl. Acad. Sci. U.S.A. 2, 5–8. https://doi.org/10.1073/pnas.1201800109

Clough, Y., Faust, H., Tscharntke, T., 2009. Cacao boom and bust: sustainability of agroforests and opportunities for biodiversity conservation. Conserv. Lett. 2, 197–205. https://doi.org/10.1111/j.1755-263X.2009.00072.x

Clough, Y., Krishna, V. V., Corre, M.D., Darras, K., Denmead, L.H., Meijide, A., Moser, S., Musshoff, O., Steinebach, S., Veldkamp, E., Allen, K., Barnes, A.D., Breidenbach, N., Brose, U., Buchori, D., Daniel, R., Finkeldey, R., Harahap, I., Hertel, D., Holtkamp, A.M., Hörandl, E., Irawan, B., Jaya, I.N.S., Jochum, M., Klarner, B., Knohl, A., Kotowska, M.M., Krashevska, V., Kreft, H., Kurniawan, S., Leuschner, C., Maraun, M., Melati, D.N., Opfermann, N., Pérez-Cruzado, C., Prabowo, W.E., Rembold, K., Rizali, A., Rubiana, R., Schneider, D., Tjitrosoedirdjo, S.S., Tjoa, A., Tscharntke, T., Scheu, S., 2016. Land-use choices follow profitability at the expense of ecological functions in Indonesian smallholder landscapes. Nat. Commun. 7, 13137. https://doi.org/10.1038/ncomms13137

DaMatta, F.M., 2004. Ecophysiological constraints on the production of shaded and unshaded coffee: a review. F. Crop. Res. 86, 99–114. https://doi.org/10.1016/j.fcr.2003.09.001

Davis, A.P., Govaerts, R., Bridson, D.M., Stoffelen, P., 2006. An annotated taxonomic conspectus of the genus Coffea (*Rubiaceae*). Bot. J. Linn. Soc. 152, 465–512.

De Beenhouwer, M., Aerts, R., Honnay, O., 2013. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. Agric. Ecosyst. Environ. 175, 1–7. https://doi.org/10.1016/j.agee.2013.05.003

De Beenhouwer, M., Geeraert, L., Mertens, J., Van Geel, M., Aerts, R., Vanderhaegen, K., Honnay, O., 2016. Biodiversity and carbon storage co-benefits of coffee agroforestry across a gradient of increasing management intensity in the SW Ethiopian highlands. Agric. Ecosyst. Environ. 222, 193–199. https://doi.org/10.1016/j.agee.2016.02.017

Defries, R.S., Rudel, T., Uriarte, M., Hansen, M., 2010. Deforestation driven by urban population growth and agricultural trade in the twenty-first century. Nat. Geosci. 3, 178–181. https://doi.org/10.1038/ngeo756

Detlefsen, E.G., 1988. Evaluacion del rendimiento de *Coffea arabica* cv. "Caturra" bajo diferentes densidades de *Cordia alliodora* y *Erythrina poeppigiana* plantados en un diseño sistematico de espaciamientos. CATIE.

DFID, 1999. Sustainable Livelihoods Guidance Sheet. https://doi.org/10.1002/smj

Di Marco, M., Watson, J.E.M., Currie, D.J., Possingham, H.P., Venter, O., 2018. The extent and predictability of the biodiversity-carbon correlation. Ecol. Lett. https://doi.org/10.1111/ele.12903

Dolia, J., Devy, M.S., Aravind, N.A., Kumar, A., 2008. Adult butterfly communities in coffee plantations around a protected area in the Western Ghats, India. Anim. Conserv. 11, 26–34. https://doi.org/10.1111/j.1469-1795.2007.00143.x

Eakin, H., 2005. Institutional change, climate risk, and rural vulnerability: Cases from Central Mexico. World Dev. 33, 1923–1938. https://doi.org/10.1016/j.worlddev.2005.06.005

Eakin, H., Tucker, C.M., Castellanos, E., Diaz-porras, R., Barrera, J.F., Morales, H., 2014. Adaptation in a multi-stressor environment: perceptions and responses to climatic and economic risks by coffee growers in Mesoamerica. Environ. Dev. Sustain. 123–139. https://doi.org/10.1007/s10668-013-9466-9

Eakin, H., Winkels, A., Sendzimir, J., 2009. Nested vulnerability: exploring cross-scale linkages and vulnerability teleconnections in Mexican and Vietnamese coffee systems. Environ. Sci. Policy 12, 398–412. https://doi.org/10.1016/j.envsci.2008.09.003

Edwards-Jones, G., 2006. Modelling farmer decision-making: concepts, progress and challenges. Anim. Sci. 82, 783–790. https://doi.org/DOI: 10.1017/ASC2006112

Ehrenbergerová, L., Cienciala, E., Kučera, A., Guy, L., Habrová, H., 2016. Carbon stock in agroforestry coffee plantations with different shade trees in Villa Rica, Peru. Agrofor. Syst. 90, 433–445. https://doi.org/10.1007/s10457-015-9865-z

Ehrenbergerová, L., Šenfeldr, M., Habrová, H., 2017. Impact of tree shading on the microclimate of a coffee plantation: A case study from the Peruvian Amazon. Bois Forets des Trop. 4, 13–22.

Ellis, F., 2000. Rural livelihoods and diversity in developing countries. Oxford University PRess, Oxford, England.

Fang, Y.P., Fan, J., Shen, M.Y., Song, M.Q., 2014. Sensitivity of livelihood strategy to livelihood capital in mountain areas: Empirical analysis based on different settlements in the upper reaches of the Minjiang River, China. Ecol. Indic. 38, 225–235. https://doi.org/10.1016/j.ecolind.2013.11.007

FAO, n.d. Volume estimation [WWW Document]. URL http://www.fao.org/forestry/17109/en/ (accessed 6.12.17).

Farfán-Valencia, F., Sánchez Arciniégas, P.M., 2007. Certificación de fincas de producción de café orgánico- Avances técnicos no. 363. Chinchiná, Caldas, Colombia.

Faria, D., Paciencia, M.L.B., Dixo, M., Laps, R.R., Baumgarten, J., 2007. Ferns, frogs, lizards, birds and bats in forest fragments and shade cacao plantations in two contrasting landscapes in the Atlantic forest, Brazil. Biodivers. Conserv. 2335–2357. https://doi.org/10.1007/s10531-007-9189-z

Feola, G., Binder, C.R., 2010. Towards an improved understanding of farmers' behaviour: The integrative agent-centred (IAC) framework. Ecol. Econ. 69, 2323–2333. https://doi.org/10.1016/j.ecolecon.2010.07.023

Feola, G., Lerner, A.M., Jain, M., Montefrio, M.J.F., Nicholas, K. a., 2015. Researching farmer behaviour in climate change adaptation and sustainable agriculture: Lessons learned from five case studies. J. Rural Stud. 39, 74–84. https://doi.org/10.1016/j.jrurstud.2015.03.009

Foley, J. a, Ramankutty, N., Brauman, K. a, Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. https://doi.org/10.1038/nature10452

Fox, J., Weisberg, S., Adler, D., Bates, D., Baud-Bovy, G., Ellison, S., Firth, D., Friendly, M., Gorjanc, G., Graves, S., Heiberger, R., Laboissiere, R., Monette, G., Murdoch, D., Nilsson, H., Ogle, D., Ripley, B., Venables, W., Winsemium, D., Zeileis, A., R-Core, 2016. An R Companian to Applied Regression.

Fraley, C., Raftery, A.E., Scrucca, L., Murphy, T.B., Fop, M., 2017. Mclust -Gaussian mixture modelling for model-based clustering, classification and density estimation.

Frank, E., Eakin, H., López-Carr, D., 2011. Social identity, perception and motivation in adaptation to climate risk in the coffee sector of Chiapas, Mexico. Glob. Environ. Chang. 21, 66–76. https://doi.org/10.1016/j.gloenvcha.2010.11.001

Gabriel, D., Sait, S.M., Kunin, W.E., Benton, T.G., 2013. Food production vs. biodiversity: comparing organic and conventional agriculture. J. Appl. Ecol. 50, 355–364. https://doi.org/10.1111/1365-2664.12035

Gardner, T.A., Barlow, J., Chazdon, R., Ewers, R.M., Harvey, C.A., Peres, C.A., Sodhi, N.S., 2009. Prospects for tropical forest biodiversity in a human-modified world. Ecol. Lett. 12, 561–582. https://doi.org/10.1111/j.1461-0248.2009.01294.x

Garnett, S.T., Sayer, J., Toit, J. Du, 2007. Improving the Effectiveness of Interventions to Balance Conservation and Development : a Conceptual Framework. Ecol. Soc. 12.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., Sodhi, N.S., 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478, 378–381. https://doi.org/10.1038/nature10425

Gliessman, S.R., 1992. Agroecology in the Tropics : Achieving a Balance Between Land Use and Preservation. Environ. Manage. 681–689.

Gobbi, J.A., 2000. Is biodiversity-friendly coffee financially viable? An analysis of five different coffee production systems in western El Salvador. Ecol. Econ. 33, 267–281. https://doi.org/10.1016/S0921-8009(99)00147-0

Gobierno Regional de San Martín, 2012. San Martín Forestal en Números, Año 2012. Boletin Semestral I-2012.

Gobierno Regional de San Martín, 2008. Climate data San Martín [WWW Document]. Perú. URL http://es.climate-data.org/ (accessed 2.3.17).

Gomiero, T., Pimentel, D., Paoletti, M.G., 2011. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. CRC. Crit. Rev. Plant Sci. 30, 95–124. https://doi.org/10.1080/07352689.2011.554355

Gockowski, J., Afari-Sefa, V., Sarpong, D.B., Osei-Asare, Y.B., Agyeman, N.F., 2013. Improving the productivity and income of Ghanaian cocoa farmers while maintaining environmental services: what role for certification? Int. J. Agric. Sustain. 11, 2013, 331– 346. doi:10.1080/14735903.2013.772714

Gordon, C., Manson, R., Sundberg, J., Cruz-Angón, A., 2007. Biodiversity, profitability, and vegetation structure in a Mexican coffee agroecosystem. Agric. Ecosyst. Environ. 118, 256–266. https://doi.org/10.1016/j.agee.2006.05.023

Green, R.E., Cornell, S.J., Scharlemann, J.P.W., Balmford, A., 2005. Farming and the fate of wild nature. Science 307, 550–555. https://doi.org/10.1126/science.1106049

Grothmann, T., Patt, A., 2005. Adaptive capacity and human cognition: The process of individual adaptation to climate change. Glob. Environ. Chang. 15, 199–213. https://doi.org/10.1016/j.gloenvcha.2005.01.002

Häger, A., Fernández Otárola, M., Stuhlmacher, M.F., Acuña Castillo, R., Contreras Arias, A., 2014. Effects of management and landscape composition on the diversity and structure of tree species assemblages in coffee agroforests. Agric. Ecosyst. Environ. 199, 43–51. https://doi.org/10.1016/j.agee.2014.08.022

Haggar, J., Jerez, R., Cuadra, L., Alvarado, U., Soto, G., 2012. Environmental and economic costs and benefits from sustainable certification of coffee in Nicaragua. Food Chain 2, 24–41. https://doi.org/10.3362/2046-1887.2012.004

Haggar, J., Medina, B., Aguilar, R.M., Munoz, C., 2013. Land use change on coffee farms in southern Guatemala and its environmental consequences. Environ. Manage. 51, 811–823. https://doi.org/10.1007/s00267-013-0019-7

Haggar, J., Soto, G., Casanoves, F., Virginio, E. de M., 2017. Environmental-economic benefits and trade-offs on sustainably certified coffee farms. Ecol. Indic. 79, 330–337. https://doi.org/10.1016/j.ecolind.2017.04.023

Hairiah, K., Dewi, S., Agus, F., Velarde, S., Ekadinata, A., Rahayu, S., Noordwijk, M. Van, 2010. Measuring carbon stocks across land use systems: a manual. World Agroforestry Centre (ICRAF); SEA Regional Office, Bogor, Indonesia.

Hairiah, K., Sulistyani, H., Suprayogo, D., Widianto, Purnomosidhi, P., Widodo, R.H., Van Noordwijk, M., 2006. Litter layer residence time in forest and coffee agroforestry systems in Sumberjaya, West Lampung. For. Ecol. Manage. 224, 45–57. https://doi.org/10.1016/j.foreco.2005.12.007

Harold, L.T., 2013. Comparison of economic efficiency of organic and conventional coffee farming systems in Moshi rural district, Tanzania. University of Nairobi, Kenya.

Harvey, C. a, Komar, O., Chazdon, R., Ferguson, B.G., Finegan, B., Griffith, D.M., Martínez-Ramos, M., Morales, H., Nigh, R., Soto-Pinto, L., Van Breugel, M., Wishnie, M., 2008. Integrating agricultural landscapes with biodiversity conservation in the Mesoamerican hotspot. Conserv. Biol. 22, 8–15. https://doi.org/10.1111/j.1523-1739.2007.00863.x

Harvey, C.A., Gonzalez, J., Somarriba, E., 2006. Dung beetle and terrestrial mammal diversity in forests, indigenous agroforestry systems and plantain monocultures in Talamanca, Costa Rica. Biodivers. Conserv. 15, 555–585. https://doi.org/10.1007/s10531-005-2088-2

Hernandez, O.R., 1995. Rendimiento y análisis financiero del sistema agroforestal café (*Coffea arabica* cv *caturra*) con poró (*Erythrina poeppigiana*) bajo diferentes densidades de laurel (*Cordia alliodora*). Thesis. CATIE, Turrialba, Costa Rica.

Hernández-Martínez, G., Manson, R.H., Hernández, A.C., 2009. Quantitative classification of coffee agroecosystems spanning a range of production intensities in central Veracruz, Mexico. Agric. Ecosyst. Environ. 134, 89–98. https://doi.org/10.1016/j.agee.2009.05.020

Hicks, A., 2002. Post-harvest Processing and Quality Assurance for Speciality Organic Coffee Products. AU J. Technol. 5.

Hoekstra, D.A., 1987. Economics of agroforestry. Agrofor. Syst. 300, 293–300.

ICC, 2014. World coffee trade (1963 – 2013): A review of the markets, challenges and opportunities facing the sector, in: Reviev of the 112th International Coffee Council. International Coffee Organization, London, p. 29.

ICO, 2017. Coffee marketing report.

ICO, 2016. Assesing the economic sustainability of coffee growing, in: International Coffee Council. London, United Kingdom.

Imbach, P., Fung, E., Hannah, L., Navarro-Racines, C.E., Roubik, D.W., Ricketts, T.H., Harvey, C.A., Donatti, C.I., Läderach, P., Locatelli, B., Roehrdanz, P.R., 2017. Coupling of pollination services and coffee suitability under climate change. Proc. Natl. Acad. Sci. 114, 201617940. https://doi.org/10.1073/pnas.1617940114

Jackson, D., Skillman, J., Vandermeer, J., 2012. Indirect biological control of the coffee leaf rust, Hemileia vastatrix, by the entomogenous fungus *Lecanicillium lecanii* in a complex coffee agroecosystem. Biol. Control 61, 89–97. https://doi.org/10.1016/j.biocontrol.2012.01.004

Jaramillo-Botero, C., Santos, R.H.S., Martinez, H.E.P., Cecon, P.R., Fardin, M.P., 2010. Production and vegetative growth of coffee trees under fertilization and shade levels. Sci. Agric. 67, 639–645. https://doi.org/10.1590/S0103-90162010000600004

Jaramillo, J., Muchugu, E., Vega, F.E., Davis, A., Borgemeister, C., Chabi-Olaye, A., 2011. Some like it hot: the influence and implications of climate change on coffee berry borer (*Hypothenemus hampei*) and coffee production in East Africa. PLoS One 6, e24528. https://doi.org/10.1371/journal.pone.0024528

Jezeer, R., Verweij, P., 2015. Shade-grown coffee: Double dividend for biodiversity and small-scale farmers in Peru. The Hague, the Netherlands.

Jezeer, R.E., Santos, M.J., Boot, R.G.A., Junginger, M., Verweij, P.A., 2018. Effects of shade and input management on economic performance of small-scale Peruvian coffee systems. Agric. Syst. 162, 179–190. https://doi.org/10.1016/j.agsy.2018.01.014

Jezeer, R.E., Verweij, P.A., Santos, M.J., Boot, R.G.A., 2017. Shaded coffee and cocoa – double dividend for biodiversity and small-scale farmers. Ecol. Econ. 140, 136–145. https://doi.org/10.1016/j.ecolecon.2017.04.019

Jha, S., Bacon, C.M., Philpot, S.M., Ernesto Mendez, V., Laderach, P., Rice, R.A., 2014. Shade coffee: update on a disappearing refuge for biodiversity. Bioscience 64, 416–428. https://doi.org/10.1093/biosci/biu038

Jha, S., Bacon, C.M., Philpott, S.M., Rice, R.A., Ernesto Méndez, V., Laderach, P., 2011. A review of ecosystem services, farmer livelihoods, and value chains in shade coffee agroecosystems., in: Campbell, B.W., López Ortíz, S. (Eds.), Integrating Agriculture, Conservation and Ecotourism: Examples from the Field. Springer, pp. 141–208. https://doi.org/10.1007/978-94-007-1309-3

Johnson, J.B., Omland, K.S., 2004. Model selection in ecology and evolution. Trends Ecol. Evol. 19, 101–108. https://doi.org/10.1016/j.tree.2003.10.013

Jonsson, M., Raphael, I.A., Ekbom, B., Kyamanywa, S., Karungi, J., 2015. Contrasting effects of shade level and altitude on two important coffee pests. J. Pest Sci. (2004). 88, 281–287. https://doi.org/10.1007/s10340-014-0615-1

Jose, S., 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor. Syst. 76, 1–10. https://doi.org/10.1007/s10457-009-9229-7

Juhrbandt, J., 2010. Economic valuation of land use change - A case study on rainforest conversion and agroforestry intensification in Central Sulawesi , Indonesia Dissertation Jana Juhrbandt. Georg-August-Universität Göttingen.

Kassambara, A., Mundt, F., 2017. package “factorextra”: Extract and visualize the results of mutivariate data analyses.

Kellerman, J.L., Johnson, M.D., Stercho, A.M., Hackett, S.C., 2008. Ecological and economic services provided by birds on Jamaican Blue Mountain coffee farms. Conserv. Biol. 22, 1177–1185. https://doi.org/10.1111/j.1523-1739.2008.00968.x

Kessler, M., Abrahamczyk, S., Bos, M., Buchori, D., Putra, D.D., Gradstein, S.R., Ho, P., Orend, F., Pitopang, R., Saleh, S., Schulze, C.H., Sporn, S.G., Steffan-dewenter, I., Tjitrosoedirdjo, S.S., Tscharntke, T., Karspu, U., Robbert Gradstein, S., Höhn, P., Kluge, J., Orend, F., Pitopang, R., Saleh, S., Schulze, C.H., Sporn, S.G., Steffan-dewenter, I., Tjitrosoedirdjo, S.S., Tscharntke, T., 2011. Cost-effectiveness of plant and animal biodiversity indicators in tropical forest and agroforest habitats. J. Appl. Ecol. 48, 330–339. https://doi.org/10.1111/j.1365-2664.2010.01932.x

Kjeldahl, J. (1883) A new method for the determination of nitrogen in organic matter. Journal of Analytical Chemistry.

Kremen, C., Miles, A., 2012. Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. Ecol. Soc. 17, art40. https://doi.org/10.5751/ES-05035-170440

Krishnan, S., Kushalappa, C.G., Shaanker, R.U., Ghazoul, J., 2012. Status of pollinators and their efficiency in coffee fruit set in a fragmented landscape mosaic in South India. Basic Appl. Ecol. 13, 277–285. https://doi.org/10.1016/j.baae.2012.03.007

Kumar, P., Singh, R.P., Kumar, A., Kumar, V., 2014. Quantification and distribution of agroforestry systems and practices at global level. HortFlora Res. Spectr. 3, 1–6.

Larrea, C., Eckhardt, K., Arana, A., 2014. El impacto económico del cambio climático en la selva alta para el cultivo del café 1–22.

Laurance, W.F., 1999. Effects on the tropical deforestation crisis. Biol. Conserv. 91, 109–117. https://doi.org/10.1016/S0006-3207(99)00088-9

Levine, S., 2014. How to study livelihoods: bringing a sustainable livelihoods framework to life (No. 22). London, United Kingdom.

Lin, B.B., 2010. The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. Agric. For. Meteorol. 150, 510–518. https://doi.org/10.1016/j.agrformet.2009.11.010

Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agric. For. Meteorol. 144, 85–94. https://doi.org/10.1016/j.agrformet.2006.12.009

Lin, B.B., Perfecto, I., Vandermeer, J., 2008. Synergies between Agricultural Intensification and Climate Change Could Create Surprising Vulnerabilities for Crops. Bioscience 58, 847–854. https://doi.org/10.1641/B580911

López-Bravo, D.F., Virginio-Filho, E.D.M., Avelino, J., 2012. Shade is conducive to coffee rust as compared to full sun exposure under standardized fruit load conditions. Crop Prot. 38, 21–29. https://doi.org/10.1016/j.cropro.2012.03.011

Lyngbæk, A.E., Muschler, R.G., Sinclair, F.L., 2001. Productivity and profitability of multistrata organic versus conventional coffee farms in Costa Rica. Agrofor. Syst. 53, 205–213. https://doi.org/10.1023/A:1013332722014

Magrach, A., Ghazoul, J., 2015. Climate and Pest-Driven Geographic Shifts in Global Coffee Production: Implications for Forest Cover, Biodiversity and Carbon Storage. PLoS One 10, e0133071. https://doi.org/10.1371/journal.pone.0133071

Mann, L.K. (1986) Changes in soil carbon storage after cultivation. *Soil Science*, 142.

Marín, L., Philpott, S.M., De la Mora, A., Ibarra Núñez, G., Tryban, S., Perfecto, I., 2016. Response of ground spiders to local and landscape factors in a Mexican coffee landscape. Agric. Ecosyst. Environ. 222, 80–92. https://doi.org/10.1016/j.agee.2016.01.051

Martínez Acosta, M.H., 2005. Contribución económica del componente forestal en diferentes tipos de fincas cafetaleras en la bocacosta pacifica de Guatamala. CATIE, Turrialba, Costa Rica.

Mas, A., Dietsch, T., 2003. An index of management intensity for coffee agroecosystems to evaluate butterfly species richness. Ecol. Appl. 13, 1491–1501. https://doi.org/10.1890/01-5229

Mas, A.H., Dietsch, T. V, 2004. Linking shade coffee certification to biodiversity conservation: Butterflies and birds in Chiapas, Mexico. Ecol. Appl. 14, 642–654.

McGregor, M.J., Rola-Rubzen, M.F., Murray-Prior, R., 2001. Micro and maceo-level approaches to modelling decision making. Agric. Syst. 2001, 63–83.

McNeely, J. a., Schroth, G., 2006. Agroforestry and Biodiversity Conservation – Traditional Practices, Present Dynamics, and Lessons for the Future. Biodivers. Conserv. 15, 549–554. https://doi.org/10.1007/s10531-005-2087-3

Mehta, N.G., Leuschner, W.A., 1997. Financial and economic analyses of agroforestry systems and a commercial timber plantation in the la Amistad biosphere reserve, Costa Rica. Agrofor. Syst. 37, 175–185. https://doi.org/10.1023/A:100584052

Méndez, V.E., Shapiro, E.N., Gilbert, G.S., 2009. Cooperative management and its effects on shade tree diversity, soil properties and ecosystem services of coffee plantations in western El Salvador. Agrofor. Syst. 76, 111–126. https://doi.org/10.1007/s10457-009-9220-3

Mercer, D.E., 2004. Adoption of agroforestry innovations in the tropics: A review. Agrofor. Syst. 61–62, 311–328. https://doi.org/10.1023/B:AGFO.0000029007.85754.70

Meyfroidt, P., Carlson, K.M., Fagan, M.E., Gutiérrez-Vélez, V.H., Macedo, M.N., Curran, L.M., Defries, R.S., Dyer, G.A., Gibbs, H.K., Lambin, E.F., Morton, D.C., Robiglio, V., 2014. Multiple pathways of commodity crop expansion in tropical forest landscapes. Environ. Res. Lett. 9 074012. https://doi.org/10.1088/1748-9326/9/7/074012

Meylan, L., Gary, C., Allinne, C., Ortiz, J., Jackson, L., Rapidel, B., 2017. Evaluating the effect of shade trees on provision of ecosystem services in intensively managed coffee plantations. Agric. Ecosyst. Environ. 245, 32–42. https://doi.org/10.1016/j.agee.2017.05.005

Moguel, P., Toledo, V.M., 1999. Biodiversity conservation in traditional coffee systems of Mexico. Conserv. Biol. 13, 11–21. https://doi.org/10.1046/j.1523-1739.1999.97153.x

Mora, O., Zamora, L. comps, Muschler, R.G., Echeverri, J., 1997. Efectos de sombra de *Erythrina poeppigiana* sobre *Coffea arabica* vars. caturra y catimor, in: Memorias Del 18 Simposio Latinoamericano de Caficultura. IICA/PROMECAFE, San José, Costa Rica, pp. 157–162. https://doi.org/10.1023/A:1010603320653

Morton, J.F., 2007. The impact of climate change on smallholder and subsistence agriculture. Proc. Natl. Acad. Sci. 104, 19680–19685. https://doi.org/10.1073/pnas.0701855104

Muschler, R.G., 2001. Shade improves coffee quality in a sub-optimal coffee-zone of Costa Rica. Agrofor. Syst. 51, 131–139. https://doi.org/10.1023/A:1010603320653

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858. https://doi.org/10.1038/35002501

Naeem, S., 2012. The Functions of Biological Diversity in an Age of Extinction 1401, 1401–1407. https://doi.org/10.1126/science.1215855

Nelson, V., Haggar, J., Martin, A., Donovan, J., Borasino, E., Hasyim, W., Mhando, N., Senga, M., Mgumia, E., Quintanar Guadarrama, E., Kendar, Z., Valdez, J., Morales, D., 2016. Fairtrade Coffee: A study to assess the impact of Fairtrade for coffee smallholders and producer organisations in Indonesia, Mexico, Peru and Tanzania. Chatham, United Kingdom.

Obiri, B., Geoff, O.Æ., Mcdonald, M.A., Anglaaere, Æ.L.C.N., 2007. Financial analysis of shaded cocoa in Ghana. *Agrofor. Syst.* **71**, 2007, 139–149. doi:10.1007/s10457-007- 9058-5

O'Brien, Timothy, G., Kinnaird, M.F., 2003. Caffeine and Conservation. Science (80-.). 300, 587. https://doi.org/10.1126/ science.1082328

Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Wagner, H., 2017. Community Ecology Package "vegan". Version 2.4-3. R Packag. https://doi.org/10.4135/9781412971874.n145

Olsson, K., 2008. Soil fertility and changes caused by slash and burn agriculture in two watersheds of the upper Amazon, Peru. University of Kalmar.

Ovalle-Rivera, O., Läderach, P., Bunn, C., Obersteiner, M., Schroth, G., 2015. Projected shifts in *Coffea arabica* suitability among major global producing regions due to climate change. PLoS One 10, e0124155. https://doi.org/10.1371/journal.pone.0124155

Padrón, B.R., Burger, K., 2015. Diversification and labor market effects of the Mexican coffee crisis. World Dev. 68, 19–29. https://doi.org/10.1016/j.worlddev.2014.11.005

Panhuysen, S., Pierrot, J., 2014. Coffee barometer 2014. Hivos, The Hague.

Pannell, D.J., 1999. Social and economic challenges in the development of complex farming systems. Agrofor. Syst. 45, 393–409. https://doi.org/A2

Paul, F., Ruf, F., Yoddang, 2013. Diversification et cycle de cultures pérennes à Aceh, Indonésie, in: Ruf, F., Schroth, G. (Eds.), Cultures Pérennes Tropicales: Enjeux Économiques et Écologiques de La Diversification. Éditions Quae, Versailles, France, pp. 265–279.

Pennington, T.D., Reynel, C., Daza, A., 2004. Illustrated guide to the trees of Peru. DH Books, Sherborne, England.

Perfecto, I., Mas, A., Dietsch, T., Vandermeer, J., 2003. Conservation of biodiversity in coffee agroecosystems : a tri-taxa comparison in southern Mexico. Biodivers. Conserv. 12, 1239–1252.

Perfecto, I., Rice, R.A., Greenberg, R., van der Voort, M.E., 1996. Shade coffee: a disappearing refuge for biodiversity. Bioscience 46, 598–608.

Perfecto, I., Vandermeer, J., 2015. Coffee Agroecology- A New approach to understanding agricultural biodiversity, ecosystem services and sustainable development. Routledge, New York, US.

Perfecto, I., Vandermeer, J., 2008. Biodiversity conservation in tropical agroecosystems: a new conservation paradigm. Ann. N. Y. Acad. Sci. 1134, 173–200. https://doi.org/10.1196/annals.1439.011

Perfecto, I., Vandermeer, J., Mas, A., Pinto, L.S., 2005. Biodiversity, yield, and shade coffee certification. Ecol. Econ. 54, 435–446. https://doi.org/10.1016/j.ecolecon.2004.10.009

Perfecto, I., Vandermeer, J.H., Bautista, G.L., Nuñez, G.I., Greenberg, R., Bichier, P., Langridge, S., 2004. Greater predation in shaded coffee farms: The role of resident neotropical birds. Ecology 85, 2677–2681. https://doi.org/10.1890/03-3145

Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333, 1289–91. https://doi.org/10.1126/science.1208742

Philpott, S.M., Armbrecht, I., 2006. Biodiversity in tropical agroforests and the ecological role of ants and ant diversity in predatory function. Ecol. Entomol. 31, 369–377.

Philpott, S.M., Bichier, P., Rice, R. A., Greenberg, R., 2008. Biodiversity conservation, yield, and alternative products in coffee agroecosystems in Sumatra, Indonesia. Biodivers. Conserv. 17, 1805–1820. https://doi.org/10.1007/s10531-007-9267-2

Philpott, S.M., Bichier, P., Rice, R., Greenberg, R., 2007. Field-testing ecological and economic benefits of coffee certification programs. Conserv. Biol. 21, 975–85. https://doi.org/10.1111/j.1523-1739.2007.00728.x

Pinard, F., Boffa, J.M., Rwakagara, E., 2014. Scattered shade trees improve low-input smallholder Arabica coffee productivity in the Northern Lake Kivu region of Rwanda. *Agrofor. Syst.* 2014, doi:10.1007/s10457-014-9712-7

Pinoargote, M., Cerda, R., Mercado, L., Aguilar, A., Somarriba, E., 2017. Carbon stocks , net cash flow and family benefits from four small coffee plantation types in Nicaragua. For. Trees Livelihoods 8028, 1–16. https://doi.org/10.1080/14728028.2016.1268544

Ponte, S., 2002. The "Latte Revolution"? Regulation, markets and consumption in the global coffee chain. World Dev. 30, 1099–1122. https://doi.org/10.1016/S0305-750X(02)00032-3

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., Kunin, W.E., 2010. Global pollinator declines: trends, impacts and drivers. Trends Ecol. Evol. 25, 345–353. https://doi.org/10.1016/j.tree.2010.01.007

Quiroga, S., Suárez, C., Solís, J.D., 2015. Exploring coffee farmers' awareness about climate change and water needs: smallholders' perceptions of adaptive capacity. Environ. Sci. Policy 45, 53–66. https://doi.org/10.1016/j.envsci.2014.09.007

R Core Team, 2014. A language and environment for statistical computing. In: R Foundation for Statistical Computing.

Rahman, S., Rahman, M., Codilan, A.., Farhana, K., 2007. Analysis of the economic benefits from systematic improvements to shifting cultivation and its evolution towards stable continuous agroforestry in the upland of Eastern Bangladesh. Int. For. Rev. 9, 536–547. https://doi.org/10.1505/ifor.9.1.536

Rahman, S., 2003. Farm-level pesticide use in Bangladesh: Determinants and awareness. Agric. Ecosyst. Environ. 95, 241–252. https://doi.org/10.1016/S0167-8809(02)00089-0

Rahn, E., Läderach, P., Baca, M., Cressy, C., Schroth, G., Malin, D., van Rikxoort, H., Shriver, J., 2014. Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? Mitig. Adapt. Strateg. Glob. Chang. 19, 1119–1137. https://doi.org/10.1007/s11027-013-9467-x

Rahn, E., Vaast, P., Läderach, P., van Asten, P., Jassogne, L., Ghazoul, J., 2018. Exploring adaptation strategies of coffee production to climate change using a process-based model. Ecol. Modell. 371, 76–89. https://doi.org/10.1016/j.ecolmodel.2018.01.009

Rajab, Y.A., Leuschner, C., Barus, H., Tjoa, A., Hertel, D., 2016. Cacao cultivation under diverse shade tree cover allows high carbon storage and sequestration without yield losses. PLoS One 11, 1–22. https://doi.org/10.1371/journal.pone.0149949

Ramírez, O.A., Somarriba, E., Ludewigs, T., Ferreira, P., 2001. Financial returns , stability and risk of cacao-plantain-timber agroforestry systems in Central America. *Agrofor. Syst.* 2, 2001, 141–154.

Rapidel, B., Ripoche, A., Allinne, C., Metay, A., Deheuvels, O., Lamanda, N., Blazy, J.M., Valdés-Gómez, H., Gary, C., 2015. Analysis of ecosystem services trade-offs to design agroecosystems with perennial crops. Agron. Sustain. Dev. 35, 1373–1390. https://doi.org/10.1007/s13593-015-0317-y

Reyes, G., Brown, S., Chapman, J., Lugo, A.E., 1992. Wood densities of tropical tree species, General technical report, SO-88. New Orleans, Louisiana. https://doi.org/https://doi.org/10.2737/SO-GTR-088

Ribeyre, F., Avelino, J., 2012. Impact of field pests and diseases on coffee quality, in: Thomas, O., Peter, L., Pohlan, J.H.A., Cock, J.H. (Eds.), Specialty Coffee: Managing Quality. IPNI, pp. 151–176.

Rice, R.A., 2008. Agricultural intensification within agroforestry: The case of coffee and wood products. Agric. Ecosyst. Environ. 128, 212–218. https://doi.org/10.1016/j.agee.2008.06.007

Rice, R.A., Greenberg, R., 2000. Cacao Cultivation and the Conservation of Biological Diversity. A J. Hum. Environ. 29, 167–173.

Ricketts, T.H., Daily, G.C., Ehrlich, P.R., Fay, J.P., 2001. Countryside biogeography of moths in a fragmented landscape: biodiversity in native and agricultural Habitats. Conserv. Biol. 15, 378–388. https://doi.org/10.1046/j.1523-1739.2001.015002378.x

Rodriguez, S., 2010. Impacts of deforestation on poverty: case study of the region San Martín in Perú. Erasmus, International Institute of Social Studies.

Romero-Alvarado, Y., Soto-Pinto, L., García-Barrios, L., Barrera-Gaytán, J.F., 2002. Coffee yields and soil nutrients under the shades of Inga sp. vs. multiple species in Chiapas, Mexico. Agrofor. Syst. 54, 215–224. https://doi.org/10.1023/A:1016013730154

Rosero, P.Y.G., Sánchez, S.A.M., Narváez, I.E.P., 2015. Caracterización Física De Café Especial (Coffea Arabica) En El Municipio De Chachagüí (Nariño, Colombia). Rev. Lasallista Investig. 12, 90–98.

Ruf, F., Schroth, G., 2015. Economics and Ecology of Diversification, Economics and Ecology of Diversification: The Case of Tropical Tree Crops. https://doi.org/10.1007/978-94-017-7294-5

Samnegård, U., Hambäck, P.A., Nemomissa, S., Hylander, K., 2014. Dominance of the semi-wild honeybee as coffee pollinator across a gradient of shade-tree structure in Ethiopia. J. Trop. Ecol. 30, 401–408. https://doi.org/10.1017/S0266467414000327

Sánchez-de León, Y., De Melo, E., Soto, G., Johnson-Maynard, J., Lugo-Pérez, J., Rica, C., 2006. Earthworm Populations, Microbial Biomass and Coffee Production in Different Experimental Agroforestry Management Systems in Costa Rica. Caribb. J. Sci. 42, 397–409.

Scherr, S.J., McNeely, J.A., 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of "ecoagriculture" landscapes. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363, 477–94. https://doi.org/10.1098/rstb.2007.2165

Schroth, G., da Fonseca, G.A.B., Harvey, C.A., Gascon, C., Vasconcelos, H.L., Izac, A.N., 2004. Agroforestry and Biodiversity conservation in Tropical Landscapes. Island Press, Washington, DC.

Schroth, G., Faria, D., Araujo, M., Bede, L., van Bael, S.A., Cassano, C.R., Oliveira, L.C., Delabie, J.H.C., 2011. Conservation in tropical landscape mosaics: The case of the cacao landscape of southern Bahia, Brazil. Biodivers. Conserv. 20, 1635–1654. https://doi.org/10.1007/s10531-011-0052-x

Schroth, G., Harvey, C. a., 2007. Biodiversity conservation in cocoa production landscapes: an overview. Biodivers. Conserv. 16, 2237–2244. https://doi.org/10.1007/s10531-007-9195-1

Schroth, G., Jeusset, A., Gomes, A.D.S., Florence, C.T., Coelho, N.A.P., Faria, D., Läderach, P., 2014. Climate friendliness of cocoa agroforests is compatible with productivity increase. Mitig. Adapt. Strateg. Glob. Chang. 21, 67–80. https://doi.org/10.1007/s11027-014-9570-7

Schroth, G., Ruf, F., 2014. Farmer strategies for tree crop diversification in the humid tropics. A review. Agron. Sustain. Dev. 34, 139–154. https://doi.org/10.1007/s13593-013-0175-4

Schulze, C.H., Waltert, M., Kessler, P.J.A., Pitopang, R., ShHahabuddin, S., Veddeler, D., Muhlenberg, M., Gradstein, S.R., Leuschner, C., Steffan-Dewenter, I., Tscharntke, T., 2004. Biodiversity Indocator groups of tropical land-use systems: comparing plants, birds and insects. Ecol. Appl. 14, 1321–1333.

Schulze, C.H., Waltert, M., Kessler, P.J.A., Pitopang, R., Veddeler, D., Mühlenberg, M., Gradstein, S.R., Steffan-dewenter, I., Tscharntke, T., 2004. Insects biodiversity indicator groups of tropical land-use systems: comparing plants, birds and insects. Ecol. Appl. 14, 1321–1333. https://doi.org/10.1890/02-5409

Scoones, I., 2009. Livelihoods perspectives and rural development. J. Peasant Stud. 36, 171–196. https://doi.org/10.1080/03066150902820503

Scoones, I., 1998. Sustainable Rural Livelihoods a Framework for Analysis, Analysis. https://doi.org/10.1057/palgrave.development.1110037

Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–32. https://doi.org/10.1038/nature11069

Siebert, S.F., 2002. From shade- to sun-grown perennial crops in Sulawesi, Indonesia: implications for biodiversity conservation and soil fertility. Biodivers. Conserv. 11, 1889–1902. https://doi.org/10.1023/A:102080461

Siles, P., Harmand, J.-M., Vaast, P., 2010. Effects of Inga densiflora on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica. Agrofor. Syst. 78, 269–286. https://doi.org/10.1007/s10457-009-9241-y

Snoeck, J., Lambot, C., 2004. Crop Maintenance.

Somarriba, E., Beer, J., 2010. Productivity of *Theobroma cacao* agroforestry systems with timber or legume service shade trees. Agrofor. Syst. 81, 109–121. https://doi.org/10.1007/s10457-010-9364-1

Soto-Pinto, L., Anzueto, M., Mendoza, J., Ferrer, G.J., de Jong, B., 2010. Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico. Agrofor. Syst. 78, 39–51. https://doi.org/10.1007/s10457-009-9247-5

Soto-Pinto, L., Perfecto, I., Caballero-Nieto, J., 2002. Shade over coffee: its effects on berry borer, leaf rust and spontaneous herbs in Chiapas, Mexico. Agrofor. Syst. 55, 37–45.

Soto-Pinto, L., Perfecto, I., Castillo-Hernandez, J., Caballero-Nieto, J., 2000. Shade effect on coffee production at the northern Tzeltal zone of the state of Chiapas, Mexico. Agric. Ecosyst. Environ. 80, 61–69. https://doi.org/10.1016/S0167-8809(00)00134-1

Souza, H.N., Cardoso, I.M., Fernandes, J.M., Garcia, F.C.P., Bonfim, V.R., Santos, A.C., Carvalho, A.F., Mendonça, E.S., 2010. Selection of native trees for intercropping with coffee in the Atlantic Rainforest biome. Agrofor. Syst. 80, 1–16. https://doi.org/10.1007/s10457-010-9340-9

Staver, C., Guharay, F., Monterroso, D., Muschler, R.G., 2001. Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. Agrofor. Syst. 53, 151–170. https://doi.org/10.1023/A:1013372403359

Steffan-Dewenter, I., Kessler, M., Barkmann, J., Bos, M.M., Buchori, D., Erasmi, S., Faust, H., Gerold, G., Glenk, K., Gradstein, S.R., Guhardja, E., Harteveld, M., Hertel, D., Hohn, P., Kappas, M., Kohler, S., Leuschner, C., Maertens, M., Marggraf, R., Migge-Kleian, S., Mogea, J., Pitopang, R., Schaefer, M., Schwarze, S., Sporn, S.G., Steingrebe, A., Tjitrosoedirdjo, S.S., Tjitrosoemito, S., Twele, A., Weber, R., Woltmann, L., Zeller, M., Tscharntke, T., 2007. Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. Proc. Natl. Acad. Sci. 104, 4973–4978. https://doi.org/10.1073/pnas.0608409104

Steffan-Dewenter, I., Münzenberg, U., Bürger, C., Thies, C., Tscharntke, T., 2002. Scale-dependant effects of landscape context on three pollinator guilds. Ecology 83, 1421–1432. https://doi.org/10.1890/0012-9658(2002)083[1421:SDEOLC]2.0.CO;2

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. U. S. A. 108, 20260–4. https://doi.org/10.1073/pnas.1116437108

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E.C., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agric. Ecosyst. Environ. 110, 149–165. https://doi.org/10.1016/j.agee.2005.04.001

Tscharntke, T., Clough, Y., Bhagwat, S.A., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., Wanger, T.C., 2011. Multifunctional shade-tree management in tropical agroforestry landscapes - a review. J. Appl. Ecol. 48, 619–629. https://doi.org/10.1111/j.1365-2664.2010.01939.x

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biol. Conserv. 151, 53–59. https://doi.org/10.1016/j.biocon.2012.01.068

Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity - ecosystem service management. Ecol. Lett. 8, 857–874. https://doi.org/10.1111/j.1461-0248.2005.00782.x

Tucker, C.M., Eakin, H., Castellanos, E.J., 2010. Perceptions of risk and adaptation: Coffee producers, market shocks, and extreme weather in Central America and Mexico. Glob. Environ. Chang. 20, 23–32. https://doi.org/10.1016/j.gloenvcha.2009.07.006

Tufto, J., Lande, R., Ringsby, T.H., Engen, S., Sæther, B.E., Walla, T.R., Devries, P.J., 2012. Estimating Brownian motion dispersal rate, longevity and population density from spatially explicit mark-recapture data on tropical butterflies. J. Anim. Ecol. 81, 756–769. https://doi.org/10.1111/j.1365-2656.2012.01963.x

USDA, 2014. Annual Global Agricultural Information Network (GAIN) Report on Green Coffee, Peru Targets Expanded Coffee Production.

Vaast, P., Bertrand, B., Perriot, J.J., Guyot, B., Génard, M., 2006. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica L.*) under optimal conditions. J. Sci. Food Agric. 86, 197–204. https://doi.org/10.1002/jsfa.2338

Vaast, P., Harmand, J.-M., Rapidel, B., Jagoret, P., Deheuvels, O., 2016. Coffee and cocoa production in agroforestry- a climate-smart agriculture model BT, in: Torquebiau, E. (Ed.), Climate Change and Agriculture Worldwide. Springer Netherlands, Dordrecht, pp. 209–224. https://doi.org/10.1007/978-94-017-7462-8_16

Valqui, M., Feather, C., Llanos, R.E., 2015. Revealing the hidden - indigenous perspectives on deforestation in the Peruvian Amazone; the causes and solutions. Lima, Perú.

van Asten, P.J. a., Wairegi, L.W.I., Mukasa, D., Uringi, N.O., 2011. Agronomic and economic benefits of coffee–banana intercropping in Uganda's smallholder farming systems. Agric. Syst. 104, 326–334. https://doi.org/10.1016/j.agsy.2010.12.004

van Noordwijk, M., Rahayu, S., Hairiah, K., Wulan, Y.C., Farida, A., Verbist, B., 2002. Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis. Sci. China Ser. C-Life Sci. 45, 75–86.

Vandermeer, J., Jackson, D., Perfecto, I., 2014. Qualitative Dynamics of the Coffee Rust Epidemic: Educating Intuition with Theoretical Ecology. Bioscience 64, 210–218. https://doi.org/10.1093/biosci/bit034

Vandermeer, J., Perfecto, I., Liere, H., 2009. Evidence for hyperparasitism of coffee rust (*Hemileia vastatrix*) by the entomogenous fungus, *Lecanicillium lecanii*, through a complex ecological web. Plant Pathol. 58, 636–641. https://doi.org/10.1111/j.1365-3059.2009.02067.x

Vargas, C.D., Willems, M.C., 2017. Línea de base del sector café en el Perú - documento de trabajo. Lima, Perú.

Vargas, P., 2009. El Cambio Climático y Sus Efectos en el Perú.

Vellema, W., Buritica Casanova, A., Gonzalez, C., D'Haese, M., 2015. The effect of specialty coffee certification on household livelihood strategies and specialisation. Food Policy 57, 13–25. https://doi.org/10.1016/j.foodpol.2015.07.003

Victor, A.-S., Gockowski, J., Agyeman, N.F., Dziwornu, A.K., 2010. Economic cost-benefit analysis of certified sustainable cocoa production in Ghana, in: Joint 3rd African Assoociation of Agricultural Economists (AAAE) and 48th Agricultural Economist Association of South Africa (AEASA) Conference.

Vittoz, P., Bayfield, N., Brooker, R., Elston, D.A., Duff, E.I., Theurillat, J.P., Guisan, A., 2010. Reproducibility of species lists, visual cover estimates and frequency methods for recording high-mountain vegetation. J. Veg. Sci. 21, 1035–1047. https://doi.org/10.1111/j.1654-1103.2010.01216.x

Waldron, A., Justicia, R., Smith, L., Sanchez, M., 2012. Conservation through Chocolate: a win-win for biodiversity and farmers in Ecuador's lowland tropics. Conserv. Lett. 5, 213–221. https://doi.org/10.1111/j.1755-263X.2012.00230.x

Walkley, A. & Black, I.A. (1934) an Examination of the Degtjareff Method for Determining Soil Organic Matter, and a Proposed Modification of the Chromic Acid Titration Method. *Soil Science*, 37, 29–38.

Waller, J.M., Bigger, M., Hillocks, R.J., 2007. World coffee production, in: Coffee Pests, Diseases and Their Management. CABI, Egham, Surrey, UK, pp. 17–33. https://doi.org/10.1079/9781845931292.0000

Weber, J.G., 2011. How much more do growers receive for Fair Trade-organic coffee? Food Policy 36, 677–684. https://doi.org/10.1016/j.foodpol.2011.05.007

Wielgoss, A., Tscharntke, T., Rumede, A., Fiala, B., Seidel, H., Shahabuddin, S., Clough, Y., 2013. Interaction complexity matters: disentangling services and disservices of ant communities driving yield in tropical agroecosystems. Proc. R. Soc. B Biol. Sci. 281, 20132144–20132144. https://doi.org/10.1098/rspb.2013.2144

Wintgens, J.N., 2012. Coffee: growing, processing, sustainable production - a guidebook for growers, processors, traders, and researchers, 2nd, revised edition, second. ed. Wiley, Weinheim. https://doi.org/10.1002/9783527619627

Wollni, M., Brümmer, B., 2012. Productive efficiency of specialty and conventional coffee farmers in costa rica: accounting for technological heterogeneity and self-selection. Food Policy 37, 67–76. https://doi.org/10.1016/j.foodpol.2011.11.004

World Bank, 2008. World Development report 2008- Agriculture for development, Overview, Agriculture. Washington, DC.

Wulan, Y.C., Budidarsono, S., Joshi, L., 2008. Economic Analysis of Improved Smallholder Rubber Agroforestry Systems in West Kalimantan, Indonesia - Implications For Rubber Development, in: Sustainable Sloping Lands and Watershed Management Conference. pp. 431–444.

Zanne, A.E., Lopez-Gonzales, G., Coomes, D.A., Llic, J., Jansen, S., Lewis, S.L., Miller, R.B., Swenson, N.G., Wiemann, M.C., Chave, J., 2009. Data from: Towards a worldwide wood economics spectrum. Dryad Digit. Repos. https://doi.org/10.5061/dryad.234

Summary

One of the main challenges of the coming decades is to develop agricultural systems that produce food and income to sustain smallholder livelihoods in the tropics, without further compromising ecosystem functioning and biodiversity conservation. Agroforestry systems have been put forward as a promising approach to deal with the twin challenges of local development and conservation of biodiversity and other ecosystem services. There is ample evidence supporting the ecological importance of agroforestry systems for biodiversity conservation. However, agroforestry systems are still perceived to have lower economic performance compared to intensified conventional systems, which is driving further intensification throughout the tropics. More insight in the relations between crop productivity, biodiversity and smallholder livelihoods is needed to identify systems that can minimise trade-offs between economic and environmental performance or even provide double dividends. The objectives of this thesis were therefore to assess the economic and environmental outcomes of smallholder management systems to identify trade-offs and seek opportunities for double dividends, as well as to identify opportunities and constraints faced by smallholder farmers for the adoption of management strategies. Given the economic and ecological importance of coffee and cocoa worldwide, this thesis focuses on coffee and cocoa smallholder systems. Subsequently, there is a focus on coffee systems, since empirical data from a case study on smallholder coffee systems in San Martín, Peru, was used.

Chapter 2 compared economic performance (i.e., profitability in terms of net revenue and cost-efficiency in terms of benefit cost ratio, BCR) with biodiversity performance (i.e., species richness and abundance) in small-scale shaded and intensified conventional coffee and cocoa plantations. To this regard, a meta-analysis was conducted including 23 studies on coffee and cocoa plantations over a 26 year period. Despite lower yields (-26%), shaded systems had better economic performance with significantly higher average net revenues (+23%) and a trend towards a 24% higher BCR for cocoa and coffee systems intercropped with shade trees. Looking to the separate components of net revenue and BCR, on the one hand the shaded systems had lower average costs (-13%), while on the other hand they received higher average gross benefits per hectare (+17%), which was partly a reflection of the significantly higher average price per kilogram of coffee or cocoa (+17%). Altogether, this chapter provided evidence that shaded coffee and cocoa systems can offer competitive business opportunities for small-scale farmers in comparison to the expanding sun-grown conventional plantations, while also contributing to biodiversity conservation. Additionally, this chapter showed that the traditional indicator 'yield' was an

inaccurate measure of financial performance when studying these diversified systems, and that the more detailed indicators of net revenue or benefit-cost ratio should be used instead.

To better understand the relationships between three important ecosystem services (productivity, biodiversity conservation and carbon storage) in Chapter 3 the relationships between coffee yields, butterfly species richness and above-ground carbon storage were examined, while accounting for soil fertility and yield losses due to pests and diseases. Data were collected on smallholder coffee plantations in the department of San Martín, Peru, along a gradient of shade and input management, by survey (in 162 farms) and by plot measurements (in a subsample of 62 farms). There was a trend that plantations with higher shade levels maintained higher forest butterfly species richness and had significantly higher above-ground carbon stocks compared to plantations with lower levels of shade. Importantly, there was no evidence for a negative relation between coffee yields and shade cover, across a shade range of 0-80%. Further, input use showed no relation with either biodiversity or carbon, yet coffee yields were related to inputs with highest fertilizer use in low yielding sites. Yield loss due to pests and diseases, in particular due to coffee leaf rust, was substantial, but yield losses due to pests and diseases were less pronounced when more inputs were applied. No trade-offs between coffee yields, biodiversity and carbon storage were found. This implies that it is possible to maintain and enhance the provision of multiple ecosystem services without a reduction in coffee yields, yet the importance of managing soil fertility pro-actively, prioritizing pest management, and planting rust-resilient Arabica varieties was stressed. Moreover, it was concluded that when optimizing shade and input management for coffee production, increased carbon storage and/or biodiversity conservation could be pursued simultaneously in coffee plantations.

A comprehensive economic analysis of Arabica coffee farming systems in Chapter 4 compared productivity, costs, net income and benefit-cost ratio (BCR) of 162 small-scale Peruvian coffee plantations under different shade and input management practices along an elevation gradient. Using a cluster analysis, three shade and three input classes (low, medium and high) were defined. With an average net coffee income of 702±961 € ha^{-1} y^{-1}, economic performance was similar across different shade classes. Rather, input was negatively related to economic performance. The High-Input class had significantly lower net income and BCR, mainly due to increased costs of (hired) labour, land, and fertilizer and fungicides; costs which were not fully compensated for by higher coffee yields. The opposite relation was observed for shade, as costs were lower for plantations with higher shade levels. At the same time, these relations were elevation dependent, likely due to differences in biophysical conditions. Coffee yields decreased with elevation, whereas gate coffee price and quality, as well as shade levels, increased with elevation. In line with expectations, benefits derived from other products were important as income from other products contributed 32% on average to total farm income, excluding potential income from timber. These benefits were lowest for plantations with high input levels and low shade levels. If the potential income from timber would be realized, the total yearly income could increase by another third for plantations with high shade levels, thus improving the overall economic performance of shaded plantations. Moreover, the analysis of this chapter provides evidence that for small-scale coffee production, shaded plantations perform equally well or better than unshaded plantations with high input levels, reinforcing the theory that in agroforestry systems good economic performance can coincide with conservation of biodiversity and associated ecosystem services.

The sustainable livelihoods framework was used to assess which livelihood assets of smallholders influence the adoption of shade and input management strategies, and how these choices are affected by risks and shocks, for coffee producers in San Martín, Peru (Chapter 5). On the one hand, higher shade levels were associated with higher levels of human and social capitals, more specifically farmer experience and membership to a farmer organization which is in line with other studies. On the other hand, there was a trend that higher physical and financial capitals were associated with higher input use. This study contributes to the body of literature that suggests that livelihood factors beyond financial assets are important for the adoption of management strategies for smallholder coffee farmers and that risk perception and experience with disturbances remain insufficient to motivate adoption of management strategies. The insights gained support the development of management strategies that enhance resilience and sustainability of smallholder coffee producers in Peru and elsewhere. Extending the livelihood framework can help identify management strategies that are able to reconcile livelihoods assets, so that economic and environmental performance can coincide.

Altogether, this thesis supports the theory that agroforestry systems can offer competitive business opportunities in comparison to the expanding conventionally intensified systems and can reconcile farmer livelihoods and conservation of biodiversity and other ecosystem services.

First of all, no trade-offs were found between coffee yields, forest butterfly species richness and above-ground carbon storage (Chapter 3) and shaded coffee systems supported biodiversity and carbon storage, without evidence for reduced yields. Moreover, the results imply that for this study area, farmers can manage their plantations to maintain biodiversity and carbon, before any trade-offs with coffee yields start materializing. Indeed, there was a trend that plantations with higher levels of shade were related to higher forest butterfly species richness and above-ground carbon sequestration compared to plantations with lower levels of shade, whilst amount of fertilizer and herbicide inputs showed no relation with biodiversity or carbon (Chapter 3). Importantly, there was no empirical evidence for a negative relation between coffee yields and shade across a shade cover range of 0-80% (Chapter 3). Consequently, this thesis supports the growing body of literature that suggest that yields can remain stable under increasing levels of shade, especially when grown in sub-optimal conditions. However, results from the meta-analysis (Chapter 2) showed that coffee and cocoa yields were lower when shade tree density increased (-26%) and in Chapter 4, lower coffee yields were observed at higher shade tree densities obtained from farmer surveys. These different observations suggest that the relation between shade and yield is complex and location specific, as well as can depend on the used method and the indicator chosen. Also, studies often do not take intensity of input management into account, making it difficult to draw generalizable conclusions on the relation between yield and shade.

Secondly, this thesis provides evidence that systems with high shade levels can perform equally well or better compared to plantations with lower shade levels (Chapter 2 and 4) and/or with higher input levels (Chapter 4). There were no differences between net income and BCR for plantations with different shade management practices. Rather, there was a difference in economic performance between plantations with different levels of input as net income and BCR were lower for plantations with higher input practices. Furthermore, average BCR values of 2.6 from the case study (Chapter 4) were in line with the average BCR of 1.9 for shaded coffee systems observed in the meta-analysis (Chapter 2). To some extent, the difference in economic performance was explained by higher costs of intensified systems, both for flexible (inputs and labour) and fixed costs (land and equipment), while economic performance of shaded systems was better as costs were lower for plantations with higher shade levels. Benefits derived from other products greatly contributed to the income of small-scale farmers in Peru. Potential income from timber could further increase income for plantations with high shade levels, yet there are important economic and ecological challenges that need to be overcome. There was no direct relationship between coffee and cocoa productivity, and economic performance expressed as BCR and net revenue. This questions the use of yield as a direct indicator of economic performance of these systems. More comprehensive economic assessments are needed, including more detailed indicators such as net revenue or benefit-cost ratio.

Third, there were no trade-offs between butterfly diversity and above-ground carbon storage with net income for this case study of Peruvian coffee farmers (Chapter 6). The broad spread observed of the relation between biodiversity and carbon on one hand and farmer income on the other, suggests that many options are possible, including plantations that provide double dividends for biodiversity and carbon storage, and for farmer income. In further research, it would be interesting to look into strategies that can optimise these double dividends.

Lastly, the results suggest that improving livelihood assets is important for decision making, and the actionable assets differ for shade and input management; whilst human, social and natural assets may limit or enhance adoption of environmentally-friendly management systems, financial and physical assets may affect adoption of input management strategies (Chapter 5). Moreover, adoption of agroforestry systems providing both economic and environmental benefits will depend on capacity building, and farmer organisations can play a crucial role to that regard.

Importantly, it became clear that the benefits of agroforestry systems are very diverse and location-specific and that there is no blueprint for management systems that will provide double dividends under all circumstances. In order to reconcile economic and ecological goals in coffee and cocoa systems, comprehensive multidisciplinary analyses are needed, including for other regions, to be able to draw generalizable conclusions and deepen our insight in trade-offs between economic and environmental performance. To this regard, future economic performance studies should simultaneously address the effects of shade and input management on multiple economic and environmental performance indicators and take variation in biophysical factors into account. Furthermore, extension services and training of farmers, as well as adequate certification schemes, access to finance and markets, and appropriate legislation are needed to promote the adoption agroforestry systems that provide double dividends for livelihoods and conservation of biodiversity and other ecosystems services.

Samenvatting

Een van de grootste uitdagingen van de komende tientallen jaren is het ontwikkelen van landbouwsystemen die zowel voedsel als inkomen genereren, als basis voor bestaanszekerheid voor kleine boeren in de tropen, zonder dat dit biodiversiteit en andere ecosysteemdiensten verder schade toebrengt. Agroforestry systemen (integratie van bomen in landbouwsystemen) worden aangemerkt als een veelbelovende benadering om lokale ontwikkeling te verenigen met het behoud van biodiversiteit en andere ecosysteemdiensten. Er is uitvoerig bewijs dat het ecologisch belang van agroforestry systemen voor het behoud van biodiversiteit ondersteunt, maar over de economische prestatie van agroforestry is de literatuur niet eenduidig. Er wordt vaak aangenomen dat de economische baten van agroforestry systemen lager uitvallen dan die van intensieve, conventionele systemen; dit leidt wereldwijd tot intensivering van landbouw in de tropen. Meer inzicht in de relaties tussen opbrengst, biodiversiteit en bestaanszekerheid van kleinschalige boeren is nodig om systemen te identificeren die afruilen ("*tradeoffs*") tussen economische en ecologische uitkomsten kunnen minimaliseren of zelfs kunnen leiden tot een dubbel dividend door verschillende doelen met elkaar te verenigen.

Deze thesis had daarom als doelstelling om economische en ecologische uitkomsten van kleinschalige management systemen te evalueren om zodoende *trade-offs* en kansen voor een dubbel dividend te identificeren, evenals kansen en belemmeringen voor kleine boeren voor de adoptie van verschillende beheersstrategieën. Gezien het economische en ecologische belang van koffie en cacao wereldwijd, richt dit proefschrift zich op koffie- en cacaoproductiesystemen van kleinschalige boeren. De nadruk ligt op koffiesystemen, omdat dit proefschift empirische gegevens presenteert van een case study over kleinschalige koffieteelt in San Martín, Peru.

In Hoofdstuk 2 worden de economische uitkomsten (netto inkomsten en baten-kostenratio, BCR) en de baten voor biodiversiteit (soortenrijkdom) van koffie- en cacaosystemen met schaduwbomen vergeleken met systemen met weinig tot geen schaduw. Voor dit doel werd een meta-analyse uitgevoerd, met inbegrip van 23 studies van koffie- en cacaoplantages over een periode van 26 jaar. Ondanks de lagere opbrengst (-26%) hadden de schaduwsystemen betere economische uitkomsten, met significant hogere netto inkomsten (+23%) en een trend dat BCR hoger was (+24%). Dit was deels te verklaren door de afzonderlijke componenten van netto inkomsten en BCR; schaduwsystemen hadden significant lagere kosten (-13%), terwijl de bruto inkomsten gemiddeld hoger uitvielen (+17%). Dit was gedeeltelijk een weerspiegeling van de significant hogere prijs per kilogram koffie of cacao (+17%) die de boeren met schaduwteelt ontvingen. Dit hoofdstuk laat zien dat koffie- en cacaosystemen met schaduw concurrerende economische verdienmodellen opleveren in vergelijking met de in toenemende mate geintensiveerde plantages zonder schaduw, terwijl deze schaduwsystemen ook kansen bieden voor behoud van biodiversteit. Bovendien bleek dat de traditionele indicator 'opbrengst' een onnauwkeurige economische maat is voor deze schaduwsystemen, en dat daarvoor in de plaats de meer gedetailleerde indicatoren zoals netto inkomsten of BCR gebruikt dienen te worden.

Om een beter inzicht te krijgen in de relaties tussen drie belangrijke ecosysteemdiensten (productiviteit, behoud van biodiversiteit en koolstofopslag), richt Hoofdstuk 3 zich op de relaties tussen koffieopbrengst, vlinder soortenrijkdom en (bovengrondse) koolstofopslag, rekening houdend met bodemvruchtbaarheid en verliezen in koffieopbrengst als gevolg van plagen en ziekten. Data van kleinschalige koffiesystemen werden verzameld in San Martín, Peru, door het afnemen van interviews met 162 boeren, aangevuld met veldmetingen voor een subset van 62 koffieplantages. Deze plantages varieerden in schaduwbeheer (dichtheid van schaduwbomen, soortenrijkdom, en hoogte) en input management (gebruik van meststoffen, pesticiden, fungiciden en onkruidbestrijding). Er was een trend dat koffie plantages met meer schaduw een hogere bosvlinder soortenrijkdom hadden, evenals een significant hogere bovengrondse koolstofvoorraad, in vergelijking met plantages met minder schaduw. In tegenstelling tot wat vaak wordt aangenomen, was er geen negatieve relatie tussen koffieopbrengst en de hoeveelheid schaduw op een koffieplantage, voor een beschaduwing van 0-80%. Daarnaast was er geen verband tussen input management en biodiversiteit of koolstofopslag, maar de koffieopbrengst was gerelateerd aan input beheer: kunstmestgebruik was het het meest intensief op koffieplantages met een lagere koffieopbrengst. Opbrengstverliezen als gevolg van plagen en ziekten- in het bijzonder als gevolg van de recente 'koffieroest' epidemie- waren aanzienlijk. Desalniettemin waren opbrengstverliezen als gevolg van plagen en ziekten minder bij een intensiever gebruik van inputs. Er werden geen *trade-offs* gevonden tussen koffieopbrengst, vlinderbiodiversiteit en koolstofopslag. Dit impliceert dat er kansen zijn voor kleinschalige koffiesystemen om diverse ecosysteemdiensten te behouden en verbeteren zonder in te leveren op de koffieopbrengst. Tegelijkertijd dient de nadruk te liggen op het belang van pro-actief management voor bodemvruchtbaarheid, het prioriteren van ziekte- en plaagbestrijding en het planten van koffieroest bestendige *Arabica* varieteiten. Bovendien wordt in dit hoofdstuk geconcludeerd dat bij het optimaliseren van schaduw - en input management voor productiviteit, op de koffieplantages tegelijkertijd een hogere koolstofopslag en/of biodiversiteit behoud nagestreefd kan worden.

Hoofdstuk 4 omvat een uitgebreide economische analyse van *Arabica* koffiesystemen om zodoende de opbrengst, kosten, netto-inkomen en baten-kostenratio (BCR) van 162 kleinschalige Peruaanse koffieplantages te vergelijken voor systemen met verschillend schaduwbeheer en input management, met inachtneming van een gradient in hoogteligging. Met behulp van een clusteranalyse zijn drie schaduw- en drie input niveaus (laag, gemiddeld en hoog) gedefinieerd. Met een gemiddeld netto koffie-inkomen van 702 ± 961 € ha^{-1} y^{-1} waren de economische uitkomsten vergelijkbaar voor de verschillende schaduwklassen. Dit was in tegenstelling tot input management, waar de economische baten lager waren voor plantages met intensiever gebruik van externe inputs. De Hoge-Input plantages leverden significant lagere netto inkomsten en BCR op, als gevolg van hogere kosten van (ingehuurde) arbeidskrachten, landbouwgrond, en kunstmest en fungiciden; kosten die niet volledig gecompenseerd werden door hogere koffieopbrengsten voor Hoge-Input plantages. Voor schaduwbeheer werd het tegenovergestelde waargenomen, omdat de kosten voor plantages met meer schaduw juist lager waren. Tegelijkertijd bleken deze relaties afhankelijk te zijn van de hoogteligging, waarschijnlijk als gevolg van verschillen in biofysische omstandigheden; de koffieopbrengst was lager voor plantages in lager gelegen gebieden, terwijl de prijs en kwaliteit van de koffie toenamen voor hoger gelegen plantages, evenals de beschaduwing. In lijn met de verwachtingen bleken de inkomsten uit andere producten (bijvoorbeeld brandhout en andere voedselgewassen, geen hout) belangrijk, resulterend in een bijdrage van 32% in aanvulling op de totale koffieinkomsten. Deze inkomsten waren het laagst voor plantages met hoge input en lage schaduwniveaus. Het realiseren van de potentiële inkomsten uit hout, kan de totale jaarlijkse inkomsten voor plantages met hoge schaduwniveaus met nog een derde verhogen, wat de totale economische baten van schaduwplantages verder zou kunnen vergroten. De analyse van dit hoofdstuk biedt bewijs dat kleinschalige koffieproductie in beschaduwde plantages in economisch opzicht even goed of beter kan presteren dan in onbeschaduwde plantages met een hoog inputniveau. Dit ondersteunt de theorie dat economische baten en behoud van biodiversiteit en andere ecosysteemdiensten verenigd kunnen worden in agroforestry systemen.

Het 'sustainable livelihoods' raamwerk werd toegepast op koffiesystemen in San Martín, Peru om te analyseren welke middelen van bestaan van kleinschalige boeren hen beïnvloeden bij de adoptie van schaduw- en input management en hoe deze keuzes worden beïnvloed door risico's en plotselinge tegenslagen (Hoofdstuk 5). Aan de ene kant werden systemen met meer schaduw geassocieerd met hogere scores op factoren die betrekking hebben op menselijk kapitaal (ervaring, onderwijs, leeftijd) en sociaal kapitaal (inbedding in sociale netwerken), met name met betrekking tot ervaring met koffieproductie en lidmaatschap van een boerenorganisatie. Aan de andere kant was er een trend dat hogere scores op fysiek kapitaal (zoals kwaliteit van de woning en infrastructuur) en financieel kapitaal (spaargeld, schulden, inkomen) geassocieerd waren met meer intensief input management. Daarmee ondersteunt deze studie de literatuur die suggereert dat niet alleen financiële factoren belangrijk zijn voor de adoptie van management strategieën van kleinschalige boeren, en dat enkel de perceptie van risico's en ervaringen met plotselinge tegenslagen onvoldoende zijn om de adoptie van specifieke management strategieën te verklaren. Deze inzichten kunnen bijdragen aan de ontwikkeling en ondersteuning van adoptie van management strategieën door kleinschalige koffieboeren die hun systemen veerkrachtiger en duurzamer maken, zowel in Peru als elders. Uitbreiding van het sustainable livelihoods raamwerk kan helpen om management strategieën te identificeren die uitkomsten voor verschillende middelen van bestaan kunnen verenigen, zodat ecologische en economische baten gecombineerd kunnen worden.

Samengevat ondersteunt dit proefschrift de theorie dat agroforestry systemen in economisch opzicht kunnen concurreren in vergelijking tot meer conventionele, intensieve systemen, en dat er kansen zijn om bestaanszekerheid van kleinschalige boeren te verenigen met behoud van biodiversiteit en andere ecosysteemdiensten.

Allereerst zijn er geen *trade-offs* gevonden tussen productiviteit, biodiversiteit en koolstofopslag (hoofdstuk 3); beschaduwde koffie systemen kenden een hogere bosvlinder soortenrijkdomen en sginificant hogere bovengrondse koolstofopslag, wat niet ten koste ging van de koffie opbrengst. Echter, er was geen relatie tussen de hoeveelheid gebruikte input (kunstmest en herbiciden) en vlinder soortenrijkdomof bovengrondse koolstofopslag. Deze resultaten impliceren dat kleinschalige boeren schaduw- en input management toe kunnen passen ten behoeve van behoud van biodiversiteit en koolstofopslag, voordat *trade-offs* met koffie-opbrengsten optreden. Belangrijk is dat er geen empirisch bewijs was voor een negatief verband tussen de koffie-opbrengst en de mate van beschaduwing, voor schaduwniveaus van 0-80% (hoofdstuk 3). Daarmee vult dit proefschrift het groeiende aantal studies aan dat suggereert dat de koffie-opbrengsten stabiel kunnen blijven onder toenemende beschaduwing, vooral wanneer koffie in suboptimale omstandigheden geproduceerd wordt. Echter, de resultaten van de meta-analyse (Hoofdstuk 2) lieten zien dat de koffie- en cacao-opbrengsten lager waren wanneer de dichtheid van schaduwbomen toenam (-26%) en in Hoofdstuk 4 werden lagere koffie-opbrengsten waargenomen bij hogere dichtheden van schaduwbomen. Deze verschillende resultaten suggereren dat de relatie tussen beschaduwing en opbrengst complex en locatiespecifiek is, en eveneens kan afhangen van de gebruikte methode en indicator. Daarnaast werd het duidelijk dat input management vaak niet wordt meegenomen in bestaande analyses, waardoor het moeilijk is om generieke conclusies te trekken over de relatie tussen opbrengst en beschaduwing. Deze analyse (hoofdstuk 2, 3 en 4) laat zien dat de opbrengst van kleinschalige koffieproductie in beschaduwde plantages even goed of beter kan zijn dan die van onbeschaduwde plantages met hoge inputniveaus. Dit ondersteunt de theorie dat economische baten en behoud van biodiversiteit en andere ecosysteemdiensten verenigd kunnen worden in agroforestry systemen.

Ten tweede toont dit proefschrift dat in het geval van kleinschalige koffie- en cacaoplantages, systemen met meer schaduw in economisch opzicht even goed of beter kunnen presteren in vergelijking met plantages met minder schaduw/ lagere schaduwniveaus (Hoofdstuk 2 en 4), al dan niet in combinatie met hogere inputniveaus (Hoofdstuk 4). Er waren geen verschillen tussen de netto-inkomsten en BCR voor plantages met verschillend schaduwbeheer. Wel was er sprake van een verschil in economische uitkomsten voor plantages met verschillend input management: netto inkomsten en BCR waren namelijk lager voor plantages met hogere input. Daarbij was de gemiddelde BCR-waarde van 2.6 uit de Peruaanse case study (hoofdstuk 4) in overeenstemming met de gemiddelde BCR van 1.9 uit de meta-analsye voor koffieplantages met meer schaduw (hoofdstuk 2). Tot op zekere hoogte werd het verschil in economische prestatie verklaard door hogere kosten van intensievere systemen, zowel voor flexibele - (input en arbeid) als vaste kosten (landbouwgrond en materiaal), terwijl de schaduwsystemen leidden tot betere economische uitkomsten, met name omdat de kosten lager waren. De inkomsten gegenereerd uit andere producten droegen in grote mate bij aan het inkomen van de kleinschalige koffie boeren in Peru. Inkomsten uit hout kunnen een grote bijdrage kan leveren aan het inkomen van kleinschalige boeren met schaduwplantages, maar er zijn belangrijke economische en ecologische uitdagingen die dan moeten worden geadresseerd om dit potentieel te realiseren. Verder was er geen directe relatie tussen de koffie- en cacao-opbrengst en economische prestatie zoals uitgedrukt in netto inkomsten en BCR. Dat maakt het gebruik van de opbrengst als een directe indicator voor economische prestatie discutabel. Kortom, er zijn uitgebreidere economische analyses nodig, die gebruik maken van meer gedetailleerde indicatoren zoals de netto inkomsten of de verhouding tussen kosten en baten zoals uitgedrukt in de BCR.

Ten derde waren er geen *trade-offs* tussen vlinder soortenrijkdomen bovengrondse koolstofopslag enerzijds, en netto inkomsten anderzijds, voor deze case study van kleinschalige Peruaanse koffieboeren (hoofdstuk 6). De brede spreiding van de relatie tussen ecologische (biodiversiteit en koolstof) en economische indicatoren (inkomsten en BCR), suggereert dat er vele opties mogelijk zijn, waaronder management systemen die potentie hebben om biodiversiteit en koolstofopslag te verenigen met bestaanszekerheid voor kleinschalige boeren. Het verdient aanbeveling om toekomstig onderzoek te richten op management strategieën die de relatie tussen economische en ecologische uitkomsten kunnen optimaliseren.

Ten slotte suggereren de resultaten van dit proefschift dat het verbeteren van factoren gerelateerd aan de middelen van bestaan belangrijk is voor de adoptie van management systemen door kleinschalige boeren en dat er verschillende handelingsperspektieven zijn voor schaduw- en input management; terwijl menselijke, sociale en natuurlijke factoren de adoptie van milieuvriendelijk schaduwbeheer kunnen beïnvloeden, kunnen factoren gekoppeld aan financieel en fysiek kapitaal de adoptie van input strategieën beïnvloeden (hoofdstuk 5). Bovendien zal de adoptie van agroforestry systemen die zowel economische als ecologische voordelen bieden, afhankelijk zijn van capaciteitsversterking, waarbij boerenorganisaties in het bijzonder een belangrijke rol kunnen spelen.

Een essentieel inzicht is dat de voordelen van agroforestry systemen zeer divers en locatiespecifiek zijn, en dat er geen blauwdruk is voor management systemen die onder alle omstandigheden een dubbel dividend zullen opleveren. Om economische en ecologische doelen in koffie- en cacaosystemen te verenigen, zijn uitgebreide multidisciplinaire analyses in verschillende regio's nodig, om meer generieke conclusies te kunnen trekken en ons inzicht te vergroten in de *trade-offs* tussen economische en ecologische uitkomsten. Een belangrijke aanbeveling is daarom, om in toekomstige economische analyses tegelijkertijd de effecten van schaduw- en input management op verschillende economische en ecologische indicatoren mee te nemen, waarbij ook rekening wordt gehouden met verschillen in biofysische factoren.

Resumen

Uno de los principales desafíos de las décadas venideras es el desarrollo de sistemas agrícolas para la producción de alimentos y la generación de ingresos que sostengan los medios de vida de pequeños agricultores en los trópicos, al mismo tiempo sin comprometer el funcionamiento de los ecosistemas y la conservación de biodiversidad. Los sistemas agroforestales han sido resaltados como un acercamiento prometedor para lidiar con el doble desafío de desarrollo local y conservación de biodiversidad y otros servicios ecosistémicos. Existe amplia evidencia que apoya la importancia ecológica de los sistemas agroforestales para la conservación de biodiversidad. Sin embargo, todavía existe la percepción de que los sistemas agroforestales tienen un bajo desempeño económico en comparación con los sistemas convencionales de producción intensiva, lo cual está impulsado a una mayor intensificación a lo largo de los trópicos. Se necesita mayor profundidad en el conocimiento de las relaciones entre la productividad de los cultivos, la biodiversidad y los medios de vida de pequeños agricultores para identificar sistemas productivos que minimicen la disyuntiva (trade-off) entre el desempeño económico y ambiental o que incluso provean doble dividendo. Dado lo anterior, el objetivo de esta tesis fue evaluar los resultados económicos y ambientales de sistemas de manejo a pequeña escala para la identificación de disyuntivas y oportunidades de doble beneficio, así como, identificar oportunidades y limitaciones que enfrentan los pequeños agricultores en la adopción de estrategias de manejo. Debido a la importancia económica y ecológica del café y el cacao a lo largo del mundo, esta tesis se centra en sistemas de café y cacao a pequeña escala. Subsecuentemente, hay un enfoque en los sistemas de café, ya que los datos empíricos aquí empleados provienen de un caso de estudio de un sistema de café a pequeña escala en San Martín, Perú.

El capítulo 2 comparó el desempeño económico (i.e., rentabilidad en términos de ingresos netos y costo-eficiencia en términos de la razón beneficio-costo, BCR) con el desempeño de la biodiversidad (i.e., riqueza y abundancia de especies) en plantaciones a pequeña escala de café y cacao en sistemas con sombra y sistemas intensivos convencionales. En este respecto, se realizó un meta-análisis que incluyó 23 estudios en plantaciones de café y cacao sobre un período de 26 años. A pesar de la baja producción (-26%), los sistemas con sombra mostraron mejor desempeño económico, con un promedio de ingresos netos significativamente más alto (+23%) y una tendencia hacia un 24% más alto de BCR para los sistemas de cacao y café intercalados con árboles para sombra. Observando los componentes separados de ingresos netos y BCR, los sistemas con sombra presentaron, por un lado, menores costos promedio (-13%) y, por otro lado, recibieron mayores beneficios brutos promedio

por hectárea (+17%), lo cual fue parcialmente una reflexión del precio promedio significativamente más alto (+17%) por kilogramo de café o cacao. En su conjunto, este capítulo provee evidencia de que los sistemas de café y cacao con sombra pueden ofrecer oportunidades de negocio competitivas para agricultores a pequeña escala en comparación con los sistemas convencionales de plantaciones expuestas al sol, actualmente en expansión, y simultáneamente contribuir a la conservación de biodiversidad. Adicionalmente, este capítulo muestra que el indicador tradicional de "rendimiento" fue una medida inadecuada para el desempeño financiero cuando se estudian estos sistemas diversificados, y que los indicadores más detallados de ingresos netos o la razón de beneficio-costo deberían ser implementados en su lugar.

Para entender mejor las relaciones entre tres importantes servicios ecosistémicos (productividad, conservación de biodiversidad y almacenamiento de carbono), en el capítulo 3, se examinó las relaciones entre el rendimiento de los sistemas de café, la riqueza de especies de mariposas y el carbono almacenado arriba del suelo, tomando en cuenta la fertilidad del suelo y las pérdidas de rendimiento a causa de pestes y enfermedades. Los datos fueron colectados en plantaciones de café a pequeña escala en el departamento de San Martín, Perú, a lo largo de un gradiente de manejo de sombra e insumos, a través de entrevistas (en 162 fincas) y a través de mediciones en parcelas (en una submuestra de 62 fincas). Plantaciones con mayores niveles de sombra mostraron una tendencia hacia una mayor riqueza de especies de mariposas y una mayor reserva de carbono almacenado arriba del suelo en comparación con plantaciones con menores niveles de sombra. Es importante resaltar que no hubo evidencia de una relación negativa entre el rendimiento de las plantaciones de café y la cobertura de sombra, a lo largo de un rango de sombra de 0-80%. Adicionalmente, el uso de insumos no mostró relación con la biodiversidad ni el carbono, pero el rendimiento del café fue relacionado a los insumos, con un mayor uso de fertilizantes en lugares de bajo rendimiento. La pérdida en el rendimiento como resultado de pestes y enfermedades, particularmente debido a la roya del café, fue substancial, pero menos pronunciada cuando más insumos fueron implementados. No se encontró ninguna disyuntiva entre el rendimiento del café, la biodiversidad y el almacenamiento de carbono. Esto implica que es posible mantener y mejorar la provisión de múltiples servicios ecosistémicos sin una reducción del rendimiento del café, pero se resalta la importancia de manejar proactivamente la fertilidad del suelo, priorizar el manejo de pestes y plantar variedades de Arábica resilientes a la roya. Además, se concluyó que cuando se optimiza el manejo de la sombra e insumos para la producción de café, podría simultáneamente llevarse a cabo el aumento del almacenamiento de carbono y/o la conservación de biodiversidad en las plantaciones de café.

En el capítulo 4, un exhaustivo análisis económico de los sistemas de café Arábica comparó el rendimiento, los costos, los ingresos netos y la razón beneficio-costo (BCR) de 162 plantaciones de café a pequeña escala en Perú, bajo diferentes prácticas de manejo de sombra e insumos a lo largo de una gradiente de elevación. Usando un análisis de conglomerados, se definieron tres categorías de sombra y tres categorías de insumos (bajo, medio y alto). Con un promedio de ingresos netos para el café de 702±961 € ha^{-1} y^{-1}, el desempeño económico fue similar a través de diferentes categorías de sombra. En cambio, los insumos estuvieron negativamente relacionados con el desempeño económico. La categoría de Alto-Insumos presentó ingresos netos y BCR significativamente más bajos, principalmente debido a los incrementos en costos de la mano de obra (contratada), tierra, y fertilizantes y fungicidas; costos que no fueron completamente compensados por mayores rendimientos del café. Una relación opuesta fue observada para la sombra, ya que los costos fueron menores para plantaciones con niveles más altos de sombra. Al mismo tiempo, estas relaciones fueron dependientes de la elevación, probablemente debido a diferencias en las condiciones biofísicas. El rendimiento del café decreció con la elevación, mientras que el precio del café en puerta de finca y la calidad, así como los niveles de sombra, incrementaron con la elevación. En concordancia con lo esperado, los beneficios derivados de otros productos fueron importantes, ya que los ingresos provenientes de otros productos contribuyeron en promedio un 32% al ingreso total de la finca, excluyendo aquí el ingreso potencial de la madera. Estos beneficios fueron menores para las plantaciones con niveles altos de insumos y niveles bajos de sombra. Si se lograra el ingreso potencial de la madera, el ingreso anual total podría incrementar otro tercio para las plantaciones con niveles altos de sombra, mejorando así el desempeño económico general de las plantaciones con sombra. Más aún, el análisis en este capítulo provee evidencia de que para la producción de café a pequeña escala, las plantaciones con sombra se desempeñan igualmente bien o mejor que las plantaciones expuestas al sol con niveles altos de insumos, reforzando la teoría de que en los sistemas agroforestales el buen desempeño económico puede coincidir con la conservación de biodiversidad y los servicios ecosistémicos asociados.

El marco de los medios de vida sostenibles fue usado para evaluar cuales activos de los medios de vida de los pequeños agricultores influyen en la adopción de estrategias de manejo de sombra e insumos, y cómo estas decisiones son afectadas por riesgos y perturbaciones, para los productores de café en San Martín, Perú (Capítulo 5). Por un lado, niveles altos de sombra fueron asociados con niveles altos de capital social y capital humano, más específicamente la experiencia del agricultor y el pertenecer a una organización de agricultores, lo que concuerda con otros estudios. Por otro lado, hubo una tendencia hacia que mayores capitales físicos y financieros fueran asociados con mayor uso de insumos. Este estudio contribuye con el cuerpo de literatura que sugiere que factores de los medios de vida más allá de los activos financieros son importantes para la adopción de estrategias de manejo por los pequeños agricultores y que la percepción de riesgo y la experiencia ante perturbaciones siguen siendo insuficientes para motivar la adopción de estrategias de manejo. Los conocimientos aquí adquiridos respaldan el desarrollo de estrategias de manejo que mejoren la resiliencia y la sostenibilidad de los productores de café a pequeña escala en Perú y en otras partes. Extender el marco de los medios de vida podría ayudar a identificar estrategias de manejo que son capaces de reconciliar los activos de los medios de vida, de tal forma que el desempeño económico y ambiental puedan coincidir.

En su conjunto, esta tesis respalda la teoría de que los sistemas agroforestales pueden ofrecer oportunidades de negocios competitivos, en comparación con los sistemas intensivos convencionales en expansión, y a su vez pueden reconciliar a los medios de vidas de los agricultores con la conservación de biodiversidad y otros servicios ecosistémicos.

Primero, no se encontraron disyuntivas entre el rendimiento del café, la riqueza de especies de mariposas del bosque y el almacenamiento de carbono arriba del suelo (Capítulo 3) y los sistemas de café con sombra sostuvieron a la biodiversidad y el almacenamiento de carbono, sin evidencias de una reducción en el rendimiento. Más aún, los resultados sugieren que, para esta área de estudio, los agricultores pueden manejar sus plantaciones para mantener la biodiversidad y el carbono, antes de que alguna disyuntiva con el rendimiento del café comience a materializarse. En efecto, hubo una tendencia hacia que las plantaciones con mayores niveles de sombra se relacionaran con una mayor riqueza de especies de mariposas y secuestro de carbono arriba del suelo comparado con plantaciones con menores niveles de sombra, mientras que la cantidad de insumos de fertilizantes y herbicidas no mostró relación con la biodiversidad o el carbono (Capítulo 3). Más importante, no hubo evidencia empírica para una relación negativa entre el rendimiento del café y el nivel de sombra a través de un rango de sombra de 0-80% (Capítulo 3). Consecuentemente, esta tesis respalda el creciente cuerpo de literatura que sugiere que el rendimiento puede permanecer estable bajo un incremento de los niveles de sombra, especialmente cuando se cultiva en condiciones sub-óptimas. Sin embargo, resultados del meta-análisis (Capítulo 2) mostraron que el rendimiento del café y el cacao fueron menores cuando la densidad de la sombra de los árboles incrementaba (-26%) y en el Capítulo 4, se observaron menores niveles de rendimiento del café a mayores niveles de densidad de sombra, obtenido de encuestas a los agricultores. Estas diferentes observaciones sugieren que la relación entre la sombra y el rendimiento es compleja y sitio-específica, así mismo puede depender del método empleado y del indicador escogido. Además, a menudo los estudios no toman en cuenta la intensidad del manejo de insumos, haciendo difícil extraer conclusiones generalizables sobre la relación entre rendimiento y sombra.

Segundo, esta tesis provee evidencia de que los sistemas con altos niveles de sombra pueden desempeñarse igualmente bien o mejor en comparación con plantaciones con menores niveles de sombra (Capítulo 2 y 4) y/o con más altos niveles de insumos (Capítulo 4). No hubo diferencias entre ingresos netos y BCR para plantaciones con diferentes prácticas de manejo de sombra. En cambio, hubo una diferencia en el desempeño económico entre plantaciones con diferentes niveles de insumos, ya que el ingreso neto y el BCR fueron menores para las plantaciones con mayores prácticas de insumos. En adición, los valores promedios de BCR de 2.6 del estudio de caso

(Capítulo 4) estuvieron acorde con el BCR promedio de 1.9 para sistemas de café con sombra observados en el meta-análisis (Capítulo 2). Hasta cierto punto, la diferencia en el desempeño económico fue explicado por los mayores costos de los sistemas intensivos, debido tanto a los costos flexibles (insumos y mano de obra) como a los costos fijos (tierra y materiales), mientras el desempeño económico de los sistemas con sombra fue mejor ya que los costos fueron menores para las plantaciones con mayores niveles de sombra. Los beneficios derivados de otros productos contribuyeron grandemente a los ingresos de los agricultores a pequeña escala en Perú. El potencial ingreso proveniente de la madera podría aumentar más aún los ingresos para las plantaciones con altos niveles de sombra, pero todavía hay importantes desafíos económicos y ecológicos que deben superarse. No hubo una relación directa entre el rendimiento del café y el cacao y el desempeño económico expresado como BCR e ingresos netos. Esto cuestiona el uso del rendimiento como un indicador directo del desempeño económico de estos sistemas. Evaluaciones económicas más exhaustivas son necesarias, incluyendo indicadores más detallados tales como el ingreso neto y la razón beneficio-costo.

Tercero, no hubo disyuntivas entre la diversidad de mariposas y el almacenamiento de carbono arriba del suelo con el ingreso neto de los agricultores de café peruanos en el estudio de caso (Capítulo 6). La amplia dispersión observada de la relación entre biodiversidad y carbono, por un lado, y el ingreso de los agricultores, por el otro lado, sugiere que muchas opciones son posibles, incluyendo plantaciones que provean doble beneficios para biodiversidad y almacenamiento de carbono y para el ingreso de los agricultores. En futuras investigaciones, sería interesante buscar estrategias que puedan optimizar estos dobles beneficios.

Por último, los resultados sugieren que el mejoramiento de los activos de los medios de vida es importante para la toma de decisión, y que los activos accionables difieren para el manejo de sombra e insumos; mientras que los activos humanos, sociales, y naturales podrían limitar o mejorar la adopción de sistemas de manejo ambientalmente amigables, los activos financieros y físicos pueden afectar la adopción de estrategias de manejo de insumos (Capítulo 5). Además, la adopción de sistemas agroforestales que provean tanto beneficios económicos como ambientales dependerá de la construcción de capacidades, y que las organizaciones de agricultores pueden jugar un papel crucial en este aspecto.

Principalmente, se hizo claro que los beneficios de los sistemas agroforestales son muy diversos y sitio-específicos, y que no existe un esquema de referencia para sistemas de manejo que proporcionará doble beneficios bajo todas las circunstancias. En función de reconciliar las metas económicas y ecológicas en sistemas de café y cacao, son necesarios análisis multidisciplinarios exhaustivos, incluyendo en otras regiones, para poder extraer conclusiones generalizables y profundizar nuestro entendimiento de las disyuntivas entre el desempeño económico y ambiental. A este respecto, estudios futuros de desempeño económico deberían de simultáneamente dirigirse hacia los efectos del manejo de sombra e insumos sobre múltiples indicadores del desempeño económico y ambiental, y tomando en cuenta la variación de los factores biofísicos. Adicionalmente, son necesarios servicios de extensión, capacitaciones para agricultores, así como esquemas adecuados de certificación, acceso a financiamiento y mercados, y una apropiada legislación, para promover la adopción de sistemas agroforestales que provean doble beneficios para los medios de vida y la biodiversidad y otros servicios ecosistémicos.

Acknowledgements

For as long as I can remember I have been interested in nature (conservation), particularly in the south. I feel thankful for the freedom and opportunity to pursue my dreams and for the experiences I have gained along the way. With regards to this dissertation, I feel particularly grateful towards the people I've met in Peru, as they have given me a peek into their lives and the landscape they live in. Luckily, I have not been through this bumpy PhD adventure alone, and I want to use this opportunity to express my gratitude to the people surrounding me as they provided support and inspiration over the years in many different ways.

I would like to start by thanking my supervisors, Pita, Maria, Martin and René.

Pita, first of all, thank you for giving me the opportunity to start with this PhD in the first place. Although I was not necessarily looking to do a PhD this topic was of immediately interest to me- and still is. Thank you for giving me the freedom, inspiration and motivation to find my own path- bit by bit. I've also very much appreciated your personal approach of supervision.

Maria, you joined the team a bit later, but nonetheless you dove right in and I'm glad you did. Your sharp and critical eye was sometimes confronting, but invaluable to my learning process and the quality of my dissertation. Your personal involvement helped me through the struggle that was the writing process and, most of all, made me feel that this is a team effort and that you have got my back. Thank you for that.

Martin, although the topic of this PhD is not fully your expertise, your outside view provided new and refreshing insights. You helped maintain the overview, provided stability to the process and were always available despite your busy schedule. Thank you.

Rene, where to begin? Without involving you at an early stage in the PhD, I know this book would not have been written. Aside from the practical and financial support you helped provide, you most of all continuously motivated and inspired me. Your persistent faith in my capabilities provided me with the confidence to pull through this oftentimes turbulent PhD. I am very grateful for the opportunity you provided me to come work at Tropenbos International, an environmental in which I'll continue to learn a lot and I'm very much looking forward to continue to work together.

Floor, you gave me guidance and support at crucial moments, often during walks around the Uithof. I always returned with more clarity and renewed energy, thanks!

Willy, Sjoerd and Juan Pablo, I very much appreciated the interaction with Hivos, which provided an important link for me between this academic research and practice. The meetings we had provided inspiration, motivation and helped me direct the research towards societal relevance. Thank you for that.

Yann, thank you for the opportunity to collaborate with you and take a peek at Swedish academic life, at your research group in Lund. You taught me a lot about advanced statistics and the ins-and-outs of R, which helped me greatly with my data analysis. Let's get our paper published quickly!

Steffie, Rutger, Claudia en Vincent; not only did I experience your involvement as master students as very pleasant, I also learned a lot from working with you. Thank you for your contributions, which can be traced back to different sections throughout this book. Vincent, how nice that we later became colleagues and even roommates!

Aisha, you bring the people at our department together. Your door was always open, both for practical and personal matters. Thank you! Siham and Fiona at the secretary's office, thank you for your support. The 9th floor (not anymore) would run a lot less smooth without your work behind the scenes.

Many thanks to my (former) colleagues, Anna, Will, Sara, Anne-Sjoerd, Niels, Gert-Jan, Gijs, Barano, Boudewijn, Ric, Atse, Lotte, Tarek, Marnix, Sierk, Jonathan, Ana, Ody, Meindert, Janske, and many more. I was happy to go through the struggles of a PhD alongside of you and I am glad that I consider many of you as friends. I very much enjoyed the lively atmosphere in the office and the many activities outside of it: dinners, mojito nights, soccer, running, game nights, dancing and much more.

Muchas gracias a Víctor, Benjamín, Gundo, Jorge, Karen, Jesús, Shirley, Julio, July, Lister, Percy y a otros del equipo de Solidaridad en Moyobamba. Sin su contribución práctica y sustancial, hubiera sido imposible recopilar estos datos. Me sentí muy bienvenida en su oficina y, gracias a ustedes, no solo eche un vistazo a la vida agrícola peruana, sino también más allá. Gracias. También me gustaría dar las gracias a Martin y a otros de Aproeco por su franqueza y por la valiosa información que me han ofrecido. Ronald, gracias por su esfuerzo en las encuestas de mariposas y gracias a la gente de Cedisa por su compromiso, que nos ayudó mucho en la fase de puesta en marcha.

Luis, muy rara vez te logras encontrar con personas que te dan la bienvenida con los brazos abiertos como lo hizo usted; siempre me he sentí muy bienvenida y siempre estuviste preparado, no solo para mí, sino también para mis padres y varios estudiantes. Sin tí, y Paula, Adriana y Bruno, el trabajo en Perú no solo hubiera sido más difícil, sino sobre todo, muy aburrido. ¡Sinceramente espero poder ofrecerte la misma recepción en los Países Bajos en cualquier momento!

Jeffrey en Jojanneke, ook jullie maakten Peru een beetje meer thuis, want wat was het fijn om na een lange vlucht bij jullie aan te kunnen bellen in Lima! Mooi om de ervaring van een PhD in Peru zo te kunnen delen met jullie, en ik heb genoten van onze ontdekkingstochten op verschillende plekken in Peru.

Beste Ellen, Henk, Juanita, Henk, Hans, Bas, Maartje, Nian, Lyda, Stanley, Herman, Trudi en Roderick, dankjewel voor jullie geduld en steun over de afgelopen maanden, en Juanita in het bijzonder bedankt voor je bijdrage aan de opmaak. Ik bof met zulke fijne collega's van wie ik ook nog eens ontzettend veel kan leren- ik heb zin in de tijd die voor me ligt bij Tropenbos.

Carina, wat een jaren zijn dit geweest! Het was erg fijn met jou als kamergenoot in onze Unnik jungle kamer; ons eigen groene eilandje op de afdeling, samen turend door de verrekijker over het grasdak en de botanische tuinen. Je warmte, open houding en positiviteit inspireren me. Fijn dat onze avonturen niet zijn opgehouden bij het inleveren van de sleutel van kamer 927, en ik ben erg blij dat je naast me staat als paranimf!

Hercules Dames 2, ik heb het afgelopen jaar bij lange na niet genoeg mee kunnen doen, mede door de tijd die ik aan dit proefschrift heb gespendeerd. Desalniettemin was voetbal een echte sportieve en sociale uitlaatklep in de afgelopen jaren: vol hoofd heen, leeg hoofd terug, en gezelligheid voorop. Wat een top team, met als hoogtepunt ons kampioenschap!

Lieve Els, Esmee en Charlotte, voetbal-chickies. Sporten, wandelen, spelletjes, dansen, kamperen; het was er allemaal en het was erg gezellig! De afgelopen maanden heb ik het virus-verslaan wat rustiger aan moeten doen, maar ik ben er weer klaar voor!

Lisette, lieve buuf. Je bracht veel rust en steun en de nodige afleiding in de afgelopen jaren- zo om de hoek! Avondjes op de bank met een kop thee, met een wijntje op het balkon of een avondwandelingetje door het park, het kon allemaal. We hebben elkaar veel te weinig gezien de afgelopen maanden, maar daar komt hopelijk nu weer verandering!

Lieve Maaike, in best wat opzichten zijn we tegenpolen van elkaar en daarom ben je vaak een bron van inspiratie voor me en heb ik in de afgelopen jaren veel van je geleerd, dankjewel daarvoor. Bovenal ben blij dat we nu allebei in Utrecht wonen en vind het fijn dat we nog meer naar elkaar toe zijn gegroeid!

De lieve biologie meisjes, lieve An, Katrui, Inge en Franca, wat fijn is het om er met net zulke natuur freaks erop uit te trekken! En niet alleen dat, maar ook qua sporten en op de dansvloer weten we elkaar te vinden, met mud-races, voetbal, hardlopen, wandelen, kamperen, UBV feesten en nu andere dansavonden! Lieve An, wat fijn dat we samen vanuit Delft naar Utrecht zijn gegaan- wat een goede beslissing is dat geweest. Helaas wonen we nu bij elkaar om de hoek, maar als we elkaar zien is het altijd goed! Ik kijk uit naar alle feestjes samen- waar dan ook ter wereld.

Leonie, mijn lieve twerkende bioloog, wat een mooie herinneringen hebben we samen; festivals, kampeer tripjes, wandelweekenden en dansavonden, en natuurlijk ons avontuur in Panama- inclusief boombiggen, eckies en awacatés! Ik heb het geluk veel momenten tijdens mijn gehele biologen avontuur met je te kunnen delen, en ik ben erg blij dat je ook vandaag als paranimf naast me staat.

Lieve Sanne, Froukje, Renske en Lisa, voetbal Meisjes, mijn Brummeltjes. Wat een geluk dat ik jullie al zo lang in mijn leven heb. Ik vind het bijzonder hoe we allemaal door de jaren heen onze eigen weg hebben gevonden, zonder elkaar uit het oog te verliezen. Sterker nog, ik heb van dichtbij mogen meemaken hoe drie van jullie moeder zijn geworden- hoe mooi is dat! Ook de afgelopen jaren heb ik bij jullie veel ontspanning, afleiding en vrolijkheid gevonden, en ik weet zeker dat hier nog veel van zal volgen!

Lieve broers Bram en Paul, en Sam en Myrna; onze levens zijn heel verschillend en we zien elkaar niet heel vaak, maar de momenten die we samen zijn koester ik en jullie vormen een stabiele basis. Lieve Jess en Liv, vrolijke dames. Hopelijk nu ook eindelijk meer tijd voor jullie, want wat groeien jullie hard en wat wil ik daar graag meer van zien!

Liefste Pap en Mam, ik sta hier omdat jullie me het meest waardevolle hebben gegeven wat ik me maar kon wensen: onvoorwaardelijke steun en liefde, en de vrijheid om mijn eigen weg te gaan; het heeft me gebracht waar ik nu ben en daarvoor kan ik jullie niet genoeg bedanken. Ik ben blij dat we Peru samen hebben kunnen ervaren en heb bijzondere herinneringen onze vakantie.

Liefste Joeri, jij bent zonder twijfel het allerbeste en allerleukste wat ik aan mijn PhD heb overgehouden. Jouw bijdrage is de meest diverse geweest van allemaal. Jouw heldere kijk, geduld en vertrouwen hebben me ontelbare keren vooruit geholpen als ik weer eens vastzat. Daarnaast maakte je ons huis tot een warm thuis met volop steun en liefde. Maar bovenal was het gewoon een heel stuk leuker met jou! Ik heb ongelooflijk veel zin in alle tijd die voor ons ligt!

About the author

Rosalien Jezeer was born on June 26th, 1986 in Arnhem, the Netherlands. She conducted her Bachelor Biology at Utrecht University (2007-2010), followed by a research master in Environmental Biology (2010-2012) also in Utrecht. She followed the track 'ecology and natural resources management' focusing on the tropics. Her first research internship concerned leaf litter decomposition in tropical secondary forests, which included six months of field work in Panama. Her second research internship was conducted externally at Tropenbos and was about the influence of financial mechanisms on the success of timber plantation development. This study included three months of data collection in Ghana, both by fieldwork measurement in tree plantations, as well as by conducting semi-structured questionnaires. With this second internship, her interest in reconciling livelihoods, agriculture and forests conservation was further fueled. This made the decision to take the junior position in 2013 on the Business for Biodiversity project in collaboration with Hivos an easy one. This 2.5 year project yielded a report and workshops, organized both in the Netherlands and in the research area, and was later on turned into this PhD research at Utrecht University. Since 2017, she is working at Tropenbos International as programme coordinator. Here, she continues to work on issues related to sustainable land use in the tropics, for the benefit of local people and the global community.

Publications

Jezeer, R., Verweij, P., 2015. Shade-grown coffee: Double dividend for biodiversity and small scale farmers in Peru. Hivos, The Hague, the Netherlands

Jezeer, R., Verweij, P.A., 2015. Café en sistemas agroforestales: Doble dividendo para la biodiversidad y los pequeños agricultores en Perú. Hivos, the Hague, the Netherlands

Jezeer, R.E., Santos, M.J.., Boot, R.G.A., Junginger, M., Verweij, P.A., 2018. Effects of shade and input management on economic performance of small-scale Peruvian coffee systems. Agricultural Systems. 162, 179–190. https://doi.org/10.1016/j.agsy.2018.01.014

Jezeer, R.E., Verweij, P.A., Santos, M.J., Boot, R.G.A., 2017. Shaded coffee and cocoa – double dividend for biodiversity and small-scale farmers. Ecological Economics. 140, 136–145. https://doi.org/10.1016/j.ecolecon.2017.04.019