The potential of shade trees to improve microclimate in coffee production systems and contribute to the protection of coffee yield and quality in a changing climate

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The potential of shade trees to improve microclimate in coffee production systems and contribute to the protection of coffee yield and quality in a changing climate

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General Abstract

Climate change is a major challenge to which global coffee production must adapt. With *Coffea arabica* being especially sensitive to rising temperatures, shade trees present a promising adaptation strategy, as there is some evidence that they can modify microclimate. Employing an interdisciplinary approach, combining biophysical and sociological research, this study investigated the effect of shade on coffee production on the southern slope of Mt. Kilimanjaro with the aim of finding suitable strategies to optimise coffee production systems and ensure optimal yield and quality, thus assuring farmers' livelihoods into the future, in the face of climate change. Precipitation records from coffee plantations were analysed for changes in weather patterns in the last two decades. The influence of shade on microclimate, leaf temperature, coffee yield and physical quality aspects was assessed in coffee plantations and smallholder systems. Additionally, focus group discussions and interviews with small-scale farmers were conducted to explore farmers' knowledge on the impacts of weather extremes on coffee production and the ecosystem services different tree species provide. This research shows that climate change at Mt. Kilimanjaro manifests as droughts and shorter wet seasons with less frequent but heavier rainfall events, challenges to which coffee farmers will have to adapt. Shade trees show potential in adaptation of coffee production systems to climate change, as they reduce maximum air temperatures and can reduce leaf temperature extremes during hot periods, without having negative effects on nocturnal temperatures, which are beneficial for coffee production. In coffee plantations, no effect of shade on yields was observed while a slight reduction was observed for smallholder systems. Coffee quality benefits from shade, as different shade components are associated with an increase in bean size and weight. Farmers identified *Albizia schimperiana* as an important tree species, providing regulatory ecosystem services to improve coffee production. Recommendations need to take farmers' priorities into account, including their willingness to trade some reduction in coffee production for other services, such as food, fodder or firewood, which were identified as the most important ecosystem services for farmers at Mt. Kilimanjaro.

CORRIGENDUM

The potential of shade trees to improve microclimate in coffee production systems and contribute to the protection of coffee yield and quality in a changing climate. PhD Thesis 2020, Sigrun Klara Wagner.

The author identified an error in the calculations of tree density. This affects the numerical results reported in Chapters 3, 4 and 5; significant tests, correlations, and conclusions, however, are not affected, as the tree density was multiplied by a constant (9.87). This error will be corrected in the publications of these Chapters, currently in process.

Below is the corrected Table 3.1. Table 5.1 has the same values for trees per ha.

***Table 3.1**: Summary of mean shade components (±SD) for different production systems*

	Shade Density in %*	Number of gaps in 1000*	Canopy cover in %	Distance to closest tree in m*	Trees per ha*	Mean tree dbh in cm*
Coffee plantations	36 ± 26	6.9 ± 6.1	42 ± 36	9.5 ± 6.2	33 ± 24	62.8 ± 21.1
Homegardens	72 ± 15	2.1 ± 1.7	46 ± 33	6.5 ± 3.9	112 ± 97	41.0 ± 17.8
	t_{86} = 8.66	t_{64} = 5.44	t_{88} = 0.53	t_{90} = 2.86	t_{43} = 5.04	t_{90} = 5.43

* significant differences (p-value < 0.01) between coffee plantations (n = 54) and homegardens (n = 40)

Due to this error, the effect of tree density on microclimate was slightly underestimated. For homegardens, a 10 tree per hectare increase rather than 100 trees per ha is expected to increase the minimum temperature by 0.01°C (Appendix B, page 71). Similarly, for coffee plantations, an increase in 10 trees per ha is expected to reduce the mean temperature, maximum temperature, and the temperature range by 0.04°C, 0.20°C, and 0.20°C respectively. The minimum humidity in coffee plantations is also expected to be increased by 0.48 % (Appendix A, page 70).

Below is the corrected Table 4.1. In Chapter 5, the scale for tree density in Figure 5.8 b) and Figure 5.10 needs to be divided by 9.87; the correlations presented, however, are correct.

***Table 4.2**: Summary of the characteristics of the different coffee fields.*

	Elevation in m asl	Tree density per ha	Mean tree dbh in cm	Shade density in %	Shade density range in %
Field 1	1123 ± 5 [a]	78 ± 17 [a]	39.6 ± 3.6 [a]	41 ± 22 [a]	7 - 76
Field 2	1239 ± 5 [b]	12 ± 4 [b]	54.4 ± 12.9 [b]	35 ± 31 [a]	0 - 87
Field 3	1299 ± 7 [c]	25 ± 4 [c]	65.9 ± 10.0 [c]	42 ± 25 [a]	1 - 86
	F_{117} = 10472, $p < 0.001$	F_{117} = 449.1, $p < 0.001$	F_{117} = 74.5, $p < 0.001$	F_{117} = 0.98, $p = 0.380$	

* significant differences (p-value < 0.01) between coffee fields are marked with different letters.

Author's declaration

I hereby declare that this work has been done by myself and no portion of the work contained in this thesis has been submitted in support of any application for any other degree or qualification in this or any other university or institution of learning.

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This thesis is dedicated to my parents, Alfons and Hildegard Wagner, without whom I would never have reached where I am today and whom I cannot thank enough for their continuous support.

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Chapter 1: General introduction

1.1. *Coffea arabica*

1.1.1. Economic importance

Coffee is a popular beverage worldwide and global consumption is constantly rising (Figure 1.1). Growth in demand for coffee is around 2% annually, reaching about 4.3% in the coffee year 2018/19 (ICO 2020a). Mainly produced by developing countries, coffee often significantly contributes to the countries' GDP, directly and/or indirectly supporting the livelihood of millions of people. According to estimates, around 80% of global coffee output is produced by 25 million smallholder farmers (Fairtrade 2020).

In Tanzania, approximately 450,000 smallholder families produce 90% of the country's coffee and export earnings generate 100 million USD per year (TCB 2012; USDA 2020). In 2011, the Tanzanian government announced plans to double the country's coffee production by 2021 as well as increase the quality (TCB 2012). As Figure 1.1 shows, they are still far from this goal and reports state, that quality remains low (USDA 2020). While the southern regions managed to increase production, the northern highlands, including Mt. Kilimanjaro are seeing a severe production dip (TCB 2012).

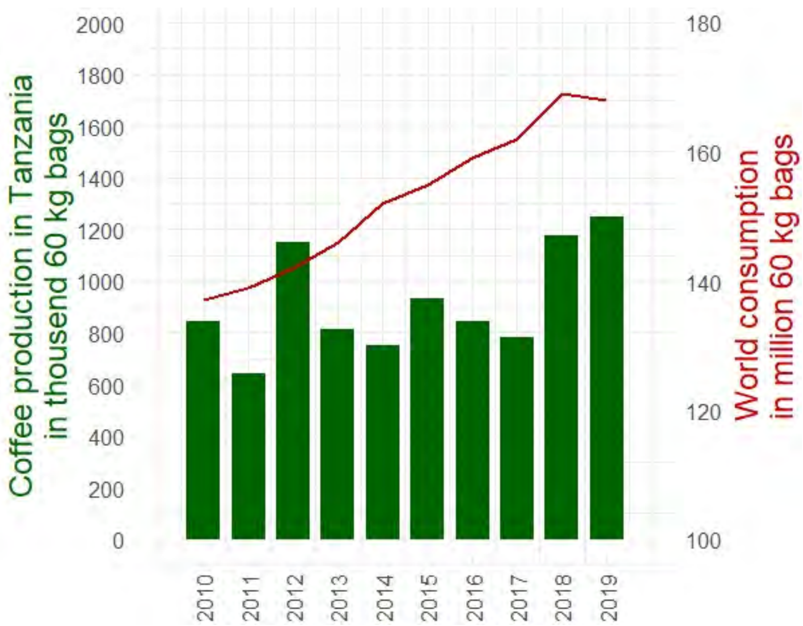

***Figure 1.1**: Bars show coffee production in Tanzania in the last 10 years. The red line illustrates the increase in global coffee consumption (ICO 2020b, 2020c).*

1.1.2. Biological background

The coffee plant is part of the *Rubiaceae* family, the two commonly grown species are *Coffea arabica* and *Coffea canephora* var. Robusta (DaMatta 2004; Dharani 2011). *Coffea arabica* currently accounts for 57% of global production (ICO 2020a). Tanzania produces both, Robusta and Arabica coffee (TCB 2012). *Coffea arabica* is mainly cultivated in the northern highland region (including Mt. Kilimanjaro, Mt. Meru, and Ngorongoro Crater highlands) and in the southern highland regions (Mbinga and Mbeya) (TCB 2012; Craparo et al. 2015).

Coffea arabica is an evergreen shrub with white flowers located in clusters, which develop into red berries containing the coffee bean (Figure 1.2) (Dharani 2011). Flowering is triggered by rains after a dry period (Crisosto et al. 1992; Siles et al. 2010; Jassogne et al. 2013). In Tanzania, this is around October. Depending on the temperature, flower initiation can already start half a year prior (Drinnan and Menzel 1995). Some fruit shedding takes place during the first three months after flowering (Cannell 1985). After the fruit expansion stage, however, the coffee plant is committed to filling all the beans (DaMatta et al. 2007). This is due to the evolution of *Coffea arabica* under shaded conditions, where it originally did not set a lot of fruits and therefore did not develop adequate mechanisms for fruit shedding (DaMatta et al. 2007).

Figure 1.2*: Flower, berries and roasted coffee (Source: author).*

1.1.3. Microclimate requirements

Coffea arabica is a climate sensitive plant with a narrow tolerable temperature range. DaMatta (2004) in a review on coffee ecophysiology, reports that the optimum average annual temperature is between 18°C and 21°C. The optimum daily temperature range is given as 18°C at night and 22°C during the day with extremes of 15°C to 30°C still within tolerable range (Descroix and Snoeck 2004). Other researchers however, report optimal mean night-time temperature as 15°C with negative consequences for yield and quality as temperature increases reduce ripening time (Vaast et al. 2006; Craparo et al. 2020). During the day, temperatures above 24°C for extended periods can negatively impact productivity and temperatures continuously exceeding 30°C can cause depressed and/or abnormal growth, negatively affecting yield and quality (Alègre 1959; Nunes et al. 1968; Descroix and Snoeck 2004; DaMatta and Cochicho Ramalho 2006). Coffee plants can also be adversely affected by low temperatures. Growth can be depressed on mean annual temperatures below 18°C and they can experience severe frost damage if the temperature drops below 4°C (Descroix and Snoeck 2004; DaMatta and Cochicho Ramalho 2006; Vaast et al. 2006; Rigal et al. 2020).

The optimum relative humidity for *Coffea arabica* ranges between 70 and 80% (Alègre 1959). Besides the effect relative humidity can have on transpiration rates and plant growth, the main challenges are potential pests and diseases. Optimal management strategies for improving humidity will depend on the dominant pests and/or diseases present on the field, as different species thrive under different conditions. For example, while the survival time of coffee berry borer (*Hypothenemus hampei*) (Baker et al. 1994) and the incidence of coffee berry moth (*Prophantis smaragdina*) increases with higher humidity (Mendesil and Tesfaye 2009), dispersal of *Hemileia vastatrix* (Coffee leaf rust) uredospores increase on low relative humidity (Waller 1982).

1.2. Climate change and coffee production

Climate change poses a significant challenge for agriculture globally. Considering the microclimate requirements of *Coffea arabica*, rising temperatures will have severe negative implications for coffee yield and quality (Descroix and Snoeck 2004; DaMatta and Cochicho Ramalho 2006; Vaast et al. 2006; Craparo et al. 2015). East Africa will be increasingly affected by climate change in the coming decades, with temperatures already increasing and predicted to rise further (Hemp 2009; Adhikari et al. 2015; Craparo et al. 2015). Mean temperatures in Tanzania's *Coffee arabica* growing regions already increased by 1.42°C between 1960 and 2010 and are predicted to further rise by over 2°C by 2050 (Läderach et al. 2012; Craparo et al. 2015). This will render areas currently under coffee cultivation unsuitable for coffee production, pushing production into higher elevations (Craparo et al. 2015; Magrach and Ghazoul 2015; Bunn et al. 2015). These areas are often forested with high and unique biodiversity, leading to conflicts between agriculture and biodiversity conservation (Magrach & Ghazoul 2015).

Changes in rainfall pattern and intensity causes additional challenges for farmers. Projections for East Africa indicate that annual precipitation will increase (Shongwe et al. 2011; Dai et al. 2018). However, the onset of rains is expected to be delayed more frequently and they are likely to cease earlier, causing droughts (Wainwright et al. 2019). This means farmers very likely will have to adapt to both extremes; heavier rainfall and floods as well as droughts (Hirabayashi et al. 2013; Nicholson 2017; Dunning et al. 2018; Shelleph Limbu and Guirong 2019). Changes in rainfall patterns and intensity would be a huge challenge for the different stages of coffee production. Increased precipitation during flowering can cause flower abortions, increased vegetative growth and an extension of the flowering period, leading to unsynchronised berry ripening (Jassogne et al. 2013; Craparo et al. 2015). Drought and increased temperatures during the expansion stage can cause fruit abortions, increased bean defects, reduced berry growth and acceleration of ripening, leading to a reduction in coffee yield and quality (Cannell 1985; DaMatta et al. 2007; Jassogne et al. 2013; Craparo et al. 2020).

1.3. Coffee agroforestry systems

Suitable adaptation strategies to climate change need to be developed to ensure optimum coffee production into the future. Agroforestry presents an opportunity as a possible mitigation strategy. Agroforestry systems are agricultural production systems, where woody perennials and crops and/or animals are spatially or sequentially grown and/or raised together, with significant ecological and/or economic interactions (Nair 1993). *Coffea arabica* evolved as an understory species in the Ethiopian highlands, is shade tolerant (DaMatta 2004) and therefore well adapted to grow in agroforestry systems. In coffee production systems around the world, shade trees are often abandoned due to potentially higher yields obtainable in mono-culture systems (Albertin and Nair 2004; DaMatta 2004). In recent years, however, the trend is reverting to including shade trees, due to the ecological and economic benefits provided by trees (Albertin and Nair 2004).

1.3.1. Coffee production systems at Mt. Kilimanjaro

The area under coffee production on the slopes of Mt. Kilimanjaro, Tanzania, is located between 1000 m and 1800 m asl and covers an area of nearly 80,000 ha (Hemp 2006; Hemp et al. 2017). There are two main distinguishable coffee production systems, commercial coffee plantations and smallholder farming systems (Figure 1.3). Both of these systems include shade trees. Coffee plantations only have shade trees in addition to their coffee rows (Figure 1.3a). Homegardens are much more diverse systems, including a variety of fruit trees, banana plants and other food crops besides shade trees and coffee plants (Figure 1.3b) (Fernandes et al. 1985). Smallholder farmers, mostly Chagga people, established these homegardens (the so-called Chagga homegardens) centuries ago by converting former forest (Fernandes et al. 1985; Hemp and Hemp 2009).

Figure 1.3*: Characteristic pictures of a) commercial coffee plantations and b) Chagga homegardens at Mt. Kilimanjaro (Source: author).*

1.3.2. Benefits and challenges

There is a wide range of shade tree benefits as well as trade-offs for coffee production reported in the literature.

Some mention the benefit of improved environment condition by mitigating temperature and humidity extremes as well as variability in soil moisture (Beer et al. 1998; Campanha et al. 2004; Lin 2007; Siles et al. 2010; de Souza et al. 2012). Others raise the issue of shade trees increasing nocturnal temperatures, as this could have negative implications for coffee yield and quality (Craparo et al. 2015, 2020). Trees in coffee agroforestry systems can serve as wind breaks, increasing humidity, reducing evapotranspiration and water demand (Beer et al. 1998; DaMatta 2004). The potential benefit or disadvantage depends on the situation as it could also have an effect on pest and diseases (Beer 1987; Staver et al. 2001; Soto-Pinto et al. 2002; Jaramillo et al. 2009; Mariño et al. 2016).

Shaded coffee systems might not attain the same yield potential as unshaded systems, but shade might buffer biannual variation and improve coffee quality (Muschler 2001; DaMatta 2004; Vaast et al. 2006). Lower yields can be observed as flowering intensity is lower under shade trees than under direct sunlight (DaMatta 2004; Vaast et al. 2006; Rigal et al. 2020). As explained above (1.1.2. Biological background), *Coffea arabica* did not develop adequate mechanisms for balancing increased fruit load under full sun exposure with available resources as it evolved in a shaded environment (Cannell 1985; DaMatta 2004). At high intensity, flowering can become an excessive sink for resources, leading to overbearing and energy shortage for vegetative growth, which is important for fruiting in the following year (DaMatta 2004). This can cause stronger biannual yield variations in unshaded coffee (DaMatta 2004). Shade trees can buffer this and reduce the exhaustion of overbearing, branch die-back and excessive leaf shedding, potentially leading to a longer lifespan of coffee plants (DaMatta 2004).

Coffee quality can be enhanced by shade trees as they can reduce heat stress and prolong the maturation period, significantly improving physical as well as sensory coffee quality (Muschler 2001; Vaast et al. 2006). Bigger bean size and increased weight under shade might also be attributable to a lower fruit load reducing competition for carbohydrates and nutrients (Vaast et al. 2006).

Several factors determine whether benefits of shade trees can be maximized or the shortcomings outweigh. Positive effects of shade on coffee yield appear to be strongest under suboptimal conditions (Beer 1987; Muschler 2001; DaMatta 2004). Geographical location, weather conditions, and management of coffee and shade plants all affect coffee yield and quality (Muschler 2001; Avelino et al. 2005; Vaast et al. 2006; DaMatta et al. 2007; Rahn et al. 2018). Shade tree species, shade density and competition among associated species need to be considered (Beer et al. 1998; Schroth et al. 2001; Vaast et al. 2008; Rigal et al. 2020).

Ultimately, it is important that the farmer benefits from the agroforestry system. This might be either through improved coffee productivity and/or quality and/or other ecosystem services provided. Direct ecosystem services provided by the associated shade tree species might include additional products such as food, fodder, or fuelwood (Reed et al. 2017; Wagner et al. 2019). Diverse systems can offer diverse income sources, potentially increasing farmers' economic resilience in the face of coffee price volatility in global markets and possible crop failures (Bacon 2005; Tscharntke et al. 2011; Charles et al. 2013; Reed et al. 2017).

1.4. Knowledge gap

The effects of shade on coffee production is highly dependent on the local environment and the species included in the system. This explains the divergence of observations on the effect of shade on yield reported by various researchers. Some found positive (Vaast et al. 2008; Liu et al. 2018), while others found negative (Campanha et al. 2004; Vaast et al. 2006; Siles et al. 2010) effects of shade on coffee yield and some found no difference between systems (Meylan et al. 2017; Rigal et al. 2020). Thus, locally adapted management strategies are needed, including the selection of shade plant species and shade density.

For valid recommendations for the adaptation of coffee systems to future climate change, the question on what effect shade trees have on important nocturnal temperatures needs to be addressed (Craparo et al. 2015, 2020). If nocturnal temperatures are indeed increased, recommendations of shade tree inclusion need to be made with caution.

Few studies investigated the effects of different aspects of shade simultaneously. The two aspects mainly reported are shade density and/or tree density (Barradas and Fanjul 1986; Caramori et al. 1996; Campanha et al. 2004; Vaast et al. 2006; Lin 2007; Siles et al. 2010; de Souza et al. 2012; López-Bravo et al. 2012; Karungi et al. 2015; Mariño et al. 2016; Sarmiento-Soler et al. 2019). When both aspects were measured, it emerged, that high shade density does not necessarily translate into high tree density. To fully represent the system, it would therefore be important to investigate several shade aspects at the same time.

Most authors further only compare discrete shade levels (Caramori et al. 1996; Lin 2007; Karungi et al. 2015; Sarmiento-Soler et al. 2019) or shaded and unshaded systems (Barradas and Fanjul 1986; Campanha et al. 2004; Vaast et al. 2006; Siles et al. 2010; Bote and Struik 2011; de Souza et al. 2012; López-Bravo et al. 2012) rather than looking at continuous shade gradients. Investigating a range of shade densities, rather than comparing groups, allows us to see influences along the shade gradient and therefore improves our ability to tailor recommendations.

1.5. Thesis aim and chapters

The aim of this thesis is to get insight into the impact of climate change on coffee production systems at Mt. Kilimanjaro, Tanzania and the role of shade within these systems. This is important to find potential strategies to adapt these systems, ensuring optimal coffee yield and quality, and assuring farmers' livelihoods in the face of climate change.

The different aspects of this work are addressed in five data chapters as follows:

In Chapter 2, I identify the extent to which farmers at Mt. Kilimanjaro experienced climate change and the impacts of extreme weather events on coffee production.

In Chapter 3, I analyse the effect of shade components on microclimate variables. The goal was to ascertain the contribution of the different shade aspects to microclimate to identify possibilities for optimised shade management to equip coffee production systems for the future.

In Chapter 4, I address the effect of shade density on coffee leaf temperature, with a view to improving recommendations to optimise coffee production systems and improve plant health.

In Chapter 5, I assess the effects of different aspects of shade on coffee yield and physical quality features to understand the potential benefits and trade-offs of shade for coffee production.

In Chapter 6, I investigate the role of different tree species in the provision of ecosystem services as perceived by farmers to tailor recommendations for important shade tree species to individual farmers' needs.

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Chapter 2: Impact of climate change on coffee production at Mt. Kilimanjaro, Tanzania

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2.1. Abstract

Adapting coffee production to climate change is a significant challenge that requires in depth understanding of the climatic changes taking place and the consequences for coffee production. To this end, we examined changes in precipitation at Mt. Kilimanjaro over the last two decades and conducted twelve focus group discussions to obtain farmers' perceptions on climate change, the impact extreme weather events have on coffee production and the potential of shade trees as an adaptation strategy. Despite an increase in total annual precipitation, farmers are still confronted with droughts, due to a shift in seasons. We found a delayed onset of the main rainy season and showed that a positive Indian Ocean Dipole contributes to the increase in precipitation during the short rainy season. Farmers clearly described the impacts of drought or excess rainfall on coffee production during flowering, maturation and harvest. This means adaptation strategies have to be tailored to the specific coffee development stages to buffer the effects of droughts and shorter wet seasons with less frequent but heavier rainfall events. More research on the potential of shade trees as an adaptation strategy will be required to ascertain the optimum shade density, species and management practices.

Keywords: Climate change, East Africa, *Coffea arabica*, Shade trees, Farmers' perceptions

2.2. Introduction

Globally, climate change poses a serious challenge to crop production with agriculture-dependent countries, like Tanzania, hit especially hard. East Africa will be increasingly affected by climate change in the coming decades, with temperatures already increasing and predicted to rise further (Hemp 2009; Adhikari et al. 2015; Craparo et al. 2015). The effect on rainfall is more difficult to predict (Dai et al. 2018). Warmer air means quicker water evaporation from surfaces, causing dry spells or droughts (Zhao and Dai 2015). However, warmer air can hold more humidity, which can cause heavier rainfall events, leading to flooding (Dunning et al. 2018). Farmers in East Africa will likely have to adapt to both extremes (Hirabayashi et al. 2013; Nicholson 2017; Dunning et al. 2018; Shelleph Limbu and Guirong 2019). Another challenge is the increasing fluctuation and intensity of the El Niño–Southern Oscillation (ENSO), and Indian Ocean Dipole (IOD) due to climate change, leading to a stronger variation of climate patterns and a shift in seasons that farmers will need to adapt to (Shongwe et al. 2011; Cai et al. 2018; Freund et al. 2019).

Coffee is an especially important agricultural commodity for Tanzania. It generates about 100 million USD annually in export earnings and supports the livelihoods of about 2.4 million individuals from mostly smallholder farming households (TCB 2012). While climate change poses a significant threat to coffee production in this region (Craparo et al. 2015), a possible mitigation strategy could be agroforestry, as shade trees might buffer rising temperatures and weather extremes. Agroforestry systems show potential to mitigate temperature and humidity extremes as well as variability in soil moisture (Beer et al. 1998; Lin 2007).

The aims of the study were 1) to identify the extent of climate change and extreme weather events farmers at Mt. Kilimanjaro experienced in the last two decades, 2) to relate changes in weather to ENSO and IOD extremes to determine possible effects on future climate, 3) to better understand the impacts of climate change on coffee production in the region, by surveying farmers' perceptions of climate change and the impacts of extreme weather events on coffee production, and 4) to understand farmers' perceptions of potential climate change mitigating effects of shade trees.

2.3. Material and Methods

2.3.1. Study area

In Tanzania, *Coffea arabica* is cultivated in the northern highland region (including Mt. Kilimanjaro, Mt. Meru, and Tanga / Ngorongoro Crater highlands) and in the southern highland regions (Mbinga and Mbeya) (Craparo et al. 2015). This study focuses on the northern highland region, specifically on the southern slope of Mt. Kilimanjaro where coffee is cultivated in commercial plantations and by smallholder farmers between 1000 and 1800 m asl (Hemp 2006).

2.3.2. Historic climate data

We obtained monthly precipitation records from 2001 to 2019 from three coffee plantations covering twelve coffee growing areas on the southern slope of Mt. Kilimanjaro (Figure 2.1). We examined the total annual rainfall per year for each area to identify any significant increases or decreases in precipitation. We further calculated average annual precipitation and compared this with the overall average precipitation to identify extremely wet and dry years.

We calculated the percentage of months per year with high or low rainfall by considering the areas separately and marking the 25% highest values of all recordings for each area as wet months and the lowest 25% as dry. This approach helps to account for natural variation in rainfall amount between areas. Years were classified as wet if more than 30% of the months of all areas were marked as wet and classified as dry if more than 30% of the months were marked as dry.

We identified a shift in seasons by two different methods. First, we compared the average monthly precipitation within the timeframes 2001-2009 and 2010-2019. Secondly, we looked at correlations between years and precipitation per month for all years.

Figure 2.1*. Location of the study area within Tanzania, locations of the focus group discussions (FGD) and the areas for which we obtained historical climate data. The three coffee plantations are African Plantation Kilimanjaro Ltd. (APK), Kilimanjaro Plantation Ltd. (KPL), and Blue Mountain Coffee Farms Ltd. (Organic).*

2.3.3. Comparison with El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phenomena

Monthly sea-surface temperature anomalies from 2001 to 2019 were obtained from the World Meteorological Organization (WMO). For ENSO the zone NINO3.4 (5°N-5°S; 120-170°W) was used, as it is highly representative, especially for effects on precipitation patterns in East Africa (Bamston et al. 1997; Fer et al. 2017). The dipole mode index (DMI) shows the difference between sea-surface temperature anomalies of the western equatorial Indian Ocean (10°N-10°S; 50-70°E) and the southeastern equatorial Indian Ocean (0°N-10°S; 90-110°E) and indicates the intensity of the IOD (Saji et al. 1999).

We compared the temperature anomalies with the rainfall of the corresponding month, as well as the following six months, to identify the time lag between the sea-surface temperature anomaly and the rainfall event. For NINO3.4, the best connection was observed between the sea-surface temperature anomalies one to two months prior to the reported monthly rainfall and we therefore took the average index of these two months. For DMI the strongest correlation was found between the monthly rainfall and the index of the corresponding and the prior month. We therefore used their average for monthly comparisons. As the IOD is expected to strongly influence the short rainy season (October to December) in East Africa (Shongwe et al. 2011; Otte et al. 2017; Shelleph Limbu and Guirong 2019), we combined the rainfall data of these three months comparing it to the average of the DMI from September to December to confirm if this is also the case for Mt. Kilimanjaro.

2.3.4. Focus group discussion

To get farmers' perceptions on climate change, we conducted twelve focus group discussions (FGDs) in March 2019, with coffee farmers from six communities on the southern slope of Mt. Kilimanjaro (Isuki, Lemira Mroma, Masama Mula, Mudio, Kiwakabo, and Mbokomu) (Figure 2.1). These communities work with the non-governmental organisation Hanns R. Neumann Stiftung (HRNS), who organised the farmers for the FGDs. Each FGD had between four and eight participants, with a total of 56 participants. Each group made a climate calendar marking the rainy and dry seasons in a normal year (Mwongera et al. 2016). For farmers in the region, the year starts with the main rainy season; the calendars therefore start in March and continue to January and February of the following year. The groups then identified when last they experienced an extremely wet and an extremely dry year and marked the rainy and dry seasons for those particular years (Mwongera et al. 2016). During analyses, a month was considered wet or dry if more than half of the FGDs indicated it as such, otherwise we considered the month neither wet nor dry. The farmers were further asked for their perception of how the climate changed in general in the last 10 years.

To learn from farmers' experiences, we discussed if and how extreme events (wet or dry) affected coffee yields and quality in the different production stages. To understand how farmers cope with climate change, we discussed adaptation strategies they employed in the past to overcome extreme weather events. We focused especially on the role of shade trees and asked what influence shade trees have on coffee productivity (yield and quality) and if it affects coffee yield variations between years. We furthermore inquired if shade density or tree type plays a role. The main points mentioned during the FGDs were identified and reoccurring concepts are presented.

2.3.5. Ethical Approval

Ethical approval for this study was obtained from the Faculty Research Ethics and Governance Committees of the Manchester Metropolitan University, Faculty of Science and Engineering, on 26 May 2017, with application code SE1617108C.

2.4. Results

2.4.1. Influence of shade on yield

2.4.1.1. Change in annual precipitation

Observable from data of the past 19 years (2001-2019) is a trend of increasing precipitation at the investigated area at Mt. Kilimanjaro ($r = 0.25$; $p = 0.0004$) (Figure 2.2). There also seems to be an increasing number of wet years and fewer dry years in recent years, including years with high or low total precipitation as well as years with longer rainy seasons or dry spells (Figure2.2).

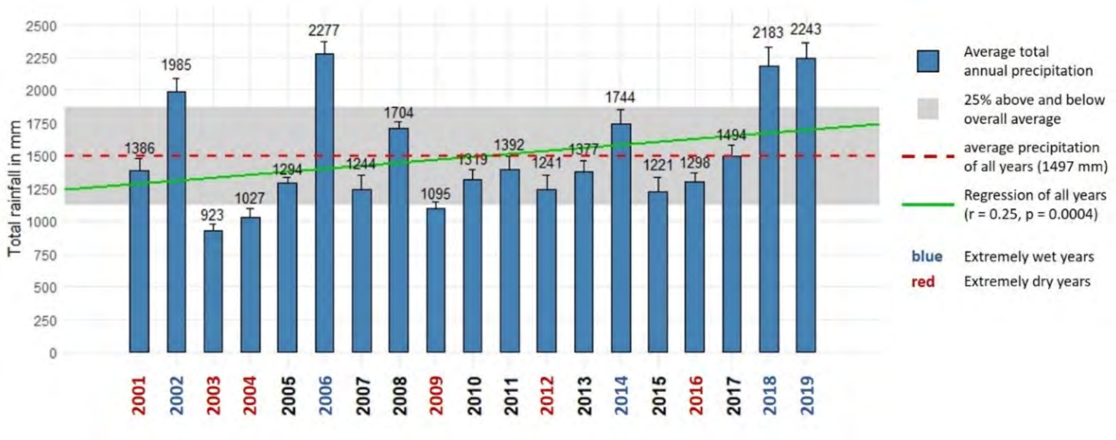

***Figure 2.2**. Average annual precipitation for all reported areas with standard error on the southern slope of Mt. Kilimanjaro. The red line shows the average precipitation for 2001-2019 and the grey bar shows 25% above and below average. The green regression line indicates the increase of precipitation for the entire period. Years with extreme rainfall or drought are marked blue and red respectively.*

2.4.1.2. Seasonal changes in precipitation

Total rainfall as well as monthly rainfall distribution are important for agricultural production. Unfavourable rainfall distribution and erratic or unpredictable rainfall patterns are a significant challenge for farmers. The average monthly precipitation for 2001-2009 and 2010-2019 indicate that the main rainy season shifted from a peak in April to a peak in May (Figure 2.3). This is confirmed by the correlations of years and monthly precipitation from 2001 to 2019. The precipitation in May and June towards the end of the main rainy season increased significantly ($r = 0.35$, $p < 0.0001$; and $r = 0.19$, $p = 0.0076$, respectively) (Figure 2.3). Farmers also experience more rainfall in the short rainy season, which shifts slightly forward. September, the driest month, became wetter in recent years, as did October and November ($r = 0.25$, $p = 0.0004$; $r = 0.25$, $p = 0.0004$; and $r = 0.19$, $p = 0.0071$, respectively) (Figure 2.3).

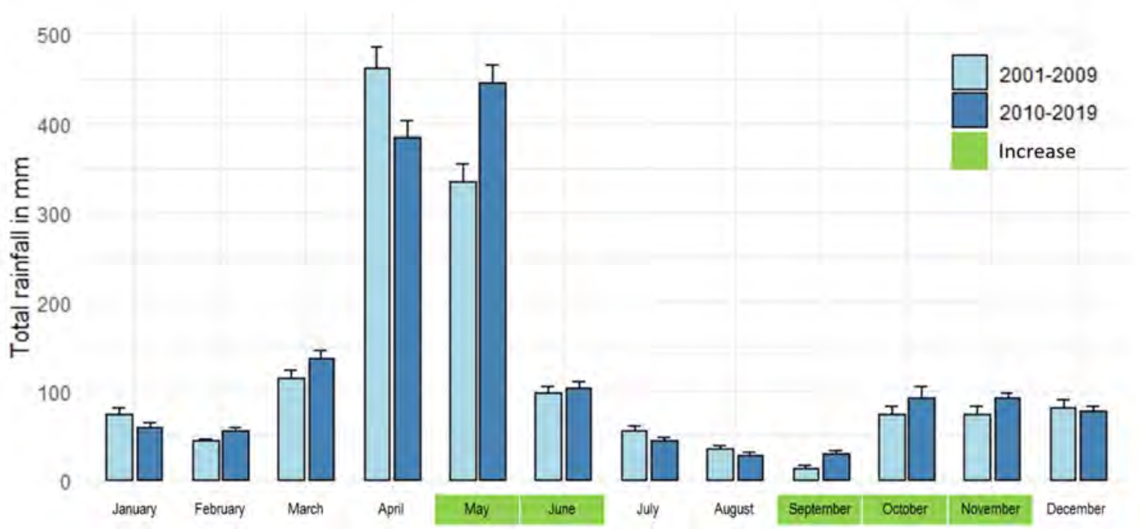

Figure 2.3. *Average monthly precipitation for all reported areas from 2001-2009 (light blue) and 2010-2019 (blue) with standard error. Months marked green show significant precipitation increases in precipitation over the last 19 years (2001-2019) ($p < 0.01$), no significant decrease was observed.*

2.4.1.3. Comparison with ENSO and IOD

Sea-surface temperature anomalies at zone NINO3.4 are significantly negatively associated with rainfall for March at Mt. Kilimanjaro (Figure 2.4a). This is a critical month for coffee production and other agricultural activities in the area, as it marks the start of the rainy season. A La Niña event (cold phase of ENSO) can reduce the rainfall amount in March, delaying the growing season. The IOD strongly influences the short rainy season from October to December (Figure 2.4b). A higher DMI is associated with higher rainfall at Mt. Kilimanjaro during this time. The DMI also influences the rainfall in May (Figure 2.4c).

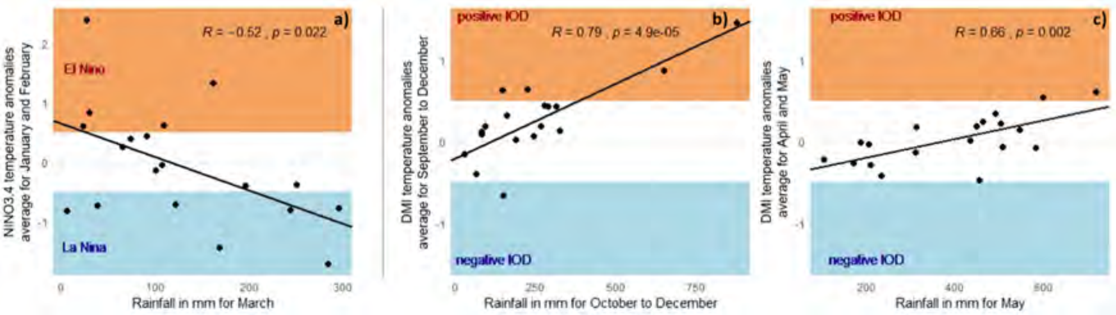

***Figure 2.4**. Correlation between sea-surface temperature anomalies and rainfall data for a) zone NINO3.4 and rainfall in March, b) DMI and rainfall in the short rainy season from October to December, and c) DMI and rainfall in May. The colours indicate when temperature anomalies are classified as La Niña and negative IOD (blue) or El Niño and positive IOD (orange).*

2.4.2. Farmers’ perceptions

2.4.2.1. Climate change

There was a strong agreement among farmers that the most recent extremely wet year was 2018 with nine of the twelve FGDs reporting this. Most farmers identified 2016 as an extremely dry year (six FGDs). The only contradiction observed was for 2017, where one FGD identified it as extremely wet, while two said it was an extremely dry year. Figure 2.5 shows how the distribution of the dry and wet seasons identified by farmers for certain years relates to the rainfall data obtained from the coffee plantations.

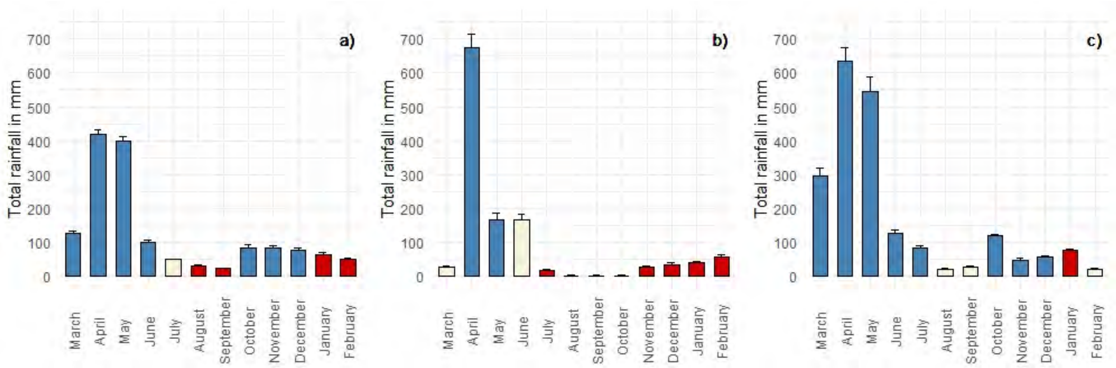

Figure 2.5. *Average precipitation in a) a normal year (average of 2001 to 2019), b) a dry year (March 2016 to February 2017) and c) a wet year (March 2018 to February 2019). The blue bars indicate months farmers consider wet, red bars show which months they consider dry and beige bars are neither wet nor dry.*

In a normal year, coffee farmers at Mt. Kilimanjaro do not experience any extreme dry season. In extremely wet years, the duration of the rainy season as well as rainfall amounts are longer and higher respectively.

Contrary to our observations from coffee plantations' climate data, most FGDs indicated that the last 10 years except 2018 were very dry. The participants mentioned a decrease in water availability with water sources like rivers and springs drying up. Besides decreasing rainfall, they further mentioned experiencing higher temperatures, which could lead to the incidence of new insects. They reported that thrips (*Thysanoptera*) only appeared in the last 10 years, causing problems for coffee and other crops.

Farmers reported more extreme events and increasing unpredictability, especially of the seasons. They mentioned delayed onset of the rains, which for example was the case in 2019. This affects cultivation and causes a lot of insecurity. When the rains do start, they are heavy, damaging plants, causing erosion, floods, and destruction of infrastructure. Farmers further mentioned that weather fluctuations were on the increase. This included some years being too cold with too much rain (2018), others too hot and dry (beginning of 2019). They also reported abrupt temperature fluctuations in short periods (from very cold to very hot, typically within one or two days).

2.4.2.2. Impact on coffee production

The impact of extreme events on coffee production depends on the season (Figure 2.6). It therefore is important to understand the timing of coffee development stages. At Mt. Kilimanjaro, coffee is harvested between June and October, with peaks in August and September. Flowering for the following year's harvest starts in August and September, with the main period being between October and December. Depending on the elevation, flowering can last until March.

The following statements under this section are concepts and/or observations reported by farmers during FGDs.

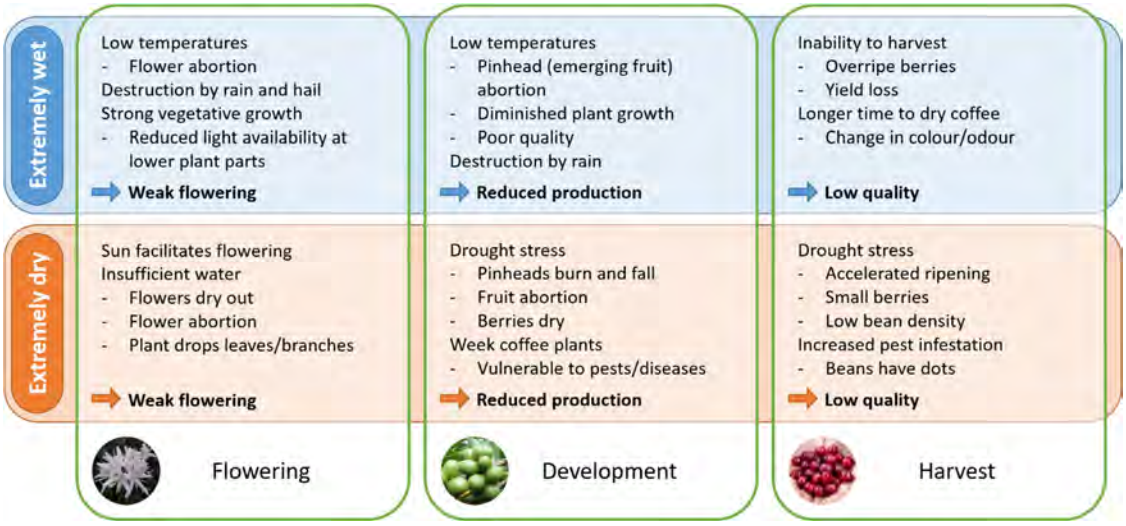

Figure 2.6. *Influence of extreme rainfall and drought on coffee production during the different developmental stages as reported by coffee farmers at Mt. Kilimanjaro during FGDs.*

It is important that coffee plants get sufficient sunlight and water during flowering; otherwise, flowering is negatively impacted (Figure 2.6). Some farmers reported experiencing excessive rainfall during the flowering period in 2018, which reduced the hours of sunshine and caused shade tree overgrowth, leading to excessive shading. They therefore expected low yields in 2019. Pruning shade trees as well as coffee plants can improve light availability during periods of excessive rainfall (Appendix 2.A). During droughts, irrigation is crucial to sustain flowering. A lack of irrigation capacity leads to huge losses. Farmers reported low yields in 2017 and 2018 if they could not irrigate during the flowering period of 2016 and 2017, due to the droughts experienced in these years.

Sufficient sunlight and water are also critical during the development and maturing of coffee berries. Drought and low temperatures hamper development, cause fruit abortion, and significantly reduce production (Figure 2.6). Farmers reported that they experienced a long drought at the beginning of 2019 during berry development, leading to massive fruit abortion and significantly reducing their expected yield.

Losses during the harvest occur, as excess rain may prevent farmers from harvesting on time, or drought accelerates the ripening process, negatively impacting on quality (Figure 2.6). Excessive wetness after harvesting also poses a challenge to farmers as drying the beans takes longer and may cause discolouration and/or bad odours, reducing the quality.

Extreme events increase the incidence of pest and disease infections. Farmers reported an increase in several pests that reproduce rapidly with excessive rains, while beneficial species like chameleons, ants and bees require warmth. Leaf rust and coffee berry disease (CBD) were reportedly a bigger problem when it is cold and wet. Leaf rust or CBD tolerant coffee varieties exist, but unfortunately they are especially susceptible to drought and only about half of the farmers plant these varieties. During droughts, coffee plants in general are more vulnerable, as the plants are easily devastated by attacks from thrips (*Thysanoptera*).

Farmers suggested that other challenges posed by extreme rainfall are soil erosion, flooding and water logging, which can also affect roads, making market access difficult. Farm management is a challenge during periods with extreme rainfall as routine operations like pruning, weeding or pest control cannot be carried out when due, leading to losses. Problems triggered by drought are high production costs, due to irrigation.

2.4.2.3. Influence of shade trees

Farmers at Mt. Kilimanjaro have employed several strategies to cope with extreme weather events in the past (Appendix 2.A). Potential adaptation strategies depend on the weather conditions faced (drought or excessive rains). Shade trees show some potential for managing difficult climatic conditions. On one hand, farmers are aware of many positive effects of shade trees but they also seem to understand the tradeoffs involved, which might make farmers hesitant to include more trees on their farms (Table 2.1). Below are experiences shared by farmers during the FGDs.

***Table 2.1**. Benefits and disadvantages of shade trees reported by coffee farmers at Mt. Kilimanjaro during FGDs.*

Benefits	Disadvantages
Improve climatic conditions (lower maximum temperatures, increased humidity). Protect from direct sun. Reduce evapotranspiration.	Shade trees are negatively affected by drought, reducing shade cover for coffee plants when they most need it.
Maintain soil moisture and fertility. Reduce erosion. Provide mulch and organic matter.	
Support healthy plant growth. Promote production of beans of optimum quality (well ripe, large and heavy). Extend the lifespan of the coffee plant.	Dense shade cover reduces sunlight, negatively affecting coffee productivity.
Contribute to pest control. Provide habitats for beneficial species like bees and chameleons.	Increase in shade density, leads to an increase in pests and diseases.
Serve as windbreaks.	On strong winds, falling tree branches could damage coffee plants and/or berries.
Improve air condition (produce oxygen). Enhance local climate (increased rainfall).	

Very important considerations are the tree species and the shade density. Farmers mentioned some tree species as particularly beneficial for coffee production, especially *Albizia schimperiana* (Appendix 2.B). Optimal shade density leads to good production and high coffee quality (optimum berry size, weight and taste). However, too dense shade provides habitats for pests and prevents sufficient sunlight from reaching the underlying coffee plants. Insufficient sunlight negatively impacts flowering, leading to production losses (some farmers reported losses of up to 90%). Poor shading and direct exposure of the soil to the sun leads to soil moisture losses due to evaporation, also negatively impacting production. Farmers suggested that both excessive and insufficient shade, affects the development of coffee berries, which remain very small and light, with an unpleasant taste.

A reduction in coffee yield variation between years due to shade trees is often reported in the literature (DaMatta 2004; Vaast et al. 2006); however, farmers at Mt. Kilimanjaro mostly attributed variations to weather conditions such as amount and pattern of rainfall. Some farmers mentioned that high production in one year leads to low production the next year as they need to prune the old branches that produced a lot and allow the tree to develop new branches for production the next year. They reported that management practices and inputs influence yields and sometimes can explain the variations. Shade can slightly reduce yield variations as it, to an extent, buffers the effects of drought, improving productivity in dry years; however, most famers did not report this as weather condition is perceived as a more dominant factor influencing yield variations.

2.5. Discussion

2.5.1. Climate change

There is a large regional and local variability in precipitation (Dai et al. 2018; Macleod and Caminade 2019) and changes observed in other parts of Tanzania or East Africa do not necessarily match what farmers at Mt. Kilimanjaro experience. At Mt. Kilimanjaro, there might be localised differences, with some areas experiencing excess rain, while others do not. This can also explain the contradiction observed for 2017, where some farmers reported it as dry, while others experienced it to be a wet year. In general, however, farmers' perceptions were similar between FGDs. There was also a strong consensus with the historical rainfall data as the distribution of the rainy and dry seasons farmers reported for the different years match the rainfall distribution reported by coffee plantations (Figure 2.5).

Previous literature on climate change and phenomena influencing extreme weather events in East Africa corresponds to our observations. The prediction is, that annual precipitation will increase in East Africa (Shongwe et al. 2011; Dai et al. 2018) and we found this to be true over the past two decades (Figure 2.2). In contrast, farmers reported less precipitation and an increase in droughts. Similar perceptions were found in the southern highlands of Tanzania where farmers reported a decline in precipitation, a shorter rainy season, delay in the onset of rains, increased droughts and rising temperatures (Kangalawe 2016). To understand this seemingly contradiction, it is important to look at the seasons and rainfall distribution.

The two rainy seasons at Mt. Kilimanjaro are connected to the movement of the Intertropical Convergence Zone (ITCZ) (Obasi 2005; Shelleph Limbu and Guirong 2019). The long rainy season is between March and May and the short season from October to December (Otte et al. 2017). We observed a shift of the long rainy season (Figure 2.3) and a correlation between the delayed onset in March and the El Niño phenomena (Figure 2.4a). Wainwright et al. (2019) report a shortening of the main rainy season (later onset and an earlier termination of the rainy season), however with a similar total precipitation amount. They attributed it to anomalously warm sea-surface temperatures south of East Africa, delaying the northward movement of the ITCZ (Wainwright et al. 2019). Even though the ENSO events have been linked to some severe droughts and floods in parts of East Africa (Mapande and Reason 2005; Obasi 2005; Macleod and Caminade 2019), the Indian Ocean also significantly influences the regional climate extremes (Obasi 2005; Williams and Funk 2011; Shelleph Limbu and Guirong 2019). Extreme IOD events especially affect the short rainy season from October to December (Shongwe et al. 2011; Otte et al. 2017; Shelleph Limbu and Guirong 2019). We observe a similar connection between interannual variability in precipitation of the short rainy season and the DMI (Figure 2.4b). In the future, with increasing global mean temperature, the frequency of extreme positive IOD is expected to significantly increase (Shongwe et al. 2011; Cai et al. 2018). This can explain the increase in precipitation during the short rains already observed at Mt. Kilimanjaro.

The contradiction between a projected precipitation increase in East Africa and the shortening of the main rainy season over the last decades is described as the "Eastern African climate paradox" (Wainwright et al. 2019). This explains the difference between the increases in drought observed by farmers and the increase in total rainfall shown from the data of the coffee plantations.

The rains in March are especially important for the start of cultivation and a delay negatively influences farmers. This is where successful adaptation measures are critical. Fewer but heavier rainfall events are not beneficial for plant growth and the increase in temperature needs to be considered as well. Higher temperatures accelerate evapotranspiration, which can lead to an increase in droughts (Zhao and Dai 2015). Considering these changes, adaptation strategies have to provide measures to overcome droughts and shorter wet seasons with less frequent, but heavier rainfall events (Dunning et al. 2018).

2.5.2. Effect of extreme events on coffee production

Farmers at Mt. Kilimanjaro have a very good understanding of the impact of extreme weather events on coffee production during the different development stages. Temperature increases, often reported as the driver of reducing yields, makes areas unsuitable for coffee production, pushing it into higher elevations (Magrach and Ghazoul 2015; Craparo et al. 2015; Bunn et al. 2015). Erratic rainfall and unpredictability of the seasons are other challenges farmers have to contend with.

Coffee flowering is triggered by the short rains in October after the dry period (Crisosto et al. 1992; Jassogne et al. 2013). An increase in rainfall during this time as observed (Figure 2.3) and predicted (Shongwe et al. 2011; Cai et al. 2018) will prompt weak flowering, due to cold temperatures and reduced sunlight similar to in shaded conditions (DaMatta 2004; Vaast et al. 2006). Flower abortions, increased vegetative growth and an extension of the flowering period, leading to unsynchronised berry ripening are possible consequences (Jassogne et al. 2013; Craparo et al. 2015). Pruning of coffee plants and shade trees during this time could help to improve light availability and support flowering.

The long rainy season from March to May on the other hand is expected to be delayed and not as substantial as it used to be (Wainwright et al. 2019). This will negatively affect the expansion stage, during which rainfall is required to sustain berry development. Drought and high temperatures during this period will cause fruit abortions, increased bean defects, reduced berry growth and acceleration of ripening, leading to a reduction in coffee yield and quality (Cannell 1985; DaMatta et al. 2007; Jassogne et al. 2013; Craparo et al. 2020). Inclusion of more shade trees might help to reduce heat stress, however, potential trade-offs due to inter-species competition needs to be considered (Beer et al. 1998).

Farmers reported some adaptive measures they already use to overcome extreme events (Appendix 2.A). These can help in finding ways of managing climate change in the future; however, more research into the feasibility and effectiveness of these measures will be required. The unpredictability of rainfall makes it necessary that farmers are aware of unexpected changes, perhaps through early warning systems. Adaptation to both extremes, droughts and floods will be necessary. Special focus should be on soil and water management to ensure better soil moisture retention during dry seasons and to reduce erosion during heavy rainfall events.

While farmers see the general challenges of weather extremes on the spread of pests and disease, their knowledge on it and especially their experience with newly occurring pests is limited. Finding a consensus on the contribution of shade trees to the spread is challenging, as it might also be context specific. A better understanding of pest and diseases that affect coffee production in this area will be required, as rising temperatures facilitate spread of pests and diseases (Descroix and Snoeck 2004; Jaramillo et al. 2011).

2.5.3. Benefits and disadvantages of shade trees

Shade tree benefits and disadvantages reported by farmers are in line with those reported in literature (Beer 1987; Beer et al. 1998; DaMatta 2004). The challenge is finding the right tree species, shade density and management practice to reduce trade-offs for coffee production, while maximizing the benefits provided by shade trees.

Farmers worldwide are very knowledgeable about the tree species on their coffee fields (Gram et al. 2018; Rigal et al. 2018; Wagner et al. 2019). Out of the seven tree species reported as beneficial in the FGDs (Appendix 2.B), five are within the top six ranked for improving coffee production by 263 small-scale farmers at Mt. Kilimanjaro (Wagner et al. 2019). To improve understanding of the influence the different species have on microclimate, soil and coffee production, more investigations are needed.

Previous research shows that shade cover buffers temperature extremes (Campanha et al. 2004; Lin 2007; Siles et al. 2010; de Souza et al. 2012). The different effects on maximum and minimum temperatures and the effect of this on coffee production needs to be considered (Craparo et al. 2015, 2020). The required density for an optimal outcome is still to be determined. This might not only differ between locations, but also during different periods of the coffee development cycle. More research in this regard will help to improve management recommendations, especially considering the challenges of drought or heavy rainfall at different times of the year.

Including a range of diverse tree species that can provide other important ecosystem services on coffee fields could be economically beneficial for farmers (Tscharntke et al.

2011; Charles et al. 2013; Reed et al. 2017; Wagner et al. 2019). Despite the potential trade-offs (yield losses in coffee production), it still might be advisable to include said trees for benefits such as additional income or food security.

2.6. References

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2.7. Appendices

2.7.1. Appendix 2.A

***Table A1**. Coping measures or strategies farmers employed in extreme years in the past*

	Dry years	Wet year
Water management	• Irrigation with channels - agreement with other farms is required (who uses the water and when) - does not work for large farms - the channels are easily damaged and blocked by eroded soil, when there is too much water	• Create a drainage system to avoid waterlogging • Build ridges to prevent water from flowing through the farm or at least reduce the speed to reduce erosion • Water catchments to reduce erosion, which also improves moisture availability during dry season
Soil protection and fertility	• Mulch to reduce evapotranspiration and keep soil moisture • Apply cow dung as it can improve soil moisture storage • Put green leaves around coffee stem, cover it with soil and add water • Some farmers do not plough	• Plant *Cenchrus purpureus* or *Dracaena fragrans* on the edge of their farms or across the slope to reduce erosion • Mulch to reduce erosion and to suppress weeds • Plough to improve infiltration - not done frequently (maybe every 3 years) - not done when the coffee has a lot of fruits • Apply animal dung or NPK around coffee plants and cover it with soil or mulch
Shade trees	• Maintain a high shade density by not pruning shade trees • Planting more shade trees - newly planted trees might not grow properly under dry conditions	• Prune shade trees and reduce banana leaves to allow sunlight to reach coffee plants • Plant more shade trees to reduce soil erosion
Coffee tree management	• Farmers do not prune coffee branches or only very few • Prepare new places with fertilizer to plant coffee trees the next year	• Prune coffee branches to improve aeration and ensure sufficient light reaches every branch • Plant new coffee trees - a lot get damaged by rain - plant in lines to reduce erosion • Plant disease resistant coffee variety, adapted to high moisture and with low input requirement - this variety is not adapted to drought
Leaf application	• Spray booster (fertilizer with water) to apply moisture to the leaves - requires capital	• Spray coffee leaves to generate heat and prevent coffee from freezing - chemicals are expensive - local mixtures (fermented cattle urine or plant material)
Other measures	• Some apply ashes around the coffee stem to prevent ants • Many abandon the coffee farm - use the coffee plants as firewood - focus on food crops	• Weeding to reduce leaf rust • Some apply oil on coffee stem to prevent ants and stem borer • Hire people to harvest berries in a short time • Some abandon the coffee farm

2.7.2. Appendix 2.B

***Table B1**. Beneficial trees for coffee production and their services.*

Beneficial tree	Services
Albizia schimperiana	coffee plants underneath get enough sunlight and produce well - has small leaves, which allow the sun to penetrate - the canopy is very high so sunlight can still reach the coffee - during the coffee flowering, it sheds leaves, which helps to get more sunlight leaves and branches are good fertilizer and can be used as mulch keeps soil moisture for a long time provides habitat for beneficial insects
Croton macrostachyus	the tree canopy is very high, making good shade cover for the coffee plants leaves and branches are good fertilizer and can be used as mulch keeps soil moisture for a long time deep roots provides habitat for beneficial insects
Cordia Africana	good shade cover - covers a big area but is not too dense leaves are good fertilizer provides habitat for beneficial insects
Margaritaria discoidea	the tree canopy is very high, making good shade cover for the coffee tree leaves are good fertilizer keeps soil moisture for a long time
Rauvolfia caffra	leaves are good fertilizer and can be used as mulch provides habitat for beneficial insects not good for coffee trees
Commiphora eminii	leaves are good fertilizer and can be used as mulch
Ficus sur	leaves are good fertilizer

***Table B2**. Non-beneficial trees for coffee production and their disservices.*

Non-beneficial trees	Disservices
Mangifera indica	leaves do not easily decompose consumes a lot of water
Persea Americana	leaves do not easily decompose consumes a lot of water coffee trees or banana underneath this tree will not produce well
Bridelia micrantha	consumes a lot of water coffee trees or banana underneath this tree will not produce well
Grevillea robusta	leaves do not easily decompose, cannot be used as fertilizer or mulch and are not good for the soil consumes a lot of water coffee trees or banana underneath this tree will not produce well

Chapter 3: Understanding shade and its impact on microclimate in optimising coffee agroforestry systems

3.1. Abstract

Agriculture production is under threat from climate change, especially *Coffea arabica,* a rather climate sensitive plant. Maintaining good yields and quality is of economic importance for coffee producing countries, including Tanzania; this requires effective strategies for adaptation to climate change. Increased use of shade trees has potential to mitigate climate change effects on local microclimates. Shade trees can modify local microclimate, but the specifics of how they modify local daily temperatures has not been explored. To improve understanding of the effect of shade on microclimate in coffee production systems at Mt. Kilimanjaro, I surveyed and analysed the different components contributing to shade and monitored microclimate in 94 plots with a gradient of shade densities over two years. This study highlights the importance of analysing different shade components and a shade gradient to more comprehensively understand the ways the systems could be optimised for the future. My results demonstrate that, despite there being differences between coffee plantations and smallholder farms, shade trees can reduce maximum daytime temperatures, without having negative effects on night-time temperatures. Further, even though shade can increase mean and minimum humidity, it seems to buffer humidity extremes, which could be beneficial to reduce water use and infestation of pests and diseases.

Keywords: *Coffea arabica*, East Africa, Shade components, Microclimate

3.2. Introduction

Coffea arabica is especially vulnerable to rising temperatures (DaMatta and Cochicho Ramalho 2006; van Rikxoort et al. 2014; Bunn et al. 2015). In an review on coffee ecophysiology, DaMatta (2004) reports that the optimum average annual temperature for *Coffea arabica* is between 18°C and 21°C. Some researchers report that the optimum daily temperature ranges between 18°C at night and 23°C during the day with extremes of 15°C to 30°C still within tolerable range (Drinnan and Menzel 1995; Descroix and Snoeck 2004). Others emphasise the importance of low night temperatures and found optimal mean nocturnal temperatures of 15°C (Craparo et al. 2020). An increase in nocturnal temperature reduces flower initiation and berry ripening time, which negatively impacts coffee yield and quality (Drinnan and Menzel 1995; Vaast et al. 2006; Craparo et al. 2020). Prolonged temperatures above 24°C can have negative impacts on productivity and continued exposure to temperatures above 30°C leads to depressed and/or abnormal growth, negatively affecting yield and quality (Alègre 1959; Nunes et al. 1968; Descroix and Snoeck 2004; DaMatta and Cochicho Ramalho 2006). Coffee growth is also depressed in regions with mean annual temperature below 18°C (DaMatta and Cochicho Ramalho 2006). Coffee plants are negatively affected when temperatures drop too low and they can experience severe frost damage at temperatures below 4°C (Descroix and Snoeck 2004; DaMatta and Cochicho Ramalho 2006; Rigal et al. 2020).

In Tanzania, mean temperatures in the *Coffee arabica* growing regions have increased by about 1.42°C between 1960 and 2010 and are projected to increase by more than 2°C by 2050 (Läderach et al. 2012; Craparo et al. 2015). Changes in minimum temperatures seem more severe, with current trends indicating an increase of 0.31°C every decade, compared to 0.24°C for maximum temperatures (Craparo et al. 2015). These temperature increases mean that climate change poses a significant threat to coffee production. Farmers will experience increased losses in yield and quality and will be faced with an increasing severity of pest attack and disease spread (Descroix and Snoeck 2004; Jaramillo et al. 2011; Craparo et al. 2015). This will lead to a decline in suitable coffee production area and may push production into new regions (Craparo et al. 2015). These new regions are likely to be forests at higher altitudes with high and unique biodiversity, causing conflicts between agriculture and biodiversity conservation (Magrach & Ghazoul 2015).

Adapting coffee production to climate change will be a vital endeavour in the coming years, especially for Tanzania for which coffee is an important agricultural commodity, generating about 100 million USD in income and supporting about 2.4 million individuals (TCB 2012). Expansion of coffee production into higher elevations at Mt. Kilimanjaro is very unlikely due to the existence of the Kilimanjaro National Park (Fernandes et al. 1985). To guarantee farmers livelihoods, suitable adaptation strategies that ensure currently used fields continue to produce high yields and good quality coffee are required.

Integration of shade trees in coffee production systems is a promising strategy as they have been shown to buffer temperature and humidity extremes (Beer et al. 1998; Campanha et al. 2004; Lin 2007; Siles et al. 2010; de Souza et al. 2012). However, there may be regional differences in their impact as shade seems to be especially beneficial under suboptimal conditions such as at low elevations with high temperatures (Beer 1987; Muschler 2001; DaMatta 2004). Another important consideration is that low temperatures are crucial for coffee production, and shade might increase night time temperatures (Craparo et al. 2015, 2020). More detailed research on the impact of shade on microclimate is therefore necessary to improve our knowledge and enable valid recommendations. Shade composition is a factor to consider, as various tree species and tree densities may provide similar amounts of shade but influence microclimate differently.

In this study at Mt. Kilimanjaro, I surveyed and analysed different components contributing to shade to improve understanding of shade composition in different coffee production systems. The goal was to ascertain the contribution of these different shade variables to different aspects of microclimate to identify possibilities to improve adaptation to climate change through optimised shade management.

3.3. Material and Methods

3.3.1. Study area

This study focuses on the *Coffea arabica* growing area in the northern highland region of Tanzania, specifically the southern slope of Mt. Kilimanjaro within an altitude range of about 1100 to 1500 m asl. In this area, coffee is cultivated in commercial plantations and by smallholder farmers in so-called homegardens.

I investigated 14 homegardens and nine fields of three different coffee plantations (Figure 3.1). In the west of the study area there were homegardens called Narum and fields managed by African Plantation Kilimanjaro Ltd. (APK), which is Rainforest alliance certified; in the East, there was a homegarden area called Mweka, fields conventionally managed by Kilimanjaro Plantation Ltd. (KPL) and fields under organic management (Blue Mountain Coffee Farms Ltd.) (Figure 3.1).

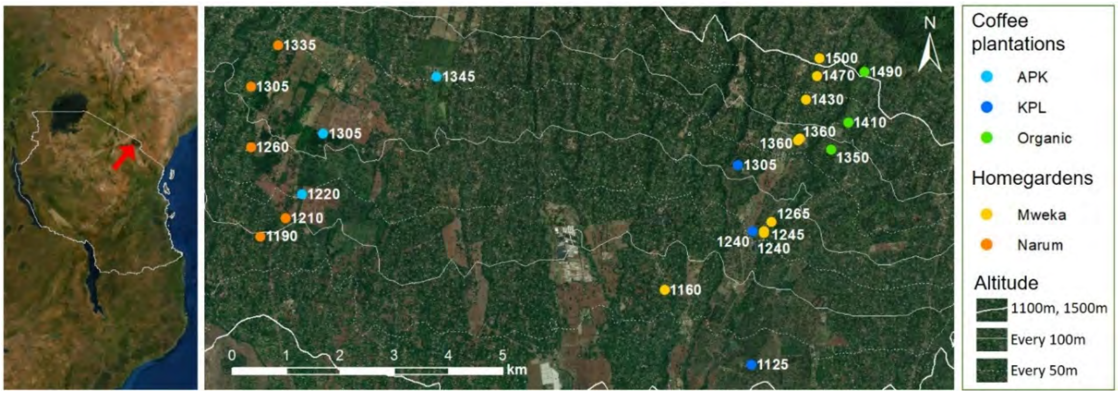

Figure 3.1: *Location of the research sites within Tanzania (red arrow) and distribution of the different production areas and management systems on the southern slope of Mt. Kilimanjaro between 1100 and 1500 m asl.*

In homegardens, the investigations were carried out in one to four plots per homegarden (40 plots in total) and in plantations, six plots per field were investigated (54 plots in total). Each plot measured 10 by 10 m, was flat and plots were at least 20 m apart. The altitude was determined with a GARMIN GPSMAP64 GPS device. I ensured that there was no significant difference in altitude between coffee plantations (1314 m asl) and homegardens (1311 m asl) in order to be able to compare the production systems.

3.3.2. Shade components

The 94 research plots were selected to cover a range of shade densities. To determine shade density, I took pictures of the canopy cover with a fish eye lens (Bosselmann et al. 2009). Nine photos per plot (in a square 2.5 m from the edge of the plot and with a distance of 2.5 m between each picture) were taken between April and August in two years (2018 and 2019). I analysed the photos to obtain the shade percentage and the number of gaps using the plug-in Hemispherical 2.0 in ImageJ (Beckschäfer 2015). The biggest possible circle at the centre of the photos that could be analysed for all photos had a diameter of 72°. I calculated the mean number of gaps and the mean shade density of the nine photos per year for each plot and took the mean of the years to represent the plot. I looked at the shade variability between years by comparing the mean of the two years for the same plot. To improve our understanding of in-plot variability of shade density, I calculated the difference between the photo taken in the centre of the plot and the mean shade density per plot.

In homegardens, the photos include shade provided by banana plants, which are a significant component for these production systems. In a study using the same locations by Wagner et al. (2019) all 263 homegarden owners interviewed had banana plants on their coffee fields. To determine shade provided only by shade trees excluding bananas, I created maps of the plots showing the canopy lines of shade trees overlapping the plots. With these lines, percentage shading of the plot exclusively provided by tree canopy cover was determined by analysing the picture with the plug-in Hemispherical 2.0 in ImageJ (Beckschäfer 2015). In these maps, I also recorded the number of coffee plants per plot, to get the density of coffee plants; this could influence microclimate due to self-shading (Akunda et al. 1979).

I determined the tree density by measuring the distance from the centre of the plot to the five closest trees in November 2018. From the distance of the farthest tree, I calculated the density in m^2 (eq. 1) and converted it to per ha. In addition, I measured the diameter at breast height (dbh) for the five trees and calculated the mean dbh per plot.

$$density = \frac{distance^2 * \pi}{5} \qquad (1)$$

As banana plants contribute significantly to shade density in homegardens, I counted the number of banana plants per plot and measured the dbh in November 2018. Only trees and bananas with a dbh of at least 10 cm were included (Soto-Pinto et al. 2009; Schmitt-Harsh et al. 2012).

Data was visually inspected for normality. I first calculated the means and standard deviations of the different shade components for the two production systems and compared them using a t-test. I then used multivariate and bivariate approaches to visualise and understand the components contributing to shading in the different management systems. I performed a principal component analysis (PCA) using the R package factoextra (Kassambara and Mundt 2020) and I did partial correlations with the R package ppcor (Kim 2015). To see the direct relationships between the different variables contributing to shade density, simple correlations of the shade components were done for coffee plantations and homegardens in R with the package corrplot (Wei et al. 2017).

3.3.3. Microclimate

Microclimate was measured from August 2017 to November 2019 on different coffee bushes using EL-USB-2+ RH Temp data loggers (USB) or Blue Maestro Tempo Disc™ Bluetooth temperature, humidity and dew point sensor beacon and data loggers (Maestro) at 50 cm below the top of the coffee plant. Due to insufficient data loggers, faulty loggers and theft, I could not simultaneously monitor each plot. I therefore had to rotate the available loggers regularly (originally 125 loggers).

I summarized the microclimate data by calculating monthly means of the daily minimum, maximum and mean temperatures, the temperature range (difference between minimum and maximum daily temperature) and the minimum and mean humidity. For all these monthly means, I only included plots that were recorded at least five days per month to ensure the data is representative of the month.

For graphic representation of seasonality, I calculated monthly means for temperature and humidity for all recorded plants combined. To analyse the influence of elevation on temperature and humidity, I calculated field and homegarden means (with at least 10 records) and tested correlations. The magnitude of the influence of elevation was quantified with a linear regression, first accounting for seasonal variation. I tested for differences between data loggers by t-tests.

The factors influencing microclimate (seasonality including year and month, type of data logger, and elevation) need to be accounted for, before the influence of shade can be determined. I therefore performed linear regressions for all microclimate variables to account for these factors and saved the residuals. I then correlated the mean microclimate residuals with the different shade variables using the R package corrplot (Wei et al. 2017). In order to quantify the extent to which shade alters microclimate, I ran linear regressions, first accounting for influencing factors (only including month and elevation for temperature measures and additionally accounting for type of data logger for humidity measures) and then including the shade variable of interest. The regressions were run separately for coffee plantations and homegardens, as the shade components in these systems are significantly different. I calculated the mean and standard deviation for temperature and humidity variables to put the magnitude of the changes due to shade components into context.

Daily temperature and humidity curves for February 2019 (a hot month with low humidity) and the coldest month (July 2018) were created for the plantation field and homegarden with the largest number of different shade records during these months. Only days with at least 20 records were included. I calculated the mean temperature and humidity per hour and plotted the results separately for each shade density, location and month using the R package ggplot2 (Wickham et al. 2016).

3.4. Results

3.4.1. Shade variables in coffee production systems

Canopy cover is the same for coffee plantations and homegardens at Mt. Kilimanjaro, but shade density and number of gaps are significantly different (Table 3.1). Homegardens have a higher mean shade density ranging from 32% to 95%, while the range in coffee plantations is between 0% and 84%. Trees in homegardens are closer together and the tree density is higher, but trees are smaller (Table 3.1).

***Table 3.1**: Summary of mean shade components (±SD) for different production systems*

	Shade Density in %*	Number of gaps in 1000*	Canopy cover in %	Distance to closest tree in m*	Trees per ha*	Mean tree dbh in cm*
Coffee plantations	36 ± 26	6.9 ± 6.1	42 ± 36	9.5 ± 6.2	327 ± 237	62.8 ± 21.1
Homegardens	72 ± 15	2.1 ± 1.7	46 ± 33	6.5 ± 3.9	1108 ± 957	41.0 ± 17.8
	t_{86} = 8.66	t_{64} = 5.44	t_{88} = 0.53	t_{90} = 2.86	t_{43} = 5.04	t_{90} = 5.43

* significant differences (p-value < 0.01) between coffee plantations (n = 54) and homegardens (n = 40)

Homegardens do not grow coffee plants as single crops; they interplant with other crops. The significantly lower coffee planting density compared to coffee plantations (1485 ± 679 and 2519 ± 748 coffee plants per ha respectively; t_{88} = 6.98, $p < 0.001$) was therefore to be expected. Coffee plantations have no banana plants on their fields, while homegardens have an average of 1515 ± 600 banana plants per ha, which ranges between 200 and 2800. The mean banana dbh is 17.6 ± 2.5 cm.

Homegardens are characterised by a higher variability of shade density between years as well as within plots. Plot means varied more than 10% between years for nearly 30% of the coffee plantation plots and for more than 50% of homegarden plots, indicating that shade is highly dynamic in homegardens. Shade density variation in homegardens for the same plot between years was up to a maximum of 43.4%. The in-plot variation determined by the difference of the shade density from the photo taken at the centre of the plot and the mean plot shade density is more than 10% for nearly 40% of homegarden plots; the same is true for less than 2% of coffee plantations plots.

I used a multivariate and a bivariate approach to understand the connection between the different shade components. While the multivariate approach can support the understanding of the connection between the variables and show which are redundant, the bivariate approach is more relevant for farmers in the field, as these are the relationships they can observe.

The principal component analysis visualises the difference of the shade variables between homegardens and coffee plantations (Figure 3.2). Cumulatively, the first two principle components explain 73.1% of the data set's variance (Figure 3.2). Tree density is higher in homegardens and while coffee plantations are dominated by a few big trees, smallholder farmers have additional smaller trees on their farms (Table 3.1, Figure 3.2). Canopy cover does not divide the systems (Figure 3.2).

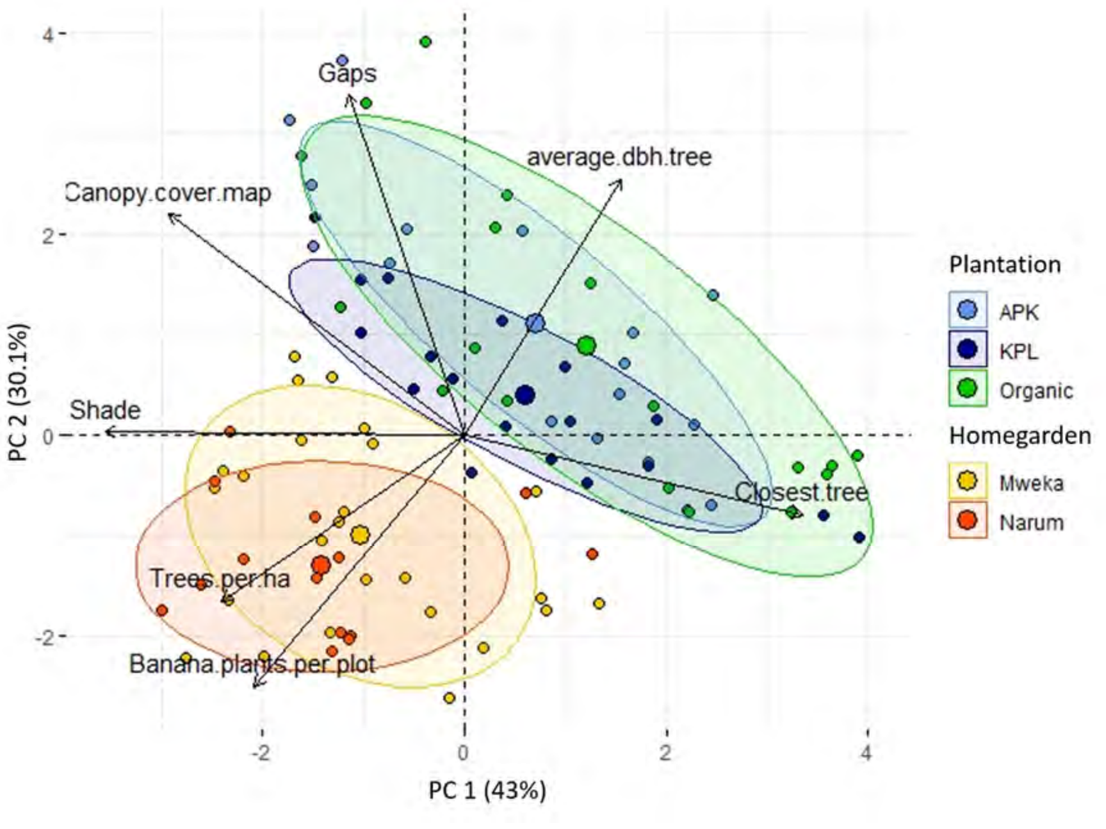

Figure 3.2*: Principal component analysis based on several shade components clearly separates the homegardens in Narum and Mweka from the three coffee plantations. Arrows indicate the factor loadings of the different shade variables.*

The partial correlations, also a multivariate approach, first accounts for the variability in the data set explained by the other shade variables before correlating the two components of interest. This graph shows the clear distinction between coffee plantations and homegardens (Figure 3.3a). A bivariate approach involves simple correlations and here multiple stronger associations can be seen (Figure 3.3b). A comparison of the correlations reveals that the negative relationship between mean tree dbh and tree density is consistent across both production systems but that relationships between canopy cover and other variables differs dramatically between them.

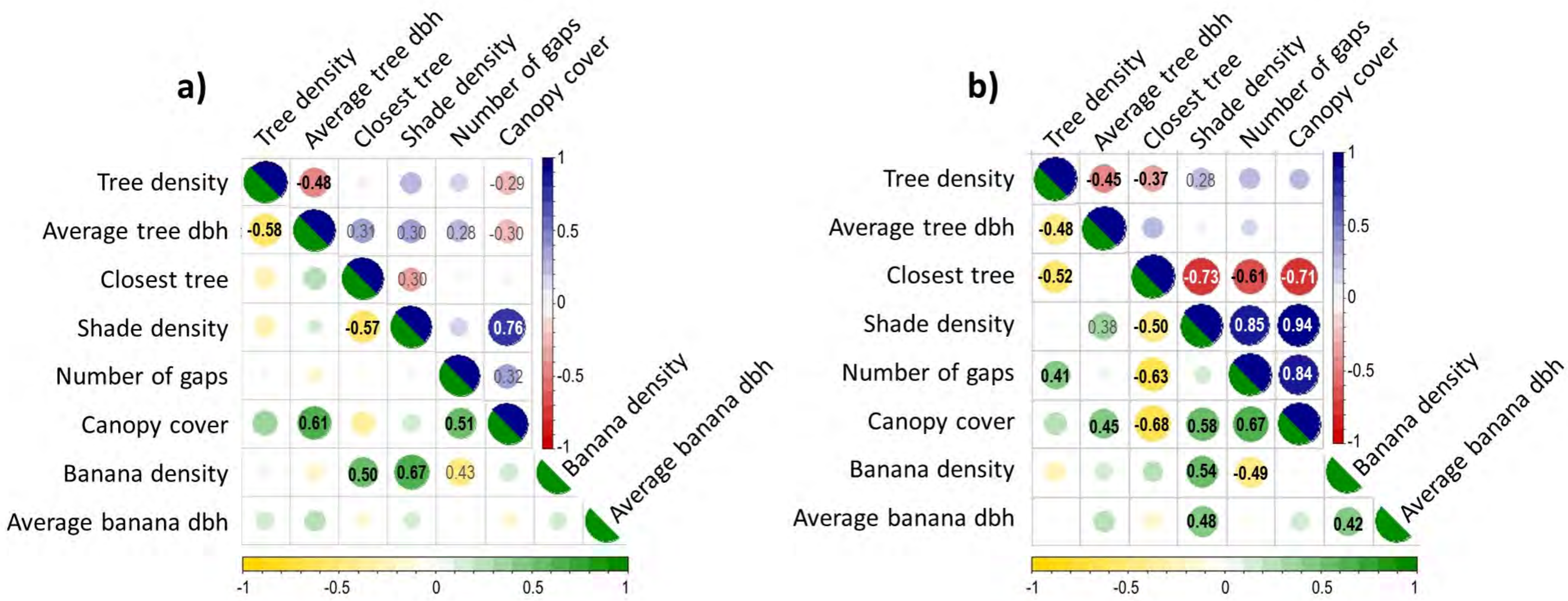

Figure 3.3*: Shows a) the partial correlations and b) simple correlations between different shade parameters for homegardens (yellow to green) and coffee plantations (red to blue). White correlation coefficients (above ± 0.7) indicate a strong correlation, bold correlation coefficients have a significant level of p < 0.01 and grey correlations coefficient of p < 0.05.*

3.4.2. Factors influencing microclimate

The seasonal variations of temperature and humidity at Mt. Kilimanjaro over the investigated period can be seen in Figure 3.4a. The months with the lowest temperatures are June and July; the highest temperatures are experienced between December and March. In the background of the graph is the monthly precipitation from plantation records (Chapter 2). February is the month with the lowest humidity. The highest humidity is connected to the highest rainfall per month, which was in April 2018 and May 2019 (Figure 3.4a).

The different types of data logger were significantly different with regard to mean humidity (t_{734} = 14.19; $p < 0.001$) (Figure 3.4c), but for temperature there was no significant difference (t_{801} = 0.94; p = 0.350) (Figure 3.4e).

The mean temperature over the period of investigation for the different fields is strongly negatively correlated with elevation (r = -0.83, $p < 0.001$, n = 29) (Figure 3.4d). The slope of the regression shows that with an increase of 100 m asl, the mean temperature reduces by 0.72 °C ($F_{1,320}$ = 245.2, $p < 0.001$). Humidity does not seem to be strongly influenced by elevation (r = 0.43, p = 0.065, n = 19, increase of 1.3% each 100 m asl for Maestro; r = 0.74, p = 0.034, n = 8, increase of 1.5% each 100 m asl for USB data logger) (Figure 3.4b).

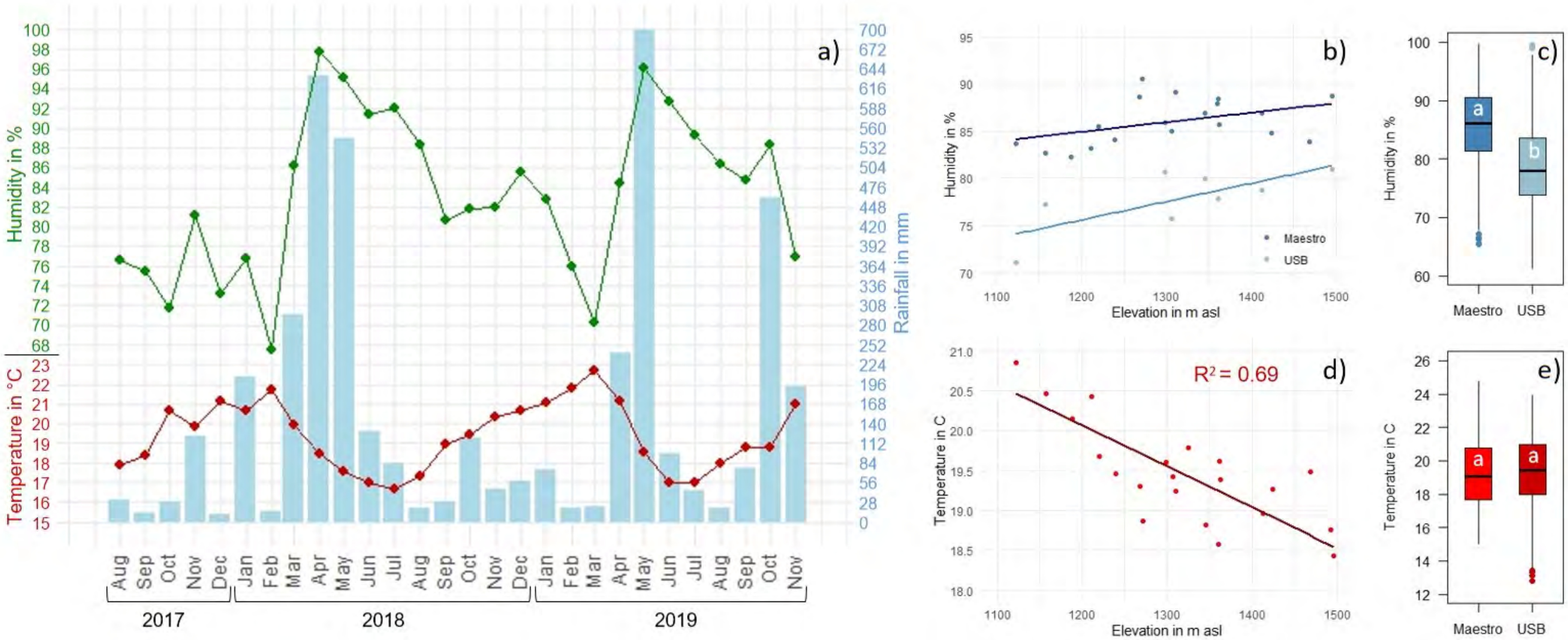

Figure 3.4*: Shows a) monthly rainfall, average monthly humidity and temperature across the study site over the investigated period; the difference between the Maestro data logger and the USB data logger for c) humidity and e) temperature; and the influence of elevation on d) temperature and b) humidity divided into the two different data loggers.*

3.4.3. Influence of shade on microclimate

Several aspects influence microclimate. In order to identify the effect of shading on microclimate, seasonal variations, elevation, and the effect of data logger type need to be controlled for. Associations can be observed between microclimate and shade variables, after accounting for the influencing factors seasonality, elevation and data logger type (Figure 3.5). Difference between homegardens and coffee plantations can be seen (Figure 3.5). Tree density and distance to the closest tree is associated with maximum temperature and does not influence minimum temperature in coffee plantations (Figure 3.5a). In homegardens, tree density is associated with an increase in minimum temperature and banana plants have a stronger connection to maximum temperature (Figure 3.5b). The effect of the tree dbh also differs between the two systems (Figure 3.5). While there are no strong significant associations between shade variables and mean humidity for coffee plantations, canopy cover as well as mean banana dbh increase the mean humidity in homegardens (Figure 3.5). Due to the strong partial correlations between canopy cover and shade density for coffee plantations (Figure 3.3a), it is not surprising, that similar effects on microclimate are observed (Figure 3.5a).

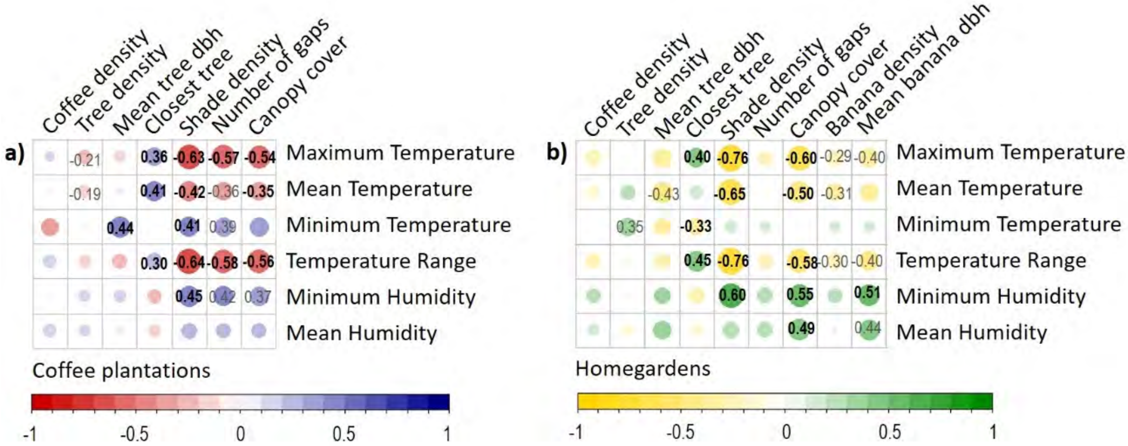

***Figure 3.5**: Correlations between shade parameters and the residuals of monthly microclimate variables after accounting for seasonality, elevation and data logger type for a) coffee plantations (red to blue) and b) homegardens (yellow to green). Bold correlation coefficients have a significant level of $p < 0.01$ and grey correlations coefficient of $p < 0.05$.*

It is important to note the extent to which the different aspects of shade influence the aspects of microclimate (Appendix 3.A, Appendix 3.B). Changes in shade density have the strongest influence for coffee plantations as well as homegardens. A 10% increase in shade density leads to a 0.46°C reduction in maximum temperatures in coffee plantations and a 0.93°C reduction in homegardens. The influence of the distance to the closest tree and the canopy cover on maximum temperatures is similar for both production types (Appendix 3.A, Appendix 3.B). For homegardens, an increase in mean banana diameter additionally contributes to the reduction of the maximum temperature by -0.16°C per 1 cm increase (Appendix 3.B).

Minimum temperature on the other hand is minimally influenced by shade variables. Despite the strong association of shade density and mean tree dbh to the minimum temperature in coffee plantations, the difference is only +0.07°C for an increase of 10% shade density and +0.01°C per cm dbh (Appendix 3.A). It is similar in homegardens; for a 0.01°C increase in minimum temperature, tree density would have to increase by 100 trees per ha and if the nearest tree is 1 m closer, the minimum temperature only increases by 0.03°C (Appendix 3.B). Mean tree dbh in homegardens even slightly reduces the minimum temperature by 0.01°C for every 1 cm increase (Appendix 3.B).

When comparing the mean temperature variables for the different production systems over the whole investigated period, the only significant difference is a slightly higher minimum temperature for homegardens compared to coffee plantations (14.55°C and 14.23°C respectively; $t_{645} = 52.26$, $p < 0.001$), despite the significantly higher shade density in homegardens. Mean humidity and minimum humidity are significantly higher for homegardens (Appendix 3.A, Appendix 3.B; $t_{641} = 3.50$, $p < 0.001$; $t_{635} = 3.29$, $p = 0.001$, respectively).

In both production systems, shade density increases the minimum humidity (Appendix 3.A, Appendix 3.B). The minimum humidity increases more in homegardens for every 10% increase in shade density compared to coffee plantations (2.34% and 1.19% respectively), while the increase due to an increase in 10% canopy cover is the same in both systems (0.80%). In homegardens, mean banana dbh also influences the minimum humidity (Appendix 3.B).

Self-shading by the coffee plants does not play a significant role for microclimate variables at Mt. Kilimanjaro. For homegardens, a reduction in maximum temperature by only 0.04°C was observed with an increase in coffee planting density of 100 plants per ha (Appendix 3.B). For coffee plantations, an increase in coffee density by 100 plants per ha reduced the minimum temperature by just 0.02°C (Appendix 3.A).

3.4.4. Effect of shade on the daily temperature and humidity dynamics

Daily temperature dynamics under different shade densities provide further insight into how shade influences microclimate. It can be observed that the peak temperature during the hottest period of the day is reduced, while few effects are observable for cooler night temperatures (Figure 3.6). This is the case for hot and cold months, the effect is only slightly less pronounced when temperatures in general are low (Figure 3.6).

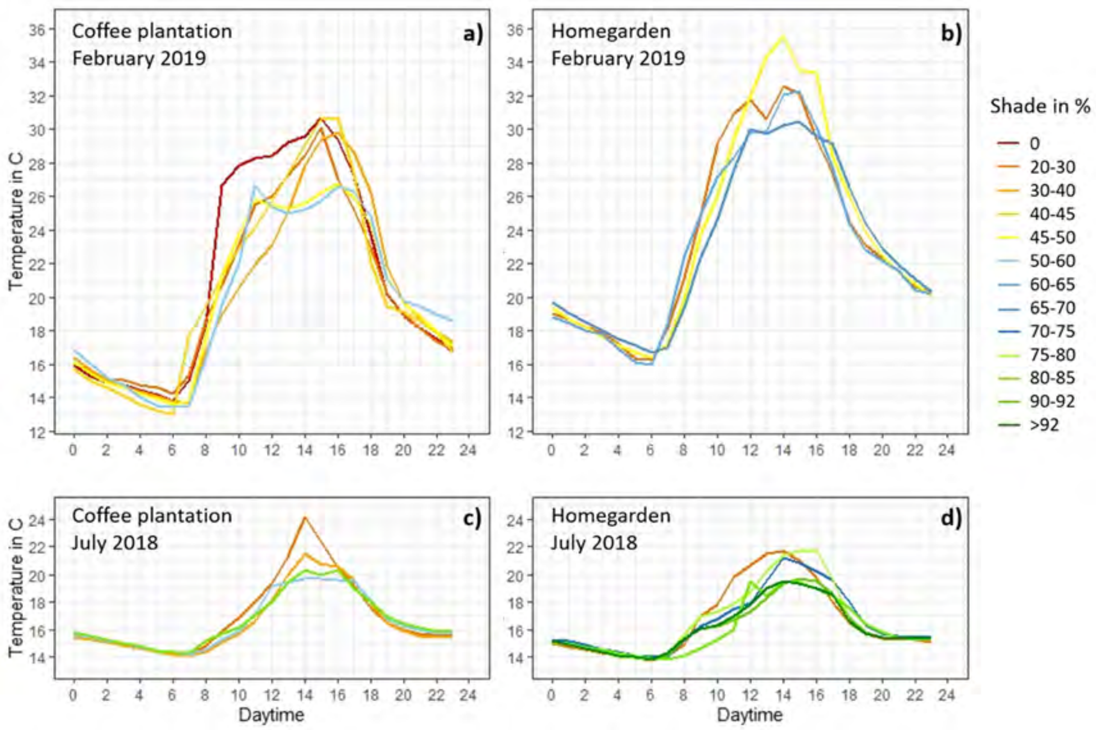

Figure 3.6*: The dynamics of daily temperatures for coffee plantations (a, c) and homegardens (b, d) for a hot month, February 2019 (a, b) and the coldest month, July 2018 (c, d). The daily curves are monthly means for each hour and separated by the shade density. Each graph presents one field in order to eliminate the effect of elevation.*

Higher shade density reduces humidity during the night, while it leads to higher humidity during the day (Figure 3.7). This effect is stronger in coffee plantations compared to homegardens and can more easily be seen during the hot and drier month (Figure 3.7).

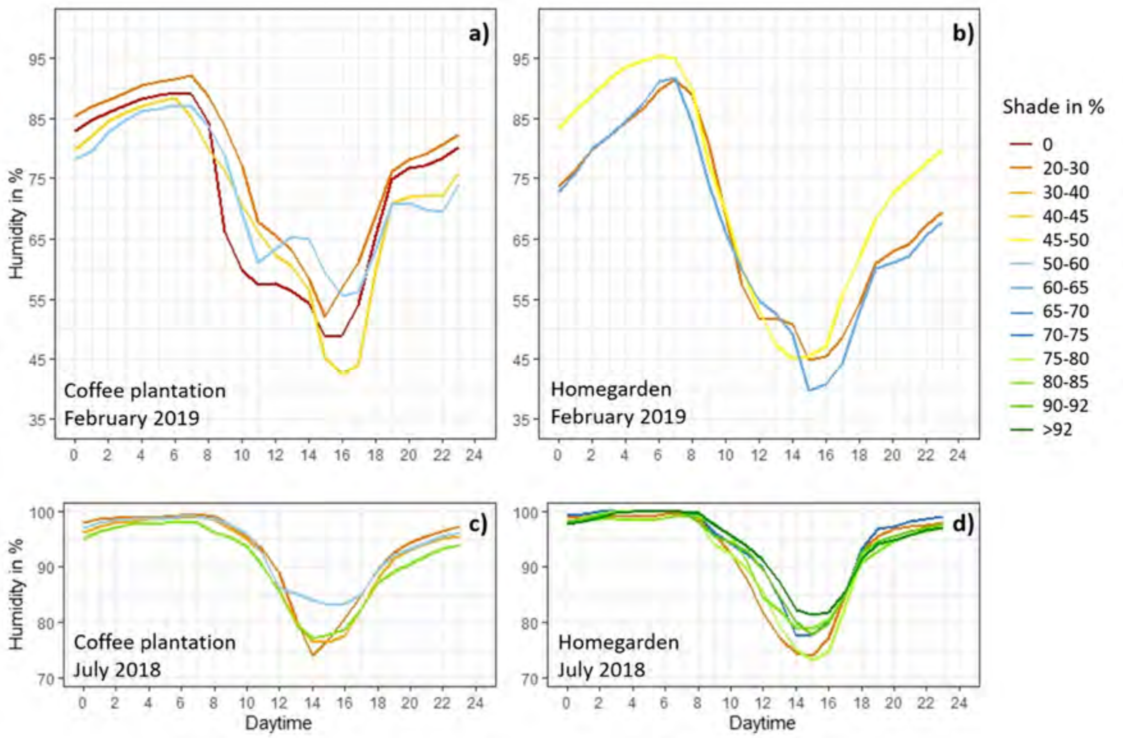

Figure 3.7*: The dynamics of daily humidity for coffee plantations (a, c) and homegardens (b, d) for a hot month with low humidity, February 2019 (a, b) and the coldest month with high humidity, July 2018 (c, d). The daily curves are monthly means for each hour and separated by the shade density. Each graph presents one field in order to eliminate the effect of elevation.*

3.5. Discussion

3.5.1. Shade variables in coffee production systems

Few studies have investigated the effects of multiple aspects of shade simultaneously. The two aspects mainly reported are shade density and/or tree density (Barradas and Fanjul 1986; Caramori et al. 1996; Campanha et al. 2004; Vaast et al. 2006; Lin 2007; Siles et al. 2010; de Souza et al. 2012; López-Bravo et al. 2012; Karungi et al. 2015; Mariño et al. 2016; Sarmiento-Soler et al. 2019). In general, tree density reported in previous studies is much lower than that found in this study, on fields at Mt. Kilimanjaro. Only Siles et al. (2010) and López-Bravo et al. (2012) report comparable densities of 278 and 417 trees per ha respectively. Smallholder farmers in Tanzania have banana plants and shade trees on their fields, it is therefore understandable that the banana density is lower than in the coffee banana system in Uganda (2450 banana plants per ha) (Sarmiento-Soler et al. 2019). There is a discrepancy between the number of trees and shade densities reported. Lin (2007), for example, compared three categories: low (10-30% shade density, 16 trees per ha), medium (35-65% shade density, 24 trees per ha) and high (60-80% shade density, 36 trees per ha) shaded fields. This demonstrates that high shade density does not necessarily translate into high tree density and it is therefore important to investigate and report several shade components, as one alone does not fully represent the shade cover. Also, most authors only compare discrete shade levels (Caramori et al. 1996; Lin 2007; Karungi et al. 2015; Sarmiento-Soler et al. 2019) or shaded and unshaded systems (Barradas and Fanjul 1986; Campanha et al. 2004; Vaast et al. 2006; Siles et al. 2010; Bote and Struik 2011; de Souza et al. 2012; López-Bravo et al. 2012) rather than looking at continuous shade gradients. Investigating a range of shade densities, rather than comparing groups, allows us to see influences along the shade gradient and therefore improve our ability to tailor recommendations.

To identify opportunities for improvement, it is important to understand the different shade components that contribute to the system. Canopy cover for coffee plantations and homegardens at Mt. Kilimanjaro are similar, because the research was designed to have similar contributions by shade trees between the different systems, to enable comparisons. Despite this, shade in these two systems is very different. While coffee plantations only maintain some big shade trees, which can be inferred from the lower tree density but higher mean tree dbh, smallholder farmers have in addition to the big trees smaller trees on their fields, leading to a lower mean dbh. The higher tree density in homegardens further means, that the five closest trees are closer to the investigation plot and their mean dbh therefore has an influence on the canopy cover from the trees, which is not the case for coffee plantations. The mean shade density in homegardens is higher than in coffee plantations, as bananas constitute shade as well. Their contribution explains the lower number of gaps in homegardens, as banana leaves cover a big area without openings for light to come through. It also explains why there is no partial correlation between shade density and canopy cover in homegardens, while it is highly significant for coffee plantations. In the latter, tree canopy lines very precisely represent the total shade density; while in homegardens banana density has a similar contribution to shade density as shade trees.

3.5.2. Influence of shade on microclimate

Seasonality of climate at Mt. Kilimanjaro has been previously reported (Reynolds et al. 2015; Appelhans et al. 2016) and the effect of elevation on temperature is very well established. It is still important to investigate and account for this, before investigating the effects of shade. It further helps to tailor recommendations to different elevations and advice on shade management during specific seasons.

It is important to understand what aspects of shade significantly influence microclimate variables, but as my results show, this does not necessarily translate into large effects. It is therefore relevant to follow up by investigating the magnitude of change.

The most crucial finding of this study is that shade trees have very little influence on low temperatures at Mt. Kilimanjaro. Minimum temperatures were hardly altered by shade density. This is important, as low temperatures are vital for coffee development. Increasing night temperatures contribute to yield reductions and reduce the time of ripening, which negatively impacts coffee quality (Vaast et al. 2006; Craparo et al. 2015, 2020). Some other researchers also observed no difference in minimum temperatures between shaded and unshaded coffee systems (Campanha et al. 2004; de Souza et al. 2012). Previous studies, however, generally report that shade trees buffer high and low temperatures (Barradas and Fanjul 1986; Beer et al. 1998; DaMatta 2004; Vaast et al. 2006; Lin 2007; Rigal et al. 2020). Barradas and Fanjul (1986) reported an average minimum temperature in the coldest month of 9.0°C in unshaded coffee compared to 10.9°C in coffee under 205 trees per ha, with the difference of yearly average minimum temperature being 1.5°C. In Uganda, shade trees slightly (less than 1°C), but significantly increased the minimum temperature compared to unshaded coffee systems, while the effect from banana plants was even smaller (Sarmiento-Soler et al. 2019). An increase in minimum temperatures might rather be the case for very low temperatures or even frost events, which can damage coffee plants. In a region in China, where the average minimum temperature of the coldest month reached 7.3°C , with some nights dropping down to 0°C in unshaded conditions, shade could increase the temperatures by up to 1°C (Rigal et al. 2020). A similar effect was observed in Brazil (Caramori et al. 1996). With a mean minimum temperature of about 14°C, temperatures do not become critical in the coffee production area of Mt. Kilimanjaro.

The observed effect on maximum temperatures in general is higher than on minimum temperatures, but still differs between regions. The magnitude of reduction might be connected to the general temperature in the area, as well as the shade density of the systems. Sometimes, the difference only amounts to 2.6°C, even when maximum temperatures reach nearly 40 °C (Campanha et al. 2004). Mariño et al. (2016) found a very strong effect with daily maximum temperature being reduced by 8.5°C with increased shade cover of 52% (38.2°C under 31% shade densities and 30.7°C under 83% shade densities). At higher elevations in Brazil and Mexico with maximum temperatures reaching 32°C to 34 °C in unshaded coffee systems, researchers reported a difference of maximum temperatures between agroforestry and unshaded coffee systems of 5.4°C (Barradas and Fanjul 1986; de Souza et al. 2012). High maximum temperatures of nearly 37.8°C during the late dry period in Uganda could be reduced to 36.8°C when coffee was intercropped with banana plants and to 34.8°C under shade trees (Sarmiento-Soler et al. 2019). I can confirm that shade has a very positive effect and can reduce maximum temperature substantially by 0.46°C in coffee plantations and 0.93°C in homegardens at Mt. Kilimanjaro for every 10% increase in shade density, even with a mean maximum temperature of less than 27°C.

Shade significantly reduces temperature fluctuation and variability by narrowing the temperature range, especially through decreased maximum temperatures. That shade trees in coffee fields at Mt. Kilimanjaro mainly affect the high temperatures is confirmed when looking at the dynamics of the daily temperatures. Here the main difference is recorded during the temperature peaks at midday. Similar daily temperature patterns were observed for shaded and unshaded coffee production systems in Costa Rica and Uganda (López-Bravo et al. 2012; Sarmiento-Soler et al. 2019). Lin (2007) also found higher temperatures during the day in coffee fields in Mexico with low shade density compared to fields with medium or high shade density; however, at night, temperatures in low shade density fields were lower. These results might have been influenced by the surrounding landscape, the tree species included in the system or the tree arrangement.

Trees in coffee agroforestry systems are very helpful as wind breaks, increasing humidity, reducing evapotranspiration and water demand (Beer et al. 1998; DaMatta 2004). Similar to other authors, I observed an increase in humidity due to shade density (Bote and Struik 2011; López-Bravo et al. 2012; Karungi et al. 2015; Mariño et al. 2016). Lower shaded coffee (31% shade density) in Puerto Rico, for example, had significantly lower minimum relative humidity (26.7%) than highly shaded coffee plots (83% shade density; 57.7% minimum relative humidity) (Mariño et al. 2016). In contrast, Lin (2007) reported significantly lower average humidity under high shade density (60-80% shade density) compared to the medium and low shaded coffee sites (35-65% and 10-30% shade density respectively) during the dry season. However, higher shade density also meant a lower fluctuation in humidity (Lin 2007). During daytime, the relative humidity was higher at the highly shaded site, as observed by other authors (López-Bravo et al. 2012), and was only lower at night-time (Lin 2007). I observed a similar pattern, especially in coffee plantations. In homegardens, the difference might not be as clear due to the influence of banana plants, which might increase the shade density, without the same effects on humidity that shade trees have and due to high in-plot variability.

More balanced humidity might be beneficial, as higher humidity during the day could reduce water use and lower humidity at night could help reduce infestation of pests and diseases that thrive at high relative humidity (Avelino et al. 2006; López-Bravo et al. 2012). Optimum relative humidity for *Coffea arabica* is between 70 and 80% (Alègre 1959).

3.5.3. Shade management to improve microclimate

The findings of this study show the benefits of shade density in improving microclimate at Mt. Kilimanjaro by reducing maximum temperatures during the hottest period of the day without altering favourable nocturnal temperatures. However, there might be certain aspects that could help to improve the systems even more through appropriate shade management.

Coffee plantations and homegardens need to be discussed separately, as their management is very different and recommendations for potential adaptation strategies to climate change may be as well. In coffee plantations, tree density has no significant effect on minimum temperatures, but reduces maximum temperature. Even though the magnitude of change is small, it might still be beneficial to include more shade trees in coffee plantations to reduce unfavourable maximum temperatures without significantly altering favourable minimum temperature. This could further help to have a homogeneous shade cover for all coffee plants. An increase in shade density could also improve humidity by increasing the minimum humidity. It might be advisable to consider what tree species to include in the system. Trees with small leaves might provide optimal shade cover as they could help increase tree density without risking too dense shade cover that could have a negative impact on minimum temperatures or increase humidity to a point where it becomes disadvantageous due to increased incidence of diseases and rotting of berries.

Homegardens already have a very high tree density and in this case, an increase might not be beneficial. In contrast to coffee plantations, homegardens have smaller trees and in this system, an increase in tree dbh seems to be quite beneficial for climate change adaptation, as it can reduce high temperatures as well as the minimum temperature, even though the magnitude of change is small. It might be advisable for smallholder farmers to reduce the number of trees but allow them to grow bigger. This could also help in increasing the canopy cover from trees, which is not only beneficial to reduce maximum temperatures, but can also increase minimum humidity. An increase in banana density might not necessarily have a strong impact on maximum temperatures, but it also does not alter the minimum temperatures. As banana plants provide food, fodder or additional sources of income, including them might be very beneficial for the farmers (Wagner et al. 2019).

More research on the effect these suggested alterations in the system have on the microclimate needs to be conducted. Furthermore, there is the need to investigate the impact they have on coffee yield and quality, as there might be competition between the species that could have a negative effect on coffee production. Microclimate alterations could affect pests and diseases as well as predator communities and the influence shade trees have in these dynamics needs to be assessed. An important consideration is the influence different tree species might have as this could improve recommendations even more. Management of shade tree in optimising the systems is critical. Pruning shade trees to address seasonality, making sure there is sufficient sunlight for coffee plants when needed is necessary to consider.

3.6. Conclusion

This study highlights the importance of analysing different shade components rather than only focusing on shade density and/or tree density. Investigating a shade gradient rather than only comparing shaded and unshaded systems gives a more comprehensive understanding of the ways the systems could be optimised for the future.

I demonstrate that inclusion of shade trees in coffee production systems is a potential adaptation strategy to climate change at Mt. Kilimanjaro, as they can reduce maximum temperatures, without jeopardising low nocturnal temperatures, which are important for coffee development. My results therefore demonstrate that shade might not only be beneficial in suboptimal conditions but can also improve microclimate for coffee production systems in other areas, like at Mt. Kilimanjaro.

Microclimate is not the only relevant aspect when investigating the potential of shade to facilitate climate change adaptation. The effect shade has on leaf temperature, light intensity and how this in turn and in combination with microclimate influences photosynthesis needs to be examined. Ultimately, the influence on coffee development and how coffee yield and quality is affected by shade needs to be assessed in order to ensure farmers benefit from the recommendations.

3.7. References

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3.8. Appendices

Appendix A: *Mean temperature and humidity variables for coffee plantations and the extent to which these variables are altered by an increase in different shade components. Only significant changes with $p < 0.01$ are reported.*

	Mean (± SD)	100 coffee plants per ha	100 trees per ha	Nearest tree 1 m closer	1 cm average tree dbh	10% canopy cover	10% shade density	1000 gaps
Maximum temperature in °C	26.75 ± 3.79	-	-0.22°C	-0.16°C	-	-0.31°C	-0.46°C	-0.16°C
Mean temperature in °C	19.39 ± 1.85	-	-0.03°C	-0.04°C	+0.00°C	-0.06°C	-0.08°C	-0.03°C
Minimum temperature in °C	14.23 ± 1.25	-0.02°C	-	-	+0.01°C	+0.03°C	+0.07°C	+0.03°C
Temperature range in °C	12.52 ± 3.79	-	-0.22°C	-0.17°C	-	-0.34°C	-0.54°C	-0.19°C
Minimum humidity in %	55.89 ± 13.21	-	+0.49%	+0.41%	-	+0.80%	+1.19%	+0.38%
Mean humidity in %	82.70 ± 7.85	-	-	+0.13%	-	+0.20%	+0.24%	-

***Appendix B**: Mean temperature and humidity variables for homegardens and the extent to which these variables are altered by an increase in different shade components. Only significant changes with $p < 0.01$ are reported.*

	Mean (± SD)	100 coffee plants per ha	100 trees per ha	Nearest tree 1 m closer	1 cm average tree dbh	10% canopy cover	10% shade density	1000 gaps	100 banana plants per ha	1 cm average banana dbh
Maximum temperature in °C	26.53 ± 4.15	-0.04°C	-	-0.17°C	-0.03°C	-0.30°C	-0.93°C	-0.25°C	-0.05°C	-0.16°C
Mean temperature in °C	19.56 ± 2.13	-	-	-	-0.01°C	-0.07°C	-0.21°C	-	-0.02°C	-0.05°C
Minimum temperature in °C	14.55 ± 1.35	-	+0.01°C	+0.03°C	-0.01°C	-	-	-	-	-
Temperature range in °C	11.98 ± 3.95	-0.04°C	-	-0.20°C	-0.02°C	-0.30°C	-0.96°C	-0.28°C	-0.05°C	-0.15°C
Minimum humidity in %	59.02 ± 12.96	-0.16%	-	+0.31%	+0.08%	+0.80%	+2.34%	+0.70%	-	+0.89%
Mean humidity in %	84.66 ± 7.61	-	-	-	+0.04%	+0.32%	+0.69%	-	-	+0.40%

Chapter 4: Case study: The influence of shade trees on coffee leaf temperature

4.1. Abstract

Climate change is a major challenge to which global coffee production must adapt. This requires investigations of suitable adaptation strategies. Integration of shade trees in coffee production systems is a possible approach, as this shows potential to reduce the impact of high air temperatures during the day. A key consideration is the effect shade has on coffee leaf temperature. To investigate this, I conducted a case study in coffee plantations at Mt. Kilimanjaro. I determined shade density using hemispherical photos, measured the air temperatures an unshaded coffee plant is exposed to as well as the air temperature around shaded coffee plants. Additionally, I recorded leaf temperatures at different canopy positions of 60 coffee plants with an infrared thermometer under clear sky during the hottest period of the day. My results demonstrate that shade trees are effective at reducing high leaf temperatures to below ambient air temperatures. I further show that there is some self-shading effect by coffee plants. Further research on the extent to which lower leaf temperatures can improve coffee plant health and development is required considering other impacts of shade trees such as light and water availability.

Keywords: Leaf temperature, Shade density, East Africa, *Coffea arabica*

4.2. Introduction

Shade trees are considered important to support adaptation of coffee production to climate change due to their influence on microclimate (Beer et al. 1998; Campanha et al. 2004; Lin 2007; Siles et al. 2010; de Souza et al. 2012). *Coffea arabica* is adversely affected by rising temperatures, as long periods with temperatures above 30°C can reduce net photosynthesis, growth and even damage the plant (Alègre 1959; Nunes et al. 1968; Descroix and Snoeck 2004; Gómez et al. 2005; DaMatta and Cochicho Ramalho 2006). Gómez et al. (2005) observed optimal photosynthetic activity at air temperatures between 26°C and 29°C. Other authors report reduced photosynthetic rates at leaf temperatures above 25°C (Kumar and Tieszen 1980). Self-shading by coffee plants could have an influence on the leaf temperature at different canopy positions (Akunda et al. 1979). Research has shown that shade cover reduces daily maximum temperatures (Chapter 3) (Barradas and Fanjul 1986; Campanha et al. 2004; de Souza et al. 2012; Mariño et al. 2016; Sarmiento-Soler et al. 2019), which might help in creating a suitable microclimatic environment and reduce leaf temperature to an optimal range.

The aim of this case study is to identify the extent to which shade density affects leaf temperature at different canopy positions in coffee plantations at Mt. Kilimanjaro. I further want to determine if the effect is uniquely due to reduction in air temperature due to shade trees, or if there is an additional effect on the temperature reduction of leaves. Understanding the effect of shade density on coffee leaf temperature can help improve recommendations to optimise coffee production systems and improve plant health.

4.3. Material and Methods

4.3.1. Study area

This case study was carried out on three coffee fields of the Kilimanjaro Plantation Ltd. (KPL), on the southern slope of Mt. Kilimanjaro in Tanzania with average annual temperature of 19.4°C and average annual precipitation of 1500 mm (Chapters 2 and 3). Four flat plots measuring 10 by 10 m, with a minimum of 20 m apart were marked on each field. In each plot, I selected five coffee plants for investigations (60 plants in total). The altitude was determined with a GARMIN GPSMAP64 GPS device and ranged from 1120 m asl to 1300 m asl (Table 4.1).

4.3.2. Shade density

Shade density was determined between April and August in 2018 and 2019 by taking photos of the canopy cover from the top of each investigated coffee plant with a fish eye lens (Bosselmann et al. 2009). I analysed a circle at the centre of the photos with a diameter of 72° with the plug-in Hemispherical 2.0 in ImageJ to get the percentage shade cover (Beckschäfer 2015). I then calculated the mean shade density for each plant.

An ANOVA followed by a Tukey test showed that the mean shade density was not significantly different between fields (Table 4.1). The shade density ranged between 0% and 87%, showing more variation between coffee plants within one field, than between fields (Table 4.1). Other aspects of the shade cover however differ between fields; Field 1 for example had shade trees with a lower mean diameter at breast height (dbh), but a much higher shade tree density (Table 4.1). For details on how tree density and mean tree dbh was determined, please refer to Chapter 3.

***Table 4.1**: Summary of the characteristics of the different coffee fields.*

	Elevation in m asl	Tree density per ha	Mean tree dbh in cm	Shade density in %	Shade density range in %
Field 1	1123 ± 5 [a]	769 ± 169 [a]	39.6 ± 3.6 [a]	41 ± 22 [a]	7 - 76
Field 2	1239 ± 5 [b]	121 ± 38 [b]	54.4 ± 12.9 [b]	35 ± 31 [a]	0 - 87
Field 3	1299 ± 7 [c]	244 ± 42 [c]	65.9 ± 10.0 [c]	42 ± 25 [a]	1 - 86
	F_{117} = 10472, $p < 0.001$	F_{117} = 449.1, $p < 0.001$	F_{117} = 74.5, $p < 0.001$	F_{117} = 0.98, $p = 0.380$	

Significant differences (p-value < 0.01) between coffee fields are marked with different letters.

4.3.3. Microclimate and leaf temperature

The temperatures of 20 leaves at the top of the coffee plant and 20 leaves at the bottom were measured with an infrared thermometer. To capture the effects of exposure to maximum temperatures and direct sun radiation, leaf temperatures were measured on days with clear skies in the afternoon, during the hottest period of the day, which was identified to be between 11:45 and 16:30 (Appendix 4.A). Field 1 was visited on 30 January 2019 between 12:50 and 14:20, Field 2 on 25 January 2019 between 13:45 and 15:10 and Field 3 on 24 January 2019 between 14:10 and 16:05. The specific timing of each measurement was recorded.

While measuring leaf temperatures, I also measured the current air temperature next to the coffee plant with a Kestrel 5000 Environmental Meter for Field 1 and 2. This was not done in Field 3 due to logistical reasons. To identify the temperature experienced by a coffee plant exposed to sun, I collected data using a Blue Maestro Tempo Disc™ Bluetooth temperature, humidity and dew point sensor beacon and data logger placed 50 cm below the top of the most sun exposed investigated coffee plants. This data logger recorded the temperature every 15 minutes. To align this temperature with the leaf temperature measurements, the five minute intervals in between were estimated as weighted averages of the 15 minute interval endpoints.

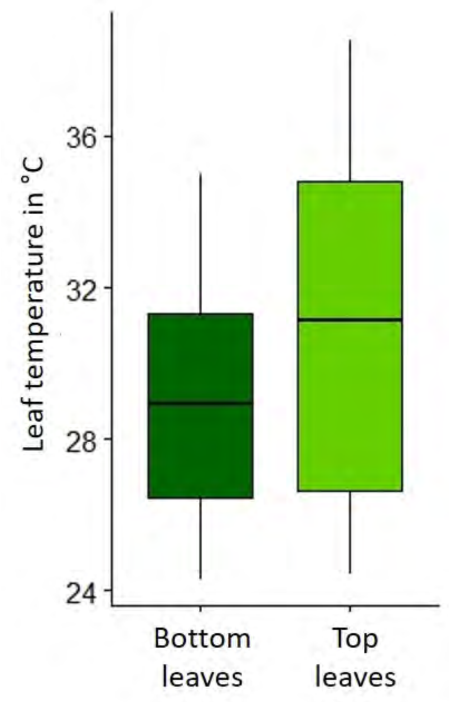
4.3.4. Statistical analysis

I conducted a t-test to identify if the temperature between leaves on top of the coffee plant and at the bottom were significantly different and I calculated the means and standard deviations. The mean leaf temperature and standard error for top and bottom leaves for each coffee plant as well as the maximum temperature and the difference between the mean leaf temperature on top and on the bottom were calculated. To identify the influence of shade density, I performed linear regressions. Differences in slopes were tested by comparing the 95% confidence intervals.

The influence of shade on air and leaf temperature was further determined by comparing the temperature of the sun-exposed plant with the air temperature next to the investigated plant and the leaf temperature. For this, I calculated the mean temperature of the sun-exposed coffee plant at the same time as the other two temperature measurements, and at five and ten minutes prior to that in order to account for sudden changes and to generate a more stable comparison. I then calculated the difference between the temperature of the sun-exposed coffee plant and the air ($n = 40$) as well as the mean leaf ($n = 60$) temperature for each investigated plant. To see if the effect of shade on leaf temperatures is stronger than only on the air temperature, I used the air temperature as baseline and calculated the differences to the leaf temperature on top and at the bottom of the coffee plant. Linear regressions were used to examine the influence of shade on leaf and air temperature. I conducted a t-test to identify if the mean air temperature differs from the mean leaf temperature at the bottom of the coffee plant.

4.4. Results

4.4.1. Difference between leaves on top and on the bottom of the coffee plant



The mean leaf temperature of coffee leaves on top of the plant was 30.8 ± 4.3 °C and was significantly higher than the temperature of the leaves at the bottom of the coffee plant, which had a mean of 29.1 ± 3.0 °C (Figure 4.1).

Figure 4.1: *Temperature of leaves at the bottom (dark green) and on top (light green) of the coffee plants are significantly different (t_{104} = 2.61, p = 0.010).*

4.4.2. Influence of shade on leaf temperature

Shade significantly reduces leaf temperature at both the bottom and the top of coffee plants (Figure 4.2a). A 10% increase in shade density leads to a 0.62°C reduction of coffee leaf temperature for leaves on top of the plant ($F_{1,58}$ = 9.43, p = 0.003) and a 0.37°C reduction for leaves at the bottom ($F_{1,58}$ = 7.16, p = 0.010). Even though these slopes are not significantly different, the difference between the temperature of leaves on top and at the bottom of the plants still reduces significantly with increasing shade density (Figure 4.2b). The maximum temperature is even more significantly affected than the mean temperature, as a 10% increase in shade density leads to 0.75°C and 0.89°C reduction for top and bottom leaves respectively ($F_{1,58}$ = 6.48, p = 0.014 and; $F_{1,58}$ = 8.01, p = 0.006) (Figure 4.2c).

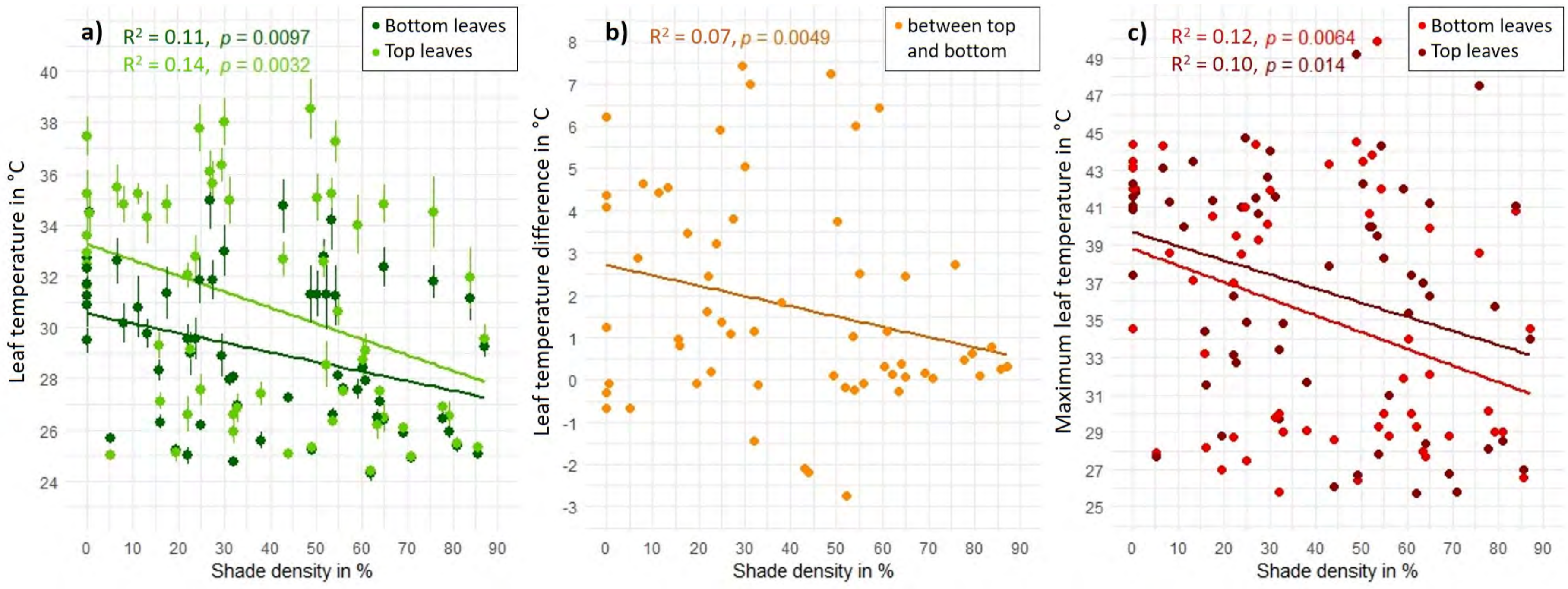


***Figure 4.2**: a) Temperatures of leaves at the bottom (dark green) and on top (green) of coffee plants are significantly reduced with increasing shade density. b) The difference between leaves on top and at the bottom and c) the maximum temperature leaves on top (dark red) and at the bottom (red) of the plant experience are also significantly reduced with increasing shade density.*

4.4.3. Comparison of air and leaf temperature

Air and leaf temperatures are lower under shade compared to on direct sun exposure (Figure 4.3a). A 10% increase in shade density reduces air temperature by 0.39°C ($F_{1,38}$ = 5.81, p = 0.021). The difference between the temperature a sun exposed coffee plant experiences and mean leaf temperature increases by 0.56°C for each 10% shade increase ($F_{1,58}$ = 8.95, p = 0.004) (Figure 4.3a). The effects of shade on air and leaf temperature are not significantly different, but when using the air temperature as baseline, a further reduction of the leaf temperature on top of the coffee plant with increasing shade density can still be observed (Figure 4.3b). The difference between air temperature and leaf temperature on top of the coffee plant increases by 0.45°C for each 10% increase in shade density ($F_{1,38}$ = 4.63, p = 0.038). The temperature of leaves at the bottom is not further reduced compared to the air temperature with an increase in shade density (Figure 4.3b). Their mean temperature, however, is already significantly lower by 1.5°C than the air temperature (t_{92} = 2.13, p = 0.036).

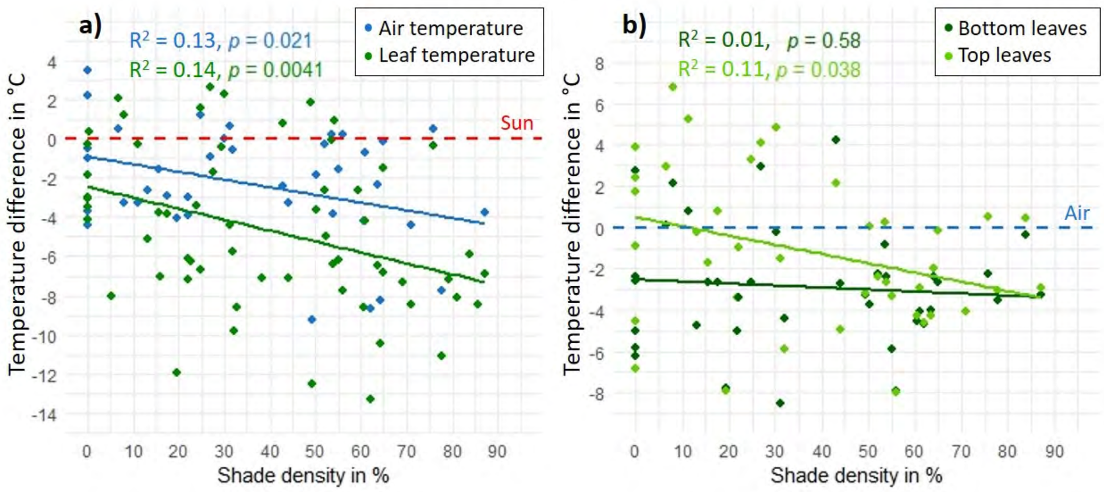


***Figure 4.3**: This shows a) the reduction of air and coffee leaf temperate under shade compared to the temperature a coffee plant experiences in full sun exposure and b) the difference between the leaf temperature on the bottom and on top of the coffee plant compared to the air temperature.*

4.5. Discussion

4.5.1. Influence of shade on air and leaf temperature

Shade density reduces air temperature in coffee plantations at Mt. Kilimanjaro. In this case study, I observed a reduction of 0.39°C for every 10% increase in shade density, similar to the larger data set over a longer time period previously reported, which shows a reduction in maximum temperatures of 0.46°C (Chapter 3). Comparison of the effect of shade on air and leaf temperature demonstrates that there is an additional temperature reduction for coffee leaves. While leaf temperature under shade trees is lower than the air temperature, it exceeds air temperature in unshaded systems (Gómez et al. 2005; Siles et al. 2010; Bote and Struik 2011).

Shade can significantly reduce coffee leaf temperature, especially during the hottest periods of the day. My data shows that unshaded or insufficiently shaded leaves in general exceeded temperatures of 30°C, while every 10% increase in shade density can potentially reduce leaf temperature by 0.62°C. Shade therefore ensures less heat stress, providing optimal conditions for the plants. Similar results were reported in previous studies: at three different locations in Costa Rica with average annual temperatures of 20.5°C, 21°C and 22°C, leaf temperature under shade was between 2-4°C, 5°C and 6.4°C lower than under unshaded conditions (Vaast et al. 2006; Siles et al. 2010; López-Bravo et al. 2012). In Ethiopia, shaded leaves also had a significantly lower average temperature than leaves exposed to direct sunlight (24.2°C and 28.1°C respectively) (Bote and Struik 2011).

Self-shading of coffee leaves was observed, as leaf temperature on the bottom of the plant was significantly lower than on top. The temperature of leaves located at lower canopy positions did not exceed air temperatures during the rainy season, even for exposed plants (Siles et al. 2010). The difference between leaf temperatures at different canopy locations reduces with increasing shade density (Figure 4.2b) and the variation within the canopy and across the leaf surface is lower for shaded compared to unshaded systems (Siles et al. 2010; Craparo et al. 2017).

The buffering of leaf temperatures can be attributed to reduced light intensity and increased humidity under shade (Chapter 3) (Beer et al. 1998; DaMatta 2004), which triggers the stomata to remain open, enhancing transpirative cooling (Hetherington and Woodward 2003). Lower light intensity under shade also reduces coffee leaves exposure to sun.

When leaf temperatures above air temperatures in shaded systems are reported, the difference is lower than for sun exposed coffee plants (3.8°C and 7.1°C respectively) (López-Bravo et al. 2012). At night, minimum leaf temperatures of shaded coffee plants can also be slightly higher than air temperature (0.5°C) (Siles et al. 2010).

Although I only monitored the effect of shade on daytime heat stress for coffee plants, night-time temperatures at Mt. Kilimanjaro do not fall below critical points (Chapter 3) and thus are unlikely to be an issue for coffee production. Others researchers found an increase in minimum night-time leaf temperature and protection from frost damage due to shade trees (Caramori et al. 1996; Rigal et al. 2020). Leaf temperatures under shade trees were reported to be 2 to 4°C higher during frost events, which had a positive impact on coffee yields (Caramori et al. 1996).

4.5.2. Effect on coffee growth and development

It is important to ensure optimal leaf temperatures, as excessive heat can reduce net photosynthesis and adversely affect coffee yield and quality (Descroix and Snoeck 2004; DaMatta and Cochicho Ramalho 2006; Vaast et al. 2006). An increase in leaf temperature reduces stomatal conductance (Silva et al. 2004) as the plant closes its stomata to reduce water loss (Hetherington and Woodward 2003). Besides temperature, relative humidity also influences photosynthesis. Low humidity first increases transpiration, then initiates stomatal closure, which prevents transpiration, inhibiting carbon dioxide (CO_2) exchange which, potentially, can reduce photosynthesis (Hetherington and Woodward 2003). This might be responsible for the reduced plant growth associated with higher air temperatures (Silva et al. 2004). Temperatures being lower and humidity being higher under shade trees could indicate an advantage for shaded coffee plants. Light intensity, however, also plays a role in photosynthesis and shade reduces light availability, reducing net CO_2 assimilation rates for shaded coffee leaves, especially at lower canopy positions (Araujo et al. 2008). *Coffea arabica*, a shade-adapted plant does not require high light intensity and can maintain good photosynthetic rates under moderate shade levels (Kumar and Tieszen 1980; Franck and Vaast 2009).

Another important consideration is the effect of temperature on coffee development. High temperatures can negatively affect flowering and fruit set with consequences for coffee yield (Descroix and Snoeck 2004; DaMatta and Cochicho Ramalho 2006). Ripening time can be accelerated by increased temperature, especially around the berries, which has a negative effect on quality (Descroix and Snoeck 2004; DaMatta and Cochicho Ramalho 2006; Vaast et al. 2006). Shade could therefore be very beneficial for coffee plants by reducing leaf temperatures and heat stress.

4.6. Conclusion

My findings show the benefit of shade trees in reducing leaf temperatures during hot periods of the day. This could prevent midday depression of photosynthesis and increase CO_2 assimilation, leading to increased plant growth. Reduced leaf temperatures could benefit coffee yield and quality; however, further studies are needed to confirm this, especially considering the reduced light availability under shade trees.

4.7. References

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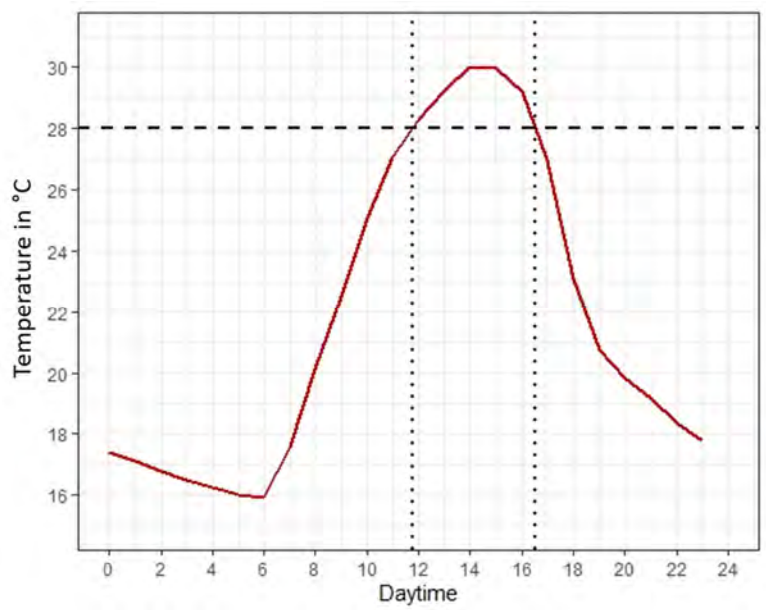
4.8. Appendix



***Appendix 4.A**: Mean daily temperature development of air temperature sun exposed coffee plants at the study site experience. The vertical lines indicate at what time temperature on average excides 28°C (11:45 and 16:30).*

Chapter 5: Influence of shade on coffee yield and quality in different coffee production systems in Tanzania

5.1. Abstract

Global coffee consumption is on the rise, but production conditions are worsening due to climate change. Farmers are facing yield losses as well as a reduction in coffee quality. Appropriate adaptation measures are necessary to overcome the challenges posed by climate change. By assessing the effect of shade density on coffee yield and quality in different coffee production systems at Mt. Kilimanjaro, I aim to improve understanding of the potentials of shade in increase resilience of different coffee production systems in the face of climate change. Different components of shade, including shade density, tree and banana density as well as distance to the closest tree were recorded. I estimated the yield of 215 coffee plants in 2018 and of 430 plants in 2019. Ripe berries were harvested and different physical quality aspects measured. While I did not observe any effect of shade on yields in coffee plantations, a slight reduction was observed for smallholder farmers. Coffee quality, on the other hand, benefited from shade density. Bean size and weight were correlated with different shade components. Banana plants were associated with a reduction in floating beans (i.e. poorly developed beans). The potential economic benefit for farmers still needs to be evaluated and further research on shade management and the effect of different tree species is required.

Keywords: *Coffea arabica*, East Africa, Shade, Coffee yield, Coffee quality

5.2. Introduction

Coffee is an important agricultural export commodity, providing livelihoods for many in developing countries. In Tanzania, approximately 450,000 smallholder families produce 90% of the country's coffee output and generate export earnings to the tune of about 100 million USD annually (TCB 2012; USDA 2020). Global coffee consumption rose by 4.3% in the fiscal year 2018/19 and the long-term average annual demand increase is around 2% (ICO 2020). In the year 2011, the Tanzanian government announced plans to double the country's coffee production within 10 years (by 2021) as well as increase its quality (TCB 2012). Climate change is a significant obstacle to attaining these goals as it causes yield and quality losses, decline of suitable production area, and facilitates the spread of pests and diseases (Descroix and Snoeck 2004; Vaast et al. 2006; Jaramillo et al. 2011; Craparo et al. 2015, 2020). Suitable adaptation strategies need to be developed for Tanzania to achieve its goal of increasing yield and quality and to maintain optimal coffee production into the future.

Integrating shade plants (trees or banana plants) into coffee production systems is one approach to mitigate the effects of climate change on coffee production. Yield potentials in shaded systems might not be as high as for sun-grown coffee, but shade cover seems to provide yield stability (DaMatta 2004; Vaast et al. 2006). Bean size and other quality parameters are often better under shade, leading to increased market prices (Muschler 2001; Vaast et al. 2006). These positive effects of shade on coffee production appear to be more pronounced in areas with suboptimal conditions (Beer 1987; Muschler 2001; DaMatta 2004). Geographical location, weather conditions, coffee and shade plant management all affect coffee yield and quality (Muschler 2001; Avelino et al. 2005; Vaast et al. 2006; DaMatta et al. 2007). Although banana plants commonly provide shade in addition to trees in smallholder farming systems, there is only limited literature on the effect of banana plants on coffee yield (van Asten et al. 2011). For shade in general, most authors focus on comparing shaded systems with unshaded coffee (Campanha et al. 2004; Vaast et al. 2006; Siles et al. 2010; Bote and Struik 2011; Mariño et al. 2016) or discrete levels of shade (Lin 2007; Karungi et al. 2015; Liu et al. 2018), while only few look at continuous shade gradients (Soto-Pinto et al. 2000).

The aim of this study is to evaluate the effects of a shade gradient on yield, yield variation and physical aspects of coffee quality in active farms in Tanzania. I investigate the differences between coffee plantations and smallholder production systems on the southern slopes of Mt. Kilimanjaro. In addition to total shade density, I examine the distinct influences of shade trees and banana plants on coffee yield and quality aspects.

5.3. Material and Methods

5.3.1. Study area

This study took place on the southern slope of Mt. Kilimanjaro, Tanzania, within an altitude range of 1100 to 1500 m asl on three different commercial coffee plantations and 14 smallholder farms called homegardens (Figure 5.1). Commercial plantations have only shade trees, whereas homegardens include banana plants in addition to shade trees. Homegardens are diverse systems with a variety of food crops and therefore have a lower coffee plant density (1485 ± 679 plants per ha, compared to 2519 ± 748 plants per ha in coffee plantations). Investigations in homegardens were carried out in one to four plots in each of the 14 homegardens (40 plots in total). In plantations, three fields of each of the three plantations were selected with four plots each in 2018 (36 plots in total) and six plots in 2019 (54 plots in total). The plots were 10 by 10 m, had no slope and were at least 20 m apart. The altitude of each plot was determined with a GARMIN GPSMAP64 GPS device. To ensure comparability between production systems, during site selection, it was ensured that there were no significant differences in altitude between coffee plantations (average ca. 1314 m asl.) and homegardens (average ca. 1311 m asl.) (Figure 5.1). Within each plot, three to five coffee plants were randomly selected and marked for continuous investigation as explained in the next sections.

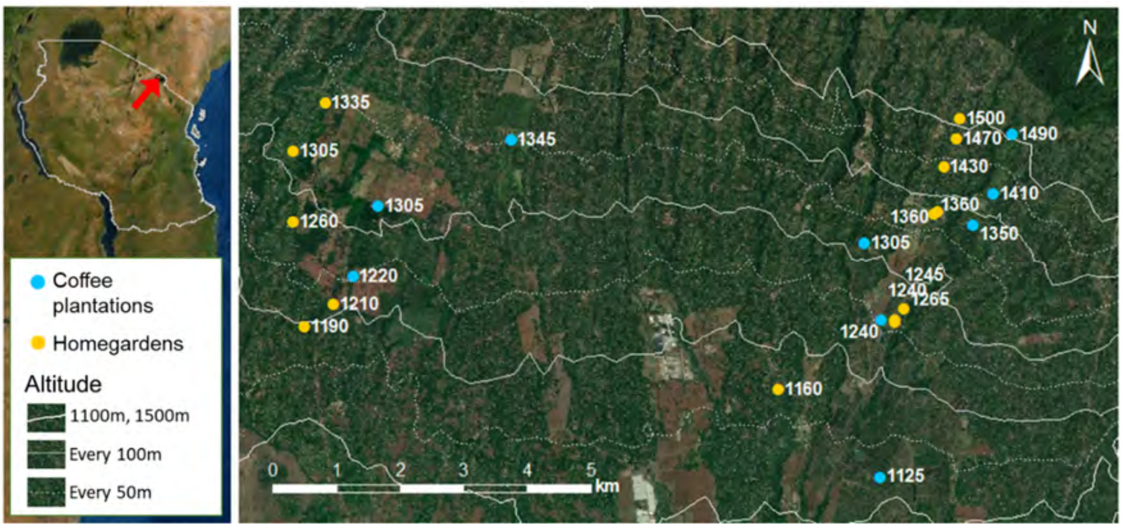


***Figure 5.1**: Location of the research sites within Tanzania (red arrow) and distribution on the southern slope of Mt. Kilimanjaro, divided into the different production systems.*

5.3.2. Shade density

I selected the research plots to cover a wide range of shade densities and measured several aspects of shade to understand their different contributions to coffee yield and quality (Table 5.1) (Chapter3).

Table 5.1*: Summary of mean shade components (±SD) for different production systems*

	Shade Density in %*	Distance to closest tree in m*	Trees per ha*	Banana density plants per ha	Average banana dbh in cm
Coffee plantations	36 ± 26	9.5 ± 6.2	327 ± 237	–	–
Homegardens	72 ± 15	6.5 ± 3.9	1108 ± 957	1515 ± 600	17.6 ± 2.5
	t_{86} = 8.66	t_{90} = 2.86	t_{43} = 5.04		

* significant differences (p-value < 0.05) between coffee plantations (n = 54) and homegardens (n = 40)

Shade density was determined using photos of the canopy cover taken with a fisheye lens from the top of each investigated coffee plant (Bosselmann et al. 2009). This was done between April and August in both years (2018 and 2019). To obtain the shade percentage, I analysed the biggest possible circle at the centre of the picture (diameter of 72°) using the plug-in Hemispherical 2.0 in ImageJ (Beckschäfer 2015).

Shade density is influenced by tree density, particularly by distance to the closest tree. I measured the distance to the five closest trees from each investigated coffee plant in November 2018. From the distance of the farthest tree, I calculated the tree density in m^2 (eq. 1) and converted it to per ha.

$$density = \frac{distance^2 * \pi}{5} \quad (1)$$

In homegardens, banana plants significantly contribute to shade. I measured the diameter at breast height (dbh) of the five closest banana plants to each investigated coffee plant in November 2018 and calculated the average dbh. Only banana plants with at least 10 cm dbh were included. I measured the distance to the fifth closest banana plant from each investigated coffee plant, calculated the banana density in m^2 (eq. 1) and converted it to banana plants per ha.

5.3.3. Coffee yield

The yield of each investigated coffee plant was estimated by counting the total number of small emerging berries (pinheads), and green, yellow and red berries and summing them. This was done for 215 plants in May and June 2018 and for 430 plants in April and May 2019. When comparing the different years, only plants counted both years were included. I further calculated the yield variation between years, by using the absolute value of the difference between the mean plot yields from plants counted both years. For correlations of the number of berries with shade variables, I included all investigated plants.

5.3.4. Coffee quality

Ripe red berries were harvested regularly during the harvest season. Investigated coffee plants in coffee plantations were harvested in 2018 and 2019 between July and November, while plants in homegardens were only harvested in 2018. Comparing production systems was done in 2018 and to get the annual difference between 2018 and 2019 I focused on coffee plantations, as homegardens had very low yields in 2019 and it was challenging to harvest enough to have representative data.

To assess coffee quality I measured variables at several coffee berry processing stages (Figure 5.2). They are explained in more detail below.

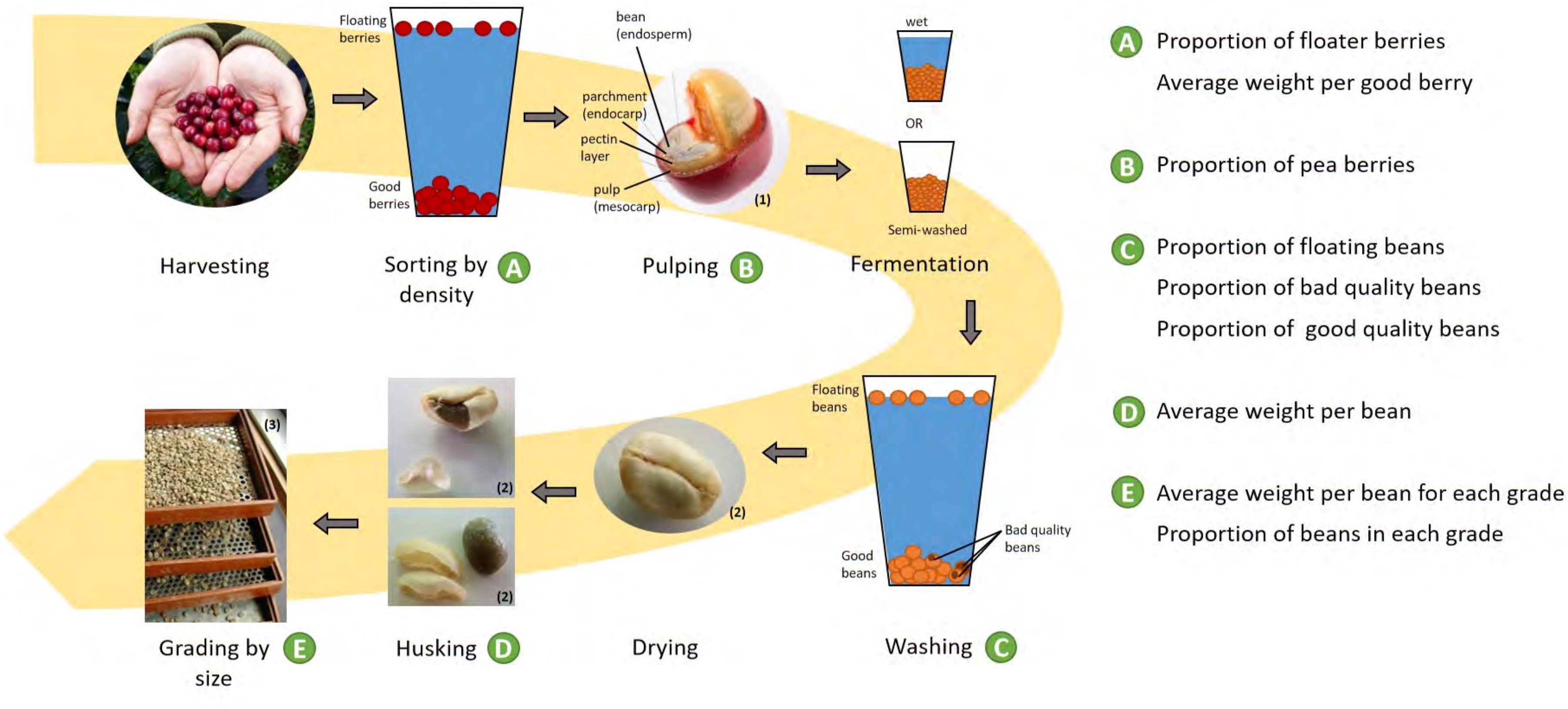


***Figure 5.2**: Different processing steps from harvested berries to green coffee.*

Measurements taken at the different steps are listed on the right.

Picture: (1) (Klingel et al. 2020); (2) Coffee Troup, 2020; (3) Mokaflor, 2019

At coffee plantations, the first step in processing coffee after harvesting is sorting berries by density. Berries are submerged in water and lower density berries float. These berries are removed and processed separately as “floater berries”, and considered to be of lower quality (Bertrand et al. 2005). Floater berries often have beans that are not fully developed or are affected by pests, which reduces the density (Bertrand et al. 2005). I calculated the proportion of floater berries compared to the total number of berries, as an indication of coffee quality. I weighed and counted the good berries, to get the mean weight per good berry for each investigated plant.

The next step is opening or pulping the berries and counting how many have only a single bean inside, so-called pea-berries. In some areas, these beans are especially valuable and can be sold at a higher price, but in areas without access to this exclusive market, a single bean means a lower total number of beans for the farmer and therefore a yield loss. Despite Mt. Kilimanjaro being known for its pea-berry coffee, smallholder farmers do not have access to the premium price; only big plantations or co-operatives benefit from this (TCB 2012). For good berries, I calculated the percentage of berries with only a single bean.

After opening the good berries, I fermented the beans and washed them separately for each investigated coffee plant. Fermentation can happen within the fruit before opening, which is called dry or natural processing (Knopp et al. 2006; Poltronieri and Rossi 2016). The husk then has to be removed after drying, while for the other processing methods, the husk is removed first (Knopp et al. 2006; Poltronieri and Rossi 2016). For semi-dry or honey processing, the beans still covered in mucilage (pectin layer) are dried (Knopp et al. 2006; Poltronieri and Rossi 2016). Pulped natural coffee is not fermented, as the mucilage is washed of immediately and the beans are then dried (Poltronieri and Rossi 2016). During semi-washed or wet hulled processing, coffee beans are kept with the mucilage on for about a day before washing (Poltronieri and Rossi 2016). Wet processing means the beans and mucilage are covered with water for fermentation for approximately 24 hours, depending on the climatic conditions and are then washed and dried (Knopp et al. 2006; Poltronieri and Rossi 2016). Fermentation influences coffee’s sensory properties very strongly. As I did not evaluate sensory properties and fermentation has no influence on physical characteristics of the coffee bean, the used methods had no influence on the results. While washing the fermented beans, I counted and removed the floating beans because they were too light or the husk was partly empty (so-called floating beans), and the beans with big black marks or rotten beans (so-called bad quality beans). I also counted the number of good beans and calculated the percentage for all three groups.

Good beans were dried and the husk or thin parchment surrounding the bean was removed. I weighed the green coffee and calculated the mean dry weight per bean separately for each investigated coffee plant. The green coffee was then sieved into different grades with a standardised coffee green bean grading hand screen. The biggest size is AA (bean diameter > 7 mm), which is premium and attracts a higher price, followed by pea-berries PB (round and with a diameter > 4.5 mm) and AB (bean diameter > 6 mm), which are good grades. The lower grade is C (bean diameter > 5.5 mm) and all the smallest leftovers are counted in grade F. I counted the number of beans for each grade per plant and weighed the different grades separately. This gave me the mean weight per bean for each grade size as well as the percent of beans in each grade size.

The total outcome as an indication for quality is the weight of dried green coffee divided by the wet weight of all harvested berries. Plantations calculate this every year and if the percent is high, the quality of the yield is considered good (personal communication with manager of the African Plantation Kilimanjaro Ltd.). My conversion is expected to be much lower than that of coffee plantations, as I disposed bad quality beans, whereas plantations include all beans. A lower percentage indicates lower quality as more beans had to be disposed of or that the beans were lighter.

To get a picture of the losses while processing, I calculated the percentage of loss at each processing stage. Firstly, the floater berries are removed. The percent of good berries becomes the new baseline from which the floating beans and the bad quality beans are removed. Lastly, the good quality beans are further divided by the percent of low grades, good grades and premium AA grade.

Plants with insufficient data for each variable to be representative were excluded. The number of berries/beans collected was independent of mean weight per berry/bean.

There was no significant difference in the mean with all data included or upon removal of data below the 5%, 10%, 15%, 20% or 25% quantile of the number of good berries or beans. I, therefore, included all data in the analysis. For percentage data, I only included plants in the analysis with at least 20 berries or beans, as granularity is insufficient below that threshold (i.e. > 5%).

5.3.5. Statistical analysis

Statistical analyses were run on plot means. The mean and standard deviation (SD) of all variables for the coffee plants within one plot was calculated and plots with less than two plants were excluded. Data was visually inspected and where data appeared to have a slight deviation from normal distribution, tests were also run using ranks. There was no difference in trends or significance using non-parametric or parametric data and therefore only parametric analysis is presented. I compared coffee plantations and homegardens and the different years by t-tests or with ANOVA followed by a Tukey test. To identify the influence of shade and elevation on coffee yield and quality, I correlated the coffee variables with elevation and different shade variables separately for different years and production systems. I calculated Pearson correlations between different coffee quality variables to understand their connection.

5.4. Results

5.4.1. Yield under different production systems and in different years

Homegardens have a significantly lower coffee yield per plant than coffee plantations in both years ($t_{36} = 4.18$, $p < 0.001$ for 2018; $t_{32} = 6.69$, $p < 0.001$ for 2019) (Figure 5.3). While coffee plantations show no yield difference between years ($t_{54} = 0.86$, $p = 0.393$), the yield is significantly reduced for homegardens in 2019 ($t_{47} = 4.69$, $p < 0.001$) (Figure 5.3).

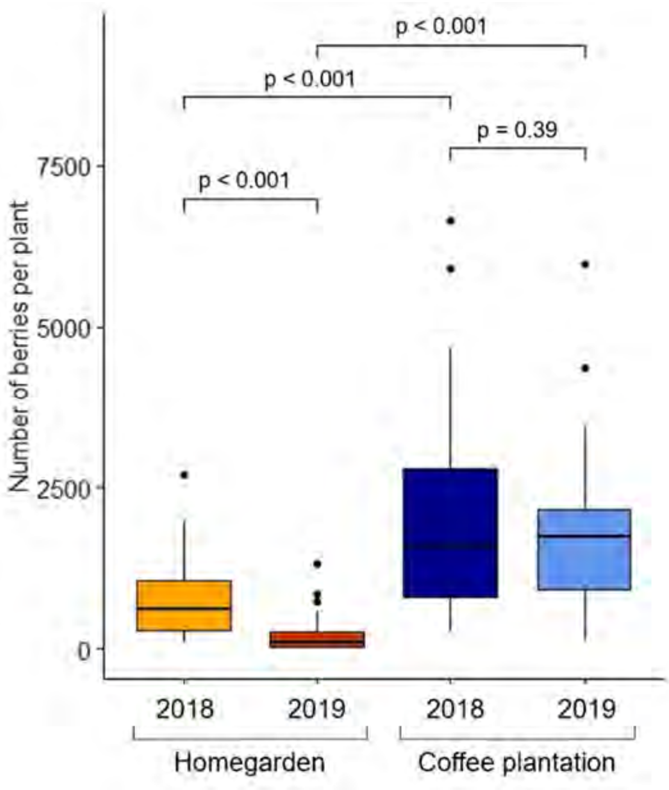


***Figure 5.3**: Coffee yield estimate for homegardens (orange and red) and coffee plantations (blue) in 2018 and 2019. The numbers on top of the brackets show the p-values of the t-test.*

5.4.2. Influence of shade on yield

I did not observe any effect of shade or tree density on yield or yield variation between years in coffee plantations (Table 5.2). For homegardens, however, yield was reduced with increasing shade density (Figure 5.4a). This was mainly due to the influence of bananas (Figure 5.4b) as tree density did not significantly influence yield (r = 0.23, p = 0.158, n = 40 in 2018; r = 0.00, p = 0.998, n = 35 in 2019). Shade density also shows a trend of reduced yield variation between years for homegardens (r = -0.30, p = 0.083, n = 35), indicating that homegardens with higher shade density might have more consistent yields.

Table 5.2*: Summary of correlation statistic for coffee plantations.*

	Shade density	Tree density	Distance to the closest tree
Yield 2018 (n = 31)	r = -0.26, p = 0.150	r = -0.17, p = 0.358	r = 0.22, p = 0.225
Yield 2019 (n = 54)	r = -0.17, p = 0.229	r = -0.06, p = 0.682	r = -0.08, p = 0.577
Yield variation (n = 31)	r = -0.17, p = 0.360	r = 0.01, p = 0.945	r = 0.02, p = 0.927

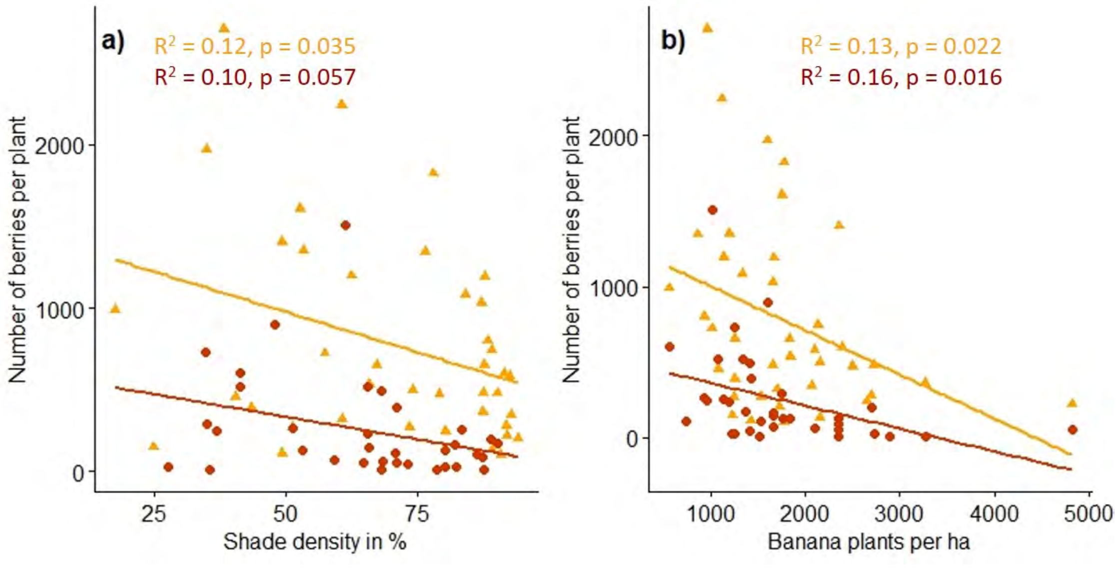


Figure 5.4*: Coffee yield estimates are correlated with a) shade density and b) banana density for homegardens in 2018 (orange, n = 40) and in 2019 (red, n = 35).*

5.4.3. Comparison of quality variables between coffee production systems and years

From harvesting to green coffee, there are several losses. The first losses are the floater berries, followed by floating beans and bad quality beans after fermenting the beans of the good berries. There are no significant differences between homegardens and coffee plantations in 2018 (Appendix 5.A). Coffee plantations in 2019 have a significantly higher proportion of floater berries than in 2018 (Appendix 5.A). They also have a significantly higher proportion of bad quality beans (Appendix 5.A); however, this difference might be explained by the fact that I employed more thorough exclusion criteria in 2019.

After drying the beans and removing the parchment, the size of the green coffee is a quality indication. Low grades (C and F) can be considered losses, as they attract low prices. The good outcomes are the sizes AB and PB, while a premium price can be realised for the biggest size AA. There is no significant difference in the distribution of grades between homegardens and coffee plantations in 2018 (Appendix 5.B). Coffee plantations in 2019, have a higher proportion of premium quality beans (Appendix 5.B).

Cumulative losses for the different production systems are presented in Figure 5.5.

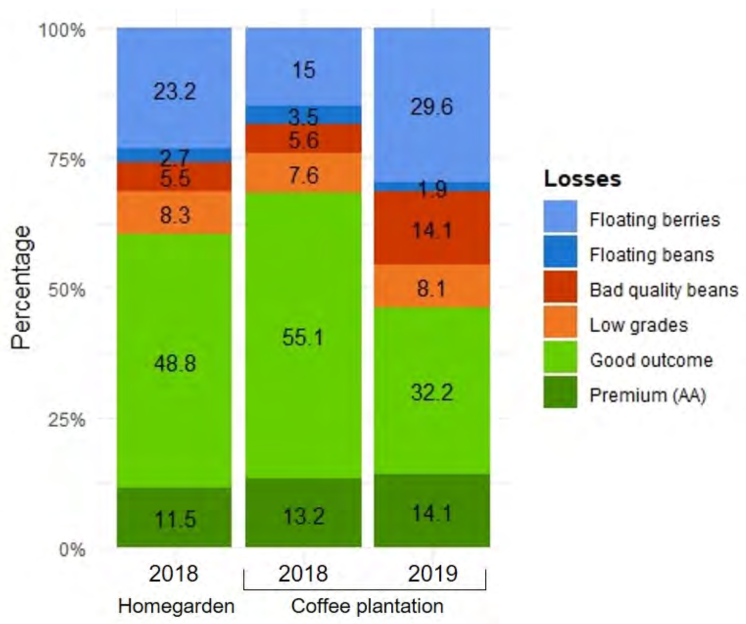


Figure 5.5: *Different losses from harvested berries and the outcome of good quality and premium coffee for homegardens in 2018 and coffee plantations in 2018 and 2019.*

Besides the percentage of losses, an important aspect is the difference in weight of coffee berries and beans. The mean weight of good coffee berries and good quality dry beans is not significantly different between homegardens and coffee plantations in 2018 (Table 5.3). When comparing years, coffee plantations in 2019 have a significantly lower mean berry weight and mean dry weight than in 2018 (Table 5.3).

***Table 5.3**: Mean weight (±SD) of good berries and beans for the different production systems and in 2018 and 2019.*

	Mean fresh weight Of berries in g	Mean dry weight of beans in g
Homegarden 2018	1.428 ± 0.179^{a}	0.161 ± 0.022^{a}
Coffee plantation 2018	1.533 ± 0.154^{a}	0.157 ± 0.018^{ab}
Coffee plantation 2019	1.323 ± 0.227^{b}	0.146 ± 0.028^{b}
	$F_{118} = 12.22$, $p < 0.001$	$F_{118} = 4.641$, $p = 0.012$

Significant differences (p-value < 0.05) between homegardens in 2018 and coffee plantations in 2018 and 2019 are marked with different letters.

The mean weight of individual grades shows no significant difference between homegardens and coffee plantations in 2018 apart from the premium grade AA, which had a significantly higher mean weight for homegardens compared to coffee plantations in 2018 (Table 5.4). The mean weight of grade AA was higher for coffee plantations in 2019 than in 2018 and the mean weight of grades AB, C and F was lower (Table 5.4).

The percent of total outcome combines weight and losses in the process from total fresh berry weight to good quality green coffee weight. There is no significant difference between homegardens and coffee plantations in 2018 ($t_{60} = 0.26$, $p = 0.799$), but the percent of total outcome is significantly lower for coffee plantations in 2019 compared to 2018 ($t_{80} = 3.14$, $p = 0.002$).

***Table 5.4**: Average bean weight (±SD) for grade sizes for the different production systems and in 2018 and 2019*

	Grade AA in g	Grade PB in g	Grade AB in g	Grade C in g	Grade F in g
Homegarden 2018	0.200 ± 0.016 [a]	0.172 ± 0.019 [a]	0.154 ± 0.015 [a]	0.117 ± 0.016 [a]	0.093 ± 0.021 [ab]
Coffee plantation 2018	0.191 ± 0.013 [b]	0.168 ± 0.019 [a]	0.151 ± 0.013 [a]	0.116 ± 0.012 [a]	0.098 ± 0.015 [a]
Coffee plantation 2019	0.199 ± 0.014 [a]	0.163 ± 0.019 [a]	0.138 ± 0.016 [b]	0.104 ± 0.014 [b]	0.085 ± 0.014 [b]
	$F_{112} = 4.89$, $p = 0.009$	$F_{116} = 2.33$, $p = 0.101$	$F_{117} = 14.40$, $p < 0.001$	$F_{116} = 10.71$, $p < 0.001$	$F_{108} = 6.68$, $p = 0.002$

Significant differences (p-value < 0.05) between homegardens in 2018 and coffee plantations in 2018 and 2019 are marked with different letters.

5.4.4. Influence of elevation on quality variables

Most quality variables are not significantly influenced by elevation. The average weight of good quality dry beans, however, increases with elevation for all production systems and all years (Figure 5.6).

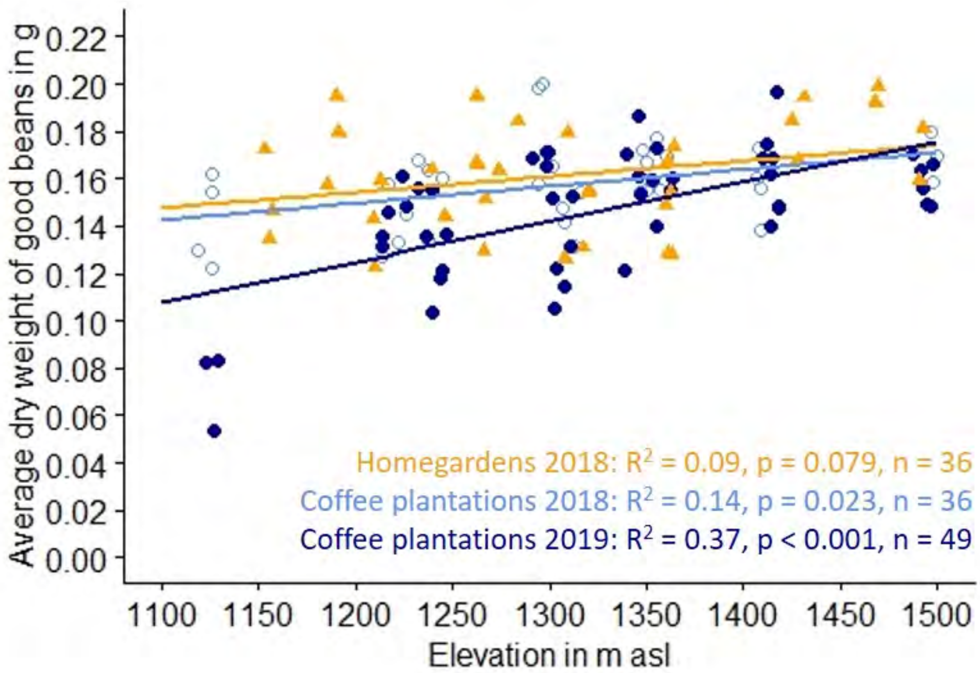


***Figure 5.6**: Average dry bean weight increases with increasing elevation.*

5.4.5. Influence of shade on quality variables in homegardens

In homegardens, increased shade density improves coffee quality. The percent of floating beans is significantly reduced with increasing shade density, mainly attributed to the presence of banana plants (Figure 5.7). Shade trees have a positive impact on coffee quality as well. The berry weight of the good berries is increased, the nearer the closest tree is (Figure 5.8a). With increasing tree density, the percent of the biggest size beans (AA) is augmented (Figure 5.8b).

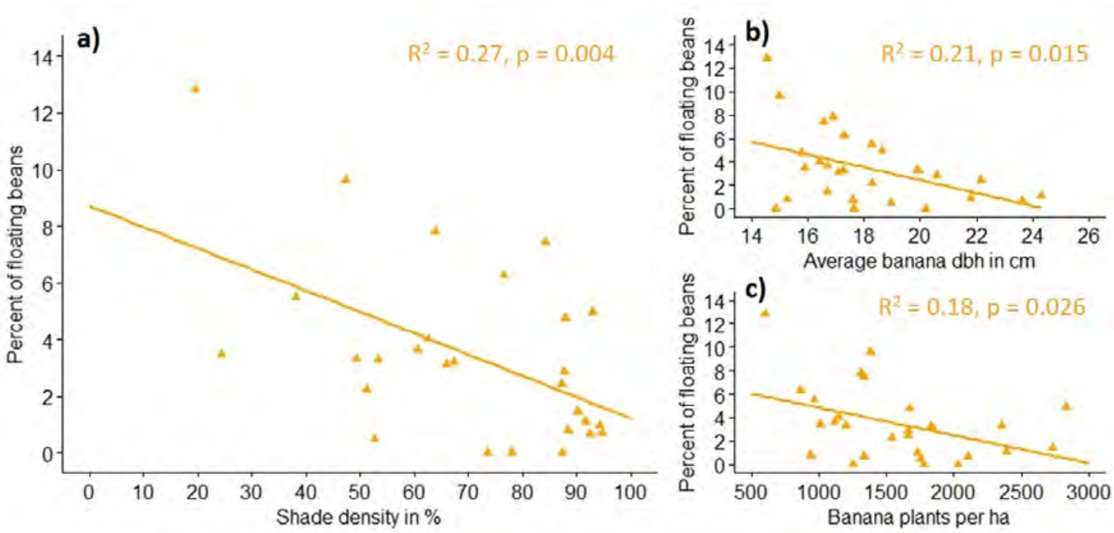


***Figure 5.7**: a) Shade density, b) banana density, and c) average banana dbh influence the proportion of floating beans in homegardens (n = 28).*

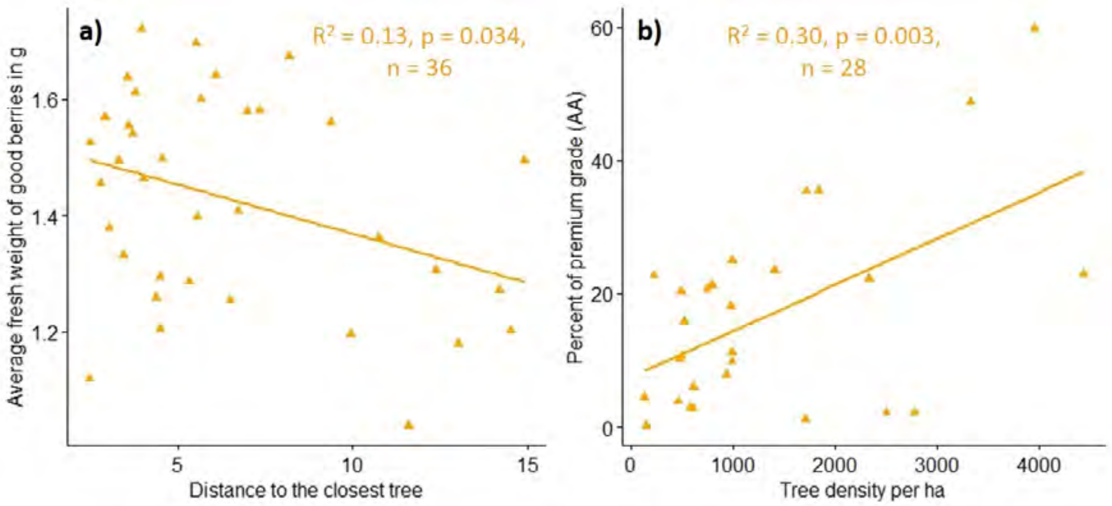


***Figure 5.8**: For homegardens a) average weight of good berries increase with reducing distance to the closest tree and b) percent of premium size (AA) increases with an increase in tree density.*

5.4.6. Influence of shade on quality variables in coffee plantations

For coffee plantations, shade has several benefits for coffee quality, especially on weight and size. Increased shade density increased the average fresh weight of good berries in 2018 (Figure 5.9a) and the average weight of dry green coffee beans of the most common grade AB in both years (Figure 5.9b). The percent of the low grades C and F were lower for coffee plantations in 2019 and 2018 respectively the closer the closest tree was (Figure 5.9c, Figure 5.9d).

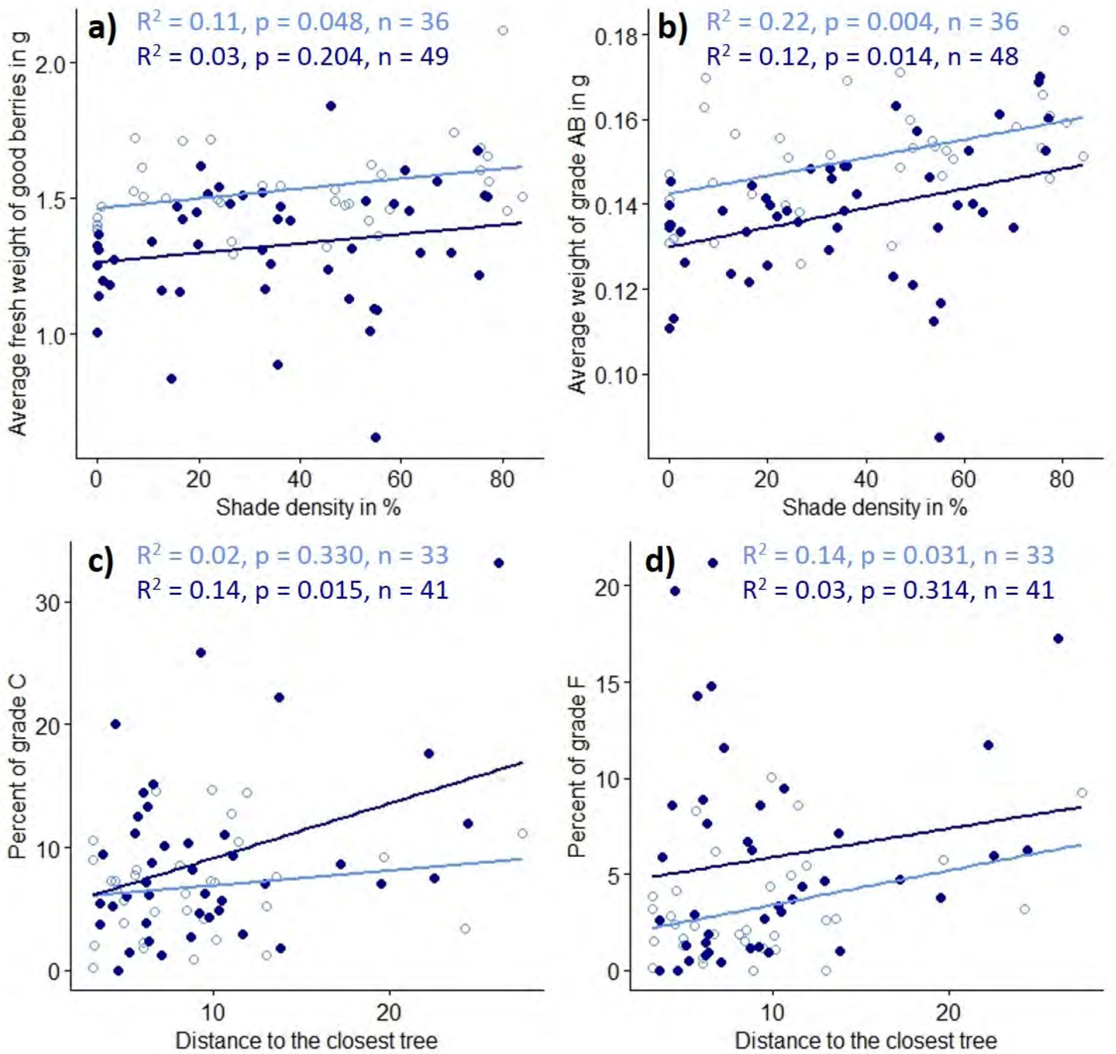


***Figure 5.9**: Effect of shade density (a, b) and distance to the closest tree (c, d) on physical quality aspects for coffee plantations in 2018 (light blue) and in 2019 (dark blue).*

5.4.7. Development of single beans

A very specific topic is the proportion of single beans (pea-berries). Homegardens had a higher proportion of single beans (27.3 ± 11.1%) than plantations in 2018 (22.1 ± 8.3%) ($t_{45} = 2.00$, $p = 0.052$). For coffee plantations, the difference between years is not significant ($t_{67} = 1.12$, $p = 0.27$) (24.2 ± 8.0% in 2019).

An increase in proportion of single beans within good berries is associated with an increase in proportion of floating beans ($r = 0.33$, $p < 0.001$, $n = 98$). A higher average berry weight of good berries is associated with a reduction of proportion of single beans ($r = -0.40$, $p < 0.001$, $n = 98$).

An interesting relationship is the reduction of pea-berries with increasing tree density for coffee plantations in 2018 and 2019 (Figure 5.10). There is an indication that shade density and shorter distance to the closest tree reduces the percent of pea-berries for homegardens, but it is only significant at individual plants rather than plot level ($r = -0.25$, $p = 0.028$, $n = 75$ for shade density; $r = 0.29$, $p = 0.011$, $n = 75$ for distance to closest tree).

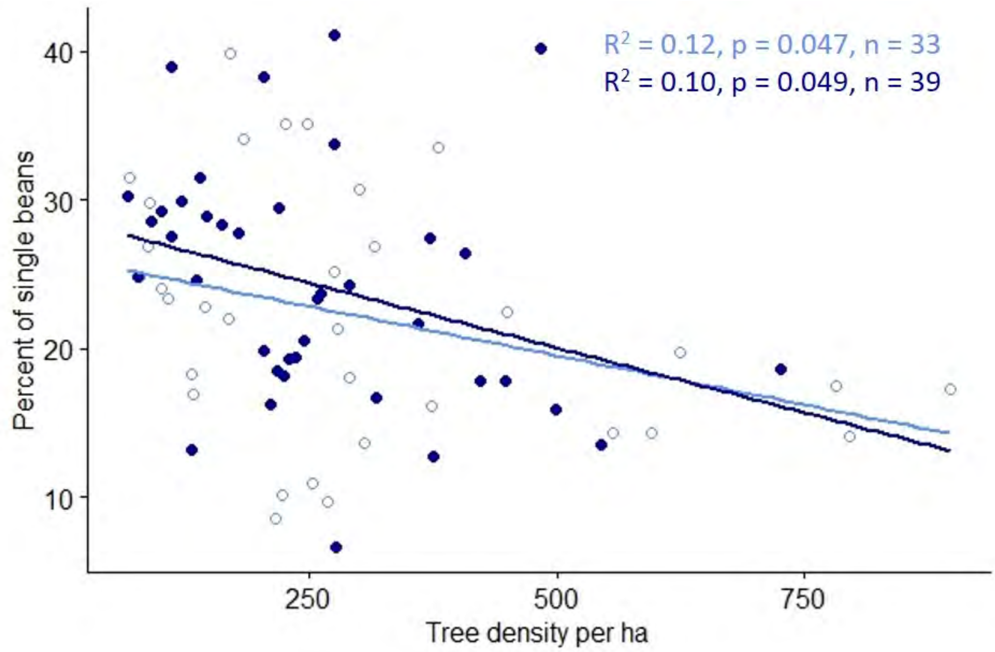


***Figure 5.10**: Increasing tree density reduces the proportion of single beans for coffee plantations in 2018 (light blue) and 2019 (dark blue).*

5.5. Discussion

5.5.1. Coffee yield in different systems

Coffee plantations and homegardens are very different coffee production systems and therefore need to be examined separately. The number of berries per coffee plant in homegardens is significantly lower than in coffee plantations and was also significantly lower in 2019 compared to 2018, while no significant difference in the yield between the years was observed for coffee plantations.

There are several possible explanations for the lower yield per plant in homegardens. Coffee plantations regularly renew their plants, either by replanting or by stumping them (cutting the coffee plant and letting a new stem grow from the stump). Homegardens on the other hand often have very old plants. The most productive years for coffee plants are between five and ten years after which yields start to reduce (Arcila-pulgarín et al. 2002). The varieties also influence yields. While coffee plantations often plant new varieties, homegarden owners still have mostly very old varieties on their fields. Irrigation was a very important factor for coffee production, especially in 2019 as it was very dry during fruit set and at the beginning of fruit development. Drought during the expansion stage can lead to increased fruit shedding and reduced berry growth, causing lower yields and smaller beans (Cannell 1985). Coffee plantations have irrigation systems in place to reduce water stress, while if at all, homegarden owners have archaic irrigation channels and do not always have access to sufficient water. This explains the reduced number of berries per plant for homegardens in 2019. Plantations further have an effective fertilisation plan in place that makes sure adequate nutrients are supplied at the right time, while smallholder farmers only fertilise when they can afford to, or they apply insufficient amounts of manure. This can cause a lack of nutrients in the development phase, increasing competition for nutrients between coffee and shade plants. Competition for light might be another factor as shade density and tree density are higher in homegardens compared to coffee plantations (Siles et al. 2010). Contrary to plantations, coffee yield in homegardens is affected by shade. An important component affecting coffee yield might be the competition with banana plants, as they provide additional shade in homegardens. The total planting density of coffee plants and banana plants combined is significantly higher than the coffee planting density in coffee plantations (3159 and 2520 plants per ha on average, respectively).

5.5.2. Effect of banana plants on coffee yield

I observed that the negative influence of shade density on coffee yield comes from increased banana density. Studies from Tanzania confirmed a strong reduction in coffee yield when intercropping with bananas (Robinson 1961; Mitchell 1963). In Uganda, the opposite effect was shown (van Asten et al. 2011). Here coffee yield increased with increasing banana density. A reason for the difference could be the difference in planting density. While the current study in Tanzania has an average banana density of 1515 banana plants per ha, the *Coffea arabica* growing area in Uganda had an average of 1055 banana plants for intercropped systems and no additional shade trees were included (van Asten et al. 2011). An increase in banana density could further indicate a shift in farmers' attention away from the coffee plants, which could affect the coffee yield. The recommended planting density for optimal productivity at Mt. Kilimanjaro is one banana plant to six coffee plants (Chipungahelo 2004). This is predicted to increase coffee revenue by 42% compared to the traditional system of one banana to one coffee plant (Chipungahelo 2004).

Besides competition for light, there could also be competition for soil nutrients and water between the plants (Beer et al. 1998). A study conducted in Uganda did not observe water competition between coffee and banana plants or shade trees as they also reported that rainfall amount and soil water content were sufficient to meet water requirements (Sarmiento-Soler et al. 2019). They reported that transpiration of the coffee-banana system was higher than for coffee mono-cropping or intercropping with *Cordia africana* (Sarmiento-Soler et al. 2019). Lower rainfall or drought events could cause water competition. However, farmers in Uganda also reported that coffee under banana plants suffers less from drought periods (Jassogne et al. 2012).

Including banana plants in coffee production systems can have several positive benefits for the farmers. Bananas are an important staple crop in the region and therefore can contribute to improving food security. Having a second crop besides coffee can improve land use efficiency and reduce the impact of coffee price volatility (Schroth et al. 2009; Jassogne et al. 2012). Farmers also use banana plants as fodder for their animals and as mulch for soil enhancement (Wagner et al. 2019). Another benefit of bananas is improved coffee quality (Jassogne et al. 2012; Wagner et al. 2019), which will be discussed in more detail below. Due to the advantages of banana plants, coffee farmers at Mt. Kilimanjaro will very likely continue to include them in their fields, despite the apparent lower coffee yield.

5.5.3. Effect of shade trees on coffee yield

I did not observe any influence of shade trees on the number of berries per plant. Potential benefits from shade trees for coffee production has been highly controversial for many years (DaMatta et al. 2007). Some researchers found positive (Vaast et al. 2008; Liu et al. 2018), while others found negative (Campanha et al. 2004; Vaast et al. 2006; Siles et al. 2010) effects of shade on coffee yield and some found no difference (Meylan et al. 2017; Rigal et al. 2020).

The difference in observations may be due to climatic and soil conditions, coffee and shade management, including shade density and shade species. More shade benefits can be observed when the environment is less favourable for coffee production (Beer et al. 1998; DaMatta 2004). Lower yields are reported under tree species with denser canopy, while tree species providing light shade did not negatively influence yields (Vaast et al. 2008; Rigal et al. 2020). Shade density for optimal production varies between locations. Under optimal conditions, in Costa Rica, shade density of 60% can reduce yield by 30% (Siles et al. 2010). In Mexico, a positive effect of shade was found for densities between 23-38% with decreasing production above 50% (Soto-Pinto et al. 2000), while models of coffee adaptation strategies to climate change at Mt. Kilimanjaro show that under current conditions 50% shade cover is the optimum at lower elevations (1000 m asl.) if water supply is not limited (Rahn et al. 2018). Therefore, optimal management to reduce competition between shade trees and coffee and to ensure adequate shade density is required.

The climate conditions at the current study site seem to be close to optimum due to the lack of influence by tree density. It needs to be emphasised that, despite potential yield losses caused by shade, shaded systems might not perform worse in overall economic terms and due to additional sources of income, can increase economic resilience (Jezeer et al. 2017).

5.5.4. Coffee yield variations

Under unshaded conditions, coffee tends to be exhausted by overbearing, leading to alternating yields and shorter tree lifespan (DaMatta 2004). Coffee flowers are initiated on vegetative parts grown in the previous coffee year, at the beginning of the rainy season (Siles et al. 2010). Under shade cover, flowering intensity is lower than under direct sunlight (DaMatta 2004; Vaast et al. 2006; Rigal et al. 2020). *Coffea arabica* evolved in a shaded environment and therefore did not develop adequate mechanisms for balancing increased fruit load under full sun exposure with available resources (Cannell 1985; DaMatta 2004). Some fruit shedding takes place during the first three months after flowering, but after the fruit expansion stage, the coffee plant will be committed to filling all the beans (Cannell 1985; DaMatta et al. 2007). It is reported, that more fruits are shed under the sun than under shaded conditions during the development, buffering some of the effects of lower flowering and leading to similar yields (Rigal et al. 2020). However, unshaded coffee has higher yield potentials due to increased flowering (DaMatta 2004). At high intensity, flowering can become an excessive sink for resources, leading to overbearing and energy shortage for vegetative growth, which is important for fruiting in the following year (DaMatta 2004). The exhaustion of overbearing leads to the stronger biannual yields often observed in unshaded coffee, it also causes branch die-back and excessive leaf shedding (DaMatta 2004). Shaded coffee might have lower yields, but buffers biannual variation, leading potentially to longer tree productivity, due to reduced exhaustion (DaMatta 2004; Vaast et al. 2006). This can also be seen from my results, showing slightly lower yield variation with increasing shade density for homegardens. Coffee plantations did not show any influence of shade on yield variation. For plantations, factors like weather condition or coffee plant age might have influenced the yield even more than the biannual variation due to overbearing in one year. Furthermore, the shade density for coffee plantations is lower than for homegardens and might not limit the flowering to the point where biannual variation is reduced.

5.5.5. Factors influencing coffee quality

The main assessment criteria for coffee quality in producing countries are physical aspects including bean colour, size, density and percentage of physical defects, while for consuming countries the main considerations are the sensory attributes (Vaast et al. 2006). These aspects are influenced by several factors including coffee variety and management (Bertrand et al. 2005, 2006; Clemente et al. 2015), elevation (Bertrand et al. 2006; Bosselmann et al. 2009), fruit load (Vaast et al. 2006; Bote and Jan 2016), environmental factors like soil, climate and geographical location (Avelino et al. 2005; DaMatta et al. 2007), and shade management (Muschler 2001; Vaast et al. 2006). An important aspect influencing beverage quality is the timing of the harvest and post-harvest processing (Knopp et al. 2006; Poltronieri and Rossi 2016).

Increasing elevation benefits coffee quality due to the lower temperatures, which facilitate a longer maturation period allowing for increased grain filling (DaMatta et al. 2007; Bosselmann et al. 2009). This leads to larger, heavier and denser beans (DaMatta et al. 2007; Bosselmann et al. 2009) (Figure 5.6) and more intense flavour (DaMatta et al. 2007). Bertrand et al. (2012) reported that positive features such as acidity, fruity character and flavour were typical for coffee produced under lower air temperature, especially during seed development. Higher temperatures and solar radiation were related to compounds that negatively influence the sensory profile (Bertrand et al. 2012).

A long dry period during maturation was observed at Mt. Kilimanjaro in 2019, which led to high losses due to insufficient fruit filling, causing an increased number of floater berries. The average berry weight and the percent of the most common good quality grade AB was lower in 2019. Interestingly, the total outcome of premium grade on coffee plants was maintained, irrespective of the overall losses. Rigal et al. (2020) also found no difference in the percentages of large beans, irrespective of fruit set and shade intensity. The only difference I observed in coffee quality between coffee plantations and homegardens in 2018 is a higher average bean weight for the premium grade AA.

Many of the factors I examined are and will be, influenced by climate change. Temperatures are rising, weather conditions are more variable and the spread of pests and diseases increases (Jaramillo et al. 2011; Craparo et al. 2015). Coffee quality is very important for the revenue farmers can generate as coffee prices increasingly depend on the quality (Ponte 2002).

5.5.6. Shade and coffee quality

In warmer climates, shade can reduce heat stress and prolong the maturation period, significantly improving coffee physical as well as sensory qualities (Muschler 2001; Vaast et al. 2006). Bigger bean size and increased weight under shade are potentially caused by a lower fruit load reducing competition for carbohydrates and nutrients (Vaast et al. 2006).

Location and elevation play a role on the influence of shade. Rigal et al. (2020) did not observe any effect of shade trees on physical and cup quality in China. At higher elevation in Colombia (1590–1730 m asl.), bean size was also not influenced by shade, but shade had a negative effect on fragrance, acidity, body, sweetness and preference of the beverage (Bosselmann et al. 2009). However, at lower elevations (1270–1630 m asl.), shade significantly reduced the percentage of smaller beans and did not have a significant effect on sensory attributes (Bosselmann et al. 2009). Under sub-optimal conditions in Costa Rica, shade improved coffee appearance and taste (Muschler 2001). Farmers and managers in Uganda reported thicker berries from intercropping coffee and bananas compared to coffee mono-cropping (Jassogne et al. 2012).

My results show that the effect of shade on coffee quality also differs between shade species. While banana plants improve the filling of beans and therefore reduce the percent of floating beans; shade trees improve bean weight and size.

Shade further influences pest infestation and disease. Shade seems to favour coffee berry borer, leading to higher infestations in shaded compared to sun-grown coffee (Staver et al. 2001; Soto-Pinto et al. 2002; Bosselmann et al. 2009; Mariño et al. 2016). Mariño et al. (2016) however, found that the total population per fruit is higher in sun-grown coffee berries and the sex ratio is more biased to females. They also observed more natural enemies of coffee berry borer (ants and entomopathogenic fungi) in shaded coffee systems (Mariño et al. 2016). Jaramillo et al. (2009) suggests the inclusion of shade trees in East African coffee systems to reduce the pressure of berry borer. Shade trees can reduce the temperature within coffee systems and each reduction of 1°C is expected to lead to an 8.5% reduction of the intrinsic rate of increase of the coffee berry borer (Jaramillo et al. 2009). Management of landscape and shade trees to reduce pest and disease incidence need to be adapted to site conditions and need to be balanced considering all relevant predators, pests and diseases that occur, as their responses to shade might differ (Beer et al. 1998; Staver et al. 2001; Karungi et al. 2015).

5.5.7. Special case of pea-berries

My data shows a reduction of pea-berries, on increasing shade density, especially for coffee plantations. It is important to note, that this is the actual single bean and not the pea-berry grade. The percent of the pea-berry grade (PB) is not significantly influenced by shade or tree density, because many pea-berries were smaller and part of the grade C or F. Muschler (2001) also observed a lower number of deformed beans such as pea-berries for shaded coffee.

Development of pea-berries similar to floating berries or beans show that the plant faced challenges during the development of the coffee bean. This can also explain the correlation I observed between those variables. While pea-berries develop during the early pinhead stage, when cell division takes place, floating berries or beans show defects during the second phase of cell expansion (Bertrand et al. 2005; DaMatta et al. 2007). The challenges could be due to heat or water stress, which explains the higher proportion of floating berries in 2019 compared to 2018. Elevation could play a role as well as heat stress might increase at lower elevations, but I did not observe this for this study site. When the fruit load is higher than the coffee plant can support, low fertilisation rates can be another stress factor causing incomplete filling of beans.

Other reported factors influencing pea-berry occurrence are genetics (Santa Ram et al. 1990; Bertrand et al. 2005) and, despite *Coffea arabica* being self-pollinating, presence of pollinators, as they seem to reduce the proportion of pea-berries (Ricketts et al. 2004; Olschewski et al. 2006).

5.6. Conclusion

This study shows that shade density can influence various aspects of coffee yield and quality. A general conclusion regarding whether increasing shade density is beneficial or disadvantageous for coffee production is not possible, as a multitude of factors determine potential benefits or disadvantages.

While yield reduction might be observed on excessively high shade density, as seen in homegardens, a proper management regime can help reduce potential trade-offs. If coffee plants are provided with sufficient nutrients and water, as is the case in coffee plantations, even high shade densities would not negatively impact coffee yield.

Some positive effects of shade have been observed for coffee quality. Shade trees were beneficial for the size and weight of coffee beans. Banana plants seem to be favourable during bean development and filling, as the percentage of floating beans was reduced. This might be very beneficial for the farmers, as coffee quality can be important for the price they can obtain. An evaluation if the quality gains can offset the potential yield losses needs to be conducted; including the required premium price point for an offset. Other aspects, like the importance of a diverse system for smallholder farmers' resilience need to considered as well. Farmers might accept lower coffee yields in exchange for the benefits provided by banana or other shade plants.

More research will be required on how shade management can be optimised to improve the systems and increase the value from shade. Examining the effect of various shade species is important as I have shown that banana plants and tree species can have different effects on coffee production.

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5.8. Appendices

Appendix 5.A: *Mean proportions of losses during coffee processing for different production systems and in 2018 and 2019 (±SD)*

	Floating berries in %	Floating beans in %	Bad quality beans in %
Homegardens 2018	23.2 ± 16.8 ^{a}	3.5 ± 3.1 ^{a}	7.2 ± 11.0 ^{a}
Coffee plantations 2018	15.0 ± 8.6 ^{a}	4.1 ± 3.5 ^{a}	6.6 ± 5.3 ^{a}
Coffee plantations 2019	29.6 ± 18.4 ^{b}	2.7 ± 1.5 ^{a}	20.0 ± 9.1 ^{b}
	$F_{101} = 8.31$, $p < 0.001$	$F_{100} = 2.74$, $p = 0.070$	$F_{100} = 28.69$, $p < 0.001$

Significant differences (p-value < 0.05) between homegardens in 2018 and coffee plantations in 2018 and 2019 are marked with different letters.

Appendix 5.B: *Mean proportions of coffee grades for different production systems and in 2018 and 2019 (±SD). The categories add up to 100% and therefore cannot be considered independent of each other.*

	Grade AA in %	Grade PB in %	Grade AB in %	Grade C in %	Grade F in %
Homegardens 2018	16.7 ± 14.7 ^{a}	14.5 ± 6.2 ^{a}	56.7 ± 16.6 ^{a}	6.9 ± 5.6 ^{a}	5.1 ± 5.8 ^{a}
Coffee plantations 2018	17.4 ± 14.9 ^{a}	12.0 ± 7.9 ^{a}	60.6 ± 13.7 ^{a}	6.8 ± 4.0 ^{a}	3.2 ± 2.7 ^{a}
Coffee plantations 2019	25.9 ± 12.4 ^{b}	14.3 ± 5.4 ^{a}	44.9 ± 11.8 ^{b}	9.0 ± 6.9 ^{a}	5.8 ± 5.5 ^{a}
	$F_{99} = 4.98$, $p = 0.009$	$F_{99} = 1.49$, $p = 0.231$	$F_{99} = 12.93$, $p < 0.001$	$F_{99} = 1.76$, $p = 0.177$	$F_{99} = 2.69$, $p = 0.073$

Significant differences (p-value < 0.05) between homegardens in 2018 and coffee plantations in 2018 and 2019 are marked with different letters.

Chapter 6: Ecosystem services and importance of common tree species in coffee-agroforestry systems: local knowledge of small-scale farmers at Mt. Kilimanjaro, Tanzania

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6.1. Abstract

Research Highlights: Global coffee production, especially in smallholder farming systems, is vulnerable and must adapt in the face of climate change. To this end, shaded agroforestry systems are a promising strategy. *Background and Objectives:* Understanding local contexts is a prerequisite for designing locally tailored systems; this can be achieved by utilizing farmers' knowledge. Our objective is to explore ecosystem services (ESs) provided by different shade tree species as perceived by farmers and possible factors (elevation, gender, and membership in local farmers groups) influencing these perceptions. We related these factors, as well as farmers' ESs preferences, to planting densities of tree species. *Materials and Methods:* During interviews with 263 small-scale coffee farmers on the southern slope of Mt. Kilimanjaro, they ranked the most common shade tree species according to perceived provision of the locally most important ESs for coffee farmers. We asked them to estimate the population of each tree species on their coffee fields and to identify the three ESs most important for their household. *Results:* Food, fodder, and fuelwood emerged as the most important ESs, with 37.8% of the respondents mentioning all three as priorities. Density of tree species perceived to provide these three ESs were significantly higher for farmers prioritizing these services compared to farmers that did not consider all three ESs in their top three. *Albizia schimperiana* scored the highest for all rankings of regulatory ESs such as coffee yield improvement, quality shade provision, and soil fertility improvement. Influence of elevation, gender, and farmer group affiliation was negligible for all rankings. *Conclusions:* This study shows the need to understand factors underlying farmers' management decisions before recommending shade tree species. Our results led to the upgrade of the online tool (shadetreeadvice.org) which generates lists of potential common shade tree species tailored to local ecological context considering individual farmers' needs.

Keywords: shade tree species; farmers' knowledge; East Africa

6.2. Introduction

Agroforestry is a promising agricultural production system due to its potential for climate change mitigation and adaptation (Lin 2007; Mbow et al. 2014; Rahn et al. 2014). Besides carbon sequestration (Jose and Bardhan 2012), shade trees also improve local climatic conditions and reduce variability in microclimate and soil moisture (Lin 2007). Agroforestry is particularly important for coffee (*Coffea arabica* L.) production as climate change is expected to reduce the suitable production area for crops such as coffee (Adhikari et al. 2015; Craparo et al. 2015; Bunn et al. 2015). In addition to regulatory services, the associated shade tree species can provide various direct ecosystem services (ESs) such as food, fodder, or fuelwood (Reed et al. 2017). Furthermore, due to their diversity, agroforestry systems have the potential to provide diverse income sources which may act as social safety nets, increasing farmers' economic resilience in the face of coffee price volatility in global markets and possible crop failures (Bacon 2005; Tscharntke et al. 2011; Charles et al. 2013; Reed et al. 2017). However, ecological conditions, competition among associated species in the system, and farmers' individual objectives need to be considered in designing agroforestry systems to maximize the benefits and minimize the shortcomings of these systems (Beer et al. 1998; Schroth et al. 2001).

Farmers can be very knowledgeable on factors that influence coffee productivity. From experience, they are aware of interaction(s) between shade tree species and coffee, as well as many direct ESs provided by specific tree species (Cerdán et al. 2012; Lamond et al. 2016). In some areas, however (e.g., the impact of individual tree species on pests and diseases), their knowledge might be limited (Liebig et al. 2016; Gram et al. 2018; Rigal et al. 2018). Nevertheless, exploring farmers' knowledge might provide novel insights into interactions between shade tree species and coffee productivity. This local knowledge is vital in tailoring recommendations to local conditions.

Although several studies have investigated how the Chagga people living on Mt. Kilimanjaro in Tanzania use their natural environment (Fernandes et al. 1985; Hemp 1999; Hemp and Hemp 2009; Mollel et al. 2017), research has so far not identified which tree species are considered superior in providing relevant ESs for the local coffee farmers. Our aim is to assess indigenous knowledge of local farmers on Mt. Kilimanjaro regarding selection of shade trees that enhance coffee production and provide other ESs. A participatory approach based on van der Wolf et al. (2016) allowed us to collect and study farmers' knowledge regarding shade tree species' provision of ESs. Following this approach, we identified shade tree species with high potential for coffee agroforestry systems on the southern slopes of Mt. Kilimanjaro. Similar studies have been conducted in other East African countries and the differences in findings (Lamond et al. 2016; Gram et al. 2018; Bukomeko et al. 2019; Smith Dumont et al. 2019) demonstrate the importance of locally specific investigations.

In this study, we explore the ESs provided by different shade tree species as perceived by farmers. We further examine if elevation, gender, and membership in local farmers' groups influence the perceived ESs provided, and the planting density of different shade tree species. Farm management may be based on farmers' knowledge and preference for specific shade tree species (Lamond et al. 2016). Therefore, we expect that the planting density of tree species will depend on the perceived ESs the tree species provides, as well as farmers' ESs preference.

The study aims to contribute to expanding the database of the online decision-support tool for tree selection in smallholder farming systems (shadetreeadvice.org) (van der Wolf et al. 2016) and help tailor recommendations for important shade tree species for coffee farmers on Mt. Kilimanjaro.

6.3. Material and Methods

6.3.1. Study site

The research took place on the southern slopes of Mt. Kilimanjaro in Tanzania (Latitude 3°13'9" S–3°17'41" S; Longitude 37°9'24" E–37°25'19" E) (Figure 6.1). Here, the Chagga people have cultivated and converted the former forest into an agroforestry system (the so-called Chagga homegardens) over several centuries (Hemp and Hemp 2009). The main cultivation zone of *C. arabica* in these traditional coffee-banana plantations is located between 1000 m and 1800 m asl (Hemp 2006) and covers an area of nearly 80,000 ha (Hemp et al. 2017). Kilimanjaro National Park prevents expansion of coffee cultivation into higher elevations (Fernandes et al. 1985). For our study area, Hemp Hemp (2006) reports annual rainfall in the lower slopes (800 m to 1300 m asl) of between 900 mm to 1580 mm, and 1580 mm to 2200 mm at the higher slopes (1300 m to 1800 m asl) and mean annual temperatures of 23.4 to 18.8 °C and 18.8 to 16.1 °C, respectively.

Coffee farmers from eight communities participated in this study. Six communities work with the non-government organization Hanns R. Neumann Stiftung (HRNS) (Isuki, Lemira Mroma, Masama Mula, Mudio, Kiwakabo, and Mbokomu); two communities have no connection to the HRNS, are located in the center of the southern slope (Narum and Mweka), and were included in the study to have a wider representation of the study area (Figure 6.1).

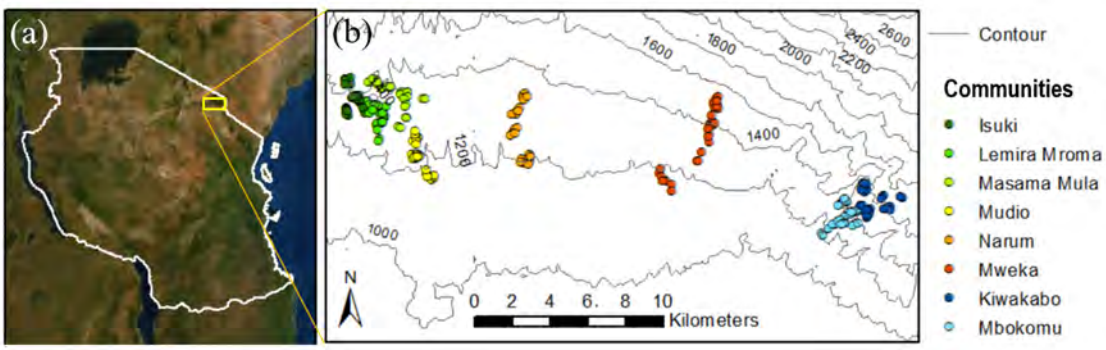

***Figure 6.1**. Location of the research area within Tanzania (a) and the distribution of the respondents along the southern slope of Mt. Kilimanjaro, divided into the eight communities (b).*

6.3.2. Identification of Common Tree Species and Important Ecosystem Services

To identify the most common tree species and most important ESs for coffee farmers of the study area for subsequent data collection, we conducted focus group discussions (FGDs) (Smithson 2008). In March 2019, we conducted three FGDs in the west (Isuki, Masama Mula and Mudio) and two FGDs in the east (Kiwakabo and Mbokomo). Participants were coffee farmers representing farmers' groups and independent farmers from the same community. Each FGD had between 9 and 15 attendees, leading to a total of 56 attendees.

The list of tree species that participants could choose from was based on Hemp (Hemp 2006), and the results of an investigation of 40 plots of Chagga homegardens in Narum and Mweka (unpublished data). As small-scale farmers in this region commonly intercropped coffee and banana (*Musa* spp.), we included the latter as a shade species. This resulted in an initial list of 58 shade tree species. We prepared technical sheets for each shade tree species showing pictures of the plant or plant parts, as well as the local name. We presented these sheets to the focus groups and asked them to rank the shade tree species according to their frequency in coffee fields in their area. Tree species shown to each FGD were then added or removed from the presented list of trees based on their rankings during previous FDGs. In subsequent data collection interviews with individual farmers, we only used the most common shade tree species. This list was composed of 22 tree species that were either ranked in the top 20 in at least three FGDs or in the top 10 of any single FGD (see the species listed in Table S1).

For identification of the locally most important ESs for farmers, we presented 25 ESs to the focus groups and asked the participants to add any additional ESs they considered important. The groups then ranked the services according to their perceived importance, giving us the final list of the 12 locally most important ESs for subsequent data collection interviews. The list included nine ESs that were ranked in the top 12 of at least four FGDs (food provision, shade provision, protection against wind, protection from heat, fodder supply, mulch provision, increased coffee yield, soil fertility improvement, and weed suppression); one ES ranked number four in one FGD and in the top 10 of two other FGDs (increasing coffee quality); one ES ranked as number two in two FGDs, but below 10 in all other FGDs (firewood supply); and one ES ranked as number one in one FGD, but only in the top 10 in one other FGD (soil moisture enhancement) (see all ESs listed in Table S2).

6.3.3. Shade Tree Species Ranking for Ecosystem Services

Ranking the most common tree species according to the most important ESs was the focus of data collection interviews with 263 small-scale coffee farmers along the southern slope of Mt. Kilimanjaro (Figure 6.1). In March and April 2019, we conducted at least 30 individual interviews in each community (Figure 6.1). We began with farmers that participated in the FGDs or whose farm we investigated; we then interviewed occupants of the fifth house away in each direction along the road. If the person in the fifth house was not a coffee farmer, declined participation, or was absent at the time, we asked at the next house(s) until a respondent was identified.

The respondents were asked to select the 10 tree species that they knew best out of the list of 22 most common shade tree species (van der Wolf et al. 2016). They were then asked to rank the 10 chosen shade tree species for each of the 12 locally most important ESs from the best (high provision of this ES) to the least performing (low provision of this ES) (van der Wolf et al. 2016; Gram et al. 2018). We also recorded gender, membership of the HRNS, and elevation of the respondents' home (using a GARMIN GPSMAP 64). We asked the respondents to name the three most important ESs for their household and the estimated number of individuals of the different tree species they had on their coffee fields, as well as the size of their coffee farm.

6.3.4. Data Analysis

We noted the number of tree species each farmer had of the 22 most common shade tree species, the percentage of farmers having each tree species in their fields, and the planting density of each tree species, using farmers' estimated number of trees and farm size. To identify the influence of elevation on the tree planting density of different tree species, we did linear regressions for each common shade tree species in R 3.5.0 (R Core Team 2018). We summarized the ESs respondents considered most important and tested gender differences with a chi-square test in R 3.5.0 (R Core Team 2018).

Based on the method of van der Wolf, et al. (van der Wolf et al. 2016), we used the BradleyTerry2 package in R 3.5.0 (R Core Team 2018) to identify shade tree species best at providing specific ESs, as perceived by the farmers. We excluded interview respondents with less than five years of experience as well as tree species that were ranked less than 10 times for a particular ESs (Rigal et al. 2018); this left 20 of the 22 tree species in the analysis. As explained by Rigal el al. (Rigal et al. 2018), the ranks for each ESs need to be converted into pairwise comparisons to fit the Bradley-Terry model. For each tree species and ES, this model calculates scores, which are comparative values representing the likelihood that one tree species performs better than another tree species in providing an ES (Rigal et al. 2018). We normalized the scores between 0 and 1 to be able to compare them (Rigal et al. 2018). Besides the scores, quasi-standard errors were calculated to indicate how frequently a species was included in the ranking and how consistently the respondents ranked this species (Rigal et al. 2018). We compared the scores pairwise using a Wald test. The more pairs that are significantly different, the more it reflects an agreement of farmers upon the ranking of the tree species. Therefore, large numbers of pairs that are significantly different indicate that the analysis is robust (Rigal et al. 2018). In our results, the lowest percent of pairs that were different was 67%, and the highest was 89%.

To assess the influence of farmers' objectives on their management practices, we compared shade tree densities on coffee farms between groups of farmers with different sets of priorities. More specifically, we split respondents into two groups: those who had selected the combination of the three most important ESs for small-scale coffee farmer households at Mt. Kilimanjaro as their top three priorities and those who had not. We then compared the shade tree density of species perceived to perform high for the combination of these ESs and tested differences between the two farmer groups using t-tests in R 3.5.0 (R Core Team 2018).

To identify if gender, affiliation to a farmers' group, or elevation influenced perceived provision of ESs by shade tree species, we split the data sets by gender, membership of the HRNS, and into two elevation groups (threshold was the median 1336 m asl). We ran the BradleyTerry analysis for these subgroups of respondents and compared the resulting scores (Lamond et al. 2016; Gram et al. 2018).

6.3.5. Ethical Approval

Ethical approval for this study was obtained from the Faculty Research Ethics and Governance Committees of the Manchester Metropolitan University, Faculty of Science and Engineering, on 26 May 2017, with application code SE1617108C.

6.4. Results

6.4.1. Main Characteristics of Respondent

Of the total respondents, 96 were women (36.5%) and 167 men (63.5%). The farm size ranged between 0.1 and 8 ha, the average farm size was 0.7 ha with 83.3% (219 respondents) having less than 1 ha. The elevation ranged from 1148 m to 1748 m asl, with an average elevation of 1343 m asl and a median elevation of 1336 m asl (Figure 6.2). Ninety-seven respondents (37%) were members of the HRNS, while 166 were non-members (63%).

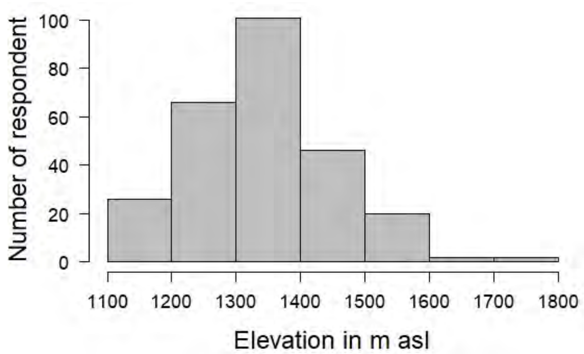

***Figure 6.2**. Distribution of respondents along elevation.*

6.4.2. Tree Species Distribution

Sixty percent of the farmers reported that they had 10 or more of the 22 most common shade tree species on their coffee farms. The most common shade tree species is *Musa* spp. grown by all respondents, followed by *Grevillea robusta* A. Cunn. ex R. Br., *Albizia schimperiana* Oliv., and *Persea americana* Miller with 94.3%, 90.9%, and 83.7%, respectively (Figure 6.3). *Musa* spp. is by far the shade species with the highest density (1089 ± 106 tree ha^{-1}) (Figure 6.3). *Grevillea robusta* is second densest (39.1 ± 3.29 tree ha^{-1}), closely followed by *Markhamia lutea* (Benth.) K. Schum. (26.6 ± 4.90 tree ha^{-1}). Just a few farmers (about 20 percent) grow *M. lutea*. However, those that do grow it have a high density of the species on their fields. Despite their presence on more than 83% of coffee farms, the densities of *A. schimperiana* (7.9 ± 0.46 tree ha^{-1}) and

P. americana (12.3±0.98 tree ha^{-1}) are significantly lower than those of the above species (Figure 6.3).

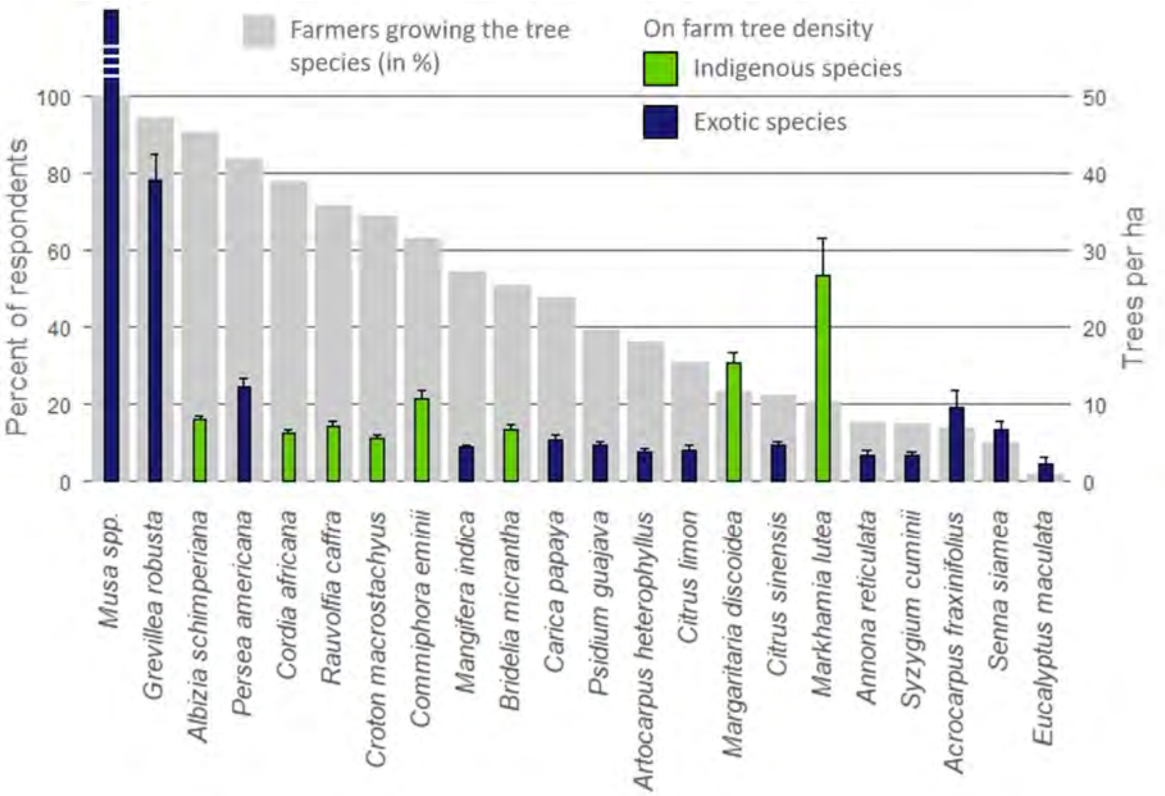

Figure 6.3. *Percent of respondents reporting each species on their farm and average (+SE) tree density on those farms. The density of Musa spp. is much higher than the scale shown in the graph (1089 trees per ha on average).*

Neither the total shade tree density nor the *Musa* spp. density are significantly influenced by elevation. However, we observed differences in density of some tree species. Linear regressions show significant reduction in densities of *Cordia africana* Lam. ($F_{(1,261)} = 12.91$, $p < 0.001$), *Mangifera indica* L. ($F_{(1,261)} = 5.03$, $p = 0.026$) and *Senna siamea* (Lam.) H. S. Irwin & Barneby ($F_{(1,261)} = 3.96$, $p = 0.048$) with increasing elevation—the densities are reduced by 1.1 tree ha^{-1}, 0.4 tree ha^{-1} and 0.3 tree ha^{-1} respectively for every 100 m increase. We detected a significant increase in density towards higher elevations for *Margaritaria discoidea* (Baill.) G. L. Webster ($F_{(1,261)} = 30.88$, $p < 0.001$) and *P. americana* ($F_{(1,261)} = 11.77$, $p < 0.001$) (with an increase of 100 m, the density increases by 2.4 tree ha^{-1} and 2.7 tree ha^{-1} respectively).

6.4.3. Important Ecosystem Services

On the southern slope of Mt. Kilimanjaro, food provisioning is by far the most essential ES for coffee farmers. Of the 263 respondents, more than 75% selected food provision as the most important ES for their household, and more than 95% ranked it in the top three (Table 6.1). The second locally most important ESs is fuelwood supply, which was ranked first by 10% of the respondents and within the top three ESs by nearly 60% of the respondents (Table 6.1). More than 50% of the respondents also ranked fodder supply among the top three ESs, followed by shade provision, soil fertility improvement and increased coffee yield (Table 6.1). A chi-square test showed no significant differences in ES preference between genders. The only significant difference between the two elevation groups was that respondents at a higher elevation included soil moisture enhancement more often in the top three ESs than respondents at lower elevation (4.4% and 1.0% respectively, $X^2 = 7.2$, $p < 0.01$).

***Table 6.1**. Ranking of Ecosystem services on a household level.*

Ecosystem services (ESs)	Selected as first ES	Among the first 3 ESs
Food provision	76.4%	95.4%
Firewood supply	10.3%	59.5%
Fodder supply	2.7%	55.3%
Shade provision	3.4%	31.7%
Soil fertility improvement	2.7%	17.2%
Increased coffee yield	0.0%	15.6%
Soil moisture enhancement	1.5%	8.0%
Increased coffee quality	0.8%	5.7%
Protection against wind	1.1%	5.3%
Mulch provision	0.8%	3.4%
Protection from heat	0.0%	1.5%
Weed suppression	0.4%	1.1%

6.4.4. Pairwise Comparison

The analysis shows that the ranking of shade tree species is consistent for most ESs. We observed the clearest discrimination between tree species in the ranking for mulch provision and protection from heat with 89.1% and 87.9% of the pairwise comparisons of tree species' scores being significantly different ($p < 0.05$), followed by increase in coffee yield and quality (Table 6.2). Most difficult to rank were weed suppression, food provision, and protection against wind with 66.7%, 71.1%, and 72.5% of all pairs being significantly different ($p < 0.05$) (Table 6.2).

***Table 6.2**. Percent of significantly different pairwise comparisons of species' scores*

Ecosystem service	**Number of tree species included in the ranking**	**Percent of significant differences between pairs ($p < 0.05$)**
Mulch provision	11	89.1
Protection from heat	12	87.9
Increased coffee yield	11	87.3
Increased coffee quality	10	86.7
Soil moisture enhancement	11	85.5
Shade provision	12	84.8
Fodder supply	11	83.6
Firewood supply	13	82.1
Soil fertility improvement	13	76.9
Protection against wind	16	72.5
Food provision	10	71.1
Weed suppression	13	66.7

6.4.5. Tree Ranking

Scores of the tree species ranked according to the three most important ESs for small-scale coffee farmers at the southern slopes of Mt. Kilimanjaro show major differences (Figure 6.4). Of the most common tree species providing food, all are exotic. Firewood is mainly obtained from indigenous species, except for *G. robusta*, which is exotic.

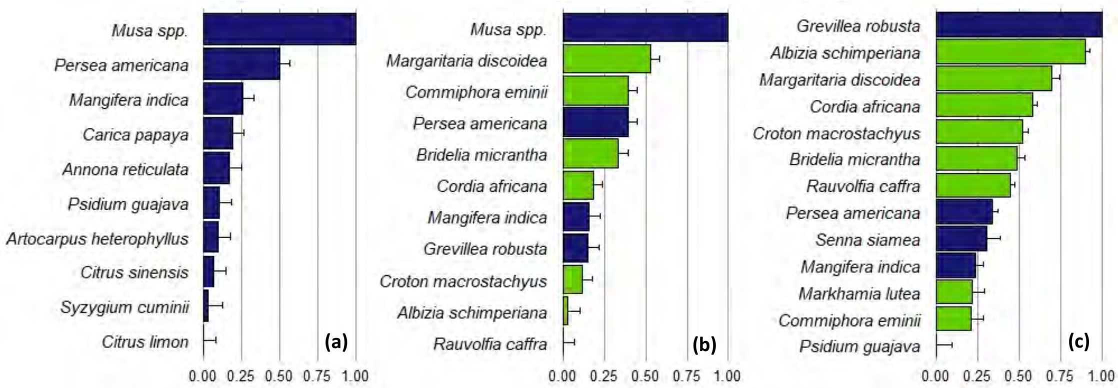

***Figure 6.4**. Scores and quasi-standard errors of tree species for (a) food provision, (b) fodder supply and (c) firewood supply. Dark blue bars represent exotic, and green bars indigenous tree species.*

For a better recommendation of tree species regarding multiple regulatory ESs associated with coffee production, the following ESs were combined into three categories: (a) coffee production enhancement (combining increase in coffee yield and quality), (b) protection from climatic hazards (combining protection from heat, wind and shade provision), (c) soil quality enhancement (combining mulch provision, soil fertility and soil moisture enhancement). For each ES category, the scores of shade tree species were averaged over the set of combined ESs (Figure 6.4).

Albizia schimperiana is the highest ranked tree species for all three ES categories. Also within the top five for all three ES categories are *C. africana*, *Croton macrostachyus* Hochst. ex Delile, and *Rauvolfia caffra* Sond.. All of these tree species are indigenous. *Musa* spp. is important for coffee yield and quality, as well as for soil enhancement, while *G. robusta* contributes to protection from climatic hazards and soil quality enhancement.

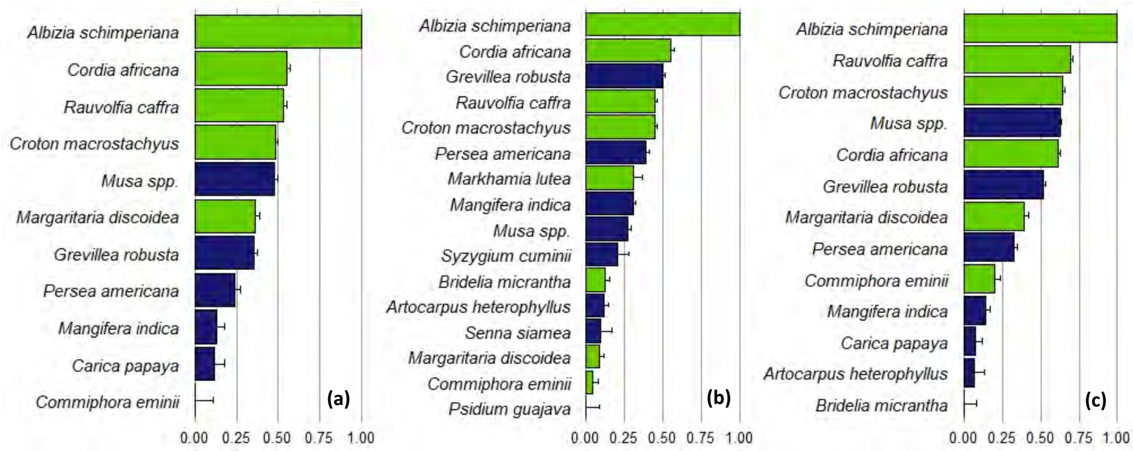

Figure 6.4*. Scores and quasi-standard errors of the tree species ranked according to: (a) increase of coffee yield and quality, (b) protection from heat, wind and shade provision and (c) mulch provision, soil fertility and soil moisture enhancement. Green bars represent indigenous, and dark blue bars exotic tree species.*

6.4.6. Effect of Priorities on Shade Tree Density

Food, fodder, and firewood are the most important ESs for small-scale coffee farmer households (99 respondents (37.8%) selected this combination). To assess the influence ES priorities have on tree species selection, we averaged the scores of each shade tree species for the combination of these three ESs and compared the density of the five best performing tree species between two groups: respondents that selected these three ESs as most important versus those that did not. The planting density of three of these five tree species is significantly higher (*t*-test, $p < 0.05$) for respondents that selected these ESs as most important compared to those that did not (Figure 6.5). We found differences for exotic, but not indigenous species.

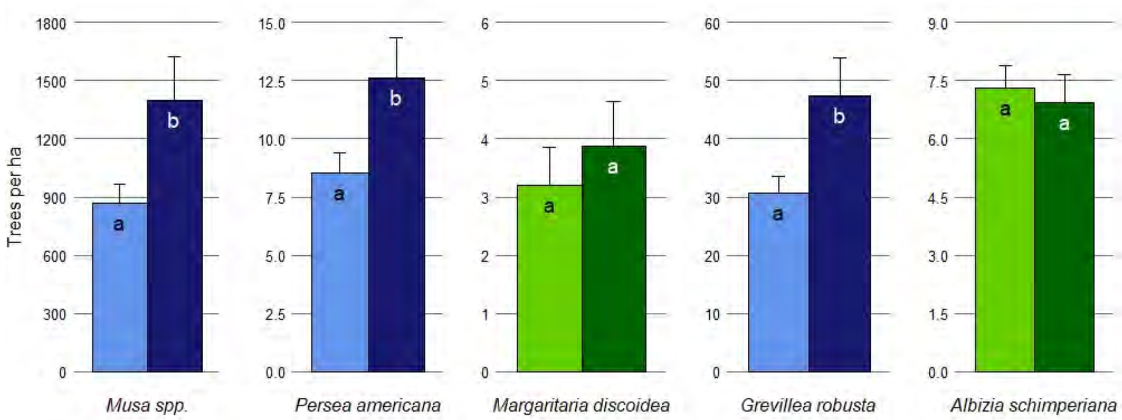

***Figure 6.5**. Average (+SE) plant density of the five highest ranked tree species providing the services food, fodder and firewood. The dark bars show respondents who selected the three ESs as the three most important for their family, while the light bars indicate the plant density for respondents who did not select all three. Significant difference between plant density is shown by difference in letters (a and b) ($p < 0.05$). Blue bars represent exotic, and green bars indigenous species.*

6.4.7. Elevation, Gender, and Farmer Group Affiliation

The ranking in higher elevations was not significantly different from the lower elevations. The only deviation we observed is that *M. indica* was included in the ranking of shade tree species providing fodder for the lower elevations, while *R. caffra* was included in the higher elevations (Figure S1). Farmers did, however, rank both of these tree species low for this ES.

There were slight differences considering gender and affiliation to a farmers group of the HRNS. Women included *Annona reticulata* L. in their ranking for food provision, and they ranked *Musa* spp. significantly higher for shade provision and soil fertility compared to men. Men ranked *G. robusta* significantly higher for shade provision, while *R. caffra* was ranked higher for soil fertility (Figure S2). Respondents that were members of HRNS ranked *M. discoidea* significantly higher than non-members for protection from heat (Figure S3). For coffee quality, members of HRNS ranked *C. macrostachyus* significantly higher and *Musa* spp. significantly lower than non-members (Figure S3).

6.5. Discussion

6.5.1. Important Ecosystem Services

Nearly all the farmers in our study area considered food provision by shade trees their top priority, followed by the provisioning services fodder and fuelwood supply (Table 6.1). These ESs were considered more important than regulatory services for coffee production such as shade provision, soil fertility improvement, and increased coffee yield. ES priorities were not significantly different between genders. Respondents of other studies have various priorities. At Mt. Elgon (Uganda), farmers rather prioritized ESs such as mulch provision, erosion control and temperature regulation (Gram et al. 2018), coffee yield, soil moisture enhancement, and quick leaf decomposition in Central Uganda (Bukomeko et al. 2019). Differences in the importance of ESs may reflect differences in environmental conditions, as well as market access (Graefe et al. 2017; Gram et al. 2018). One reason participants of the FGDs mentioned for excluding timber from the list of important ESs was the political limitation of tree harvesting (Parliament of the United Republic of Tanzania 2002). The complexity of agroforestry systems and diverse interactions between different pests and predators on a land-scale level (Staver et al. 2001; Teodoro et al. 2009; De la Mora et al. 2015; Martínez-Salinas et al. 2016) might be the reason coffee farmers at Mt. Kilimanjaro did not observe any effect of shade tree species on pests and did not consider it an important ESs provided by shade trees.

6.5.2. Highly Ranked Tree Species

Albizia schimperiana is the most important shade tree species for coffee production on the southern slope of Mt. Kilimanjaro for the provision of most ESs included in this study. Several studies also report the importance of *A. schimperiana* for coffee production in Ethiopia (Tadesse et al. 2014; De Beenhouwer et al. 2016; Belay et al. 2018). As a leguminous plant, *A. schimperiana* can form a symbiotic relationship with rhizobia bacteria to fix atmospheric nitrogen, resulting in increased soil fertility. Other studies also show that, with an open wide-spreading crown, *A. schimperiana* provides good shade cover for coffee production, leading to improved microclimate and coffee yield (Hemp 2006; Kufa et al. 2007). Another advantage of *A. schimperiana* is that its leaves emerge in the dry season (Belay et al. 2018). This means it can provide shade when there is a lot of sun and prevents coffee from being too densely shaded during the rainy season.

Despite the benefits of *A. schimperiana* and the perceived provision of multiple regulatory ESs by coffee farmers at Mt. Kilimanjaro, other tree species occurred at a much higher density (Figure 6.3). From general observations, it seems that the farms have mostly mature trees and that a new generation of *A. schimperiana* is missing. More research on the population structure of *A. schimperiana* in this area is required to get a better understanding of future development and challenges. Belay et al. (2018) found for their study region in Ethiopia that the population structure of *A. schimperiana* had a U-shape with more stems in lower and higher diameter classes, showing selective cutting or extraction of medium sized individuals. Potential explanations could be the increased exploitation of *A. schimperiana* for timber and fuelwood, and its low growth rate (Mbuya et al. 1994; Tadesse et al. 2014). Other important aspects to examine are natural regeneration and the success of propagation.

A closely related species that commercial coffee plantations commonly include in their fields is *Albizia gummifera* (J. F. Gmel.) C. A. Sm.. This species is favored by farmers in Ethiopia (Ango et al. 2014; Denu et al. 2016). Other *Albizia* species are considered important for providing multiple ESs in East Africa, such as, but not limited to, mulch, shade, improvement of microclimate, coffee yield and soil moisture in Uganda (Gram et al. 2018; Bukomeko et al. 2019). Unfortunately some *Albizia* species are also alternative hosts for black coffee twig borer in the closely related Robusta coffee (*Coffea canephora* Pierre ex Froehn.) posing a potential risk (van der Wolf et al. 2016).

The other three shade tree species associated with improvements of conditions for coffee production are also indigenous (*C. africana*, *C. macrostachyus* and *R. caffra*). *Rauvolfia caffra* ranked as an important shade tree species which is in line with other findings from Mt. Kilimanjaro (Hemp 2006; Mollel et al. 2017). Fernandes et al. (1985)

report the potential of *R. caffra* to suppress various coffee pests. Its contribution to the production of traditional banana beer underlines its importance in traditional Chagga homegardens (Fernandes et al. 1985; Mbuya et al. 1994; Mollel et al. 2017). *Croton macrostachyus* provides good litter, preserves soil moisture, facilitating high coffee yield and high bean weight (Ebisa 2014). *Cordia africana* is also reported as an essential shade tree in coffee production in Kenya (Lamond et al. 2016), Uganda (Gram et al. 2018) and Ethiopia (Teketay and Tegineh 1991; Denu et al. 2016). Even though Kufa et al. (2007) found high coffee yields under *C. africana*, they also reported the highest yield variations under this tree species. As *C. africana* is a high quality timber tree, the economic value might be a major reason for farmers to grow it (Ebisa 2014; Denu et al. 2016).

Even though the four tree species discussed above (*A. schimperiana*, *C. africana*, *C. macrostachyus,* and *R. caffra*) are multipurpose tree species and considered the best to enhance soil quality, create a suitable environment for coffee production and benefit coffee yield and quality, their densities in coffee farms were lower than that of the exotic fast growing *G. robusta* (Figure 6.3). In Kenya, native tree species were also considered to provide a healthy environment, but their abundance was low due to their slow growth rate (Lamond et al. 2016). In Tanzania, another reason for the preference of *G. robusta* might be that the wood can be utilized more easily than for native tree species, as native tree species require a permit to be cut down (Parliament of the United Republic of Tanzania 2002; Nath et al. 2016).

Farmers' management decisions to plant or remove a certain tree species in their plantations is usually based on their knowledge or tree preference (Cerdán et al. 2012; Valencia et al. 2015; Lamond et al. 2016). We therefore need to look at their ESs priorities as socio-economic factors might influence farmers' choices for on-field composition. Our results confirm that the density of exotic tree species perceived to provide food, fodder and fuelwood are higher when farmers prioritize these ESs (Figure 6.5). This is especially the case when the tree species are exotic, as their presence in the field is usually due to management rather than natural occurrences. Some other studies also show the importance of shade tree species for coffee production is matched with their planting densities (Denu et al. 2016; Belay et al. 2018). Bukomenko, et al. (Bukomeko et al. 2019), however, found a mismatch between ESs that are important for respondents and the trees they have on their fields. Graefe et al. (2017) used a similar methodology for cocoa production in Ghana and also reported disparities between higher ranked tree species suitable for cocoa intercropping and their abundance in the northern part of the cocoa belt with marginal conditions for cocoa production. This might be an adaptation strategy to diversify income, since they confirmed our findings for farms in the wetter southern region with optimal cocoa production conditions (Graefe et al. 2017). The match between shade tree density and prioritized ESs appears to be more consistent with direct short- or mid-term benefits for farmers, such as food, fodder, and firewood supply, rather than regulatory service provisioning, such as climate modification and soil fertility improvement (Lamond et al. 2016). This becomes evident from the lower density of *A. schimperiana* (the most highly ranked tree species for regulatory services) in comparison to *G. robusta* and *P. americana*, which provide direct outputs like fuelwood and food (Figure 6.3). Our findings stress the importance of understanding the socio-economic component when investigating tree species distribution.

6.5.3. Factors Influencing Tree Species Ranking and Distribution

The first factor influencing tree species distribution, as just discussed, is farmers' preference and the ESs they consider important for their household.

In general, there is agreement on the ranking of tree species among small-scale coffee farmers at Mt. Kilimanjaro. We can confirm the finding by Gram et al. (2018) that local knowledge regarding ranking of tree species is gender blind, as there were negligible differences in our study. Besides gender, participation in a farmer group did not influence the ranking. Farmers participating in farmer groups meet regularly, receive trainings and exchange knowledge and therefore might have better access to different information sources. This could have led to ranking differences, as other researchers have shown the influence of promotion activities of certain tree species on the perception and distribution of those species (Valencia et al. 2015; Rigal et al. 2018). In

Kenya, *G. robusta* was considered suitable for intercropping with coffee, despite having similar traits to those of tree species believed to negatively affect coffee production (Lamond et al. 2016). For example, the root system for both *Eucalyptus* spp. and *G. robusta* are perceived to be wide spreading (Lamond et al. 2016). This discrepancy in perception of different tree species could be due to promotion activities from extension services (Lamond et al. 2016). Such biases need to be considered when using local knowledge to inform recommendations.

Some studies report an influence of elevation on the distribution and ranking of tree species in East Africa (Hemp 2006; Gram et al. 2018). However, we found that neither the presence nor density of tree species in the coffee fields of small-scale farmers at Mt. Kilimanjaro varied much across elevations for most investigated species. The reason could be that our focus was on the most common tree species that are well known by many farmers rather than the whole natural flora as reported by Hemp (Hemp 2006). *Mangifera indica* and *S. siamea* are known to grow better at lower elevations (Mbuya et al. 1994); it is therefore not surprising that their density is higher at lower elevations. Rather unexpected is the reduced presence and density of *C. africana* with increased elevation as the suitable range for this tree species in the Kilimanjaro regions is reported to be between 1200 m and 2000 m asl. (Mbuya et al. 1994). We therefore conclude that the density of *C. africana* is influenced by socio-economic factors rather than by environmental factors. In Uganda, *C. africana* was perceived to perform well for all ESs (Gram et al. 2018) and is therefore found in farms at all elevations. Even though this tree species is also perceived to perform highly for regulatory services at Mt. Kilimanjaro, this was not a priority for most farmers. Food being the highest priority explains the presence of either *M. indica* or *P. americana* in 90% of the coffee farms, and the climatic needs for these two species explain the decrease in density of *M. indica* and the increase of density of *P. americana* along the elevation gradient (Mbuya et al. 1994). Another influencing aspect might be increased distance to markets at higher elevations and therefore increased importance of self-sufficiency to farmers. The increased density of *M. discoidea* with increased elevation might be due to its importance for fodder supply. At lower elevations, farmers might have better access to other sources of fodder.

Rankings were not influenced by elevation, despite the relationship between shade tree distribution and elevation. This confirms the findings of Lamond et al. (2016) that farmers' knowledge of tree attributes affecting field interactions between shade tree and coffee is consistent along an elevation gradient.

6.5.4. Tree Species Ranking in East Africa

Shade tree species in coffee agroforestry systems vary greatly among regions and even within East Africa; hence, it is not possible to generalize findings for the region. Studies with a similar approach to farmers' knowledge of tree species have been carried out in Rwanda (Smith Dumont et al. 2019), Uganda (Gram et al. 2018; Bukomeko et al. 2019), and Kenya (Lamond et al. 2016). Figure 6.6 combines the tree species included in the rankings and shows the overlaps in the species reported. Only seven shade tree species were commonly recorded in all countries and most of them are exotic. There are also very important tree species that only appear in the ranking of one country, for example *A. schimperiana*, the most important shade tree species for the Mt. Kilimanjaro region.

The comparison of our results with those from similar research done in other East African countries shows the importance of considering the local context in this type of research based on local knowledge. The results linked to specific shade tree species are specific to locations and cannot be generalized. Including an approach based on functional ecology, linking the scores of shade tree species with their attributes can help generalizing results in future studies. This may lead to recommendations of characteristics of tree species that are generally more acceptable. Lamond et al. (2016) already focused more on ranking attributes rather than tree species and Albertin and Nair (2004) investigated which tree characteristics are important for coffee farmers. Focusing on tree characteristics might also help to recommend shade tree species that are not very common, but might be a good fit for farmers since ranking is limited to the most common shade tree species, neglecting the importance of rather rare species.

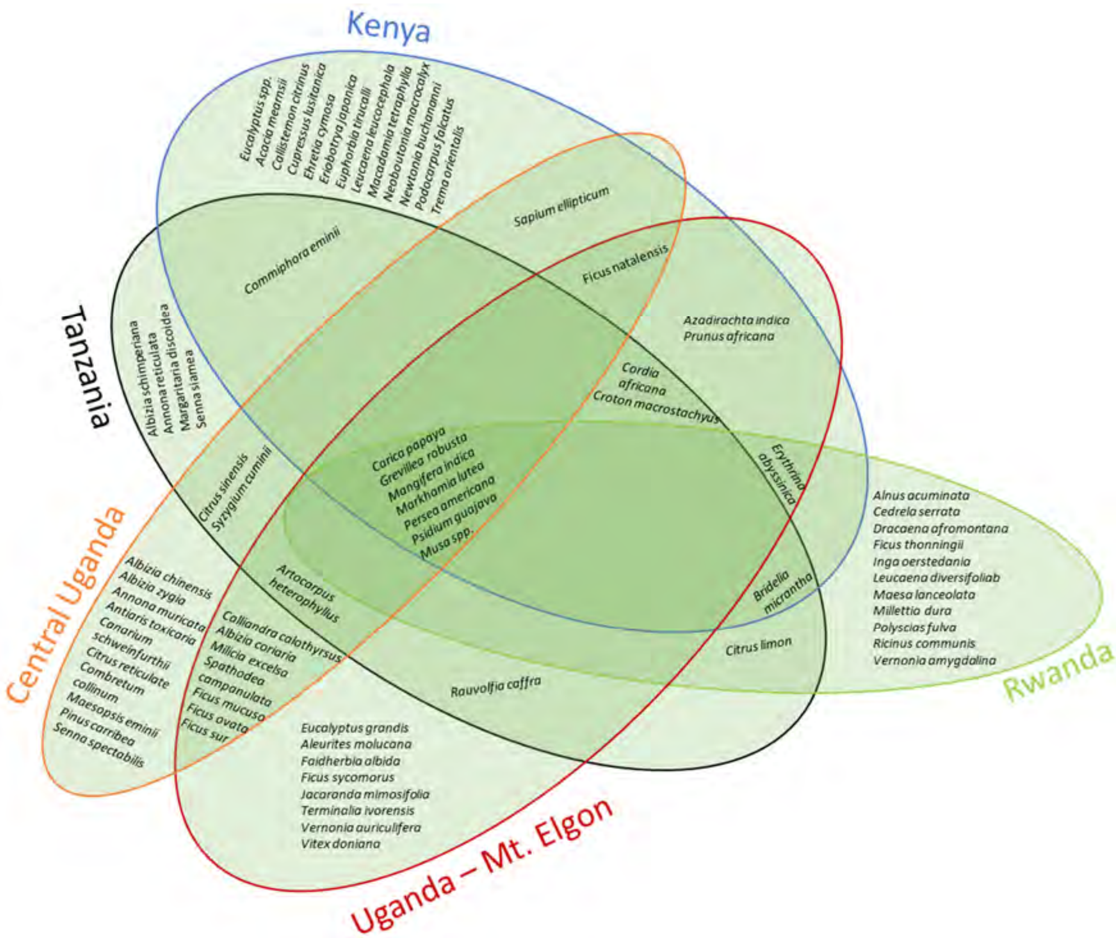

***Figure 6.6**: Shade species included in different rankings in East Africa* (Lamond et al. 2016; Gram et al. 2018; Bukomeko et al. 2019; Smith Dumont et al. 2019).

6.5.5. Resilience of Coffee Agroforestry Systems

Some of the ESs shade tree species can provide, such as temperature regulation or soil moisture enhancement, might help mitigate the impacts of climate change (Lin 2007; Mbow et al. 2014). However, not all shade tree species are perceived as similarly effective in providing said services as the scores show (Figure 6.4). Tree species not influenced by elevation are considered more climate change resilient (Gram et al. 2018). This is the case for all investigated shade tree species for our study area within the investigated elevation range, besides *C. africana*, *M. indica, S. siamea*, *P. americana,* and *M. discoidea*.

A challenge of the present methodology is the small number of shade tree species that can be included in ES rankings. In order to enhance the ability of the agroforestry system to recover from external pressure and be more resilient in the face of climate change, it is important to protect the biodiversity of the farming systems (Fischer et al. 2006). It is therefore important to not only recommend the common species mentioned in this paper, but to retain a variety of tree species in the local ecosystem.

A better understanding of the optimal shade intensity and therefore the optimal shade tree density is also essential to tailor advice to farmers. Even though *A. schimperiana* can provide several services, knowledge of the optimal planting density and best management practices in terms of pruning will still be required to achieve optimal shade levels and utilize all potential benefits for coffee production.

For socio-economic resilience, it is important to consult with farmers about their preferences prior to recommending a list of shade tree species, to ensure that the advice fits with their objectives and their constraints. The online decision-support tool for tree selection (shadetreeadvice.org) (van der Wolf et al. 2016) is a first step in tailoring recommendations for important shade tree species to farmers' preferences. It also needs to be considered that with recurring low coffee prices, focusing primarily on shade tree species that optimize coffee production might not be economically sustainable. The emphasis might shift towards other ESs and shade tree species that increase the economic resilience of coffee farms.

6.6. Conclusion

This study demonstrated the link between farmers' preference for certain ESs and the planting density of shade tree species that provide these ESs. This shows the importance of understanding the factors underlying farmers' management decisions before recommending shade tree species. Despite being aware of negative crop-tree interactions, farmers might include tree species that are not necessarily beneficial to coffee production in order to acquire other services such as food, fodder, and firewood provisioning, all considered priorities for farmers on the southern slopes of Mt. Kilimanjaro.

Local knowledge of tree species' benefits can be very valuable to local producers; however, it needs to be complemented with expert knowledge to identify biases and fill in knowledge gaps. Even though our study has confirmed that local knowledge of tree species is gender blind, it could still be influenced by other factors such as differences in access to information, access to markets, and/or other socio-economic factors. Contrary to other studies, we did not observe an influence of elevation on the perceptions of tree species' provisioning of ESs. Nevertheless, it will be important to consider environmental aspects in future studies. Another limitation of this methodology is that it only includes the most common shade tree species, leaving aside rare indigenous species with high potential for agroforestry systems. This underestimates the importance of less common species, which might even be superior in providing certain ESs. It may also give the impression that the common tree species alone are enough to support a resilient coffee production system. One approach to improving recommendations might be focusing on the traits shown by highly ranked tree species. This will not only help comparing results from different regions and generalizing recommendations, but also ensure that a wider range of species are included.

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6.8. Appendix I: Supplementary materials

The following are available online at www.mdpi.com/xxx/s1, Table S1: Tree species used for the ranking, Table S2: Ecosystem services used for the ranking, Figure S1: Scores and quasi-standard errors of tree species for fodder supply at (a) lower elevations (1148–1335 m asl) and (b) higher elevations (1336–1748 m asl). Red bars show tree species with significantly different scores between the two groups, Figure S2: Scores and quasi-standard errors of tree species for food provision (a,b), shade provision (c,d), and soil fertility (e,f) divided by gender (women are presented in a, c and e; men are presented in b, d and f). Red bars show tree species with significantly different scores between the two groups, Figure S3: Scores and quasi-standard errors of tree species for protection from heat (a,b), and increasing coffee quality (c,d) divided by affiliation to a farmers group (non-members are presented in a and c; members are presented in b and d). Red bars show tree species with significantly different scores between the two groups.

***Table S3**. Tree species used for the ranking.*

Tree species
Acrocarpus fraxinifolius
Albizia schimperiana
Annona reticulata
Artocarpus heterophyllus
Bridelia micrantha
Carica papaya
Citrus limon
Citrus sinensis
Commiphora eminii
Cordia africana
Croton macrostachyus
Eucalyptus maculata
Grevillea robusta
Mangifera indica
Margaritaria discoidea
Markhamia lutea
Musa spp.
Persea americana
Psidium guajava
Rauvolfia caffra
Senna siamea
Syzygium cuminii

***Table S4**. Ecosystem services used for the ranking.*

Ecosystem services
Firewood supply
Fodder supply
Food provision
Increasing coffee quality
Increasing coffee yield
Mulch provision
Protection against wind
Protection from heat
Shade provision
Soil fertility improvement
Soil moisture enhancement
Weed suppression

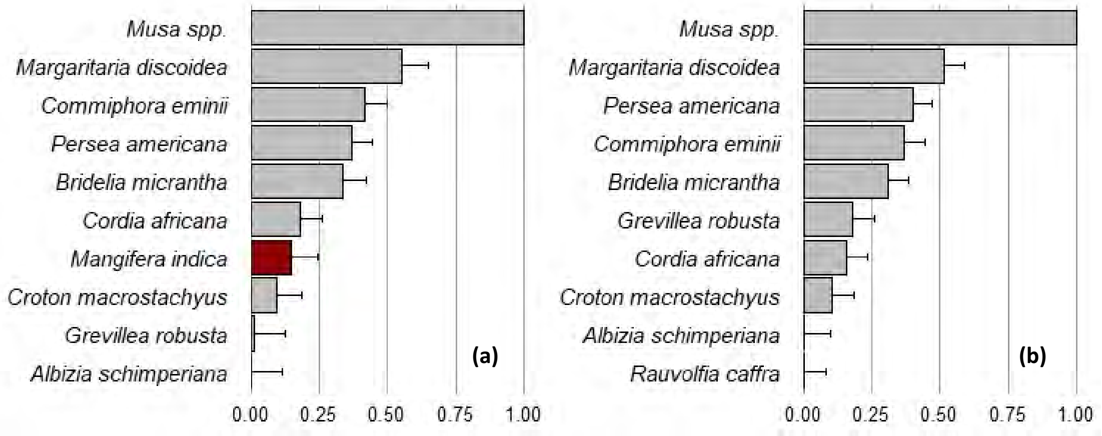

***Figure S7**. Scores and quasi-standard errors of tree species for fodder supply at (a) lower elevations (1148 – 1335 m asl) and (b) higher elevations (1336 - 1748 m asl). Red bars show tree species with significantly different scores between the two groups.*

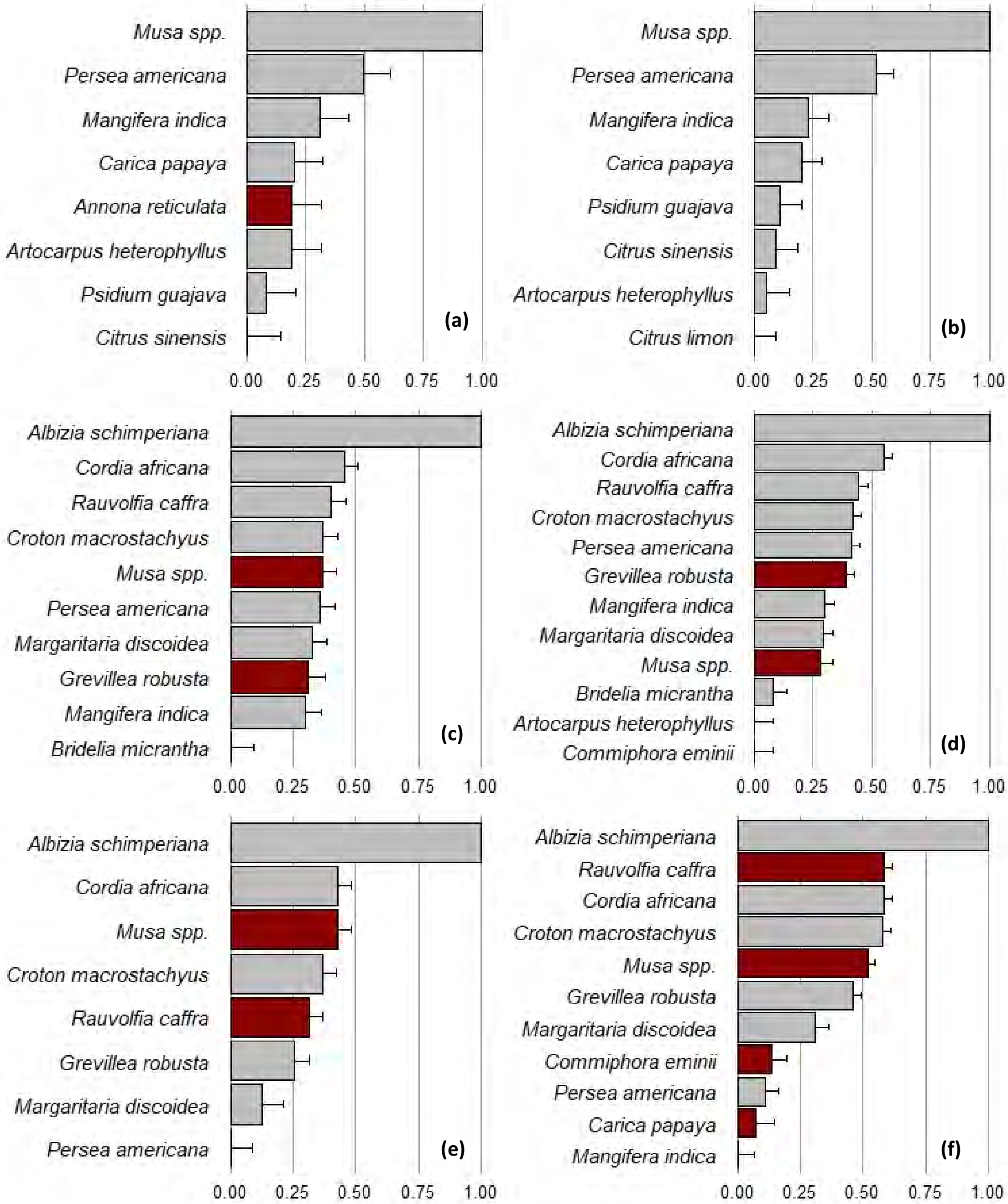

***Figure S8**. Scores and quasi-standard errors of tree species for food provision (a, b), shade provision (c, d), and soil fertility (e, f) divided by gender (women are presented in a, c and e; men are presented in b, d and f). Red bars show tree species with significantly different scores between the two groups.*

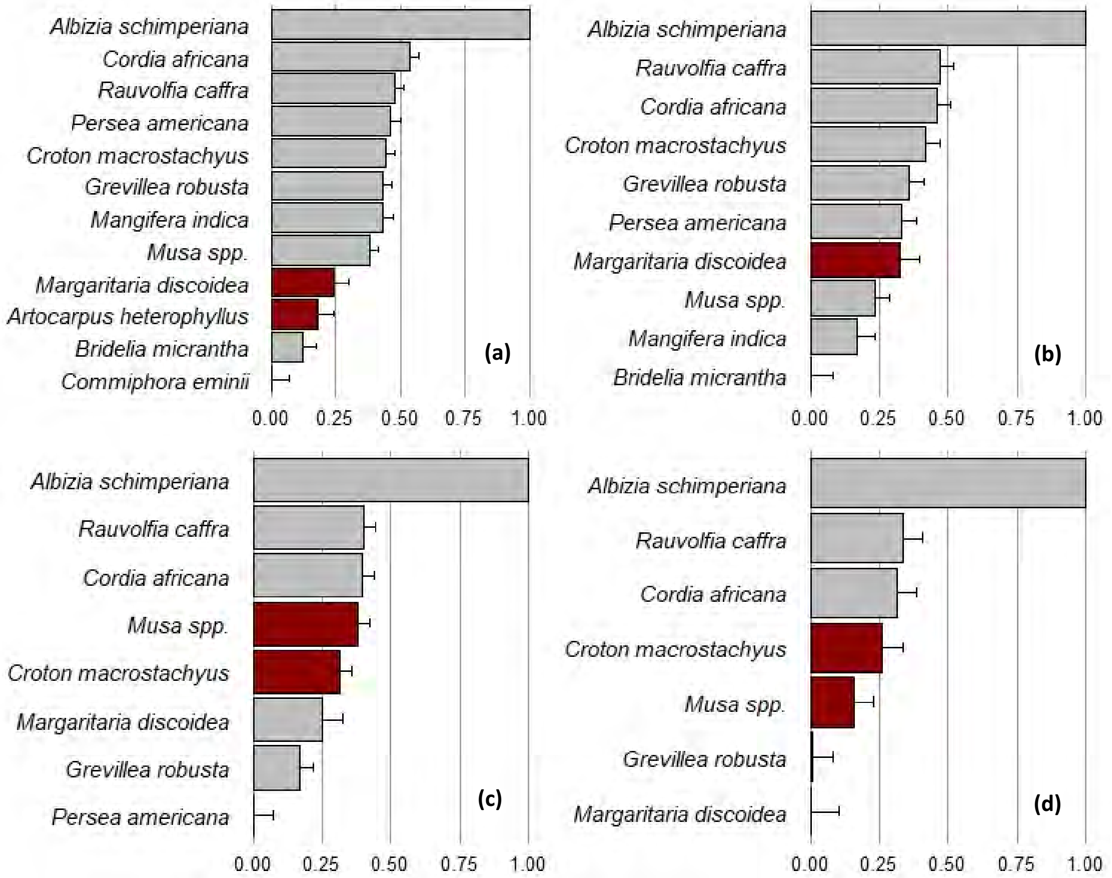

***Figure S9**. Scores and quasi-standard errors of tree species for protection from heat (a, b) and increasing coffee quality (c, d) divided by affiliation to a farmers group (non-members are presented in a and c; members are presented in b and d). Red bars show tree species with significantly different scores between the two groups.*

6.9. Appendix II: Forest publication

forests

MDPI

Article

Ecosystem Services and Importance of Common Tree Species in Coffee-Agroforestry Systems: Local Knowledge of Small-Scale Farmers at Mt. Kilimanjaro, Tanzania

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Abstract: *Research Highlights:* Global coffee production, especially in smallholder farming systems, is vulnerable and must adapt in the face of climate change. To this end, shaded agroforestry systems are a promising strategy. *Background and Objectives:* Understanding local contexts is a prerequisite for designing locally tailored systems; this can be achieved by utilizing farmers' knowledge. Our objective is to explore ecosystem services (ESs) provided by different shade tree species as perceived by farmers and possible factors (elevation, gender, and membership in local farmers groups) influencing these perceptions. We related these factors, as well as farmers' ESs preferences, to planting densities of tree species. *Materials and Methods:* During interviews with 263 small-scale coffee farmers on the southern slope of Mt. Kilimanjaro, they ranked the most common shade tree species according to perceived provision of the locally most important ESs for coffee farmers. We asked them to estimate the population of each tree species on their coffee fields and to identify the three ESs most important for their household. *Results:* Food, fodder, and fuelwood emerged as the most important ESs, with 37.8% of the respondents mentioning all three as priorities. Density of tree species perceived to provide these three ESs were significantly higher for farmers prioritizing these services compared to farmers that did not consider all three ESs in their top three. *Albizia schimperiana* scored the highest for all rankings of regulatory ESs such as coffee yield improvement, quality shade provision, and soil fertility improvement. Influence of elevation, gender, and farmer group affiliation was negligible for all rankings. *Conclusions:* This study shows the need to understand factors underlying farmers' management decisions before recommending shade tree species. Our results led to the upgrade of the online tool (shadetreeadvice.org) which generates lists of potential common shade tree species tailored to local ecological context considering individual farmers' needs.

Keywords: shade tree species; farmers' knowledge; East Africa

1. Introduction

Agroforestry is a promising agricultural production system due to its potential for climate change mitigation and adaptation [1–3]. Besides carbon sequestration [4], shade trees also improve local climatic conditions and reduce variability in microclimate and soil moisture [1]. Agroforestry is particularly important for coffee (*Coffea arabica* L.) production as climate change is expected to reduce the suitable production area for crops such as coffee [5–7]. In addition to regulatory services, the associated shade tree species can provide various direct ecosystem services (ESs) such as food, fodder, or fuelwood [8]. Furthermore, due to their diversity, agroforestry systems have the potential to provide diverse income sources which may act as social safety nets, increasing farmers' economic resilience in the face of coffee price volatility in global markets and possible crop failures [8–11]. However, ecological conditions, competition among associated species in the system, and farmers' individual objectives need to be considered in designing agroforestry systems to maximize the benefits and minimize the shortcomings of these systems [12,13].

Farmers can be very knowledgeable on factors that influence coffee productivity. From experience, they are aware of interaction(s) between shade tree species and coffee, as well as many direct ESs provided by specific tree species [14,15]. In some areas, however (e.g., the impact of individual tree species on pests and diseases), their knowledge might be limited [16–18]. Nevertheless, exploring farmers' knowledge might provide novel insights into interactions between shade tree species and coffee productivity. This local knowledge is vital in tailoring recommendations to local conditions.

Although several studies have investigated how the Chagga people living on Mt. Kilimanjaro in Tanzania use their natural environment [19–22], research has so far not identified which tree species are considered superior in providing relevant ESs for the local coffee farmers. Our aim is to assess indigenous knowledge of local farmers on Mt. Kilimanjaro regarding selection of shade trees that enhance coffee production and provide other ESs. A participatory approach based on van der Wolf et al. [23] allowed us to collect and study farmers' knowledge regarding shade tree species' provision of ESs. Following this approach, we identified shade tree species with high potential for coffee agroforestry systems on the southern slopes of Mt. Kilimanjaro. Similar studies have been conducted in other East African countries and the differences in findings [15,16,24,25] demonstrate the importance of locally specific investigations.

In this study, we explore the ESs provided by different shade tree species as perceived by farmers. We further examine if elevation, gender, and membership in local farmers' groups influence the perceived ESs provided, and the planting density of different shade tree species. Farm management may be based on farmers' knowledge and preference for specific shade tree species [15]. Therefore, we expect that the planting density of tree species will depend on the perceived ESs the tree species provides, as well as farmers' ESs preference.

The study aims to contribute to expanding the database of the online decision-support tool for tree selection in smallholder farming systems (shadetreeadvice.org) [23] and help tailor recommendations for important shade tree species for coffee farmers on Mt. Kilimanjaro.

2. Materials and Methods

2.1. Study Site

The research took place on the southern slopes of Mt. Kilimanjaro in Tanzania (Latitude 3°13′9″ S–3°17′41″ S; Longitude 37°9′24″ E–37°25′19″ E) (Figure 1). Here, the Chagga people have cultivated and converted the former forest into an agroforestry system (the so-called Chagga homegardens) over several centuries [21]. The main cultivation zone of *C. arabica* in these traditional coffee-banana plantations is located between 1000 m and 1800 m asl [26] and covers an area of nearly 80,000 ha [27]. Kilimanjaro National Park prevents expansion of coffee cultivation into higher elevations [19]. For our study area, Hemp [26] reports annual rainfall in the lower slopes (800 m to 1300 m asl) of between

900 mm to 1580 mm, and 1580 mm to 2200 mm at the higher slopes (1300 m to 1800 m asl) and mean annual temperatures of 23.4 to 18.8 °C and 18.8 to 16.1 °C, respectively.

Coffee farmers from eight communities participated in this study. Six communities work with the non-government organization Hanns R. Neumann Stiftung (HRNS) (Isuki, Lemira Mroma, Masama Mula, Mudio, Kiwakabo, and Mbokomu); two communities have no connection to the HRNS, are located in the center of the southern slope (Narum and Mweka), and were included in the study to have a wider representation of the study area (Figure 1).

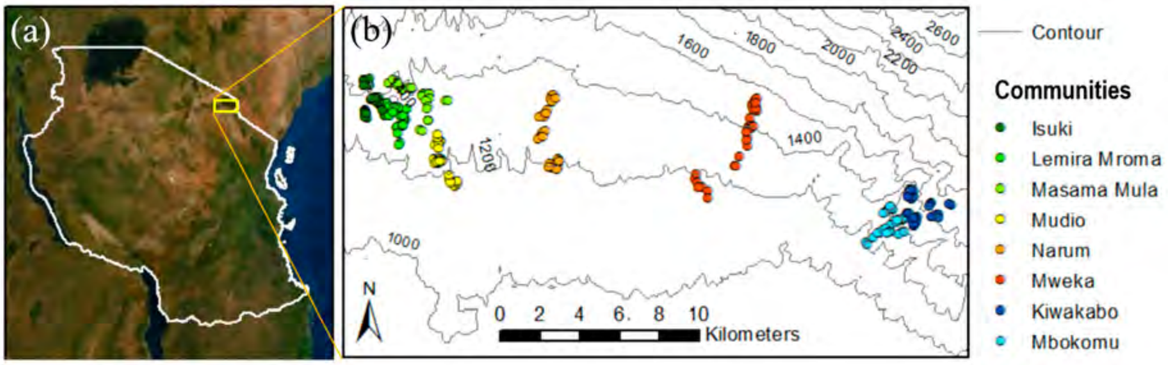

Figure 1. Location of the research area within Tanzania (**a**) and the distribution of the respondents along the southern slope of Mt. Kilimanjaro, divided into the eight communities (**b**).

2.2. Identification of Common Tree Species and Important Ecosystem Services

To identify the most common tree species and most important ESs for coffee farmers of the study area for subsequent data collection, we conducted focus group discussions (FGDs) [28]. In March 2019, we conducted three FGDs in the west (Isuki, Masama Mula and Mudio) and two FGDs in the east (Kiwakabo and Mbokomo). Participants were coffee farmers representing farmers' groups and independent farmers from the same community. Each FGD had between 9 and 15 attendees, leading to a total of 56 attendees.

The list of tree species that participants could choose from was based on Hemp [26], and the results of an investigation of 40 plots of Chagga homegardens in Narum and Mweka (unpublished data). As small-scale farmers in this region commonly intercropped coffee and banana (*Musa* spp.), we included the latter as a shade species. This resulted in an initial list of 58 shade tree species. We prepared technical sheets for each shade tree species showing pictures of the plant or plant parts, as well as the local name. We presented these sheets to the focus groups and asked them to rank the shade tree species according to their frequency in coffee fields in their area. Tree species shown to each FGD were then added or removed from the presented list of trees based on their rankings during previous FDGs. In subsequent data collection interviews with individual farmers, we only used the most common shade tree species. This list was composed of 22 tree species that were either ranked in the top 20 in at least three FGDs or in the top 10 of any single FGD (see the species listed in Table S1).

For identification of the locally most important ESs for farmers, we presented 25 ESs to the focus groups and asked the participants to add any additional ESs they considered important. The groups then ranked the services according to their perceived importance, giving us the final list of the 12 locally most important ESs for subsequent data collection interviews. The list included nine ESs that were ranked in the top 12 of at least four FGDs (food provision, shade provision, protection against wind, protection from heat, fodder supply, mulch provision, increased coffee yield, soil fertility improvement, and weed suppression); one ES ranked number four in one FGD and in the top 10 of two other FGDs (increasing coffee quality); one ES ranked as number two in two FGDs, but below 10 in all other FGDs (firewood supply); and one ES ranked as number one in one FGD, but only in the top 10 in one other FGD (soil moisture enhancement) (see all ESs listed in Table S2).

2.3. Shade Tree Species Ranking for Ecosystem Services

Ranking the most common tree species according to the most important ESs was the focus of data collection interviews with 263 small-scale coffee farmers along the southern slope of Mt. Kilimanjaro (Figure 1). In March and April 2019, we conducted at least 30 individual interviews in each community (Figure 1). We began with farmers that participated in the FGDs or whose farm we investigated; we then interviewed occupants of the fifth house away in each direction along the road. If the person in the fifth house was not a coffee farmer, declined participation, or was absent at the time, we asked at the next house(s) until a respondent was identified.

The respondents were asked to select the 10 tree species that they knew best out of the list of 22 most common shade tree species [23]. They were then asked to rank the 10 chosen shade tree species for each of the 12 locally most important ESs from the best (high provision of this ES) to the least performing (low provision of this ES) [16,23]. We also recorded gender, membership of the HRNS, and elevation of the respondents' home (using a GARMIN GPSMAP 64). We asked the respondents to name the three most important ESs for their household and the estimated number of individuals of the different tree species they had on their coffee fields, as well as the size of their coffee farm.

2.4. Data Analysis

We noted the number of tree species each farmer had of the 22 most common shade tree species, the percentage of farmers having each tree species in their fields, and the planting density of each tree species, using farmers' estimated number of trees and farm size. To identify the influence of elevation on the tree planting density of different tree species, we did linear regressions for each common shade tree species in R 3.5.0 [29]. We summarized the ESs respondents considered most important and tested gender differences with a chi-square test in R 3.5.0 [29].

Based on the method of van der Wolf, et al. [23], we used the BradleyTerry2 package in R 3.5.0 [29] to identify shade tree species best at providing specific ESs, as perceived by the farmers. We excluded interview respondents with less than five years of experience as well as tree species that were ranked less than 10 times for a particular ESs [18]; this left 20 of the 22 tree species in the analysis. As explained by Rigal el al. [18], the ranks for each ESs need to be converted into pairwise comparisons to fit the Bradley-Terry model. For each tree species and ES, this model calculates scores, which are comparative values representing the likelihood that one tree species performs better than another tree species in providing an ES [18]. We normalized the scores between 0 and 1 to be able to compare them [18]. Besides the scores, quasi-standard errors were calculated to indicate how frequently a species was included in the ranking and how consistently the respondents ranked this species [18]. We compared the scores pairwise using a Wald test. The more pairs that are significantly different, the more it reflects an agreement of farmers upon the ranking of the tree species. Therefore, large numbers of pairs that are significantly different indicate that the analysis is robust [18]. In our results, the lowest percent of pairs that were different was 67%, and the highest was 89%.

To assess the influence of farmers' objectives on their management practices, we compared shade tree densities on coffee farms between groups of farmers with different sets of priorities. More specifically, we split respondents into two groups: those who had selected the combination of the three most important ESs for small-scale coffee farmer households at Mt. Kilimanjaro as their top three priorities and those who had not. We then compared the shade tree density of species perceived to perform high for the combination of these ESs and tested differences between the two farmer groups using t-tests in R 3.5.0 [29].

To identify if gender, affiliation to a farmers' group, or elevation influenced perceived provision of ESs by shade tree species, we split the data sets by gender, membership of the HRNS, and into two elevation groups (threshold was the median 1336 m asl). We ran the BradleyTerry analysis for these subgroups of respondents and compared the resulting scores [15,16].

2.5. Ethical Approval

Ethical approval for this study was obtained from the Faculty Research Ethics and Governance Committees of the Manchester Metropolitan University, Faculty of Science and Engineering, on 26 May 2017, with application code SE1617108C.

3. Results

3.1. Main Characteristics of Respondent

Of the total respondents, 96 were women (36.5%) and 167 men (63.5%). The farm size ranged between 0.1 and 8 ha, the average farm size was 0.7 ha with 83.3% (219 respondents) having less than 1 ha. The elevation ranged from 1148 m to 1748 m asl, with an average elevation of 1343 m asl and a median elevation of 1336 m asl (Figure 2). Ninety-seven respondents (37%) were members of the HRNS, while 166 were non-members (63%).

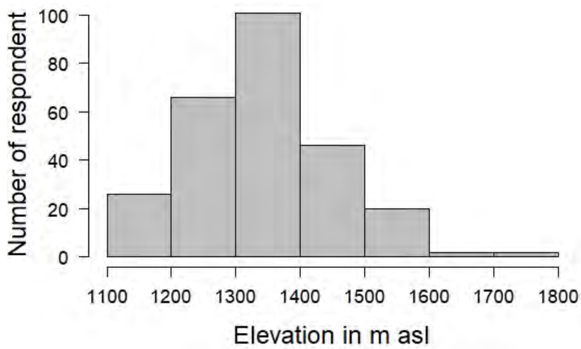

Figure 2. Distribution of respondents along elevation.

3.2. Tree Species Distribution

Sixty percent of the farmers reported that they had 10 or more of the 22 most common shade tree species on their coffee farms. The most common shade tree species is *Musa* spp. grown by all respondents, followed by *Grevillea robusta* A. Cunn. ex R. Br., *Albizia schimperiana* Oliv., and *Persea americana* Miller with 94.3%, 90.9%, and 83.7%, respectively (Figure 3). *Musa* spp. is by far the shade species with the highest density (1089 ± 106 tree ha^{-1}) (Figure 3). *Grevillea robusta* is second densest (39.1 ± 3.29 tree ha^{-1}), closely followed by *Markhamia lutea* (Benth.) K. Schum. (26.6 ± 4.90 tree ha^{-1}). Just a few farmers (about 20 percent) grow *M. lutea*. However, those that do grow it have a high density of the species on their fields. Despite their presence on more than 83% of coffee farms, the densities of *A. schimperiana* (7.9 ± 0.46 tree ha^{-1}) and *P. americana* (12.3±0.98 tree ha^{-1}) are significantly lower than those of the above species (Figure 3).

Neither the total shade tree density nor the *Musa* spp. density are significantly influenced by elevation. However, we observed differences in density of some tree species. Linear regressions show significant reduction in densities of *Cordia africana* Lam. ($F_{(1,261)} = 12.91$, $p < 0.001$), *Mangifera indica* L. ($F_{(1,261)} = 5.03$, $p = 0.026$) and *Senna siamea* (Lam.) H. S. Irwin & Barneby ($F_{(1,261)} = 3.96$, $p = 0.048$) with increasing elevation—the densities are reduced by 1.1 tree ha^{-1}, 0.4 tree ha^{-1} and 0.3 tree ha^{-1} respectively for every 100 m increase. We detected a significant increase in density towards higher elevations for *Margaritaria discoidea* (Baill.) G. L. Webster ($F_{(1,261)} = 30.88$, $p < 0.001$) and *P. americana* ($F_{(1,261)} = 11.77$, $p < 0.001$) (with an increase of 100 m, the density increases by 2.4 tree ha^{-1} and 2.7 tree ha^{-1} respectively).

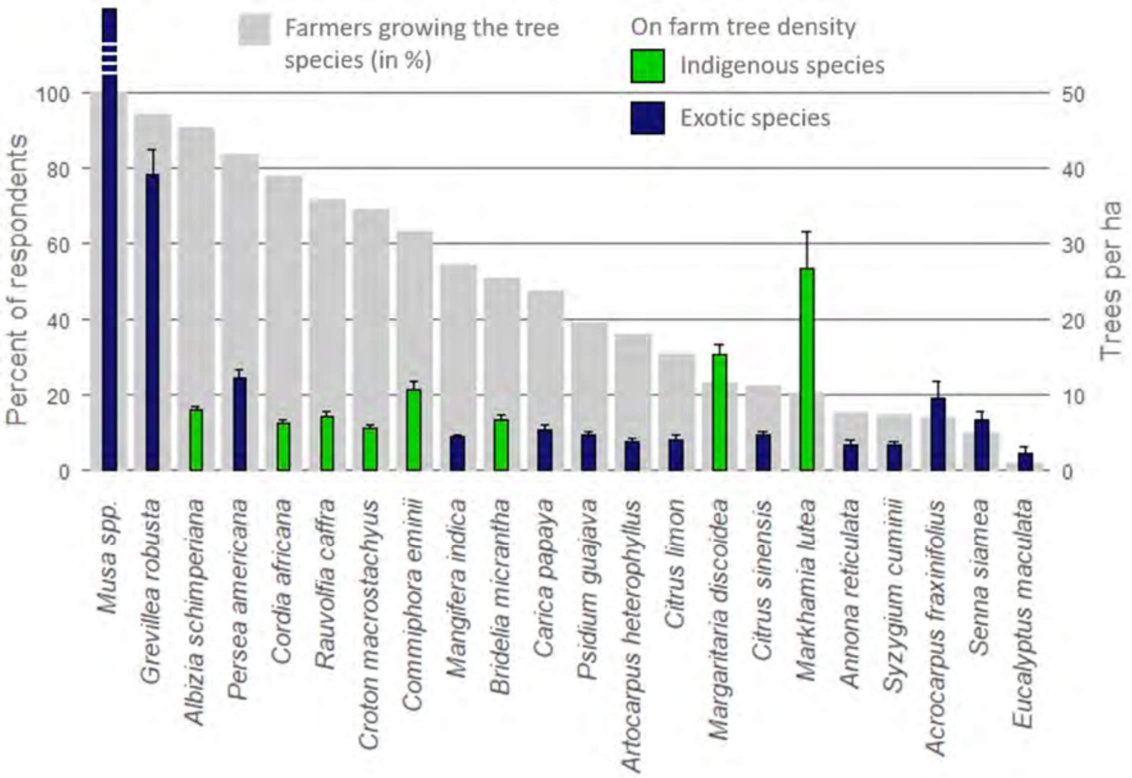

Figure 3. Percent of respondents reporting each species on their farm and average (+SE) tree density on those farms. The density of *Musa* spp. is much higher than the scale shown in the graph (1089 trees per ha on average).

3.3. Important Ecosystem Services

On the southern slope of Mt. Kilimanjaro, food provisioning is by far the most essential ES for coffee farmers. Of the 263 respondents, more than 75% selected food provision as the most important ES for their household, and more than 95% ranked it in the top three (Table 1). The second locally most important ESs is fuelwood supply, which was ranked first by 10% of the respondents and within the top three ESs by nearly 60% of the respondents (Table 1). More than 50% of the respondents also ranked fodder supply among the top three ESs, followed by shade provision, soil fertility improvement and increased coffee yield (Table 1). A chi-square test showed no significant differences in ES preference between genders. The only significant difference between the two elevation groups was that respondents at a higher elevation included soil moisture enhancement more often in the top three ESs than respondents at lower elevation (4.4% and 1.0% respectively, $X^2 = 7.2$, $p < 0.01$).

3.4. Pairwise Comparison

The analysis shows that the ranking of shade tree species is consistent for most ESs. We observed the clearest discrimination between tree species in the ranking for mulch provision and protection from heat with 89.1% and 87.9% of the pairwise comparisons of tree species' scores being significantly different ($p < 0.05$), followed by increase in coffee yield and quality (Table 2). Most difficult to rank were weed suppression, food provision, and protection against wind with 66.7%, 71.1%, and 72.5% of all pairs being significantly different ($p < 0.05$) (Table 2).

Table 1. Ranking of Ecosystem services on a household level.

Ecosystem Services (ESs)	Selected as First ES	Among the First 3 ESs
Food provision	76.4%	95.4%
Firewood supply	10.3%	59.5%
Fodder supply	2.7%	55.3%
Shade provision	3.4%	31.7%
Soil fertility improvement	2.7%	17.2%
Increased coffee yield	0.0%	15.6%
Soil moisture enhancement	1.5%	8.0%
Increased coffee quality	0.8%	5.7%
Protection against wind	1.1%	5.3%
Mulch provision	0.8%	3.4%
Protection from heat	0.0%	1.5%
Weed suppression	0.4%	1.1%

Table 2. Percent of significantly different pairwise comparisons of species' scores.

Ecosystem Service	Number of Tree Species Included in the Ranking	Percent of Significant Differences between Pairs ($p < 0.05$)
Mulch provision	11	89.1
Protection from heat	12	87.9
Increased coffee yield	11	87.3
Increased coffee quality	10	86.7
Soil moisture enhancement	11	85.5
Shade provision	12	84.8
Fodder supply	11	83.6
Firewood supply	13	82.1
Soil fertility improvement	13	76.9
Protection against wind	16	72.5
Food provision	10	71.1
Weed suppression	13	66.7

3.5. Tree Ranking

Scores of the tree species ranked according to the three most important ESs for small-scale coffee farmers at the southern slopes of Mt. Kilimanjaro show major differences (Figure 4). Of the most common tree species providing food, all are exotic. Firewood is mainly obtained from indigenous species, except for *G. robusta*, which is exotic.

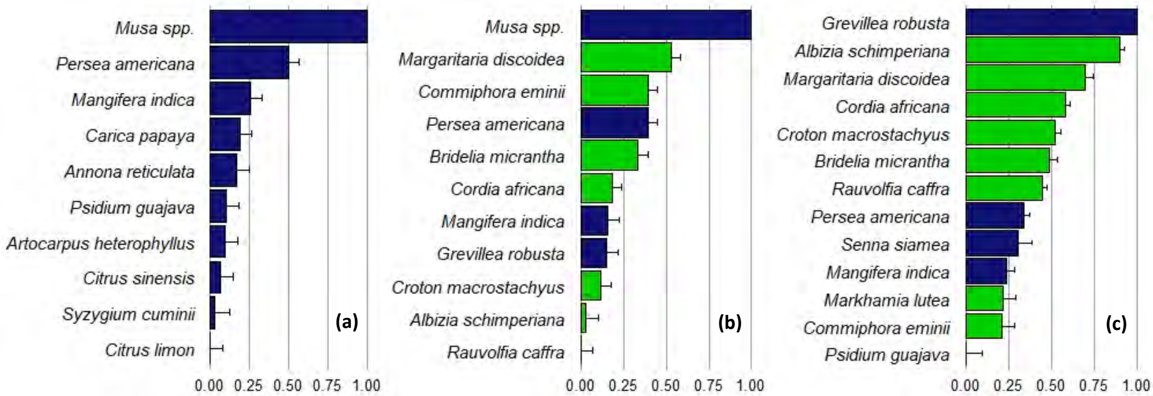

Figure 4. Scores and quasi-standard errors of tree species for (**a**) food provision, (**b**) fodder supply and (**c**) firewood supply. Dark blue bars represent exotic, and green bars indigenous tree species.

For a better recommendation of tree species regarding multiple regulatory ESs associated with coffee production, the following ESs were combined into three categories: (**a**) coffee production enhancement (combining increase in coffee yield and quality), (**b**) protection from climatic hazards (combining protection from heat, wind and shade provision), (**c**) soil quality enhancement (combining mulch provision, soil fertility and soil moisture enhancement). For each ES category, the scores of shade tree species were averaged over the set of combined ESs (Figure 5).

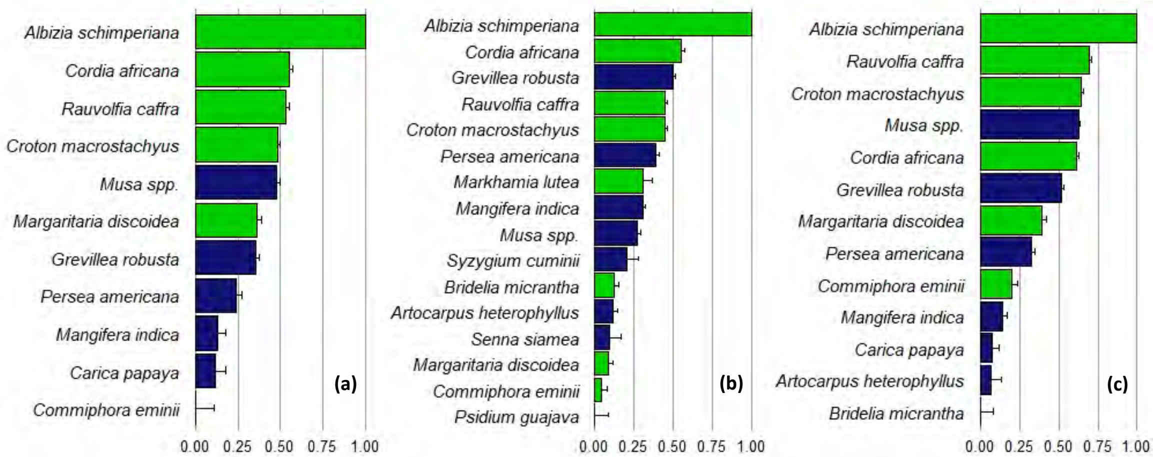

Figure 5. Scores and quasi-standard errors of the tree species ranked according to: (**a**) increase of coffee yield and quality, (**b**) protection from heat, wind and shade provision and (**c**) mulch provision, soil fertility and soil moisture enhancement. Green bars represent indigenous, and dark blue bars exotic tree species.

Albizia schimperiana is the highest ranked tree species for all three ES categories. Also within the top five for all three ES categories are *C. africana*, *Croton macrostachyus* Hochst. ex Delile, and *Rauvolfia caffra* Sond.. All of these tree species are indigenous. *Musa* spp. is important for coffee yield and quality, as well as for soil enhancement, while *G. robusta* contributes to protection from climatic hazards and soil quality enhancement.

3.6. *Effect of Priorites on Shade Tree Density*

Food, fodder, and firewood are the most important ESs for small-scale coffee farmer households (99 respondents (37.8%) selected this combination). To assess the influence ES priorities have on tree species selection, we averaged the scores of each shade tree species for the combination of these three ESs and compared the density of the five best performing tree species between two groups: respondents that selected these three ESs as most important versus those that did not. The planting density of three of these five tree species is significantly higher (t-test, $p < 0.05$) for respondents that selected these ESs as most important compared to those that did not (Figure 6). We found differences for exotic, but not indigenous species.

3.7. *Elevation, Gender, and Farmer Group Affiliation*

The ranking in higher elevations was not significantly different from the lower elevations. The only deviation we observed is that *M. indica* was included in the ranking of shade tree species providing fodder for the lower elevations, while *R. caffra* was included in the higher elevations (Figure S1). Farmers did, however, rank both of these tree species low for this ES.

There were slight differences considering gender and affiliation to a farmers group of the HRNS. Women included *Annona reticulata* L. in their ranking for food provision, and they ranked *Musa* spp. significantly higher for shade provision and soil fertility compared to men. Men ranked *G. robusta* significantly higher for shade provision, while *R. caffra* was ranked higher for soil fertility (Figure S2). Respondents that were members of HRNS ranked *M. discoidea* significantly higher than non-members for protection from heat (Figure S3). For coffee quality, members of HRNS ranked *C. macrostachyus* significantly higher and *Musa* spp. significantly lower than non-members (Figure S3).

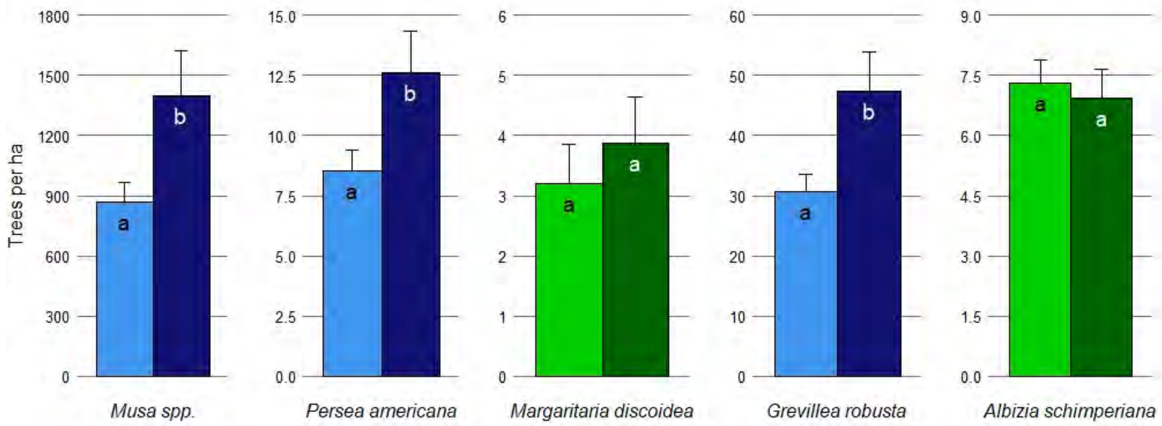

Figure 6. Average (+SE) plant density of the five highest ranked tree species providing the services food, fodder and firewood. The dark bars show respondents who selected the three ESs as the three most important for their family, while the light bars indicate the plant density for respondents who did not select all three. Significant difference between plant density is shown by difference in letters (a and b) ($p < 0.05$). Blue bars represent exotic, and green bars indigenous species.

4. Discussion

4.1. Improtant Ecosystem Services

Nearly all the farmers in our study area considered food provision by shade trees their top priority, followed by the provisioning services fodder and fuelwood supply (Table 1). These ESs were considered more important than regulatory services for coffee production such as shade provision, soil fertility improvement, and increased coffee yield. ES priorities were not significantly different between genders. Respondents of other studies have various priorities. At Mt. Elgon (Uganda), farmers rather prioritized ESs such as mulch provision, erosion control and temperature regulation [16], coffee yield, soil moisture enhancement, and quick leaf decomposition in Central Uganda [24]. Differences in the importance of ESs may reflect differences in environmental conditions, as well as market access [16,30]. One reason participants of the FGDs mentioned for excluding timber from the list of important ESs was the political limitation of tree harvesting [31]. The complexity of agroforestry systems and diverse interactions between different pests and predators on a land-scale level [32–35] might be the reason coffee farmers at Mt. Kilimanjaro did not observe any effect of shade tree species on pests and did not consider it an important ESs provided by shade trees.

4.2. Highly Ranked Tree Species

Albizia schimperiana is the most important shade tree species for coffee production on the southern slope of Mt. Kilimanjaro for the provision of most ESs included in this study. Several studies also report the importance of *A. schimperiana* for coffee production in Ethiopia [36–38]. As a leguminous plant, *A. schimperiana* can form a symbiotic relationship with rhizobia bacteria to fix atmospheric nitrogen, resulting in increased soil fertility. Other studies also show that, with an open wide-spreading crown, *A. schimperiana* provides good shade cover for coffee production, leading to improved microclimate and coffee yield [26,39]. Another advantage of *A. schimperiana* is that its leaves emerge in the dry season [36]. This means it can provide shade when there is a lot of sun and prevents coffee from being too densely shaded during the rainy season.

Despite the benefits of *A. schimperiana* and the perceived provision of multiple regulatory ESs by coffee farmers at Mt. Kilimanjaro, other tree species occurred at a much higher density (Figure 3). From general observations, it seems that the farms have mostly mature trees and that a new generation of *A. schimperiana* is missing. More research on the population structure of *A. schimperiana* in this area is required to get a better understanding of future development and challenges. Belay, et al. [36] found for their study region in Ethiopia that the population structure of *A. schimperiana* had a U-shape with more stems in lower and higher diameter classes, showing selective cutting or extraction of medium sized individuals. Potential explanations could be the increased exploitation of *A. schimperiana* for timber and fuelwood, and its low growth rate [37,40]. Other important aspects to examine are natural regeneration and the success of propagation.

A closely related species that commercial coffee plantations commonly include in their fields is *Albizia gummifera* (J. F. Gmel.) C. A. Sm. This species is favored by farmers in Ethiopia [41,42]. Other *Albizia* species are considered important for providing multiple ESs in East Africa, such as, but not limited to, mulch, shade, improvement of microclimate, coffee yield and soil moisture in Uganda [16,24]. Unfortunately some *Albizia* species are also alternative hosts for black coffee twig borer in the closely related Robusta coffee (*Coffea canephora* Pierre ex Froehn.) posing a potential risk [23].

The other three shade tree species associated with improvements of conditions for coffee production are also indigenous (*C. africana*, *C. macrostachyus* and *R. caffra*). *Rauvolfia caffra* ranked as an important shade tree species which is in line with other findings from Mt. Kilimanjaro [22,26]. Fernandes, et al. [19] report the potential of *R. caffra* to suppress various coffee pests. Its contribution to the production of traditional banana beer underlines its importance in traditional Chagga homegardens [19,22,40]. *Croton macrostachyus* provides good litter, preserves soil moisture, facilitating high coffee yield and high bean weight [43]. *Cordia africana* is also reported as an essential shade tree in coffee production in Kenya [15], Uganda [16] and Ethiopia [42,44]. Even though Kufa, et al. [39] found high coffee yields under *C. africana*, they also reported the highest yield variations under this tree species. As *C. africana* is a high quality timber tree, the economic value might be a major reason for farmers to grow it [42,43].

Even though the four tree species discussed above (*A. schimperiana*, *C. africana*, *C. macrostachyus*, and *R. caffra*) are multipurpose tree species and considered the best to enhance soil quality, create a suitable environment for coffee production and benefit coffee yield and quality, their densities in coffee farms were lower than that of the exotic fast growing *G. robusta* (Figure 3). In Kenya, native tree species were also considered to provide a healthy environment, but their abundance was low due to their slow growth rate [15]. In Tanzania, another reason for the preference of *G. robusta* might be that the wood can be utilized more easily than for native tree species, as native tree species require a permit to be cut down [31,45].

Farmers' management decisions to plant or remove a certain tree species in their plantations is usually based on their knowledge or tree preference [14,15,46]. We therefore need to look at their ESs priorities as socio-economic factors might influence farmers' choices for on-field composition. Our results confirm that the density of exotic tree species perceived to provide food, fodder and fuelwood are higher when farmers prioritize these ESs (Figure 6). This is especially the case when the tree species are exotic, as their presence in the field is usually due to management rather than natural occurrences. Some other studies also show the importance of shade tree species for coffee production is matched with their planting densities [36,42]. Bukomenko, et al. [24], however, found a mismatch between ESs that are important for respondents and the trees they have on their fields. Graefe, et al. [30] used a similar methodology for cocoa production in Ghana and also reported disparities between higher ranked tree species suitable for cocoa intercropping and their abundance in the northern part of the cocoa belt with marginal conditions for cocoa production. This might be an adaptation strategy to diversify income, since they confirmed our findings for farms in the wetter southern region with optimal cocoa production conditions [30]. The match between shade tree density and prioritized ESs appears to be more consistent with direct short- or mid-term benefits for farmers, such as food, fodder, and firewood supply, rather than regulatory service provisioning, such as climate modification and soil fertility improvement [15]. This becomes evident from the lower density of *A. schimperiana* (the most highly ranked tree species for regulatory services) in comparison to *G. robusta* and *P. americana*, which provide direct outputs like fuelwood and food (Figure 3). Our findings stress the importance of understanding the socio-economic component when investigating tree species distribution.

4.3. Factors Influencing Tree Species Ranking and Distribution

The first factor influencing tree species distribution, as just discussed, is farmers' preference and the ESs they consider important for their household.

In general, there is agreement on the ranking of tree species among small-scale coffee farmers at Mt. Kilimanjaro. We can confirm the finding by Gram, et al. [16] that local knowledge regarding ranking of tree species is gender blind, as there were negligible differences in our study. Besides gender, participation in a farmer group did not influence the ranking. Farmers participating in farmer groups meet regularly, receive trainings and exchange knowledge and therefore might have better access to different information sources. This could have led to ranking differences, as other researchers have shown the influence of promotion activities of certain tree species on the perception and distribution of those species [18,46]. In Kenya, *G. robusta* was considered suitable for intercropping with coffee, despite having similar traits to those of tree species believed to negatively affect coffee production [15]. For example, the root system for both *Eucalyptus* spp. and *G. robusta* are perceived to be wide spreading [15]. This discrepancy in perception of different tree species could be due to promotion activities from extension services [15]. Such biases need to be considered when using local knowledge to inform recommendations.

Some studies report an influence of elevation on the distribution and ranking of tree species in East Africa [16,26]. However, we found that neither the presence nor density of tree species in the coffee fields of small-scale farmers at Mt. Kilimanjaro varied much across elevations for most investigated species. The reason could be that our focus was on the most common tree species that are well known by many farmers rather than the whole natural flora as reported by Hemp [26]. *Mangifera indica* and *S. siamea* are known to grow better at lower elevations [40]; it is therefore not surprising that their density is higher at lower elevations. Rather unexpected is the reduced presence and density of *C. africana* with increased elevation as the suitable range for this tree species in the Kilimanjaro regions is reported to be between 1200 m and 2000 m asl. [40]. We therefore conclude that the density of *C. africana* is influenced by socio-economic factors rather than by environmental factors. In Uganda, *C. africana* was perceived to perform well for all ESs [16] and is therefore found in farms at all elevations. Even though this tree species is also perceived to perform highly for regulatory services at Mt. Kilimanjaro, this was not a priority for most farmers. Food being the highest priority explains the presence of either *M. indica* or *P. americana* in 90% of the coffee farms, and the climatic needs for these two species explain the decrease in density of *M. indica* and the increase of density of *P. americana* along the elevation gradient [40]. Another influencing aspect might be increased distance to markets at higher elevations and therefore increased importance of self-sufficiency to farmers. The increased density of *M. discoidea* with increased elevation might be due to its importance for fodder supply. At lower elevations, farmers might have better access to other sources of fodder.

Rankings were not influenced by elevation, despite the relationship between shade tree distribution and elevation. This confirms the findings of Lamond, et al. [15] that farmers' knowledge of tree attributes affecting field interactions between shade tree and coffee is consistent along an elevation gradient.

4.4. Tree Species Ranking in East Africa

Shade tree species in coffee agroforestry systems vary greatly among regions and even within East Africa; hence, it is not possible to generalize findings for the region. Studies with a similar approach to farmers' knowledge of tree species have been carried out in Rwanda [25], Uganda [16,24], and Kenya [15]. Figure 7 combines the tree species included in the rankings and shows the overlaps in the species reported. Only seven shade tree species were commonly recorded in all countries and most of them are exotic. There are also very important tree species that only appear in the ranking of one country, for example *A. schimperiana*, the most important shade tree species for the Mt. Kilimanjaro region.

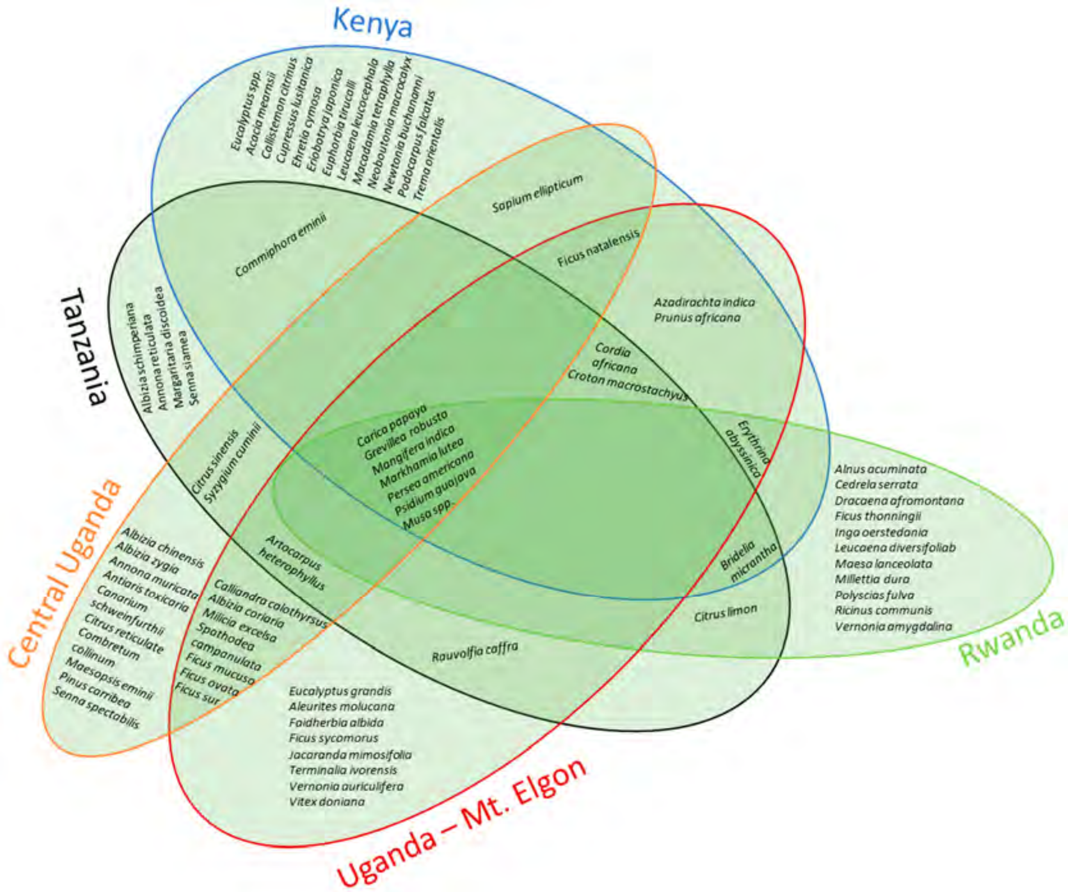

Figure 7. Shade species included in different rankings in East Africa [15,16,24,25].

The comparison of our results with those from similar research done in other East African countries shows the importance of considering the local context in this type of research based on local knowledge. The results linked to specific shade tree species are specific to locations and cannot be generalized. Including an approach based on functional ecology, linking the scores of shade tree species with their attributes can help generalizing results in future studies. This may lead to recommendations of characteristics of tree species that are generally more acceptable. Lamond, et al. [15] already focused more on ranking attributes rather than tree species and Albertin, et al. [47] investigated which tree characteristics are important for coffee farmers. Focusing on tree characteristics might also help to recommend shade tree species that are not very common, but might be a good fit for farmers since ranking is limited to the most common shade tree species, neglecting the importance of rather rare species.

4.5. Resilience of Coffee Agroforestry Systems

Some of the ESs shade tree species can provide, such as temperature regulation or soil moisture enhancement, might help mitigate the impacts of climate change [1,2]. However, not all shade tree species are perceived as similarly effective in providing said services as the scores show (Figure 5). Tree species not influenced by elevation are considered more climate change resilient [16]. This is the case for all investigated shade tree species for our study area within the investigated elevation range, besides *C. africana*, *M. indica*, *S. siamea*, *P. americana*, and *M. discoidea*.

A challenge of the present methodology is the small number of shade tree species that can be included in ES rankings. In order to enhance the ability of the agroforestry system to recover from external pressure and be more resilient in the face of climate change, it is important to protect the biodiversity of the farming systems [48]. It is therefore important to not only recommend the common species mentioned in this paper, but to retain a variety of tree species in the local ecosystem.

A better understanding of the optimal shade intensity and therefore the optimal shade tree density is also essential to tailor advice to farmers. Even though *A. schimperiana* can provide several services, knowledge of the optimal planting density and best management practices in terms of pruning will still be required to achieve optimal shade levels and utilize all potential benefits for coffee production.

For socio-economic resilience, it is important to consult with farmers about their preferences prior to recommending a list of shade tree species, to ensure that the advice fits with their objectives and their constraints. The online decision-support tool for tree selection (shadetreeadvice.org) [23] is a first step in tailoring recommendations for important shade tree species to farmers' preferences. It also needs to be considered that with recurring low coffee prices, focusing primarily on shade tree species that optimize coffee production might not be economically sustainable. The emphasis might shift towards other ESs and shade tree species that increase the economic resilience of coffee farms.

5. Conclusions

This study demonstrated the link between farmers' preference for certain ESs and the planting density of shade tree species that provide these ESs. This shows the importance of understanding the factors underlying farmers' management decisions before recommending shade tree species. Despite being aware of negative crop-tree interactions, farmers might include tree species that are not necessarily beneficial to coffee production in order to acquire other services such as food, fodder, and firewood provisioning, all considered priorities for farmers on the southern slopes of Mt. Kilimanjaro.

Local knowledge of tree species' benefits can be very valuable to local producers; however, it needs to be complemented with expert knowledge to identify biases and fill in knowledge gaps. Even though our study has confirmed that local knowledge of tree species is gender blind, it could still be influenced by other factors such as differences in access to information, access to markets, and/or other socio-economic factors. Contrary to other studies, we did not observe an influence of elevation on the perceptions of tree species' provisioning of ESs. Nevertheless, it will be important to consider environmental aspects in future studies. Another limitation of this methodology is that it only includes the most common shade tree species, leaving aside rare indigenous species with high potential for agroforestry systems. This underestimates the importance of less common species, which might even be superior in providing certain ESs. It may also give the impression that the common tree species alone are enough to support a resilient coffee production system. One approach to improving recommendations might be focusing on the traits shown by highly ranked tree species. This will not only help comparing results from different regions and generalizing recommendations, but also ensure that a wider range of species are included.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/11/963/s1, Table S1: Tree species used for the ranking, Table S2: Ecosystem services used for the ranking, Figure S1: Scores and quasi-standard errors of tree species for fodder supply at (a) lower elevations (1148–1335 m asl) and (b) higher elevations (1336–1748 m asl). Red bars show tree species with significantly different scores between the two groups, Figure S2: Scores and quasi-standard errors of tree species for food provision (a,b), shade provision (c,d), and soil fertility (e,f) divided by gender (women are presented in a, c and e; men are presented in b, d and f). Red bars show tree species with significantly different scores between the two groups, Figure S3: Scores and quasi-standard errors of tree species for protection from heat (a,b), and increasing coffee quality (c,d) divided by affiliation to a farmers group (non-members are presented in a and c; members are presented in b and d). Red bars show tree species with significantly different scores between the two groups.

Author Contributions: Conceptualization, S.W.; Data curation, S.W. and T.L.; Formal analysis, S.W. and C.R.; Funding acquisition, S.W. and R.P.; Investigation, S.W.; Methodology, S.W.; Project administration, S.W., M.J., E.P. and R.P.; Software, S.W., C.R. and T.L.; Supervision, M.J., E.P. and R.P.; Visualization, S.W.; Writing—Original Draft, S.W.; Writing—Review & Editing, S.W., C.R., T.L., R.M., A.H., M.J., E.P. and R.P.

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Table S1. Tree species used for the ranking.

Tree species
Acrocarpus fraxinifolius
Albizia schimperiana
Annona reticulata
Artocarpus heterophyllus
Bridelia micrantha
Carica papaya
Citrus limon
Citrus sinensis
Commiphora eminii
Cordia africana
Croton macrostachyus
Eucalyptus maculata
Grevillea robusta
Mangifera indica
Margaritaria discoidea
Markhamia lutea
Musa spp.
Persea americana
Psidium guajava
Rauvolfia caffra
Senna siamea
Syzygium cuminii

Table S2. Ecosystem services used for the ranking.

Ecosystem services
Firewood supply
Fodder supply
Food provision
Increasing coffee quality
Increasing coffee yield
Mulch provision
Protection against wind
Protection from heat
Shade provision
Soil fertility improvement
Soil moisture enhancement
Weed suppression

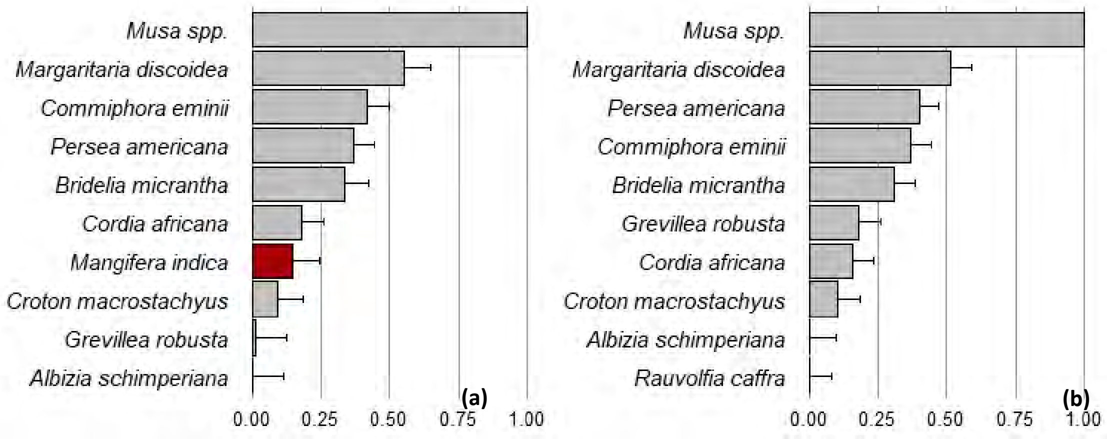

Figure S1. Scores and quasi-standard errors of tree species for fodder supply at (**a**) lower elevations (1148–1335 m asl) and (**b**) higher elevations (1336–1748 m asl). Red bars show tree species with significantly different scores between the two groups.

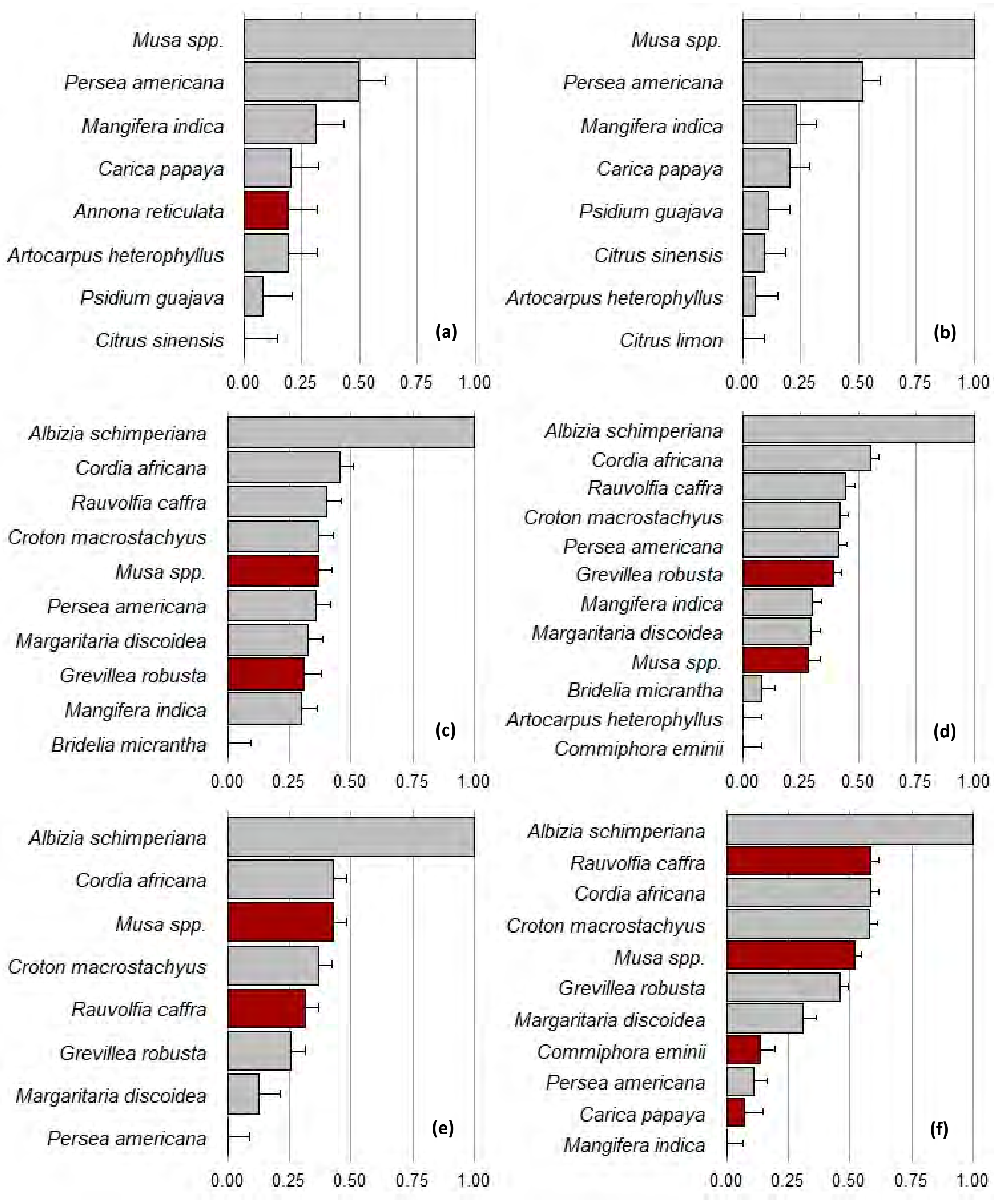

Figure S1. Scores and quasi-standard errors of tree species for food provision (**a**,**b**), shade provision (**c**,**d**), and soil fertility (**e**,**f**) divided by gender (women are presented in **a**, **c** and **e**; men are presented in **b**, **d** and **f**). Red bars show tree species with significantly different scores between the two groups.

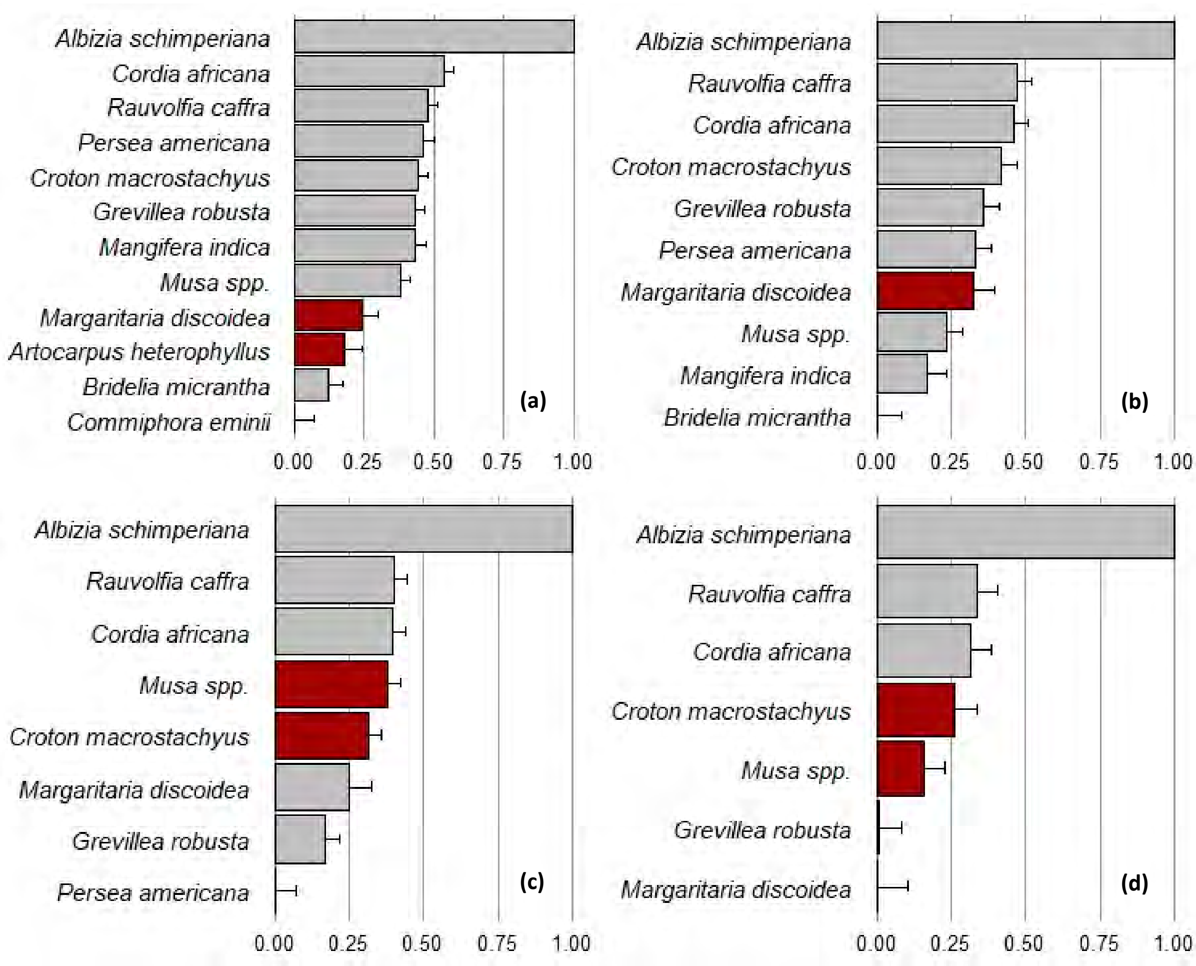

Figure S3. Scores and quasi-standard errors of tree species for protection from heat (**a,b**), and increasing coffee quality (**c,d**) divided by affiliation to a farmers group (non-members are presented in a and **c**; members are presented in **b** and **d**). Red bars show tree species with significantly different scores between the two groups.

Chapter 7: General conclusion

7.1. Thesis conclusion

Global coffee production is threatened by climate change. Farmers not only face yield losses, but could also experience a reduction in coffee quality (Descroix and Snoeck 2004; Vaast et al. 2006; Jaramillo et al. 2011; Craparo et al. 2015, 2020). Maintaining good yields and quality requires effective adaptation strategies and is of economic importance for coffee producing countries, including Tanzania. This study therefore set out to gain insight into the impact of climate change on coffee production systems at Mt. Kilimanjaro and the role of shade within agroforestry systems as a promising adaptation strategy.

Literature on different aspect of shade is limited, as most researchers only report shade density and/or tree density (Barradas and Fanjul 1986; Caramori et al. 1996; Campanha et al. 2004; Vaast et al. 2006; Lin 2007; Siles et al. 2010; de Souza et al. 2012; López-Bravo et al. 2012; Karungi et al. 2015; Mariño et al. 2016; Sarmiento-Soler et al. 2019). Most authors further only compare discrete shade levels (Caramori et al. 1996; Lin 2007; Karungi et al. 2015; Sarmiento-Soler et al. 2019) or shaded and unshaded systems (Barradas and Fanjul 1986; Campanha et al. 2004; Vaast et al. 2006; Siles et al. 2010; Bote and Struik 2011; de Souza et al. 2012; López-Bravo et al. 2012) rather than looking at continuous shade gradients. To adequately tailor recommendations, the different shade components and their contributions to changes in microclimate or coffee yield and quality need to be known. Observing effects of a range of shade densities allows us to see influences along the shade gradient.

Before adaptation strategies can be adequately tailored to farmers' specific requirements, an in-depth understanding of the climatic changes taking place and the consequences for coffee production is necessary. In Chapter 2, I investigated the extent to which farmers at Mt. Kilimanjaro experienced climate change, the impacts of extreme weather events on coffee production and the potential of shade trees as an adaptation strategy. My results show that, despite an increase in total annual precipitation, farmers are still confronted with droughts, due to a shift in the seasons.

The onset of the main rainy season gets delayed and precipitation during the short rainy season increases. These phenomena are connected to the El Niño Southern Oscillation and the Indian Ocean Dipole. The shift in seasons can significantly disrupt coffee production, as farmers clearly described the impacts of drought or excess rainfall during the different production stages (flowering, maturation and harvest) (Chapter 2). Successful adaptation measures are especially critical to overcome the delay of rains in March, at the beginning of the cultivation season.

There are differing reports on the benefits of shade trees on microclimate. Craparo et al. (2015, 2020) emphasise the importance of low night temperatures and agroforestry systems are usually reported to buffer maximum and minimum temperatures (Barradas and Fanjul 1986; Beer et al. 1998; DaMatta 2004; Vaast et al. 2006; Lin 2007; Rigal et al. 2020). In Chapter 3, I investigated this and analysed the effect of shade components on microclimate variables. My results demonstrate that despite there being differences between coffee plantations and smallholder coffee farms, shade can reduce maximum temperatures, without negative effects on night temperatures.

In the case study presented in Chapter 4, I deepened the understanding of climate modification by shade trees, by addressing the effect of shade density on coffee leaf temperatures. I showed that shade trees are effective at reducing high leaf temperatures to below ambient air temperatures during hot periods of the day. This could prevent midday depression of photosynthesis and increase CO_2 assimilation, leading to increased plant growth.

Previous research already showed that effects of shade on coffee yield and quality can be very system and location specific (Muschler 2001; Avelino et al. 2005; Vaast et al. 2006; DaMatta et al. 2007; Rahn et al. 2018). In Chapter 5, I assessed the effects of different aspects of shade on coffee yield and physical quality features in different coffee production systems. While I did not observe any effect of shade on coffee yield in coffee plantations, a slight reduction was seen for smallholder farmers, where shade density is much higher. Some positive effects of shade have been observed for coffee quality. Shade trees were beneficial for the size and weight of coffee beans. Banana plants seem to be favourable during bean development and filling, as the percentage of floating beans was reduced. This might be very beneficial for the farmers, as coffee quality can be important for the price they can obtain.

Besides the effect shade species have on coffee production, smallholder farmers also consider the ecosystem services they can obtain from the associated species when designing their farming system. In Chapter 6, I investigated the role of different tree species in the provision of ecosystem services as perceived by farmers. The most important ecosystem services for farmers at Mt. Kilimanjaro were food, fodder and fuelwood. Density of tree species perceived to provide these three ecosystem services were significantly higher for farmers prioritizing these services compared to farmers that did not consider all three ecosystem services their priority. This shows the importance of understanding the factors underlying farmers' management decisions before recommending shade tree species. Despite being aware of negative crop-tree interactions, farmers might include tree species that are not necessarily beneficial to coffee production in order to acquire other services. For regulatory services, such as coffee yield improvement, quality shade provision, and soil fertility improvement, *Albizia schimperiana* scored the highest for all rankings. Our results led to the upgrade of the online tool (shadetreeadvice.org) which generates lists of potential common shade tree species tailored to local ecological context considering individual farmers' needs.

7.2. Future directions

The recommendation for future studies investigating the effect of shade is to assess different components of shade, rather than only focusing on shade density or tree density. One aspect alone does not adequately represent the system. Additionally, investigating a shade gradient rather than only comparing shaded and unshaded systems gives a comprehensive understanding of the ways the systems could be optimised for the future. It might even be important to go one-step further and look at the surrounding landscape, as this could also be an influencing factor.

Agroforestry systems are complex with several elements and aspects to consider. There are therefore multiple ways this research could be expanded upon. Firstly, the effect of shade on microclimate and yield could be combined, rather than only examining the aspects separately. A model including the joint effect of shade and microclimate on yield could strengthen recommendations for improving the systems. Tree species is another component that should be included. Some tree features are already presented in this study, as the differences in leaf sizes can affect the number of gaps that allow light to penetrate the shade cover. Further research into the difference in species should be carried out, as I have shown that banana plants and tree species can have different effects on coffee production. The effect of different species could be compared with ecosystem services attributed to these species by the farmers, as presented in this study.

The development of the coffee berry from flower initiation to harvest takes a long time and development could be affected by shade or microclimate at any of the developmental stages. It is necessary to consider this in future research to enable precise management recommendations. Adaptation strategies further need to be tailored to different elevations and management systems (coffee plantations and smallholder farms). More research is needed into the feasibility and effectiveness of potential adaptation measures considering competition for light, water and nutrients between associated species.

To gain a comprehensive understanding of the interactions taking place in the systems, research on pest and diseases that affect coffee production in this area as well as predators and the effect of shade on this will be required, especially as rising temperatures facilitate spread of pests and diseases (Descroix and Snoeck 2004; Jaramillo et al. 2011). Considering changes in rainfall pattern, adaptation strategies have to provide measures to overcome droughts and shorter wet seasons with less frequent, but heavier rainfall events. Here special focus should be on soil and water management to ensure better soil moisture retention during dry seasons and to reduce erosion during heavy rainfall events.

An economic assessment is needed to evaluate if the gain in coffee quality can offset potential yield losses and to determine what the premium price would have to be to attain this. Additional incomes from associated species and other aspects, including the importance of a diverse system for smallholder farmers' resilience needs to considered in this analysis as well.

7.3. References

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