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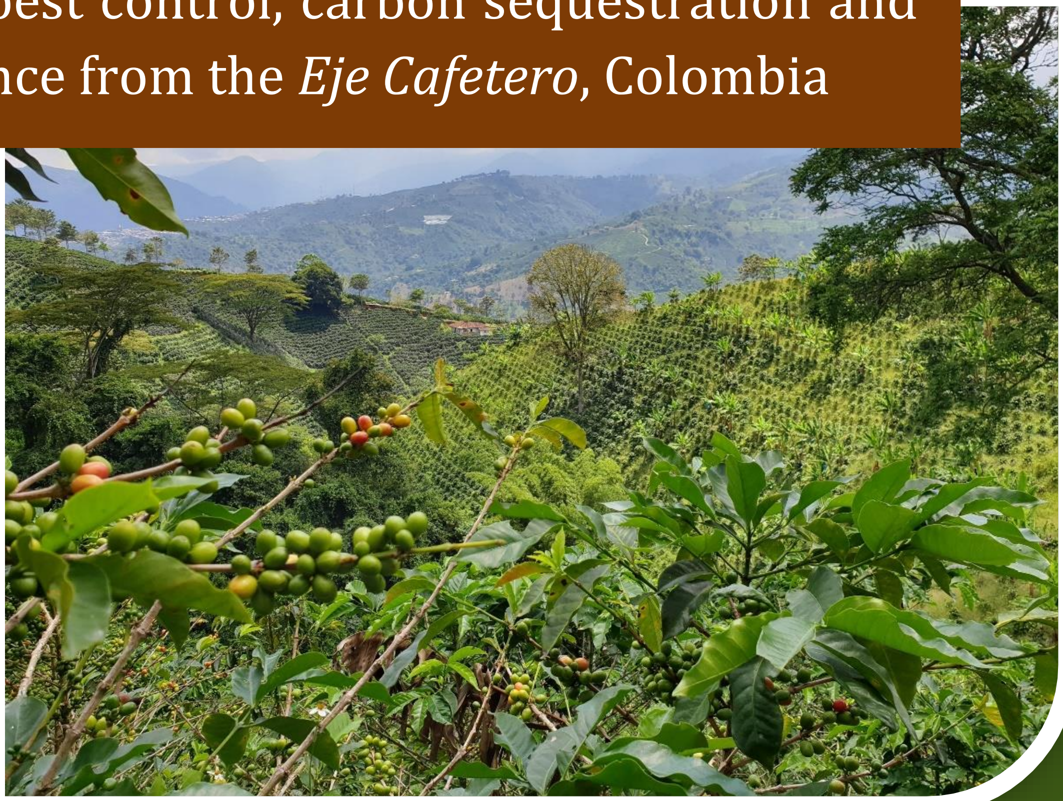
The potential of coffee agroforestry systems to enhance crop productivity, pest control, carbon sequestration and biodiversity: Evidence from the *Eje Cafetero*, Colombia



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ABSTRACT

The Colombian coffee sector is under severe stress due to the impacts of climate change, fluctuating commodity prices and an ever-increasing demand for high-quality coffee. As such, there is a need to develop more sustainable production systems. The potential of agroforestry as an alternative to monoculture systems and strategy to mitigate the effects of climate change is recognized by several authors. However, there is still a limited understanding about the extent and the conditions under which agroforestry systems can help to improve ecological functioning, without compromising in terms of crop productivity. By conducting field measurements at 55 plantations in the *Eje Cafetero*, in the department of Risaralda, Colombia, this study provides insights into the potential of coffee agroforestry systems to enhance crop productivity, pest control, carbon sequestration and biodiversity. Findings demonstrate that agroforestry systems can enhance carbon sequestration and biodiversity when compared to monocultures, and that these ecosystem services are expected to increase over time, along with shade cover and structural complexity. Crop productivity and pest control were found to be determined by management intensity and geographical location, whereas no negative effect of shade was identified. Overall, results of this research demonstrate that the implementation of agroforestry practices can lead to substantial improvements in terms of carbon sequestration and biodiversity, while maintaining comparable levels of productivity and pest control. Results have hereby shown that agroforestry systems are dynamic, rather than steady-state systems, and that their potential to provide valuable ecosystem services depends on the interaction between shade structure and composition, management practices and local climatic and geographic characteristics. In the light of global climate change, agroforestry systems are expected to gain both relevance and popularity in the development of future-proof agricultural landscapes.

Keywords: Agroforestry, Coffee, Ecosystem Services, Productivity

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ABBREVIATIONS

AFS	Agroforestry system
AGB	Aboveground biomass
AGBp	Aboveground biomass of perennial species
AGC	Aboveground carbon
AGCc	Aboveground carbon of coffee plants
AGCp	Aboveground carbon of perennial species
BA	Tree basal area
Bt	Aboveground biomass of coffee plants
CBB	Coffee berry borer
CBH	Circumference at breast height
CC	Canopy closure
CCLC	Coffee Cultural Landscape of Colombia
CGIAR	Consultative Group for International Agricultural Research
CH	Canopy height
CO2	Carbon dioxide
DBH	Diameter at breast height
EC	Epiphyte cover
ER	Epiphyte species richness
ES	Ecosystem services
FAO	Food and Agricultural Organization
GPS	Global positioning system
ICRAF	International Centre for Research in Agroforestry
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies
LC ant	Leaf cutter ant
m a.s.l.	Meters above sea level
MS	Monoculture system
RB	Root biomass
RCC	Root carbon content
RH	Relative humidity
RI	Tree species richness
SD	Species diversity
SI	Shannon Index
Sig.	Significance
SOC	Soil organic carbon
SOM	Soil organic material
YST	Years since transition

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1. INTRODUCTION

Worldwide, an estimated 25 million families in the humid tropics depend on the production of coffee for their livelihoods. With an annual retail value of 90 billion US$, coffee is hereby one the most valuable export crops in the World (Jaramillo *et al.*, 2011). Over the last few decades, agricultural intensification has led to a transformation of the global farming system. Fluctuating commodity prices, deteriorating agroecological conditions and an ever-increasing demand for high-quality coffee are hereby putting high pressure on smallholder farmers, which account for 70% of the global coffee production (Bacon, 2005).

The expansion of cropland and the intensification of agricultural production have been identified as important drivers of land degradation and resource depletion (Foley *et al.*, 2005; Kearney *et al*., 2017). Large scale land conversions are hereby threatening the availability of ecosystem services, endangering the existence of several rare and valuable species and increasing the vulnerability of farmers to the effects of climate change (Perfecto & Vandermeer, 2015). In many tropical regions, these land conversions follow a similar trajectory; due to economic forces (e.g. international markets, fluctuating commodity prices), primary forest areas and multi-layered, diversified farming systems are being replaced by high-input low-diversity cropping systems, which are often associated with higher yields (Bravo-Monroy, Potts & Tzanopoulos, 2016). Only after initial forest loss, and due to increasing welfare resulting from this agricultural intensification, national and regional authorities tend to invest in restoration and reforestation activities (CGIAR, 2019). While monoculture systems can indeed achieve higher profits in the short-term, this transition pattern can cause irreversible loss of ecosystem services (ES) and biodiversity as well as economic risk in the long run (Bommarco, Kleijn & Potts, 2013). As such, one of the greatest challenges of the 21st century is to ensure global food security and support those who are dependent on agriculture, while simultaneously enabling environmental outcomes and increasing resilience to climate change effects. Hence, there is an urgent need to curb harmful land conversions and promote a more sustainable agricultural system instead (FAO, 2016a; Meyfroidt, Rudel & Lambin, 2010).

Also in Colombia, the intensification of production, in particular coffee, has resulted in a transformation of the rural landscape. The country is responsible for 8% (818.243 tonnes) of the global coffee production, making it the third largest coffee exporter in the World, following up Brazil (3.019.228 tonnes) and Vietnam (1.460.800 tonnes) (FAO, 2016b). While internationally-renowned for its high-quality coffee (*Coffea Arabica*), the country is marked by large areas of degraded land (Bai *et al.*, 2008). As a consequence, Colombian farmers have to face large threats, including reduced crop productivity, increased susceptibility to pests and diseases and vulnerability to extreme weather events (Ramirez-Villegas *et al.*, 2012). While coffee plants can be grown in a variety of production systems, they are sensitive to changes in microclimate (Jaramillo *et al.*, 2009; Lin, 2007). As demonstrated by Ovalle-Rivera *et al.* (2015), areas at lower altitudes are losing climatic suitability for the cultivation of *Coffea Arabica*. Temperature extremes and changing precipitation patterns are hereby negatively affecting coffee yields and bean quality. In addition, coffee production in the region is increasingly threatened by the coffee berry borer *Hypothenemus hampei* (*H. hampei*), one of the most significant and devastating insect pests worldwide. The coffee berry borers are small insects (+/- 2mm) that penetrate the coffee berries to feed and lay eggs in the seeds (i.e. coffee beans), therewith damaging the berries (Jaramillo *et al.*, 2011). Another problematic pest in the region is the leaf cutter (LC) ant (*Atta* sp.). Even though the ants are considered to be keystone species in terms of ecological functioning (e.g. by causing physical disturbance, they increase soil fertility and stimulate plant growth (Fowler *et al.*, 2019), they are capable of completely defoliating a coffee shrub, herewith causes economic losses (Montoya-Lerma *et al.*, 2012). Currently, many farmers rely on synthetic pesticides to control the insects. However, due to their high environmental toxicity and increasing pesticide resistance in both species, there is a need to find alternative methods for (biological) pest control (Jaramillo *et al.*, 2011). Furthermore, the clearing of land and removal of native vegetation is resulting in increased atmospheric carbon dioxide (CO2) concentrations and an overall loss of biodiversity (Bommarco, Kleijn & Potts, 2013; Drescher *et al.*, 2016). In the context of global human-induced climate change, these problems are expected to aggravate.

Within the agricultural landscape of Colombia, and other tropical regions alike, a broad spectrum of coffee production systems can be found, ranging from high-input full-sun systems to more traditional systems, where coffee bushes are planted under the canopy of native trees (Moguel & Toledo, 1999). While monoculture systems are generally less diverse and therefore often associated with low biodiversity and limited ecological performance, shaded, i.e. agroforestry systems, are believed to provide a broader spectrum of ecosystem services (Bommarco, Kleijn & Potts, 2013; Kearney *et al.*, 2017). For instance, shade trees are known to regulate local climate conditions and therewith maintain soil fertility and ecological functioning (Barrios *et al.*, 2018; De Souza *et al.*, 2012). In addition, coffee agroforestry systems can, under certain conditions, reach comparable levels of biodiversity as observed in primary forest areas (e.g. Jose, 2009; Moguel & Toledo, 1999). Several authors have hereby proposed a positive relationship between the structural complexity of a shaded system and the rate of biodiversity in that area (e.g. Barrios *et al.,* 2018; Drescher *et al.*, 2016; McElhinny *et al.*, 2005). This is because ecosystems containing "a variety of structural features are considered likely to have a variety of resources and species that utilise these resources" (McElhinny *et al.*, 2005, p. 4). For instance, trees can create habitat for birds, insects and epiphytes which, in turn, provide a variety of ecological functions, both on farm level and on a wider scale (Goodall, Bacon & Mendez, 2015). Insects play a significant role in crop pollination and biological pest control, while epiphytes can create microhabitats and provide resources for other species (Jose, 2009; Barrios *et al.*, 2018; Moguel & Toledo, 1999). Because of their vulnerability to fragmentation and fluctuations in climate change, epiphytes are considered important indicators of (tropical) forest health (Woods, Cardelús & DeWalt, 2015) as they can provide early indications of ecosystem change (Benzing, 1998). Finally, since the integration of shade trees has been proven to result in greater aboveground carbon storage (e.g. Albrecht & Kandji, 2003; Ramachandran Nair, Mohan Kumar & Nair, 2009), agroforestry has been recognized as effective strategy to curb global climate change (Jose, 2009). Aboveground carbon stocks up to 40 Mg ha-1 were hereby found in Central American coffee agroforestry systems (Rahn *et al.*, 2013; Soto-Pinto *et al.*, 2010).

While the potential of agroforestry as an alternative to monoculture systems and strategy to mitigate the effects of climate change is recognized by several authors (e.g. Jezeer *et al.*, 2017; Jose, 2009; Toledo & Moguel, 2012; Vaast *et al.*, 2015), studies accurately describing and quantifying the role of such systems in the provision of ecosystem services remain scarce. Agroforestry systems are often associated with decreased coffee productivity due to competition for resources (i.e. water, sunlight, nutrients) between the trees and the coffee plants (Cerda *et al.*, 2017). However, the negative perception of shaded systems is often based on coffee yield only (Jezeer *et al.*, 2017). Factors related to the quality of the coffee beans (i.e. number of defects, physical appearance, chemical composition, flavour and acidity) are generally overlooked (Ribeyre & Avelino, 2012; Vaast *et al.*, 2015), even though they play an important role in establishing coffee bean prices (Perriot, Ribeyre & Montagnon, 2006). Measures of quality include, for instance, the ratio between fresh -and dry-weight of the coffee beans (Muschler, 2001) and the level of pest infestation (Ribeyre & Avelino, 2012). Furthermore, the input costs associated with the production of coffee are often not taken into account in economic analyses. For instance, in high-input full-sun systems, increased spending on pesticides and fertilizers could offset the potential increase in yield (Cerda *et al.*, 2017). Many authors hereby argue that shaded systems require lower levels of external input because they naturally maintain soil fertility and facilitate biological pest control (e.g. DaMatta, 2004; Jaramillo *et al.*, 2011; Teodoro, Klein & Tscharntke, 2008), while others found the contrary to be true (Pumariño *et al*., 2015). In addition, the amount of shade required to enhance ES provisioning while ensuring a satisfactory level of productivity, is much debated. While Lin (2007) proposes a shade-to-sun ratio of 2:3, DaMatta (2004) argues that the suitable level of shade largely depends on geographic and climatic features. While high levels of shade cover can be effective in sub-optimal production areas, similar levels of shade cover might have adverse effects on crop productivity in areas where competition for sunlight plays a larger role (i.e. at higher altitudes) (DaMatta, 2004; Ovalle-Rivera *et al*., 2015).

Hence, there is still a limited understanding about the extent and the conditions under which agroforestry systems can help to improve ecological functioning, without compromising in terms of crop productivity. In addition, while agroforestry systems are dynamic, rather than steady-state systems, they are not always treated as such. The evolution of coffee agroforestry systems, and in specific the effects of such trajectories on the provisioning of ecosystem services, has been largely overlooked. To be able to explain both the process and long-term effects of agroforestation, i.e. the transformation from a full-sun to a shaded system, it is important to take into account the changes that occur after the initial transition towards agroforestry.

In this study, the following research question will be answered: *What is the potential of coffee agroforestry systems to enhance pest control, carbon sequestration and biodiversity without compromising in terms of coffee productivity?* As such, the objective of this research is threefold: 1) to assess the differences in coffee productivity, pest incidence, biodiversity and carbon sequestration between monoculture and agroforestry systems by measuring coffee yield, dry-fresh bean weight ratio, CBB and leaf cutter ant incidence, presence of epiphytes and carbon stocks, 2) to analyse the development of these ES indicators under different shade and management conditions and 3) to evaluate the performance of agroforestry systems over time (i.e. time since implementation of agroforestry practices). The hypothesis that agroforestry systems are able to simultaneously enhance pest control, carbon sequestration and biodiversity, while maintaining or even enhancing coffee productivity, was tested by conducting field measurements in both monocultures and agroforestry systems along a gradient of ages. Variables indicating differences in vegetation structures (amount of shade cover, structural complexity) and management practices (weeding, pest control, fertilization) were hereby linked to the abovementioned performance indicators. Findings of this study contribute to understanding the potential of agroforestry systems to enhance vital ecosystem services, mitigate the impacts of climate change and support more sustainable coffee production systems.

2. METHODS

2.1 Study area

Field measurements were conducted in the department of Risaralda (5.32°N, 75.99°W) in Central Colombia (figure 2), which, together with the adjacent departments of Caldas, Quindío and Valle del Cauca, forms the Coffee Cultural Landscape of Colombia (CCLC), formally known as the Eje Cafetero or Coffee Growing Axis (Paisaje Cultural Cafetero, 2017b). The department of Risaralda is located in the Andean mountains, with an average altitude between 1000 and 2000 meters above sea level (m. a.s.l.). The region has a tropical climate and a bimodal rainfall regime (Guhl, 2008). Its mean temperature is 19.2°C, its relative humidity (RH) 83% and its average annual rainfall 2584 mm, with small peaks in May and December (FAO, n.d.). These weather conditions and geographical features make the area particularly suitable for the cultivation of high quality *Coffea Arabica* (Descroix & Snoeck, 2004). 80% of the coffee plantations in this area can be considered small (<3 hectare). Approximately 46% of the coffee is hereby produced in full sun systems, i.e. monocultures. The remaining 54% is grown in a diverse range of shaded (i.e. agroforestry or polyculture) systems (Armenteras, Rincon & Ortiz, 2005), although many of these plantations have experienced significant intensification over time (Armbrecht & Perfecto, 2003).

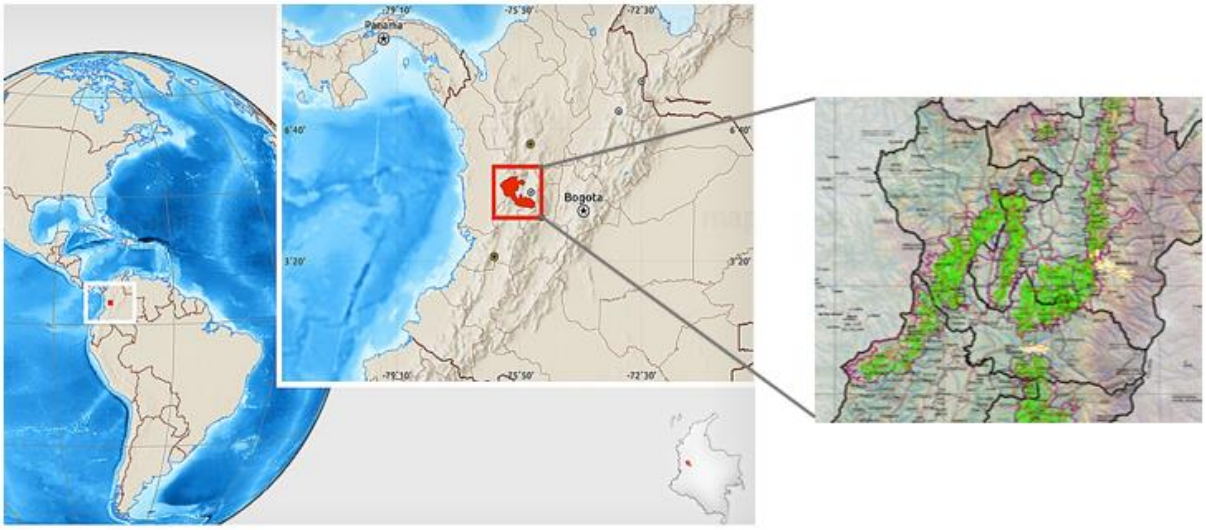

Figure 1. Study area, zoomed in at the department of Risaralda. Major coffee production areas are indicated in green. Source: Maphill, 2019; Paisaje Cultural Cafetero, 2017a

2.2 Site selection

For this study, empirical field data was collected on a total of 55 coffee plantations within the CLCC. All selected plantations had to fulfil the criteria of being productive (i.e. producing marketable coffee beans). Agroforestry plantations were selected to cover a range of ages (i.e. time since implementation agroforestry practices), whereas monoculture systems were included to serve as a baseline for this study (y=0). Plantations where *Musaceae* plants (i.e. Plantain and Banana plants) and coffee bushes were equally represented were not taken into account, since these systems can be better classified as polycultures (Moguel & Toledo, 1999). To minimize possible confounding effects, the altitudinal range was kept as small as possible. Figure 3 depicts an overview of all selected coffee plantations in the research area. Most plantations were situated in the municipalities of Santuario (n=18) and

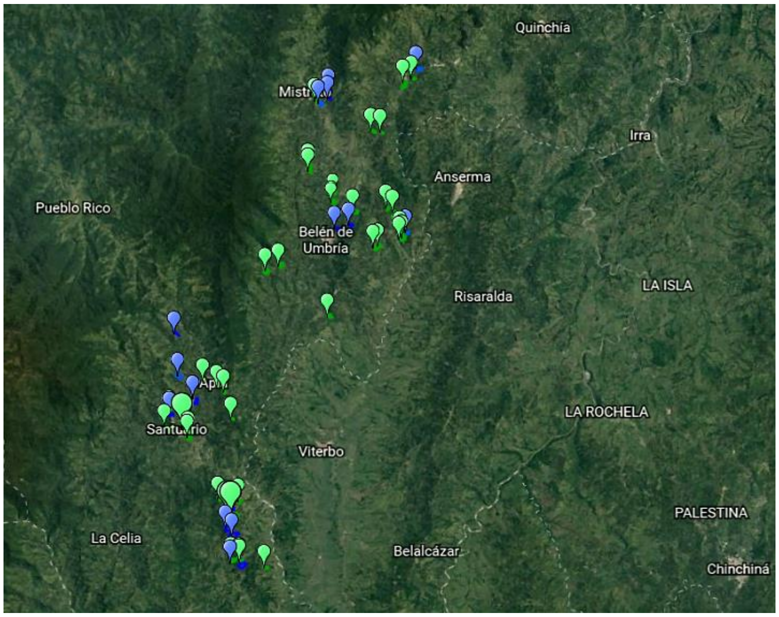

Figure 2. Selected plantations. Monoculture systems are indicated in blue, agroforestry plantations in green

Belèn de Umbría (n=21). The other plantations were located in Apía (n=7), Guática (n=4) and Mistrato (n=5). Of the selected plantations, 15 were classified as monoculture (MS) and 40 as agroforestry system (AFS).

2.3 Data collection

On all selected plantations, data was collected on general farm characteristics, management practices and a variety of biophysical variables. An overview of all measured ecosystem service indicators can be found in appendix A.

A pre-developed structured questionnaire was used to obtain information on general farm characteristics (e.g. size, years since transition (YST), coffee planting density), input management (e.g. application of fertilizers and pesticides, type of vegetation control) and coffee yield. The latter is expressed in arroba ha-1 (~10-15 kg), the weight unit used by the farmers in the region.

In addition, field data was collected within plots of 20 x 20 m, established within each representative study area (monoculture or agroforestry system). All field visits were preceded by a short interview, which included both general (farm level) questions, comparable to those in the survey, and questions regarding the specific study site (plot level). For instance, farmers were asked to identify the trees within the plot and provide additional information on their management practices in that area.

All biophysical measurements (see subsequent sections) were conducted on plot level and extrapolated to hectare (ha). The topographic location and altitude of the plot were determined with a Global Positioning System (GPS) (Garmin GPSMAP 62s). In addition, ambient temperature (°C) and relative humidity (%) were measured every half hour for the duration of the fieldwork, using a standard thermo-hygrometer.

2.3.1 Coffee plants

The planting density of the coffee plants was determined by multiplying the number of rows with the total number of plants per row in the plot, and standardizing this amount to obtain the number of coffee plants per hectare.

Further data was collected by taking 6 average looking coffee plants per plot and recording the height (m), diameter (m) and diameter of the stem at 15 cm (cm) and the amount of foliated shoots, fruit nodes and average maximum number of berries per node for each plant. The latter was determined by counting the berries on four fruit nodes per plant, selecting the fruit nodes with the largest amount of berries.

In addition, 100 ripe berries were randomly collected on each plot, weighed (g) and checked on presence of the coffee berry borer by looking for a small hole at the tip of berry. Afterwards, the coffee berries were stripped of their pulp layer and washed, following the technique of the local farmers (Romero-Alvarado *et al*., 2002). Floating berries were hereby considered defective and removed from the sample. The remaining berries were sun dried and weighed (g). By multiplying the weight with the average (maximum) amount of berries per plant, the potential yield per plant was determined. Subsequently, this number was multiplied with the estimated number of plants per hectare to obtain the potential yield per hectare (Mg ha-1).

Finally, 15 coffee plants per plantation were checked on damage from leaf cutter ants (*Atta* sp.). This was done by first estimating the amount of damaged leaves on the coffee plant (0%, 0-5%, 5-20%, 20-50%, >50%) and subsequently estimating the extent of damage on the affected leaves (0%, 0-5%, 5-20%, 20-50%, >50%) (table 1). The average scores of both indicators were combined as follows: (average 1 + average 2) / 2. The resulting damage value was rescaled to a value between 0 and 1.

Table 1. Leaf cutter ant damage score

Level of damage	Score
No damage	0
< 5% damage	1
5 – 20% damage	2
20 – 50% damage	3
> 50% damage	4

2.3.2 Other vegetation

Shade cover, expressed in terms of canopy closure (0-100%), was measured by means of a spherical crown densiometer (Paletto & Tosi, 2009). Within each plot, 9 measurements, each based on four readings facing North, East, South and West, were taken and averaged to plot level.

Densities of timber and leguminous trees, fruit trees and *Musaceae* plants were determined by simply counting the number of each species in the plot. All trees and plants with a diameter at breast height (DBH) larger than 5cm were identified by using a field guide or consulting the farmer, where possible to species level, and otherwise to genus or family level.

DBH was determined by measuring circumference at a height of 1.30 m (CBH) using measuring tape, and dividing this value by pi:

$$DBH = CBH/\pi$$

Tree basal area (m²) (BA) was determined by using the DBH:

$$BA = \pi \times (DBH^2/40000)$$

By adding up all individual BA values, the total BA per plot was obtained. Subsequently, both tree density and tree basal area were expressed in ha by multiplying the plot-level value with 0.04.

Species diversity was calculated through the Shannon diversity index (H) (Peet, 1974):

$$H = -\sum_{i=1}^{s} p_i \ln p_i$$

In this formula, p represents the proportion of individuals of one species (number of individuals of species x divided by the total number of individuals), whereas s is the total number of species determined (i.e. species richness). For the purpose of this study, only trees and shrubs were taken into account.

Additionally, epiphyte cover (EC) was visually estimated on all trees and assigned to one of four categories: no (0%), low (0-30%), medium (30-60%) or high (>60%) EC. Epiphyte species richness (ER) (total number of species) was determined by recording the presence of lichens, mosses, ferns and bromeliads.

2.3.3 Carbon sequestration calculations

Carbon stocks in trees (AGCp) (excluding *Musaceae* plants), coffee shrubs (AGCc) and roots (RCC) were estimated for all plantations (n=55). Allometric equations were used to estimate the aboveground biomass of all observed perennial tree species (AGBp) (excluding *Musaceae* plants) and coffee shrubs (Bt).

The most important predictor variables for estimating AGBp in tropical forests are tree height (H) (m), tree diameter at breast height (DBH) (cm) and specific wood density (D) (kg/m3), the latter requiring species identification. The following equation was used (Chave *et al.*, 2014):

$$AGBp = 0.0673 \times (\rho \times H \times D_{1.3}^2)^{0.976}$$

Specific wood densities were assigned to the identified species by using average values from a global wood density database (ICRAF, 2019) (appendix F). When the wood density of the specific species was not listed, the average wood density of the genus was used. When a species could not be identified, the average wood density of the plot was used and assigned to the species.

Subsequently, AGCp could be derived from the total AGBp by using an internationally accepted conversion factor of 0.47 (derived from the 2006 *IPCC guidelines for national greenhouse gas inventories* (Eggleston *et al.*, 2006)):

$$AGCp=0.47\times AGBp$$

To make an estimation of the aboveground biomass of coffee shrubs Bt (kg), the allometric equation from Segura, Kanninen and Suárez (2006) was used, where d15 represents the diameter of the stem at 15 cm height (cm) and h depicts the height of the coffee plant (m):

$$Bt =-1.113+1.578\times d15 +0.581\times h$$

To estimate AGCc, the total Bt was multiplied with the factor 0.5 (Häger, 2012):

$$AGCc=0.5\times Bt$$

Root carbon content (RCC) could be derived from the total aboveground biomass (AGB) by using the following formula (Häger, 2012):

$$RB = \exp(-1.0587 + 0.8863 * \ln(AGB/1000))$$

In this formula, RB represents root biomass in Mg and AGB is the sum of AGBp (kg) and Bt (kg). By multiplying the RB with 0.5, total RCC could be calculated:

$$RCC = 0.5 \times RBD$$

AGCp, AGCc and RCC values were all standardized to Mg ha-1.

2.4 Predictor variables

2.4.1 Age

All coffee plantations were classified on the basis of their age, i.e. time since first implementation of agroforestry practices. Age classification was hereby based on field observations, representing the average ages of all trees (excluding *Musaceae* plants) within the plot. A five-year interval was used for the clustering of the ages: 0 (representing the monoculture systems), 1-5, 6-10, 11-15, and 16 years and older. The number of plantations in each age cluster is depicted in table 2.

Table 2. Number of plantations in each age cluster.

Cluster	Age	Number of plantations
1	0	15
2	1-5	7
3	6-10	18
4	11-15	10
5	16 >	4

2.4.2 Shade structure and composition

Measurements of canopy closure generally provide a good representation of the amount of incoming light through the overstory. However, canopy closure in itself does not describe shade structure (e.g. canopy height, tree density and tree basal area) or composition (e.g. species richness and diversity). Therefore, a selection of structural attributes (table 3), based on comparable studies and literature on tropical forest structures (e.g. Bisseleua *et al.*, 2013; Hernández-Martínez *et al.*, 2009; Jezeer *et al.*, 2018; McElhinny *et al.*, 2005), was used to calculate a shade index value. This value represents the structural complexity of the shaded system, hence serves as qualitative, rather than quantitative indicator of shade.

The selected variables were scored relative to the inherent features of the region. This was done by assigning a value between 0 and 1 to each continuous variable, using the following formula: index value = (value - minimum) / (maximum - minimum). High index values were hereby assigned to the high values of the vegetation variables. The individual index values of 1) tree density (TD), 2) tree basal area (BA), 3) canopy height (CH), 4) canopy closure (CC), 5) tree species richness (RI) and 6) tree species diversity (SD) were summed to obtain the final shade index value, rescaled to a value between 0 and 1. Higher index values hereby correspond to higher structural complexity:

$$\text{Shade index value} = TD + BA + CH + CC + RI + SD$$

2.4.2 Management practices

An input management index, based on indices found in comparable studies (e.g. Cerda *et al.*, 2017; Hernández-Martínez *et al.*, 2009; Jezeer *et al.*, 2018), was calculated for each plantation, in a similar way as described under section 2.4.2. The index was based on survey and interview data and contains information on common weeding, pest control and fertilization practices (table 5). A value of 0.5 or 1 was assigned based on the type of practice (application of chemicals = 1, manual practices = 0.5). The final index value, including 1) machete use frequency (Mf), 2) scythe use frequency (Sf), 3) chemical herbicide quantity (CHq), 4) frequency of manual CBB removal (CBBf), 5) chemical CBB pesticide quantity (CBBq), 6) chemical pesticide quantity (CPq) and 7) chemical fertilizer wuantity (CFq), corresponds to the sum of all individual variable rankings, rescaled to a value between 0 and 1. Zero hereby represents the lowest and one the highest management intensity:

$$\text{Management index value} = 0.5{*}Mf + 0.5{*}Sf + CHq + 0.5{*}CBBf + CBBq + CPq + CFq$$

2.5 Data analysis

To test for differences between monocultures and agroforestry systems in terms of coffee productivity, pest incidence, carbon sequestration and biodiversity, an independent samples-t test was used. Thereafter, differences between the established age clusters were analysed by using one-way ANOVA with Tukey’s post-hoc tests (with chi-squared distance). Prior to each test, a Levene’s test with a significance level of $p < 0.05$ was performed to test for homogeneity of variance. Subsequently, fitted linear models were used to test for relationships between vegetation structure (canopy closure and shade index value), management characteristics (management index value) and all ES indicators. All data was tested for normality by running and plotting a Shapiro-Wilk normality test with a significance level of $p < 0.05$. When residuals were not normally distributed, they were log transformed. In a few cases, outliers were removed from the dataset. This was only done if the outlier was due to incorrectly measured or uncertain data, or was heavily affecting assumptions made in the study. These cases are marked in their respective appendices. In the absence of a linear trend, curve estimation was used to see whether a non-linear model could better explain the relationship. A Pearson correlation coefficient was used to check for correlations between normally distributed variables. When data was not normally distributed, a Spearman’s rank correlation test was used. If altitude was found to be related to the dependent variable, the factor was included as random effect in further analyses. Besides the single effects of age, shade and management on ES provisioning, interactions among the factors were also analysed by using generalized linear models with Wald chi-squared tests. Finally, synergies and trade-offs among coffee productivity, pest incidence, carbon sequestration and biodiversity were assessed by performing linear regression tests between the indicators. All statistical analyses were performed using SPSS Statistics 25.

3 RESULTS

3.1 General farm characteristics

The average altitude of the AFS systems was 1508.23 ± 152.60 m and that of the MS systems 1601.87 ± 137.91 m. With an average size of 18.52 ± 22.78 ha, monoculture plantations were larger than agroforestry plantations (4.16 ± 3.33 ha). In total, 851 trees and *Musaceae* plants were observed within the plots (corresponding to a total area of 880 ha). Two thirds (67%) of these trees and plants were a mix of Plantain and Banana (*Musaceae* family), the other third (33%) were timber, leguminous and fruit trees. Of the latter, 25 different species were identified to species level. The remaining species (1.4%) could not be identified. The dominant coffee varieties (*Coffea Arabica*) that were grown on the plantations were *Castillo* (*Rosario* and *Naranjo*), *Caturra*, *Catimor* and *Colombia*.

Significant differences between the established age clusters were observed for canopy closure (F(3,34 = 4.840; $p < 0.01$) (figure 3 and appendix H). Strong positive correlations were hereby found between canopy closure on the one hand and tree basal area (F(1,37) = 4.178; $R^2 = 0.101$; $p < 0.05$) and average tree height (F(1,36) = 6.703; $R^2 = 0.153$; $p < 0.05$) on the other. The shade index values did not differ significantly between the age clusters, although a trend could be observed towards higher vegetation complexity in older agroforestry systems (figure 4).

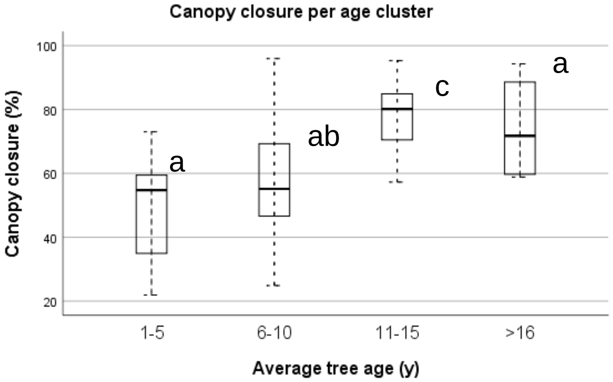

Figure 3. *Canopy closure per age cluster. Letters indicate significant differences between the age clusters.*

Figure 4. *Relationship between average tree age and structural complexity, demonstrates a trend towards higher structural complexity over time*

Additionally, findings indicated a strong negative relationship between canopy closure and the average ambient temperature (F(1,31) = 12.196; $R^2 = 0.282$; $p < 0.01$) (figure 5) and a positive relationship between canopy closure and the average relative humidity (RH) (F(1,31) = 9.144; $R^2 = 0.228$; $p < 0.01$) (figure 6) measured in the plots. Significantly higher average temperatures (F(45) = 4.201; $p < 0.05$) and lower relative humidity's (F(45) = 5.483; $p < 0.05$) were hereby found in the agroforestry plantations (figure 7 and 8), although no significant differences were found between the age clusters.

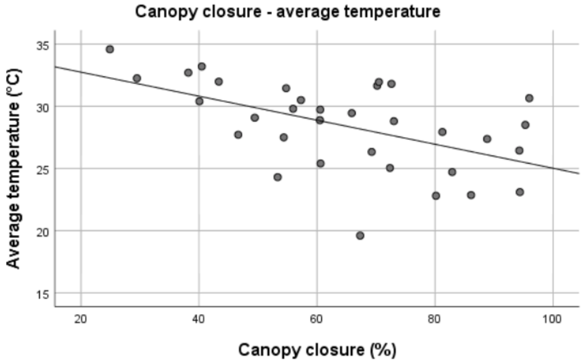

***Figure 5**. Relationship between canopy closure and average temperature. Depicts a decline in temperature with increasing shade cover.*

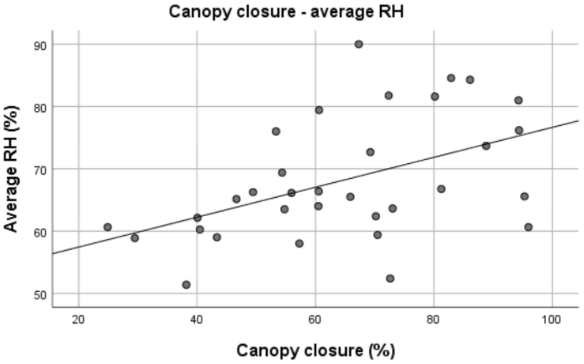

***Figure 6**. Relationship between canopy closure and relative humidity. Depicts an increase in RH with increasing shade cover*

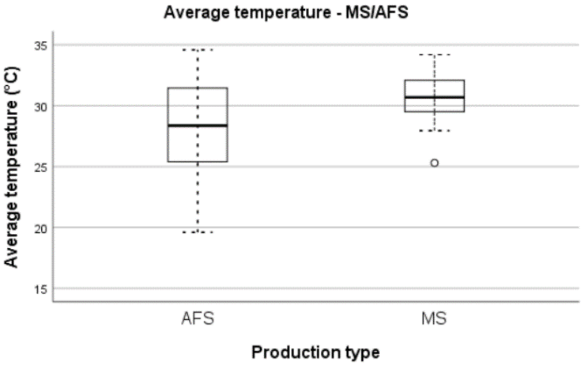

***Figure 7**. Difference in average temperature between monocultures and agroforestry systems. Depicts a significantly higher mean value in MS plantations*

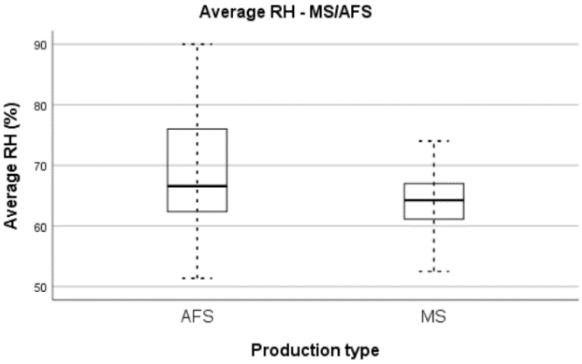

***Figure 8**. Difference in relative humidity between monocultures and agroforestry systems. Depicts a significantly higher RH in AFS plantations*

Furthermore, large differences were found between the plantations in terms of input management. Especially the application of chemical herbicides, pesticides and fertilizers varied largely. Management intensity, indicated by the management index value, hereby decreased with the size of the plantation (F(1,51) = 6.154; $R^2 = 0.108$; $p < 0.05$). However, no differences were found for management intensity between monocultures and agroforestry plantations, nor between the established age clusters.

Finally, no relationships were found between altitude and shade structure (canopy closure and shade index value), between altitude and management intensity or between altitude and the average temperature and relative humidity. More information on the plantation characteristics can be found in table 2 and appendix B, C and D.

Table 2. Descriptive statistics of general farm characteristics, structural attributes measured in the agroforestry plantations and management practices in the study area. Shade and management index values are also included. Significant differences between monocultures and agroforestry plantations are indicated under MS/AFS with * (significance level of $p < 0.05$) or with ** (significance level of $p < 0.01$). Supporting information can be found in appendix B, C and D.

	Mean	**±SD**	**Min**	**Max**	**n**	**MS/AFS**
General farm characteristics						
Plantation size (ha)	8.15	13.91	0.85	93.00	54	**
Coffee plant density (plants ha-1)	5625.55	1160.10	2112.00	9090.00	55	
Altitude (m a.s.l.)	1533.77	154.47	1205.00	1870.00	55	
Years since transition (y) (AFS only)	10.21	6.34	2.00	32.00	39	
Ambient temperature (°C)	28.65	3.60	19.60	34.58	47	
Relative humidity (%)	67.59	9.50	51.38	90.00	47	
Shade structure						
Canopy closure (%)	63.99	19.75	21.91	95.96	40	
Tree density (trees ha-1)	531.88	398.15	75.00	1950.00	40	
Tree basal area (m2 ha-1)	349.67	507.40	12.84	2901.50	40	
Canopy height (m)	6.29	2.67	2.54	13.56	40	
Species richness (no. of species)	3.20	1.38	1.00	8.00	40	
Species diversity (Shannon diversity index)	2.29	1.90	0.00	8.13	40	
Shade index value	0.57	0.23	0.00	1.00	39	
Input management						
Frequency use machete (times yr-1)	0.68	1.13	0.00	3.50	52	
Frequency use scythe (times yr-1)	2.27	1.30	0.00	6.00	52	
Quantity chemical herbicide (l ha-1 yr-1)	0.94	1.80	0.00	9.90	52	
Frequency manual CBB (times yr-1)	13.91	8.74	0.00	24.00	53	
Quantity chemical CBB (l ha-1 yr-1)	1.10	2.80	0.00	20.18	53	
Quantity chemical pesticide (l ha-1 yr-1)	1.29	2.40	0.00	13.32	53	
Quantity chemical fertilizer (kg ha-1 yr-1)	674.33	1016.43	10.04	5400.00	52	
Management index value	0.37	0.24	0.00	1.00	51	

3.2 Effects of age, shade and management on ES provisioning

The effects of shade and management varied across the different ecosystem services, as did the development of the ES indicators over time. All significant effects, including the effect of altitude as confounding variable, are depicted in table 3 and explained in more detail in their respective sections. Identified relationships were best explained by linear regression models, unless indicated otherwise.

Table 3. Differences between monocultures and agroforestry systems (MS/AFS) and single and interactive effects of canopy closure, structural complexity, management and altitude on the indicators of four ecosystem services. (+) indicates a positive relationship, (-) indicates a negative relationship. A significance level of $p < 0.05$ is indicated with *, a level of $p < 0.01$ with **.

ES indicator	**MS/AFS**	**Single effects of shade, management and altitude**				**Interactive effects**
		Canopy closure	Structural complexity	Management intensity	Altitude	
Coffee production						
Number of fruit nodes						
Berries per fruit node						
Dry weight berries (g)					(+)**	
Dry weight berries (% fresh weight)				(+)*	(+)*	Management x Altitude
Potential yield						
Yield 2018						
Pest control						
CBB incidence					(-)**	
Leaf cutter ant incidence					(-)*	
Carbon storage						
AGCp	**	(+)**	(+)**			
AGCc						
RCC	**	(+)**	(+)**			
Biodiversity						
Epiphyte cover	**	(+)**	(+)*			
Epiphyte species richness	**	(+)*	(+)**			

3.2.1 Coffee production

The number of fruit nodes per plant and the number of berries per fruit node did not differ significantly between monocultures and agroforestry systems. Also, no significant differences were found for the dry weight of the berries in grams or in percentage of fresh weight between the two systems. A positive correlation was found between the potential coffee yield based on field measurements and the actual yield (arroba ha-1) recorded in 2018 ($F(1,40) = 4.609$; $R^2 = 0.103$, $p < 0.05$). Neither potential yield nor actual yield did hereby differ significantly between MS and AFS systems (also see appendix E).

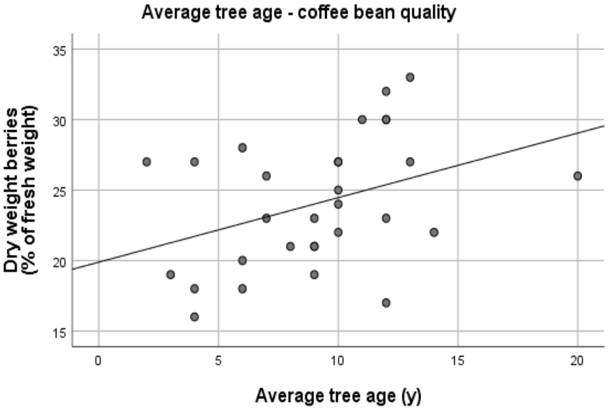

Figure 9. Relationship between average tree age and dry-fresh berry weight ratio. Depicts an increase in coffee bean quality over time

When comparing the different age clusters, findings did not indicate any significant differences in productivity. However, a significant trend could be observed towards a higher dry-fresh weight ratio (F(1,28) = 4.805; R² = 0.146, p < 0.05) in older agroforestry plantations (figure 9). Comparable results were found for shade cover and structural complexity. Although not significant, trends could be observed towards higher coffee bean weight and dry-fresh weight ratio in plantations with a higher amount of shade cover and increased structural complexity (figure 10 and 11).

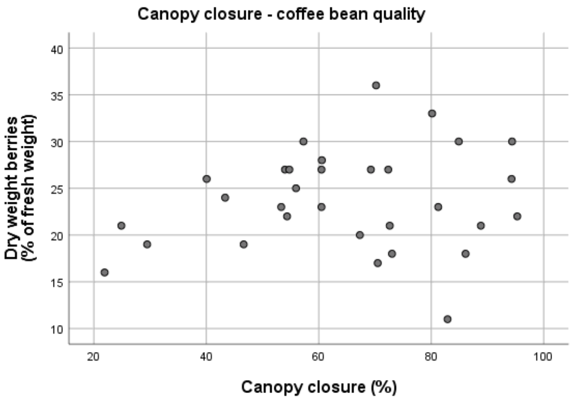

***Figure 10**. Relationship between canopy closure and dry-fresh berry weight ratio. Depicts a trend towards higher coffee bean quality with increasing shade cover*

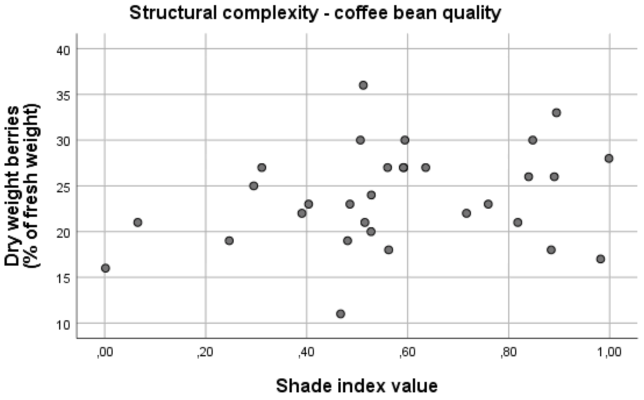

***Figure 11**. Relationship between the shade index value and dry-fresh berry weight ratio. Depicts a trend towards higher coffee bean quality with increasing structural complexity*

Dry weight of berries in % of fresh weight increased significantly with management intensity (F(1,43) = 4.330; R² = 0.091; p < 0.05) (figure 12). When looking at all management practices individually, it was found that chemical pesticide use had a stronger effect on the dry-fresh weight ratio (F(1,41) = 5.715; R² = 0.122; p < 0.05) than the management index value. In addition, both dry weight of the berries in grams (F(1,47) = 7.258); R² = 0.124; p < 0.01) and in % of fresh weight (F(1,43) = 4.119; R² = 0.087; p < 0.05) (figure 13) were found to increase with altitude (table 3). An interactive effect of management intensity x altitude on dry weight of berries in % of fresh weight was also identified (X = 6.216; p < 0.05). The effect of management on berry weight in % of fresh weight was hereby only found to be significant for plantations with an altitude below average (altitude < 1533.77) (F(1,17) = 5.609; R² = 0.230; p < 0.05).

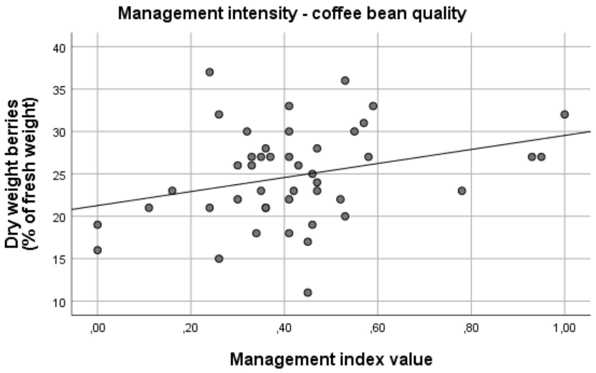

Figure 12. Relationship between the management index value and dry-fresh berry weight ratio. Depicts an increase in coffee bean quality with increasing intensity

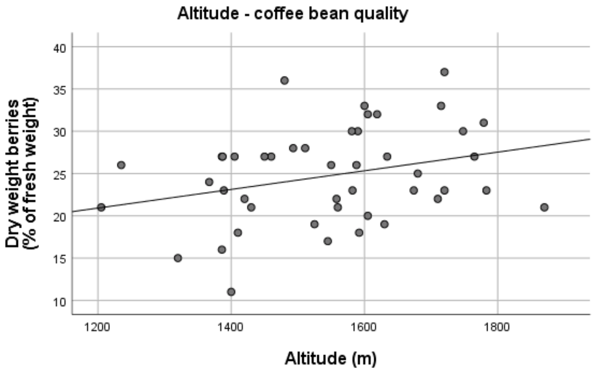

Figure 13. Relationship between altitude and dry-fresh berry weight ratio. Depicts an increase in coffee bean quality at higher altitudes

3.2.2 Pest control

The severity of the CBB pest in the region was confirmed through both the interviews with the farmers and the field measurements. Although not significant, the mean percentage of CBB incidence was much higher in agroforestry systems (29.3 ± 27.48) than in monocultures (19.08 ± 26.89), as was the leaf cutter ant damage score (AFS: 0.51 ± 0.24; MS: 0.37 ± 0.27).

No significant differences in pest incidence were found between the age clusters. However, a slight trend towards higher CBB incidence in plantations with older trees could be observed (figure 14).

Furthermore, while management intensity was not found to be significantly related to either coffee berry borer or leaf cutter ant incidence, a strong positive relationship was found between the CBB infection rate and the use of chemical CBB pesticides (F(1,38) = 8.677; $R^2 = 0.186$; $p < 0.01$) (figure 15)

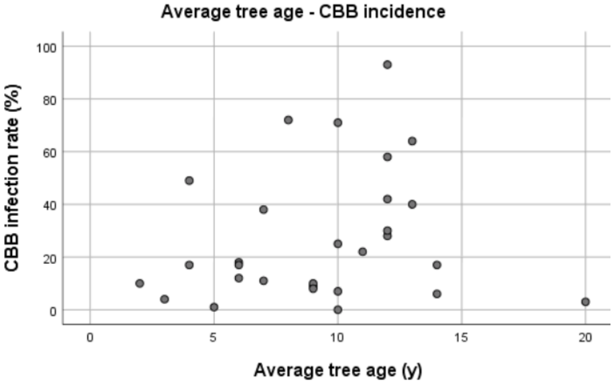

Figure 14. Relationship between average tree age and CBB infection rate. Depicts a trend towards higher CBB incidence over time

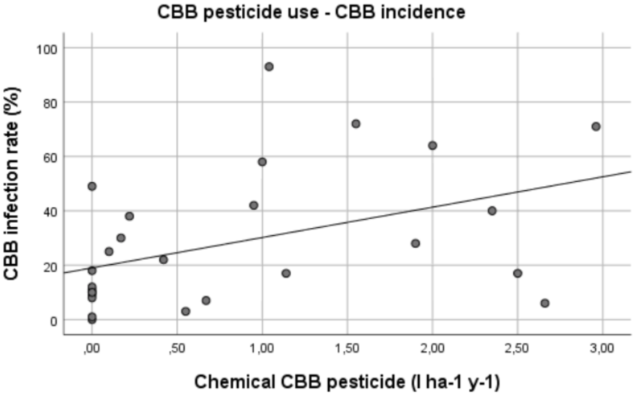

Figure 15. Relationship between chemical CBB pesticide use and CBB infection rate. Depicts a positive correlation

Neither CBB incidence nor leaf cutter ant activity did change significantly with the amount of shade (CC). In addition, neither of the pest indicators were found to be related to the shade index value.

Finally, CBB incidence did decrease significantly with altitude (F(1,40) = 14.371; $R^2 = 0.264$; $p < 0.01$) (figure 16), as did leaf cutter ant activity (F(1,20) = 5.674; $R^2 = 0.221$; $p < 0.05$) (figure 17).

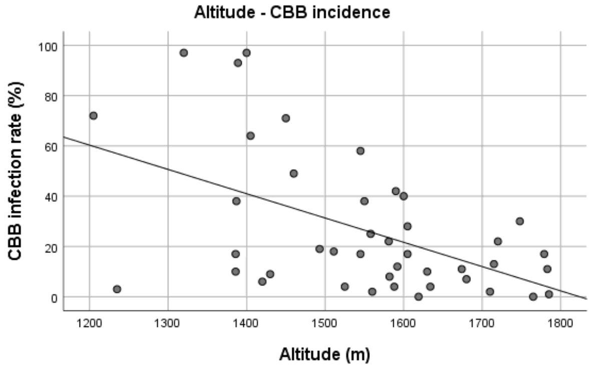

Figure 16. *Relationship between altitude and CBB infection rate. Depicts a decrease in CBB incidence with altitude*

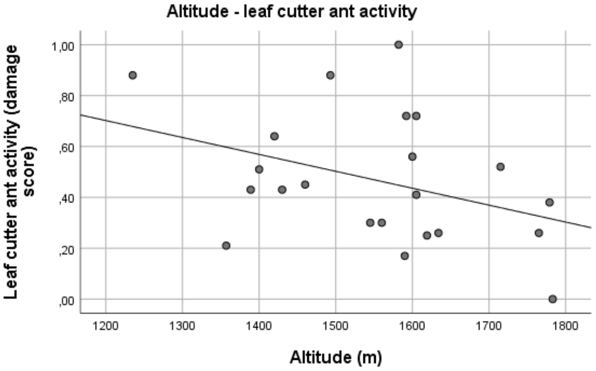

Figure 17*. Relationship between altitude and LC ant damage score. Depicts a decrease in LC ant activity with altitude*

3.2.3 Carbon sequestration

Large differences in carbon sequestration were found between the plantations (see appendix G for supporting information). With an estimated average total AGC (including AGCc, AGCp and RCC) of 32.48 ± 20.56 Mg ha-1, agroforestry plantations had much higher carbon stocks than monoculture systems (7.89 ± 4.82 Mg ha-1) (figure 18). This difference can be largely explained by the additional carbon captured in trees (AGCp) (F(52) = 0.084; $p < 0.01$) and (tree) roots (RCC) (F(52)=13.836; $p < 0.01$).

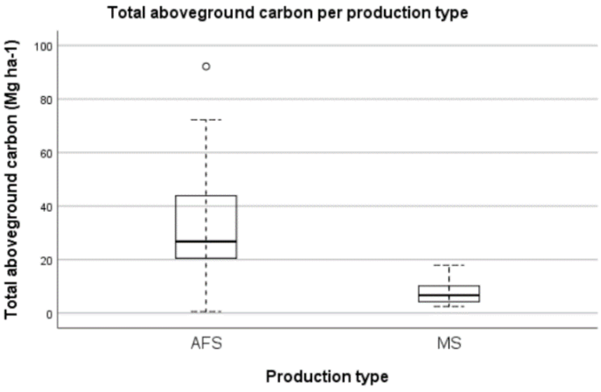

Figure 18*. Total aboveground carbon per production type. Depicts a significantly higher total AGC in Agroforestry systems.*

Figure 19 depicts the average total AGC per age cluster (F(4,49) = 14.160; $p < 0.01$). Results of the post-hoc tests demonstrate insignificant differences between monocultures and very young agroforestry systems, and between the oldest age clusters (appendix I). The relationship between average tree age and carbon storage could hereby be best explained by an S-curve model (F(1,37) = 35.522; $R^2 = 0.490$; $p < 0.01$) (figure 20).

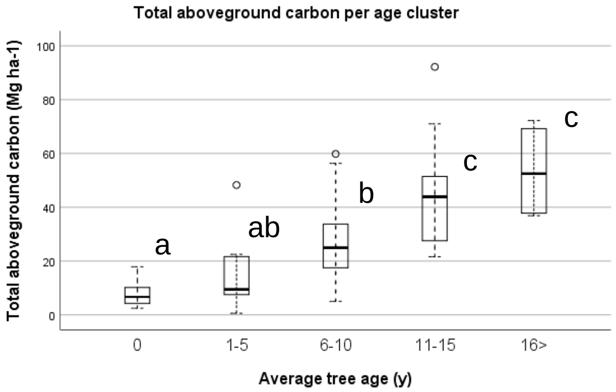

Figure 19. *Total aboveground carbon per age cluster. Letters indicate significant differences between the clusters*

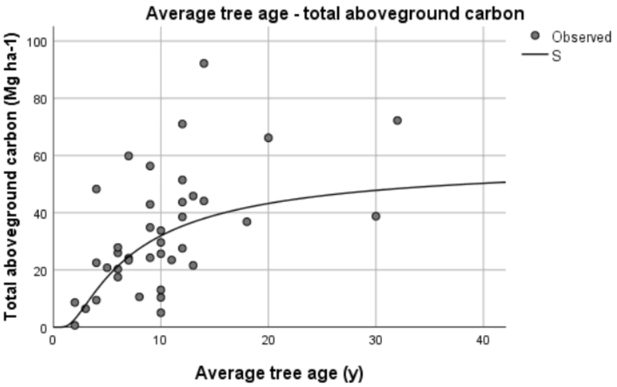

Figure 20*. Relationship between average tree age and total aboveground carbon. Depicts an increase in total AGC over time, following a saturation curve.*

Carbon stored in trees (AGCp) increased significantly with both the amount of shade cover (CC) (F(1,33) = 30.7676; $R^2 = 0.482$; $p < 0.01$) and the shade index value (F(1,33) = 10.232; $R^2 = 0.237$; $p < 0.01$). When looking at the individual variables of the index value, canopy height was found to have a particularly strong effect on AGCp (F(1,33) = 25.000; $R^2 = 0.312$; $p < 0.01$). All these relationships were best explained by logistic models (figure 21, 22 and 23).

Finally, no relationships were found between management intensity and carbon sequestration.

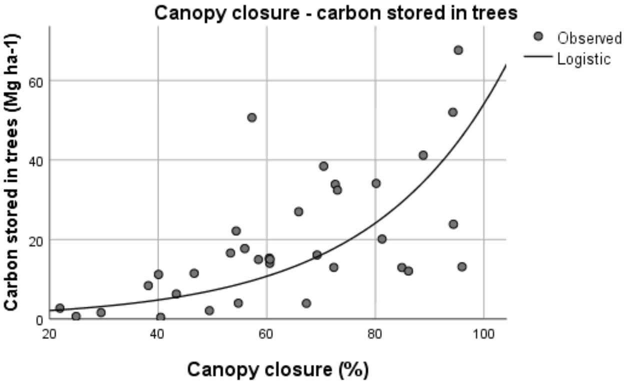

Figure 21*. Relationship between canopy closure and carbon stored in trees. Depicts an increase in AGCp with increasing shade cover*

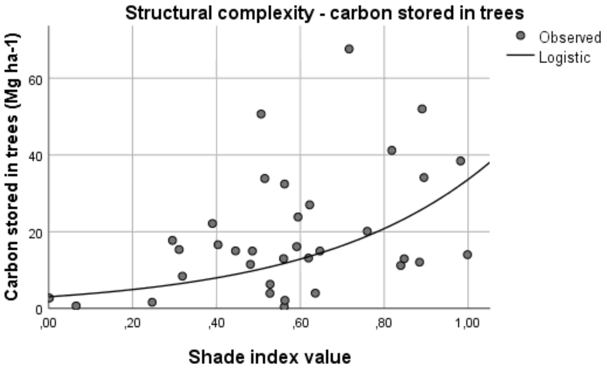

Figure 22*. Relationship between the shade index value and carbon stored in trees. Depicts an increase in AGCp with increasing shade cover*

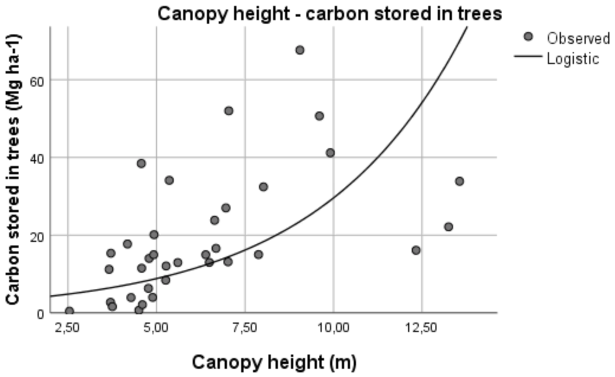

***Figure 23**. Relationship between canopy height and carbon stored in trees. Depicts an increase in AGCp with increasing canopy height*

3.2.4 Biodiversity

A strong correlation was found between the average epiphyte cover and epiphyte species richness (F(1,36) = 93.169; $R^2 = 0.721$; $p < 0.01$) (figure 24) Trees had an average epiphyte cover of 1.74 (corresponding to approximately 40%) ± 0.84 and a species richness of 1.90 ± 0.93. The trees with the highest average epiphyte cover were *Gliricidia sepium* (2.65 ± 0.67) and *Cederela odorata* (2.71 ± 0.49), whereas the highest average epiphyte species richness was covered by *Cederela odorata* (2.86 ± 1.21) and *Cordia alliodora* (2.34 ± 0.97) trees. Most trees were covered by lichens (85%) and mosses (74%), while ferns were only observed on 20% and bromeliads on 17% of the trees.

While no significant differences were found between the age clusters, both epiphyte cover (F(1,33) = 19.352; $R^2 = 0.366$; $p < 0.01$) and epiphyte species richness (F(1,33) = 19.338; $R^2 = 0.369$; $p < 0.01$) increased with the average tree age, as best explained by S-curve models (figure 25 and 26).

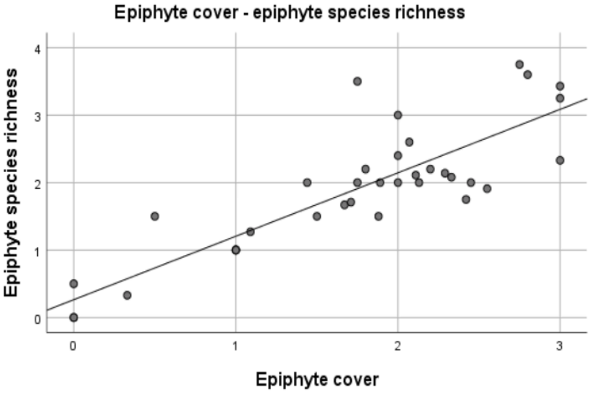

***Figure 24.** Relationship between epiphyte cover and epiphyte species richness. Depicts a strong positive correlation*

Both epiphyte cover (F(1,36) = 7.477; $R^2 = 0.172$; $p < 0.01$) (figure 27) and epiphyte species richness (F(1,36) = 6.980; $R^2 = 0.162$; $p < 0.01$) (figure 28) increased significantly with shade cover (CC). Strong positive relationships were also found between the shade index value and both epiphyte cover (F(1,36) = 5.699; $R^2 = 0.137$; $p < 0.05$) (figure 29) and epiphyte species richness (F(1,37) = 7.418; $R^2 = 0.167$; $p < 0.01$) (figure 30).

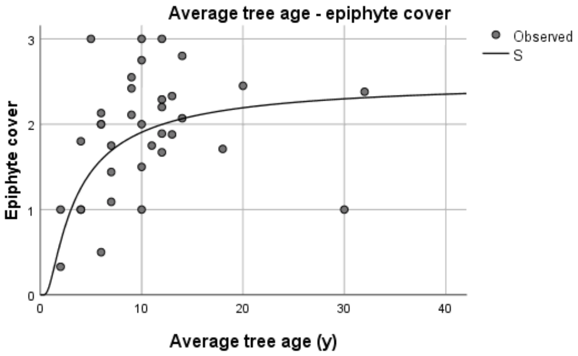

Figure 25*. Relationship between average tree age and epiphyte cover. Depicts an increase in epiphyte over time, following a saturation curve*

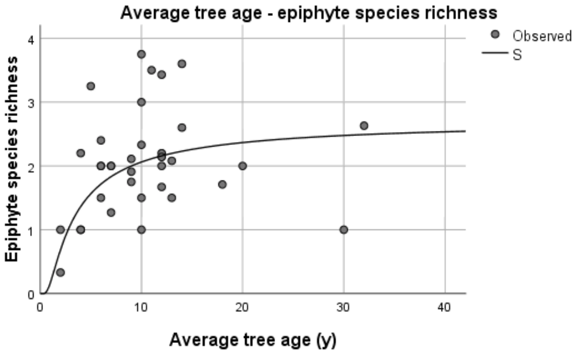

Figure 26*. Relationship between average tree and epiphyte species richness. Depicts an increase in epiphyte species richness over time.*

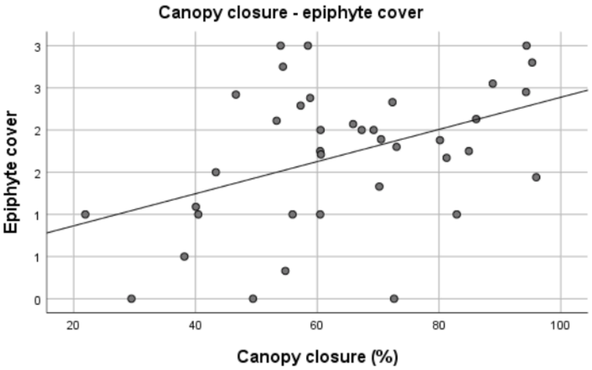

Figure 27. *Relationship between canopy closure and epiphyte cover. Depicts an increase in epiphyte cover with increasing shade cover*

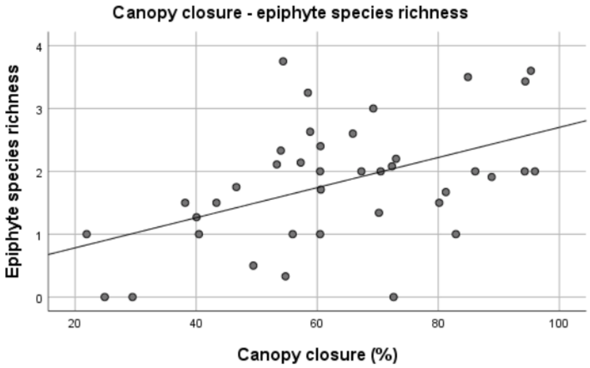

Figure 28. *Relationship between canopy closure and epiphyte species richness. Depicts an increase in epiphyte species richness with increasing shade cover*

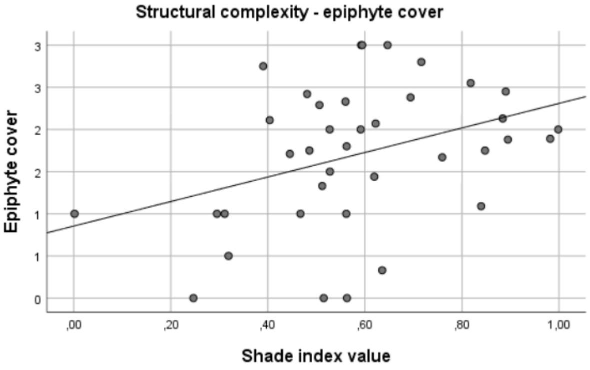

Figure 29. *Relationship between the shade index value and epiphyte cover. Depicts an increase in epiphyte cover with increasing structural complexity*

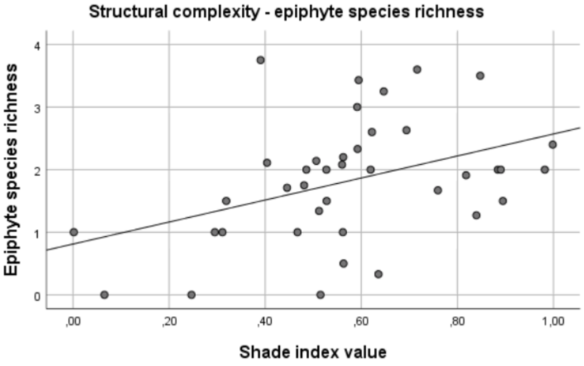

Figure 30. *Relationship between the shade index value and epiphyte species richness. Depicts an increase in epiphyte species richness with increasing structural complexity*

When looking at the individual shade indicators, tree basal area proved to be an important determinant of epiphyte cover (F(1,36) = 4.727; $R^2 = 0.129$; $p < 0.05$) (figure 31), whereas tree height was found to be closely related to epiphyte species richness (F(1,37) = 5.046; $R^2 = 0.120$; $p < 0.05$) (figure 32).

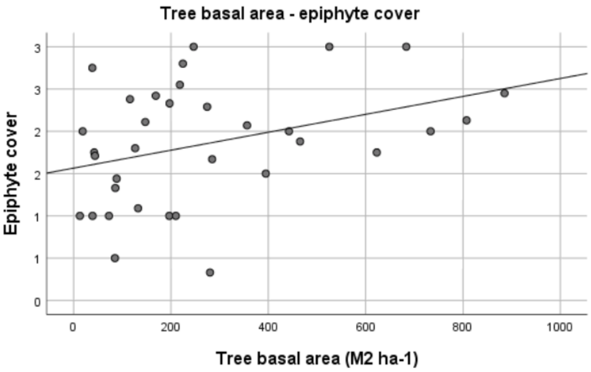

Figure 31. *Relationship between tree basal area and epiphyte cover. Depicts an increase in epiphyte cover with increasing tree basal area.*

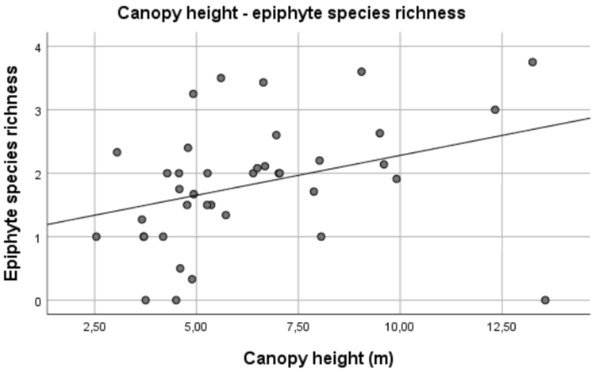

Figure 32. *Relationship between canopy height and epiphyte species richness. Depicts an increase in epiphyte species richness with increasing canopy height*

In addition, while the single effect of tree species richness on the epiphyte indicators was not significant, the combined effect of canopy closure and tree species richness on epiphyte species richness (F(2,37) = 5.595; $R^2 = 0.232$; $p < 0.01$) was much stronger than the single CC effect.

Finally, neither management intensity nor altitude was found to be related to either of the epiphyte indicators.

Synergies and trade-offs between ecosystem services

Pairwise comparison of all measured ES indicators demonstrated a strong synergy between carbon sequestration and presence of epiphytes, i.e. as total aboveground carbon storage increased, so did the amount of epiphyte cover (F(1,37) = 6.777; $R^2 = 0.155$; $p < 0.05$) (figure 33) and level of epiphyte species richness (F(1,38) = 6.663; $R^2 = 0.149$; $p < 0.05$) (figure 34).

In addition, synergies were identified between coffee productivity and pest control, as the CBB infection rate was found to be negatively related to both dry berry weight in grams (F(1,40) = 4.275; $R^2 = 0.097$; $p < 0.05$) (figure 35) and in % of fresh weight (F(1,38) = 2.905; $R^2 = 0.071$; $p < 0.05$) (figure 36).

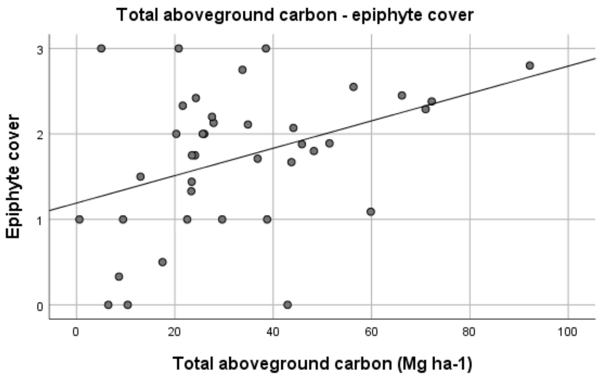

Figure 33. *Synergy between total aboveground carbon and epiphyte cover*

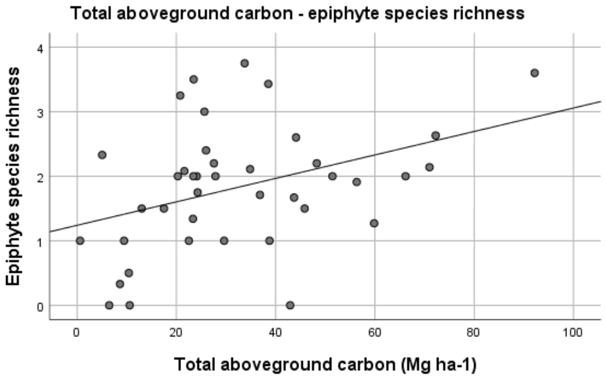

Figure 34. *Synergy between total aboveground carbon and epiphyte species richness*

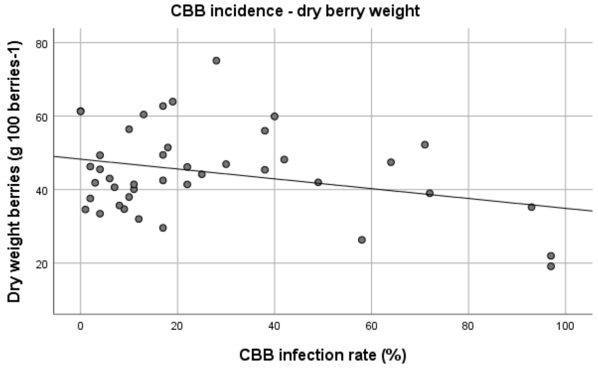

Figure 35. *Negative relationship between CBB infection rate and dry berry weight. Indicates a synergy between pest control and dry berry weight*

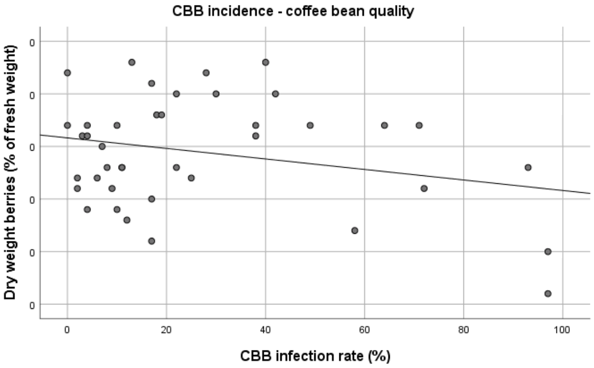

Figure 36. *Negative relationship between CBB infection rate and dry-fresh berry weight ratio.. Indicates a synergy between pest control and coffee bean quality*

4 DISCUSSION

The aim of this study was to gain insight into the potential of coffee agroforestry systems to enhance pest control, carbon sequestration and habitat provisioning without compromising in terms of coffee plant productivity. For this purpose, the effects of shade and management on coffee yield, berry weight, dry-fresh berry weight ratio, CBB and leaf cutter ant incidence, total aboveground carbon storage, epiphyte cover and epiphyte species richness were assessed. In addition, by comparing agroforestry systems of different age classes, the development of these ES indicators over time could be studied.

The remainder of this section is organised as follows: First, some general findings related to the observed shade and management characteristics in the study area are discussed. Thereafter, the effects of age, shade and management on each of the performance indicators are evaluated and compared with findings in literature. Subsequently, interactions (i.e. synergies and trade-offs) between ecosystem services and crop productivity are evaluated. The final section provides a discussion on the potential of agroforestry as more sustainable production type and an interpretation of the results in the light of global climate change.

4.1 General findings related to observed shade and management practices

First of all, while shade indices are often used to combine different vegetation parameters to as such create an overall indicator of vegetation complexity (e.g. Hernández-Martínez *et al*., 2009; Jezeer *et al*., 2018), results of this study show that the predictive power of the individual components or certain combinations of variables is often stronger than that of the index value. In most cases, the quantity of shade, measured in terms of canopy closure, had the largest effect. In addition, tree basal area (for epiphyte cover) and average canopy height (for total AGC and epiphyte species richness), which were both found to be directly related to canopy closure, proved to be important predictor variables. Furthermore, given that the individual variables of the index values can be explained in different ways (also see section 4.2.4), two completely different plantations could end up having the same shade index values, making it difficult to draw general conclusions. Therefore, even though structural complexity is considered to be a valuable indicator of ecological functioning (e.g. Barrios *et al.*, 2018; Drescher *et al.*, 2016; McElhinny *et al.*, 2005), individual factors should also be taken into consideration.

Similar arguments can be made in regard to the use of a management index. While management intensity was found to be related to the coffee bean quality (i.e. dry-fresh bean weight ratio), the individual parameter of chemical pesticide use was found to be a stronger predictor. Therefore, when looking at specific performance indicators, it might be more useful to look at the impacts of related management practices than consider management intensity as a whole. In addition, in most studies, this one included, management indices are used as predictor variables (e.g. Cerda *et al*., Jezeer *et al*., 2018). It could be debated, however, whether management should be treated as independent or dependent variable. For instance, while the positive relationship between chemical pesticide use and the infection rate of coffee berry borer can lead to the conclusion that pesticide use facilitates CBB incidence, it makes more sense to conclude that farmers use a certain level of pesticides because local production conditions require these levels of input.

To continue, full sun systems, i.e. monocultures, are generally associated with higher levels of management input than shaded systems (e.g. Bravo-Monroy, Potts & Tzanopoulos, 2016; Kearney *et al.,* 2017). However, findings of this study did not confirm this assumption as large variances in management intensity were found in both monoculture and agroforestry systems. The hypothesis that shaded systems require less external input due to their ability to naturally maintain soil fertility and control pest incidence (DaMatta, 2004; Jaramillo *et al.*, 2011; Teodoro, Klein & Tscharntke, 2008) was therefore difficult to prove. While in this study, monocultures and agroforestry systems were not found to differ significantly in terms of crop productivity or pest incidence, the question remains whether an input level of 0 in both systems would lead to a decrease in performance in any or both of the systems and under which conditions these effects could be observed.

4.2 Effects of age, shade and management on ES provisioning

4.2.1 Crop productivity

While shaded systems are often associated with decreased coffee yields (e.g. Bravo-Monroy *et al*., 2016; Jaramillo-Botero *et al*., 2010), results of this study did not demonstrate significant differences between monocultures and agroforestry systems in terms of coffee yield, dry berry weight or dry-fresh berry weight ratio, nor significant negative effects of shade (amount, structure and composition) on any of the productivity indicators. These results are in line with recent findings in literature (e.g. Barrios *et al*., 2018; Cerda *et al.*, 2017; Jezeer *et al.*, 2018). Although not significant, a trend could be observed towards higher coffee bean weight, both in grams and in percentage of fresh weight, in older agroforestry plantations with a higher amount of shade cover. According to Bosselmann *et al*. (2009), such improvements in bean weight and quality can be explained by reductions in temperature and increases in water availability, resulting in an extension of the ripening period. Findings of this study support this theory, as significant relationships were found between the amount of shade cover, temperature (negative) and relative humidity (positive).

As suggested in previous studies, adverse effects of shade trees on the production of *Coffea Arabica* are mostly found at higher altitudes (e.g. DaMatta, 2004; Bosselmann *et al*., 2009), where increases in cloud cover can lead to competition for light between shade trees and coffee plants. However, despite a relatively high average shade cover (63.99 ± 19.75) and altitude (1533.77 ± 154.47) in the study region, this interaction between shade, altitude and productivity was not observed. Overall, plantations at higher altitudes performed better in terms of coffee bean weight and quality, even though the amount of shade cover often exceeded the recommended level of approximately 40% (e.g. Farfán Valencia, 2014; Lin, 2007). The effect of altitude could not be explained by measured differences in temperature and relative humidity. This is probably due to the fact that measurements were only conducted within a range of approximately 6 hours during day time. Collecting microclimate data over a longer time-span would most likely reveal more explicit relationships between shade, altitude and productivity, as often confirmed in literature (e.g. Cerda *et al*., 2017; Ovalle-Rivera *et al*., 2015).

Furthermore, although findings did not provide support of the interactions between shade and altitude, an interactive effect was observed between the latter and management intensity in relation to the dry-fresh berry weight ratio. The effect of management intensity on physical bean quality was hereby found to be strongest at lower altitudes. This interaction effect suggests that plantations at lower altitudes require higher levels of external input and vice versa, supporting the argument of DaMatta (2004).

4.2.2 Pest control

When comparing monocultures with agroforestry plantations in terms of pest incidence, no significant differences were found. Average values of both pest indicators were found to be higher in the monoculture systems, but these differences could be largely explained by the negative relationship between altitude and pest incidence, given that monocultures were generally located at higher altitudes. Previous findings indicating lower CBB and leaf cutter ant incidence in highly diversified shaded systems (Mariño *et al.*, 2016; Montoya-Lerma *et al.*, 2012) could not be confirmed, as both pests were found to be problematic in the full range of agroforestry systems. The slight trend towards higher CBB incidence in older agroforestry systems might even contradict these findings, as older plantations in general demonstrated higher levels of shade cover and structural complexity.

4.2.3 Carbon sequestration

With an average value of 32.48 Mg ha-1, agroforestry systems within the studied area stored four times as much carbon than plantations without shade trees. These results are in line with findings from other studies on coffee agroforestry systems in Central America (e.g. Rahn *et al.*, 2013; Soto-Pinto *et al.*, 2010). While the total AGC was found to increase with both canopy closure and the shade index value, additional tests indicated that the amount of carbon storage was mostly determined by tree height. Designing an agroforestry system should therefore include careful selection of shade tree species with tall trunks and high wood densities. Vertical carbon storage could hereby help to enhance carbon stocks in coffee agroforestry systems without drastically reducing the space available for coffee production (Somarriba *et al.*, 2013). A clear relationship was identified between the time since implementation of agroforestry practices, expressed in terms of average tree age, and total AGC. Logically, this effect was found to be strongest in the middle clusters, when maturity of the tree takes place and substantial barks start to develop.

4.2.4 Biodiversity

In general, agroforestry systems are associated with increased biodiversity when compared to monocultures. As rightfully mentioned by Perfecto & Vandermeer (2015), an agroforestry plantation is a biodiverse place in itself, as a variety of tree and plant species are grown next to the main crop, which, in this case, is coffee. As expected, shade cover was found to increase over time, along with the maturing of the trees. A trend towards higher structural complexity in older plantations was also found, although not significant. This finding makes sense, given that aspects related to the size of the three (e.g. tree height, DBH) are inseparably linked to tree age, while other structural attributes, such as tree species diversity or planting density, are more likely to be dependent on farmer’s preferences.

Apart from the species that were deliberately introduced by the farmers, agroforestry systems can also provide habitat and resources for associated species (e.g. birds, insects and epiphytes). In this study, presence of epiphytes was used as an indicator of associated biodiversity. In line with expectations and previous literature (e.g. Jose, 2009; McElhinny *et al*., 2005; Woods, Cardelius & DeWalt, 2015), epiphyte cover and species richness were found to increase with shade cover, tree size and tree species diversity. These findings suggest that suitable epiphyte habitats can be found in areas with more complex vegetation structures. Furthermore, when looking at the development of epiphyte cover and epiphyte species richness over time, it was found that both indicators increased with the average age of the tree, until reaching saturation. It should hereby be noted that only four dominant epiphyte families were covered in this study. When taking into account the full range of vascular epiphyte species, a species diversity curve would most likely not saturate within the limits of this study.

4.3 Interactions among ES indicators

Results of this study demonstrated synergies between pest control and coffee productivity. These result are in line with the expectations, as pests and diseases can have detrimental effects on coffee yields and bean quality when not managed properly (Jaramillo *et al.*, 2011; Ribeyre & Avelino, 2012).

Synergies were also found between carbon sequestration and biodiversity. The implementation of agroforestry practices was hereby found to reduce net carbon emissions, while simultaneously creating suitable habitats for epiphytes. These findings are in line research from Goodall, Bacon & Mendez (2015). It is hereby important to note that while both of these indicators were found to increase with the size, and therewith with the age of the trees in the plot, this does not necessarily prove that biodiversity as a whole will increase when carbon stocks do.

Furthermore, while trade-offs between coffee yields on the one hand and carbon sequestration and biodiversity on the other are often reported in literature (e.g. Wade *et al.*, 2010), these trade-offs were not found in this study. However, while significantly higher carbon stocks can be preserved by highly shaded systems, shade trees cannot be planted indefinitely without compromising in terms of coffee yield (Rahn *et al.*, 2014).

4.4 The potential of agroforestry as a more sustainable agricultural system

Increasing temperatures and changing precipitation patterns are affecting the climatic suitability of major coffee producing areas in Central America (Rahn *et al.*, 2014). As a result, there is an increasing interest in the adoption of more sustainable coffee production systems that can deliver both ecological and economic benefits. In this context, comparisons are often made between monocultures on the one hand and agroforestry systems on the other. Findings of this study suggest, however, that the differences between these two systems are not as straightforward or static as sometimes assumed. Agroforestry systems should hereby be seen as dynamic systems that develop over time, both in terms of internal structure and composition as in relation to ES provisioning.

Overall, higher levels of shade cover and more complex vegetation structures were found to improve ecological functioning in coffee production systems, especially in terms of carbon sequestration potential and associated biodiversity, whereas coffee yield, bean quality and pest incidence were mostly determined by a combination of management and geographic location (i.e. altitude). Even though a relatively high range of shade cover was covered in this study (~20-95%), no adverse effects of shade on coffee productivity were identified. As such, this research provides evidence for the hypothesis that agroforestry systems can provide valuable ecosystem services without compromising in terms of coffee productivity.

To optimize the benefits of shade and avoid excessive competition for resources between shade trees and coffee plants, the design of an agroforestry system (i.e. tree planting density, selection of tree species) should be based on local features, such as altitude, soil type and climatic conditions (DaMatta, 2004; Ovalle-Rivera, 2015). Shaded systems are considered most effective at sub-optimal production sites, whereas monocultures or low-shaded systems are preferred under optimal conditions or in combination with higher levels of external input (DaMatta, 2004). In this study, the effects of shade on coffee yield, coffee bean weight and dry-fresh weight ratio and pest incidence were not found to be significant. However, most plantations were located at relatively high altitudes. Conducting similar measurements at lower altitudes, where climatic conditions are expected to be less suitable for the cultivation of coffee, could provide more convincing results regarding the effects of shade and help to identify potential interactions with management practices. In addition, the ability of shaded systems to enhance, rather than maintain, coffee productivity when compared to monocultures is likely to increase in the future, especially in the context of global climate change. With extreme weather events becoming more common, the beneficial effects of shade are likely to increase.

Finally, even though agroforestry systems can provide valuable ecosystem services without causing a decline in coffee productivity, such systems should not simply be promoted without taking into account socio-economic aspects (Drescher *et al.*, 2016; Ramirez-Villegas, 2012; Vaast *et al.*, 2015). For the adoption of a more sustainable production system to be successful, insights are needed into motives of change and perceptions of ecological and economic benefits, both at regional and national level. In addition, successful implementation requires education of farmers, as well as market-based incentives and environmental certification (Cerda *et al.*, 2017).

5 CONCLUSION

Results of this research confirm that coffee agroforestry systems have the potential to provide valuable ecosystem services without compromising in terms of productivity. To realize this goal, a number of aspects should be taken into account. Apart from the decision to integrate shade trees in the agricultural landscape, farmers should also consider their management practices in relation to the geographical location of the farm. Plantations at higher altitudes generally performed better, especially in terms of productivity and pest control, making them less dependent on external inputs. Productivity and pest incidence did hereby not differ significantly between systems, although a trend towards higher coffee bean quality in highly shaded systems was observed. Carbon stocks and epiphyte populations were significantly higher in plantations with high levels of shade cover and structural complexity, and increased over time. Agroforestry systems are dynamic systems, and their potential to create synergies between ecosystem services depends on a complex interaction between both natural and anthropogenic factors. Since measurements were taken in a specific range of shade cover, management intensity and altitudes, results of this study might differ from studied conducted in other areas. Therefore, further research is needed to be able to draw generalizable conclusions. Nevertheless, findings of this study contribute to the growing body of literature focusing on coffee agroforestry systems and as such help to design future-proof agricultural systems.

5 APPENDICES

Supplementary data is digitally available through R.W.Verburg@uu.nl

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