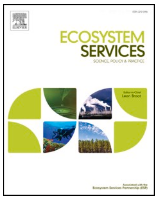
Ecosystem Services 48 (2021) 101246

Contents lists available at ScienceDirect

Ecosystem Services

journal homepage: www.elsevier.com/locate/ecoser



Ecosystem services trajectories in coffee agroforestry in Colombia over 40 years

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ARTICLE INFO

Keywords:
Rehabilitation trajectories
Multiple ecosystem services
Agroforestry
Coffee
Colombia
ES bundles and trade-offs
Restoration ecology

ABSTRACT

Agroforestry interventions may act as catalysts for ecosystem service development and changes in supply and therefore may rehabilitate degraded land. This study investigates the trajectories of ecosystem services in coffee systems with a different time since transition to agroforestry in Colombia, the interactions among ecosystem services, and the biotic and abiotic factors that explain them. Therefore, we study a chronosequence of agroforestry coffee farms, with 1–40 years since planting of shade trees. We found that aboveground carbon stock, habitat provisioning, timber volume and coffee bean quality followed positive asymptotic trajectories. Erosion control and pest control did not change over time. Coffee yield tended to decrease as the shade trees matured, but this was not significant. We found consistent positive relationships between carbon stock, erosion control and epiphyte richness. A trade-off between aboveground carbon stock and coffee yield was found for the first 10 years, while a positive relation between coffee yield and erosion control was found for the long term (10–20 years). Canopy cover best explained ecosystem service supply, but also farm agrochemical input management, altitude and slope influenced the supply. This study demonstrated that agroforestry can be used to rehabilitate ecosystem service supply.

1. Introduction

Ecosystem services link ecosystem processes directly or indirectly to people's quality of life. Globally, the majority of ecosystem services are decreasing, however, the magnitude of changes in ecosystem service supply differs between ecosystem services and across locations (IPBES, 2019). Land management that aims to improve single ecosystem services has resulted in an unbalanced provisioning of ecosystem services where the supply of few services increased at the cost of others (Renard et al., 2015). Over the past decades, the worldwide intensification of agricultural practices has caused trade-offs between food provisioning and regulating, supporting and cultural ecosystem services (Foley et al., 2005; Locatelli et al., 2017). Therefore, rehabilitation of degrading ecosystem services to improve the quality of natural systems and of people's quality of life is urgently needed. By studying the dynamics of multiple ecosystem services across time we can gain a better understanding of how ecosystem services vary over time, and options for their restoration (Bullock et al., 2011). The behavior of ecosystem service supply over time is called a trajectory, and specifically in case of increasing supply; rehabilitation. Ecosystem service trajectories as well as their mutual interactions vary across time as a function of factors such as management regimes, human use and local biotic and abiotic conditions (Fremier et al., 2013). Recent studies suggest that ecosystem services trajectories often follow non-linear paths, and that trade-offs among services may emerge over time (Bullock et al., 2011; Locatelli et al., 2017).

Ecological trajectories are pathways of ecological conditions over time and may represent degradation, adaptation or restoration in response to changes in land management or environmental conditions (Gann et al., 2019). The trajectory of ecosystem services may take linear, asymptotic and sigmoid (S-shape) trajectories (Bullock et al., 2011; Locatelli et al., 2017). For example, the development of carbon stock and wood volume in a recovering forest in Canada followed a sigmoid curve, while a provisioning service (berry producing plants) followed a U-

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https://doi.org/10.1016/j.ecoser.2021.101246
Received 19 August 2020; Received in revised form 7 January 2021; Accepted 8 January 2021

shaped curve in these forests (Sutherland et al., 2016). These curves were related to negative feedbacks; for example, carbon stock would likely develop following an asymptotic curve because plant biomass production is limited by water, nutrients and temperature, which at a certain point will have a damping effect on plant biomass increase (Heimann and Reichstein, 2008; Turner, 2010). Generally ecosystem services behave non-linearly across time, although linear shapes can be observed when study periods are short (Rau et al., 2018). For several ecosystem services, e.g. erosion control, habitat provisioning and pest control, the type of curve that can be expected and how this development is affected by biophysical factors is still largely unknown (Bennett et al., 2009; Bullock et al., 2011). As for erosion control, habitat provisioning and pest control positive linear relationships with canopy cover were often found in coffee systems (Blanco Sepúlveda and Aguilar Carrillo, 2015; Cerda et al., 2017; Jaramillo et al., 2011; Jezeer et al., 2019), we expect the trajectories of these ecosystem services to be similar to the development of the farm's vegetation structure.

We focus on one land management intervention – the implementation of agroforestry in coffee systems – which is expected to have an effect on ecosystem services as coffee agroforestry systems provide higher levels of regulating services than monocultures (Cerda et al., 2017). Compared to coffee monocultures, coffee agroforestry is reported to be associated to higher pollination activity (Jha and Vandermeer, 2009), more insect pest suppression by birds (Johnson et al., 2009), higher carbon stocks (Jezeer et al., 2019), more favorable micro-climatic conditions (Siles et al., 2010), and stronger erosion mitigation (Blanco Sepúlveda and Aguilar Carrillo, 2015). Furthermore, coffee agroforestry generally provides better habitat to fauna than monoculture coffee, as it was reported that agroforestry harbor, for example, more bird species (Wunderle and Latta, 1996), butterflies and ants (Perfecto et al., 2005), and spiders (Hajian-forooshani et al., 2013) in comparison to unshaded coffee. As coffee agroforestry can provide multiple environmental benefits, it has been proposed as a tool to rehabilitate biophysically degraded land (Rey Benayas and Bullock, 2012). Nevertheless, the effect of agroforestry on the fundamental provisioning service in coffee systems, coffee production, is variable in different regions. Some studies found that coffee agroforestry systems produced lower coffee yields than monoculture coffee (Campanha et al., 2005; Farfán, 2014), others found no significant effects on yield (Cerda et al., 2017; Clough et al., 2016; Jezeer et al., 2019), and yet other studies found a hump-shaped relationship between shade cover and coffee yield, with intermediate shade cover positively affecting yields, while high shade cover (>50%) reduced yields (Soto-Pinto et al., 2000). The interaction between coffee yield and shade cover likely results from a potential commensal relationship where coffee plants benefit from the favorable microclimatic conditions provided by shade (lower temperatures and more humid conditions), while under intermediate to dense shade covers competition for light and nutrients limit the growth of coffee plants and their fruits (López-Bravo et al., 2012; Soto-Pinto et al., 2000). Moreover, the interaction between coffee yield and shade depends on local conditions, altitude, soil characteristics, rainfall, cloudiness and farm management intensity (Beer et al., 1998; Farfán and Jaramillo, 2009).

The inconsistent relationships between coffee yields and shade cover suggest that within the same system, ecosystem services can develop in different directions. Several studies have shown that pairs of ecosystem services may interact in synergistic, trade-off, or neutral ways. Synergistic interactions are those where ecosystem services respond similarly to drivers that change their supply; all ecosystem services that show positive correlations form a bundle (Spake et al., 2017). Trade-off interactions are those where ecosystem services respond in opposite directions to a driver. Finally, no-interactions occur when ecosystem services do not respond in the same way to a given driver. In coffee agroforestry, there is empirical evidence of trade-offs (Campanha et al., 2005; Farfán, 2014) or no-interactions (Cerda et al., 2017; Clough et al., 2011; Jezeer et al., 2019) between biodiversity and coffee yield. However, most of these studies have not yet addressed how these interactions behave over time.

Temporal pathways of changes in ecosystem service supply can be investigated by using either trajectory analysis, i.e., repeated measures in time, or space-for-time substitution, i.e., spatial locations replace time by selecting locations with different age-since-intervention (Falk et al., 2006). Space-for-time substitution is less time consuming than trajectory analysis, which is an advantage. The space-for-time approach can be used to quantify general developments over longer time periods, however, for investigating subtle changes in time trajectory analysis is preferred (Pickett, 1989; Rácz et al., 2013), as different environmental conditions across locations may cause a higher level of noise in the dataset. Space-for-time substitution approach has been successfully applied to investigate ecosystem service recovery in forests (Sutherland et al., 2016), river restoration projects (Gilvear et al., 2013), and carbon storage develops in cocoa plantations (Nijmeijer and Harmand, 2019).

Here we investigate the development of ecosystem services over time in coffee agroforestry systems in Colombia. More specifically we examine the trajectories and interactions of multiple ecosystem services in coffee farms that transitioned from monoculture to agroforestry coffee using a chronosequence analysis. We use a space-for-time substitution to reconstruct the chronosequence of agroforestry coffee farms, with 1–40 years since the planting of shade trees. We analyze six ecosystem services: coffee production (coffee yield, coffee quality), timber stock (standing volume), carbon stock (above-ground carbon and belowground carbon), habitat provisioning (butterfly diversity and epiphyte richness), erosion control (potential soil loss, soil stability, litter cover, and herb cover), and pest control (coffee berry borer and leaf cutter ant incidence). First, we examine how these ecosystem services develop over time, in terms of trend (positive or negative response), shape (asymptotic or other shape) and speed of the response. Second, we investigate which ecosystem service bundles and trade-offs develop over time. Finally, we assess which biotic and abiotic factors (biotic: vegetation structure characteristics; abiotic: input management, farm characteristics and soil characteristics) explain the development of ecosystem service supply. Our findings will broaden our understanding of the behaviour of ecosystem services through time, and provide evidence of the potential benefits of agroforestry management to restore tropical (agro)ecosystem services.

2. Methods

2.1. Study area

Colombia is the world's third producer of coffee (FAOSTAT, 2020), and within Colombia the majority of the coffee is produced in the departments of Risaralda, Quindío, Caldas, and Valle de Cauca, which together are identified as the Coffee Cultural Landscape of Colombia (200.000 ha; Fig. 1). This 'Coffee Cultural Landscape' has been recognized by the UNESCO for its tradition of coffee growing in small plots in difficult mountain conditions (Paisaje Cultural Cafetero, 2020; UNESCO, 2020), but the region has also important natural value due to its high biodiversity. Colombia is also one of the 17 megadiverse countries and is expected to be inhabited by 10% of the species globally (Arbeláez-Cortés, 2013). Currently, the department of Risaralda has 47,000 ha of coffee plantations (Ministerio de Agricultura y Desarollo Rural, 2018; Fig. 1b). In 1970s, the coffee sector of the Coffee Cultural Landscape transformed as traditional shaded farms transitioned to input intensive, unshaded coffee plantations with a new rust-resistant coffee variety 'Colombia' (Avelino et al., 2015; Guhl, 2002). More recently, several reforestation projects have been executed in this region aiming to restore carbon stocks and biodiversity (Collazos Quintana, 2004; FNC, 2011). Therefore, this region has a history of unshaded coffee cultivation and newly established agroforestry systems, which makes it a good case study for our objectives.

The coffee producing region in the northwestern part of Risaralda (approx. 20.000 ha; Paisaje Cultural Cafetero, 2020), where the data of

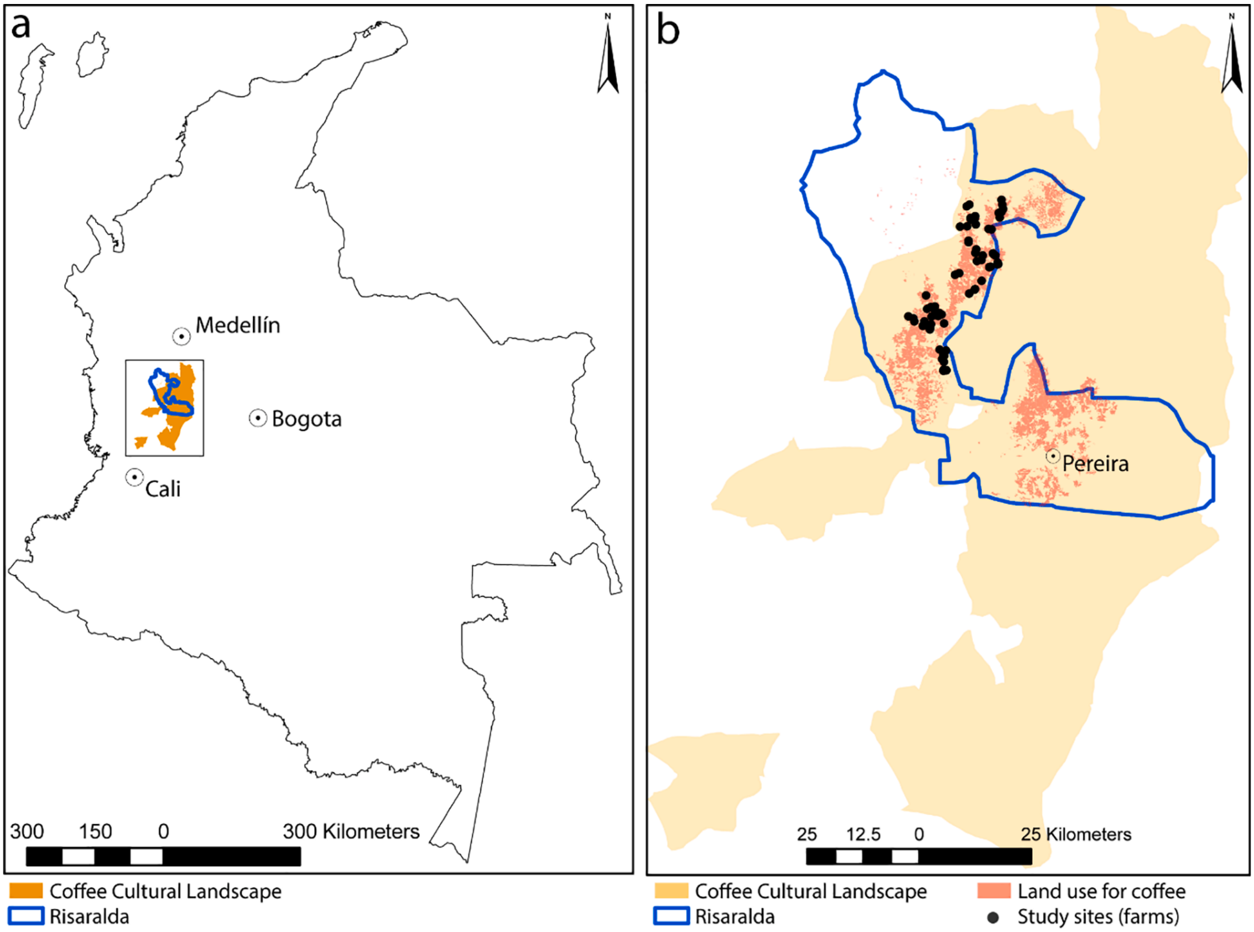

Fig. 1. Map of study area, a) location in Colombia, b) location of study sites (farms) in the Department Risaralda.

this study was collected, is typically characterized by steep slopes (15–50% inclination) and elevation between 1000–2000 m. The dominant soil type is Andosols. The mean annual precipitation in this region varies between approximately 1600–2400 mm, with average temperature of 19 ° (minimum 15 °C, maximum 25 °C), and it receives around 1500 hours of sun per year (Jaramillo, 2018). The coffee varieties cultivated in this region are 'Castillo rosario', 'Colombia', 'Castillo naranjal', 'Catimore' and 'Caturra' (in order of most abundant to less abundant), and plantations are often a mixture of these varieties. More than half of the coffee plantations in this region can be categorized as unshaded monoculture coffee plantations, but also shaded polycultures, commercial polycultures and traditional polycultures can be found in lower densities (personal observation; categories described by Moguel and Toledo, 1999).

2.2. *Experimental design*

We set our study to collect data on farms along a time gradient of 1–40 years since transitioning from monoculture to agroforestry. This meant that a minimum of 125 trees per hectare were originally planted on at least a part of the farm, but we did not consider tree species and arrangements. The selection of coffee plantations, hereafter referred to as farms, was done in collaboration with the Colombian National Coffee Growers Federation (*Federación Nacional de Cafeteros,* FNC) because this organization has been involved in several tree planting projects in the coffee region. For example, a project lead by the German Development Bank (KfW; *Kreditanstalt für Wiederaufbau*) involved planting of trees (*Cordia alliodora*, common name Laurel or Nogal cafetero, and *Eucalyptus grandis,* common name flooded gum) in coffee fields in the period between 2007 and 2015 and in another project lead by CARDER (*Corporación Autónoma Regional de Risaralda*) trees were planted (*C. alliodora*) between 2001 and 2003 (Collazos Quintana, 2004; FNC, 2011). We asked the participating owners or managers of the farms in which year they transitioned their farm from a coffee monoculture to an agroforestry system, which we used as the 'time since agroforestry' variable. For more information about the validation of the chronosequence and for a representation of the number of farms per ages classes since transition, we refer the reader to the appendix.

2.3. *Field data collection*

The data of this study was collected through field measurements and farmers surveys in April and May 2018, and again in April and May 2019. In each farm, we selected a site with productive coffee plants that the owner or manager considered representative of the farm because of its cropping density, production capacity and applied inputs, while avoiding the edge of the farm. In this site, a square plot of 20 by 20 m was randomly selected, henceforth referred to as 'plot'. Through a survey with the owner or manager of the farm, we obtained general farm and management characteristics.

2.3.1. *General farm and management characteristics*

We used a structured questionnaire to survey 74 farmers (60 agroforestry coffee, 14 monoculture coffee) who owned or managed the farms on which the biophysical data was collected. Farmers provided information about the general characteristics of their farm (farm size and coffee planting density), coffee production (coffee yields of '18 and when this was registered of '17, '16, and '15, in units of dried green coffee) and since when they planted shading trees. Further, we collected information about the management of pest control, weeding, and fertilization and pruning of coffee plants. For each management activity we collected information about how it was done (manually, mechanically, organically, or chemically), labor hours, quantity of agrochemicals, and costs of agrochemicals (Appendix Table A1). These variables were then standardized by difference to the minimum and dividing by the difference between the maximum and minimum.

Finally, we visually recorded the spatial arrangements of the shade trees using the following categories: 'Dispersed' where the majority of the trees were dispersed and randomly located throughout the farm, 'Alleys', where the majority of the trees were placed in alleys on the farm, or 'Living fences', where the majority of the trees were bordering the farm.

2.3.2. *Vegetation assessment*

Within the plots, we identified all trees which had diameter at breast height (DBH) > 5 cm to the species level and also plants of the genus Musa to calculate tree species richness, tree density and Musa density (all species in appendix Table A2). For each individual tree we measured DBH, and height using a Nikon Forestry Hypsometer, to calculate basal area. We asked the farm owner or manager when the tree was planted to obtain an estimate of the age of the individual trees. We recorded for each tree the presence of four epiphyte groups; bromeliads, lichens, ferns and bryophytes, following Goodall et al. (2015), as a course measure for epiphyte richness. Canopy cover was measured on nine locations evenly distributed in the plot in four cardinal directions using a convex spherical densiometer (Korhonen et al., 2006).

All the coffee plants within the plot were counted to calculate coffee plant density. For six randomly selected coffee plants we measured the total height and stem diameter at 15 cm height; we also counted their number of berry-bearing branches and for six of these branches the number of berries. Following Cerda et al. (2017), the average number of berries per branch was multiplied by the number of productive branches to obtain the coffee plant productivity (see 2.4.4). Then we collected 100 ripe berries from the plot, ten berries from ten different coffee plants. The berries were examined for infestation holes of the coffee berry borer, giving a percentage of infested berries. The hundred berries were weighted to obtain the fresh weight, and the berries were then peeled to remove the pulp (mesocarp) and left in water to ferment for 24 h. Floating berries were removed, following local coffee farmers' practice, as this indicates that the beans have defects (*café pasilla*). The remaining beans were then oven-dried for 24 h and weighted to obtain dry weight. The ratio between fresh weight and dry weight was used as an indicator for physical coffee bean quality.

Another fifteen coffee plants were examined to assess the damage caused by leaf cutter ants (genus *Atta*, local name *hormiga arriera*). For each coffee plant we assessed the extent of plant and leaf damage using five categories: no damage (0), <5% damage (1), 5–20% damage (2), 20–50% damage (3), and > 50% damage (4).

2.3.3. *Soil properties*

In each plot three sub-samples of the upper soil layer (0–20 cm) were taken with a minimum distance of 1 m from a coffee plant or tree. The sub-samples were then mixed and sent as one sample to the lab (Multilab Agroanalítica, Chinchiná, Colombia). In the lab we measured total N (calculated using a regression equation with soil organic matter for the study region; FNC - Cenficafé, 1994), extractable P (Bray method; Bray and Kurtz, 1945) and K (ammonium acetate method; Schollenberger and Simon, 1945) and soil organic matter (SOM; Walkley-Black method; Walkley and Black, 1933).

In each 20 × 20 m plot we also visually assessed soil and soil surface characteristics (understory vegetation cover, litter cover, soil stability and soil surface roughness) of eight 1 × 1 m sub-plots. In these sub-plots we visually assessed the percentage of soil covered with herbaceous vegetation, the cover of litter and dead woody material, and we collected eight additional soil samples to examine soil stability using the slake test (Tongway and Hindley, 2004). Following the Tongway and Hindley slake test, we used the categories: (0) no coherent fragments available, (1) fragment collapses in less than 5 seconds, (2) fragment substantially collapses in 5–10 seconds, (3) surface crust remains intact with less than 50% slumping of sub-crust, and (4) whole fragment remains intact with no swelling. In each sub-plot we measured the soil surface roughness in five classes varying from less than 3 mm to more than 100 mm relief, following Tongway and Hindley (2004).

2.3.4. *Arthropod community properties*

Data on butterfly (Lepidoptera) communities were collected in 2019, using the transect count method (Caldas and Robbins, 2003). Two 50 m transects in close proximity to the vegetation plots were walked twice spending 5 minutes per transect. The total length covered per plot was 200 m in 20 minutes. We chose for relatively short transects and more repetitions for practical reasons as slopes were steep (average 30% steepness). Due to the rainy season —in which data were collected— the butterfly community observations were done only without precipitation and after 10:00 AM, as early mornings were too cold and humid resulting in low butterfly activity. While walking the transect, butterflies that crossed the transect within a proximity of 3 m (left, right and above), were identified based on wing characteristics and morphology. When identification was not possible, the butterflies were netted, photographed and then released to be identified by local butterfly specialists. From this data we calculated butterfly species richness, abundance and diversity, the latter being calculated using the Shannon-Wiener diversity index.

2.3.5. *Abiotic conditions*

We recorded air temperature (°C) and relative air humidity (%) every 30 minutes while being on a farm using a thermo-hygrometer (TFA, Maxim II), usually between 10:00 AM and 3:00 PM. We recorded the elevation of each plot using a GPS device (Garmin GPS 62 s) and the slope on eight locations in the plot using an angle meter.

2.4. *Ecosystem service indicators*

2.4.1. *Carbon stock*

Above-ground carbon (AGC): We calculated the above-ground biomass of trees (AGB_{trees}) using the allometric equation for tropical trees of Chave et al. (2014):

$$AGB_{trees} = 0.0673 \cdot (\rho \cdot DBH^2 \cdot H)^{0.976} \quad (1)$$

where DBH is diameter at breast height and H is the height of the tree (see 2.3.1.), ρ is the specific wood density as retrieved from a wood density database (ICRAF, 2019). The above-ground biomass of coffee plants (AGB_{coffee}) was calculated using the allometric equation of Segura et al. (2006):

$$AGB_{coffee} = 10\text{^}(-1.113 + 1.578 \cdot \log_{10}(D_{15}) + 0.581 \cdot \log_{10}(H_{coffee}) \quad (2)$$

where D_{15} is the coffee stem diameter at 15 cm and H_{coffee} is the height of the coffee plant. The above-ground biomass of *Musa* plants (AGB_{musa}) was calculated using the allometric equation by Arifin (2001) and Hairiah et al. (2001):

$$AGB_{musa} = 0.0303 \cdot DBH^{2.1345} \quad (3)$$

These three components were then summed to obtain the total above-ground biomass (AGB). The above-ground carbon (AGC) was calculated by multiplying AGB by the carbon fraction of 0.47 (IPCC, 2006).

Belowground carbon (BGC): The belowground carbon stock consists of root carbon stock and soil organic carbon (SOC) stock until a depth of 20 cm. Root biomass (RB) of coffee, *Musa* plants and trees were calculated using the allometric equation of Cairns et al., (1997):

$$\mathrm{RB} = \exp(-1.0587 + 0.8863 \cdot \ln(\mathrm{AGB})) \tag{4}$$

This was then multiplied by the carbon fraction of 0.47. The SOC was expressed in ton per hectare multiplying soil organic matter (SOM) with a carbon fraction of 0.5 (Pribyl, 2010) and the average bulk density of the region of 0.9 Mg/m^3 (Soilgrids.org, 2019).

2.4.2. Erosion control and water infiltration

Based on the soil surface properties ($n = 8$ per farm), which we described in section 3.3.3, we calculated the potential soil loss using the Revised Universal Soil Loss Equation (RUSLE), following (Renard et al., 1997). This approach uses the factors rainfall erosivity (MJ mm ha^{-1} h^{-1}), soil erodibility (Mg h^{-1} MJ^{-1} mm^{-1}), slope length (m), slope steepness (rad), cover management, and soil support, to calculate potential soil loss (Mg soil ha^{-1} y^{-1}). Based on eight samples, we calculated eight potential soil loss data points per farm, which were then averaged to obtain one mean value per farm. We refer the reader to the appendix for more specific information about adjustments and assumptions in addition the RUSLE method. Further we included litter cover, understory vegetation cover and soil stability (see 2.3.1.2.) as indirect proxies for erosion control, because of their importance to preventing soil from water erosion (Blanco Sepúlveda and Aguilar Carrillo, 2015; Tongway and Hindley, 2004).

2.4.3. Habitat provisioning

We estimated biodiversity intactness as a measure for habitat provisioning (IPBES, 2019). As biodiversity proxies we measured butterfly richness, abundance, and diversity, and richness of epiphyte taxonomic groups (sections 2.3.1 and 2.3.3).

2.4.4. Pest control

Incidence of coffee berry borer and ant predation of leaf cutter ants were used as proxies for the ecosystem service of pest control. These were the most common pests and/or diseases in the region, coffee leaf rust was not common since rust-resilient coffee varieties were cultivated.

2.4.5. Provisioning service

The provisioning of coffee was assessed using a proxy for quantity (plot-level and farm-level) and for quality (plot-level), which both contribute to gross income. At the plot-level, we calculated the maximum obtainable coffee productivity as the potential coffee to be produced on a plot using the formula described by Cerda et al. (2017):

$$\mathrm{CP} = (8.58 + 3.88 \cdot \mathrm{NPS} + 1.95 \cdot \mathrm{NF_{Node}} + 0.03 \cdot \mathrm{NFN_{Plant}} - 0.18\ \mathrm{DeadB})^2 \tag{5}$$

where CP is obtainable coffee productivity, NPS the number of productive shoots, NF the number of fruits per node, NFN the number of fruiting nodes per plant, and DeadB the number of dead branches. Further, we included physical coffee bean quality as a proxy for coffee quality (section 2.3.1). At the farm-level, we recorded coffee yield as farmer's self-reported coffee yield as another proxy for quantity (section 3.3.1.4).

Additionally, we included timber volume as an indication for potential timber production. To this purpose, we calculated the timber volume of the two timber tree species that were provided in the reforestation projects: *C. alliodora* and *E. grandis* (only present on one farm). The timber volume (TV) of *C. alliodora* in coffee farms was calculated using the allometric equation of Somarriba and Beer (1987):

$$\mathrm{TV}_{C.\ alliodora} = -0.0176 + 0.000034 \cdot \mathrm{DBH}^2 \cdot \mathrm{H} - 0.000086 \cdot \mathrm{DBH}^2 + 0.00336 \cdot \mathrm{H} \tag{6}$$

where DBH is diameter at breast height and H the tree height. The timber volume of *E. grandis* in coffee plantations was calculated using the allometric equation of FNC - Cenficafé (2006):

$$\mathrm{TV}_{E.grandis} = \exp(-8.988 + 0.847 \cdot \ln(\mathrm{DBH}^2 \cdot \mathrm{H})) \tag{7}$$

2.5. Data analysis

2.5.1. Effect of time since agroforestry on canopy cover and ecosystem services

We investigated how farm vegetation characteristics varied with 'time since agroforestry', and therefore we excluded the monoculture coffee farms (Table 1). We first tested whether the development of canopy cover, canopy height, tree density, basal area, and tree species richness followed an asymptotic shape. We used a nonlinear Michaelis-Menten model, expressed generally as:

$$\mathrm{Y} = \frac{\mathrm{TSA}}{\mathrm{TSA} + \beta 1/2} \hat{\mathrm{A}} \cdot \beta \mathrm{max} \tag{8}$$

where Y is any of the vegetation characteristics variables, TSA is time since agroforestry, $\beta_{\max}$ is the asymptote at which Y is saturated, $\beta_{1/2}$ is Y at half its asymptote. If the asymptote model showed poor fit, we tested the fit of a linear relationship by using ordinary linear regression (OLR), except for tree species richness for which we used a generalized linear model (GLM) with a Poisson distribution.

We followed the same approach to test whether ecosystem services also followed a saturating response trajectory, by testing with the Michaelis-Menten model or with linear, generalized linear or sigmoid models if better fitting. We used Akaike Information Criterion (AIC) to interpret best model fit. For the variable farmer-reported coffee yield, we first used a Cook's distance test to identify outliers, as this variable was not measured but obtained through the survey. In case outliers were detected, we transformed the data and generalized its distribution. In case the transformed variable distribution was not yet following a normal distribution, we excluded outliers identified by Cook's distance (coffee yield > 700 kg/ha, $n = 2$). Then we tested the fit using GLM with a Gamma distribution, as the data was still right-skewed. We analyzed the data in R version 3.6.1 (R Core Team, 2019) using packages 'tidyverse' and 'nlstools' and 'lme4′.

2.5.2. Ecosystem service bundle development and trade-offs

We tested the development of the relations between pairs of ecosystem services using pair-wise correlations for two time periods, between 0–10 y and between 11–20 y after implementation of agroforestry. Since we had information on multiple indicators per ecosystem service and several of them were naturally correlated, we selected between highly correlated indicators for the same ecosystem service. This is to prevent accounting twice for the same effect, for example, for coffee provisioning we had two related quantitative variables (plot-level productivity and farm-level yield) and therefore used coffee yields, and for carbon we used above-ground and belowground but not total carbon. Moreover, we did not include butterfly indicators and leaf cutter ant damage, due to smaller sample sizes than the rest of the data. For the latter, we used information of all farms, including the monoculture plantations. We used Pearson correlation tests using the R-package 'psych'.

2.5.3. Factors explaining ecosystem service supply

We examined confounding factors that influenced ecosystem service supply after transition to agroforestry. To do this, we excluded the monoculture coffee farms (Table 1). We avoided doubling effects and mismatches in sample sizes by selecting ecosystem services as explained in section 2.5.2, and we standardized the indicators for ecosystem services using the ecosystem service index approach presented in Kearney et al. (2017). In these standardization calculations potential soil loss and coffee berry borer incidence were inversed to obtain a more-is-better scale. We used a principal component analysis to define the ecosystem service bundles and reduce the dimensionality of the ecosystem service indicators. We selected the orthogonal axes that together explained

Table 1
Overview of the variables that were measured, units of measurement, sample sizes (n) of agroforestry farms (AF) and monoculture farms (MC), samples per farm and year of data collection.

Ecosystem service indicator	Unit	n farmsAF/MC	n samples (plot/method)	Year of collection
Carbon stock				
Above-ground carbon (AGC)	Mg C ha^{-1}	60/14	1 (20x20m)	‘18+’19
Below ground carbon (BGC)	Mg C ha^{-1}	59/14	1 (20x20m)	‘18+’19
Erosion control				
RUSLE – potential soil loss	Mg soil loss ha^{-1} y^{-1}	44/10	8 (1 × 1m)	’19
Herb cover	% soil covered with herbs	44/10	8 (1 × 1m)	’19
Litter cover	% soil covered with litter	44/10	8 (1 × 1m)	’19
Soil stability (slake test)	Stability score	44/10	1	’19
Habitat provisioning				
Butterfly richness	# species	19/6	4 transects (50 m)	’19
Butterfly abundance	# individuals	19/6	4 transects (50 m)	’19
Butterfly diversity	Shannon index	19/6	4 transects (50 m)	’19
Epiphyte richness	# taxonomic groups (0–5)	39/–	Per tree in plot	’19
Pest control				
Coffee berry borer incidence	% infestation	59/15	100 berries	‘18+’19
Leaf miner leaf damage	Damage score (0–4)	18/4	15 coffee plants	’19
Leaf miner plant damage	Damage score (0–4)	18/4	15 coffee plants	’19
Provisioning services				
Coffee productivity (field)	kg dry weight beans plot $^{-1}$	42/10	6 coffee plants	’19
Coffee yield (survey)	kg green coffee ha^{-1}	54/14	1–3 (year ‘18-‘16)	‘18+’19
Coffee quality	Ratio fresh:dry weight	39/9	100 berries	’19
Timber volume	m^{3} timber ha^{-1}	60/14	1 (20 × 20m)	‘18+’19
Vegetation characteristics				
Canopy cover	% canopy cover	54/14	1 (20 × 20m)	‘18+’19
Average tree age in plot	y	37/14	1 (20 × 20m)	’19
Canopy height	m	54/14	1 (20 × 20m)	‘18+’19
Tree species richness	# tree species	54/14	1 (20 × 20m)	‘18+’19
Tree density	trees ha^{-1}	54/14	1 (20 × 20m)	‘18+’19
Plantain density	Musa ha^{-1}	54/14	1 (20 × 20m)	‘18+’19
Tree basal area	m^{2} trunk cover	54/14	1 (20 × 20m)	‘18+’19
Micro-climatic conditions				
Relative humidity	% air humidity	48/15	5–8	‘18+’19
Temperature	°Celsius	48/15	5–8	‘18+’19
Soil conditions				
Total soil N content	% N	59/15	1 (3 sub-samples)	‘18+’19
Soil extractable P content	mg P kg soil^{-1}	59/15	1 (3 sub-samples)	‘18+’19
Soil extractable K content	cmol K kg soil^{-1}	59/15	1 (3 sub-samples)	‘18+’19
Farm characteristics				
Farm size	ha	59/15	1	‘18+’19
Coffee planting density	plants ha^{-1}	59/15	1	‘18+’19
Last pruning of coffee plants	y since last pruning	28/8	1	‘19
Altitude	m	59/15	1	‘18+’19
Slope	% inclination	44/10	8	’19
Total input management	Score 0–1	43/10	1	’19
Weeding management	Score 0–1	43/10	1	’19
Fertilization management	Score 0–1	43/10	1	’19
Pest management	Score 0–1	43/10	1	’19

more than 50% of the variance and used these axes (principal components; PCs) to identify which biotic and abiotic factors best explain them in a multiple regression model (OLR). To do so, we used as biotic and abiotic conditions vegetation, soil, micro-climate, farm and management characteristics that were independently measured from the ecosystem services indicators (Table 1). These biotic and abiotic conditions were included as fixed factors to explain the PCs as response variables. First, we tested for correlations among the biotic and abiotic variables, using Spearman correlation, to not include variables with high collinearity and chose one representative variable of correlated biotic and abiotic variables that best correlated to the response variable. Therefore, one variable was chosen as a representative for vegetation characteristics, soil conditions, and for farm and management characteristics the individual indicators were not correlated so they were all included. Then, we used the multiple regression analysis and included a maximum of three abiotic and biotic variables as fixed factors, as our sample size did not allow for more fixed factors. We compared the models with different fixed factor combinations based on Akaike Information Criterion (AIC), which is an estimate for likelihood of the model with lower values indicating a better model fit. This process resulted in one final model that best explained a single PC. Moreover, for each variable in the model we tested whether the estimate of the coefficient was significant and its confidence interval did not cross zero, indicating a reliably estimated coefficient. We visually assessed whether the residuals of the final model met the assumptions of homoscedasticity and normal distribution by inspecting density plots and residuals vs. fitted values plots. Similarly, we separately assessed how the biotic and abiotic conditions influenced the provisioning of coffee (coffee yield and coffee productivity). The multiple regression analysis was performed using the R packages ‘lme4′ and ‘stats’. Additionally, we related each ecosystem service indicator of all the farms to their biotic and abiotic factors by using Spearman correlations.

2.5.4. Agroforestry tree planting arrangement effect on ecosystem service supply

We tested whether the tree spatial arrangement in the agroforestry farms influenced supply of ecosystem services, as well as vegetation and soil characteristics, and general farm and management characteristics (Table 1). We used either OLR or GLM, depending on the distribution and/or the characteristics of the response variable. We did this by including tree arrangement as a categorical fixed factor. The residuals of the OLR models were evaluated for their ability to meet the assumptions of homoscedasticity and normal distribution. If the models failed to meet these assumptions, or when the characteristics of the response variable required so, we considered alternative distributions (Poisson: butterfly species richness and abundance, tree species richness, and Gamma: AGC, timber volume, farm size). For statistical analysis we used the software ‘R’ (R Core Team, 2019) and the packages ‘lme4′ and ‘multcomp’.

3. Results

3.1. Trajectories

3.1.1. Vegetation characteristics

We found an asymptotic relationship between time since agroforestry and canopy closure ($P < 0.0001$, $R^2 = 0.18$, $n = 54$; Fig. 1a) and canopy height ($P = 0.006$, $R^2 = 0.27$, $n = 54$; Fig. 2b). The development of canopy cover and canopy height was characterized by a half-time coefficient lower than 5 y since implementation of agroforestry and the saturation was associated to approximately 20 y since agroforestry. Tree species richness was also positively related to time since agroforestry (GLM Poisson, coefficient $= 0.018 \pm 0.007$, $P = 0.009$, $n = 54$; Fig. 2c). Time since agroforestry was implemented did not significantly affect tree density or total basal area of trees and *Musa* plants. We provide a detailed overview of vegetation characteristics in the appendix (Table A3). Descriptive statistics of vegetation and farm characteristics are presented in Table 2.

3.1.2. Ecosystem service indicators

We found a positive relationship between above-ground carbon, biodiversity indicators (butterflies and epiphytes), and a trend for coffee quality ($P = 0.06$, $R^2 = 0.07$, $n = 39$), and time since agroforestry was implemented (Fig. 3). These relationships followed a positive asymptotic model, with half-time coefficients lower than 5 y. We also found a positive sigmoid relationship between timber volume and time since agroforestry, and a linear increase between coffee quality and time since agroforestry. Herb cover and coffee yield showed a trend towards gradual decreases with time since agroforestry ($P = 0.08$, $R^2 = 0.03$, $n = 54$). We find that the saturation coefficients of canopy characteristics, above-ground carbon, butterfly diversity, epiphyte abundance, coffee quality and timber volume coincides with approximately 20 y since agroforestry implementation (Fig. 3 and Table A4). All other ecosystem services showed no significant relationships; the graphs that visualize their trajectories and the model parameters, including the half-time coefficient and saturation coefficient, of all the ecosystem services are included in the appendix (Table A4 and Fig. A4).

3.2. Trade-offs and bundles

We found a bundle formed by above-ground carbon stocks, erosion control, along with epiphyte richness (Table 3). This bundle had a short-term (1–10 y) trade-off with coffee yield and berry borer control, but these trade-offs disappeared on the long-term (11–20 y). On the long-term above-ground carbon, erosion control and epiphyte richness remained bundled, albeit, that on the short-term epiphytes were more strongly related to erosion control and on the long term they were more strongly related to above-ground carbon. Moreover, we found that coffee yield was on the long-term also positively related to this bundle, through a correlation with erosion control. Finally, on the long-term understory vegetation was negatively related to litter cover and coffee berry borer control. We tested for relationships between ecosystem service indicators in the entire dataset, including both periods and monoculture farms; these results are included in the appendix (Table A6).

Table 2

Descriptive statistics of farm characteristics. The '*' indicates whether the values only refer to agroforestry farms, in other cases all farms are included.

	Mean ± SD	Minimum	Maximum
Canopy cover (%)*	63 ± 19	19	95
Tree density (shrubs ha^{-1})*	157 ± 130	25	525
Tree species richness (shrubs ha^{-1})*	3.0 ± 1.7	1	9
Farm size (ha)	7.5 ± 12	0.9	93
Coffee density (plants ha^{-1})	5640 ± 970	3333	9000
Altitude (m)	1540 ± 160	1212	1905
Slope (%)	29 ± 9.7	6.9	47

3.3. Factors explaining ecosystem service supply

We identified three main principal components that represent groups of ecosystem services of farms that vary in time since agroforestry was implemented (60% of the variance explained; appendix Table A7 and Fig. A3). The first principal component (PC1) included information of above-ground carbon, litter cover, erosion control and epiphyte richness, we refer to this axis as 'PC1:AGC + Erosion + Epiphyte'. Independent of PC1, the second PC axis included information on understory vegetation cover and was inversely related to litter cover, we refer to this axis as 'PC2:VegC–Litter'. The third PC axis included information on coffee berry borer control and inversely related to soil stability, we refer to this axis as 'PC3:CBBc + Soilst'. We found that canopy cover was most strongly positively related to PC1:AGC + Erosion + Epiphytes, while the slope of the farm was negatively related to PC1 (Table 4). Both altitude of the farm and understory vegetation control management were positively related to PC2:VegC–Litter, while the area of the farm was negatively related to PC2. The third PC axis could not be explained by the abiotic and biotic factors that were measured ($P = 0.16$, $R^2 = 0.03$). Coffee productivity, as measured in the plot, was best explained by soil K content, time since pruning coffee plants, pest control management and altitude ($P = 0.003$, $R^2 = 0.31$). Farmer reported-yield was best

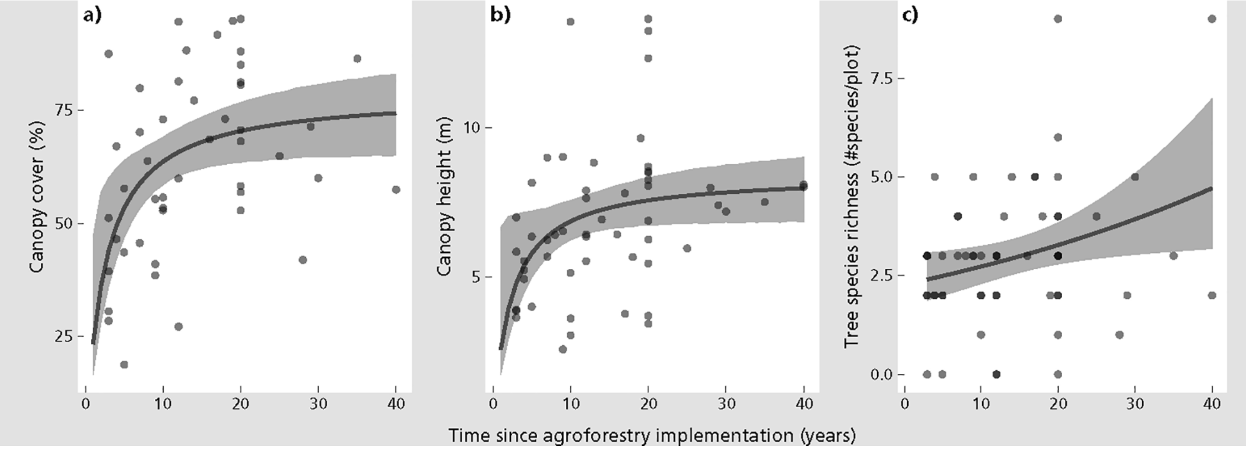

Fig. 2. Development of woody vegetation characteristics over time since agroforestry implementation. Green line is model prediction, grey dashed lines indicate 95% confidence intervals. a) Canopy closure, asymptotic nonlinear model ($P < 0.0001$, $R^2 = 0.18$, $n = 54$). b) Average canopy height in the plot, asymptotic nonlinear model ($P = 0.006$, $R^2 = 0.12$, $n = 54$). c) Tree species richness, GLM Poisson (exponential) ($P = 0.009$, $R^2 = 0.10$, $n = 54$).

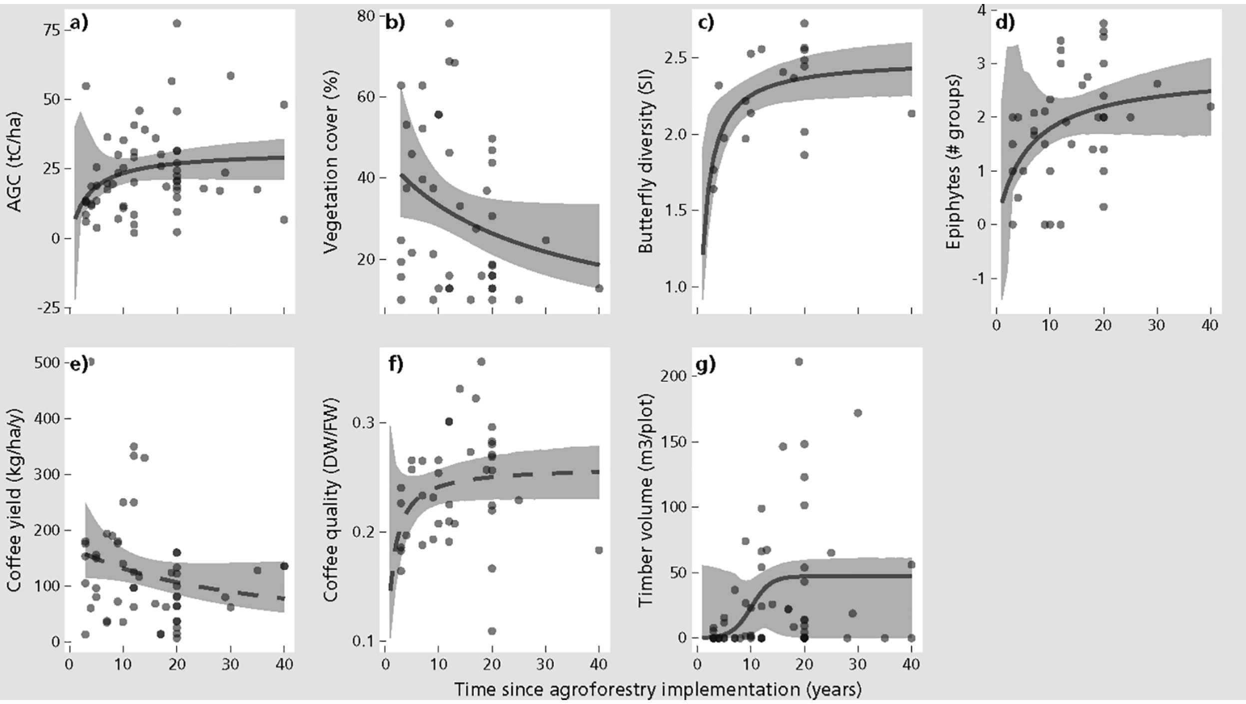

Fig. 3. Development of ecosystem services over time since agroforestry has been implemented. a) The response trajectory of above-ground carbon (AGC) follows an asymptotic shape ($P = 0.04$, $R^2 = 0.06$, $n = 60$). b) Understory vegetation cover (% soil covered with vegetation) follows a negative GLM gamma shape ($P = 0.03$, $R^2 = 0.0$. $n = 445$). c) Butterfly diversity (Shannon index) follows an asymptotic shape ($P = 0.006$, $R^2 = 0.33$, $n = 19$). d) Epiphyte richness (number of taxonomic groups; bromeliads, ferns, lichens, bryophytes) follows an asymptotic shape ($P = 0.02$, $R^2 = 0.12$, $n = 39$). e) Coffee yield reduces over time (GLM gamma) but not significantly ($P = 0.08$, $R^2 = 0.03$, $n = 54$). f) Coffee quality measured in the field (dry weight:fresh weight) increases over time (asymptote), but not significantly ($P = 0.06$, $R^2 = 0.07$, $n = 39$). g) Timber volume (m^3/plot) follows a sigmoid shape ($P = 0.03$, $R^2 = 0.03$, $n = 60$). Solid lines indicate models with P values < 0.05 and dashed lines models with P values < 0.10.

Table 3
Pair-wise correlation matrix presenting the development of ecosystem service trade-offs and bundles over time, using a short-term timeslot (1–10 y) and a long-term timeslot (11–20 y). The first column gives the description of the abbreviations used in the first row and units are given in Table 1. In the upper right half of the table sample size (n) of the correlation pair is given. In the lower left half of the table only the correlation coefficients are given that had a P-value lower than 0.10 (· is $P < 0.10$, * is $P < 0.05$, ** is $P < 0.01$). Green shading indicates positive relationships, red shading indicates negative relationships. The abbreviations used as column titles correspond to the row names. Sample sizes of correlated pairs are presented in the appendix Table A5.

			AGC	BGC	Litter	Understory	Erosion	Stability	Epiphyte	CBB	Yield	CBQ
Carbon stock	Above-ground carbon (AGC)	0–10y										
		10–20y										
	Belowground carbon (BGC)	0–10y										
		10–20y										
Erosion control	Litter cover	0–10y										
		10–20y										
	Understory vegetation cover	0–10y										
		10–20y			−0.36·							
	Potential soil loss control	0–10y	0.37*		0.77**	0.48*						
		10–20y	0.41*		0.47*	0.48*						
	Soil stability	0–10y										
		10–20y	−0.43*									
Habitat provisioning	Epiphyte richness	0–10y				0.58*	0.53*					
		10–20y	0.36*									
Pest control	Coffee berry borer control	0–10y				−0.40*						
		10–20y						−0.43*				
Provisioning services	Coffee yield	0–10y	−0.34*									
		10–20y				0.51*	0.35·					
	Coffee bean quality	0–10y	−0.34·									
		10–20y								−0.40·		

explained by altitude ($P = 0.04$, $R^2 = 0.16$). Furthermore, we performed correlation analysis between ecosystem service indicators and biotic and abiotic factors, the results of which are presented in a correlation matrix in the appendix (Table A8).

3.3.1. *Tree spatial arrangement*

We found that canopy closure was higher in ‘dispersed’ farms than in ‘living fence’ farms, and did not significantly differ from ‘alley’ farms, but no differences were found for other vegetation characteristics ($P < 0.001$; Appendix Table A11). We found higher levels of above-ground carbon in ‘dispersed’ farms (30 ± 18 Mg C ha^{-1}, $n = 26$) than for

Table 4
Multiple regression model outcomes on the principal components (PC1, PC2, PC3; appendix Table A7 and Fig. A3). The first column presents which of the ecosystem services (ES) the PC resembles (VegCov = understory vegetation cover, Cqual = coffee quality, Soilst = soil stability, CBBc = coffee berry borer control). The model's Akaike information criterion is AIC, the ΔAIC is the increase in AIC when the related dependent variable is excluded from the model, R^2 is the adjusted R^2 (· is $P < 0.10$, * is $P < 0.05$, ** is $P < 0.01$).

ES	Factors	coefficient ± SD	ΔAIC	P-value	R^2
PC1: AGC + Erosion + Epiphyte	Canopy cover	0.74 ± 0.10***	42	<0.001	0.68
	Slope	−0.57 ± 0.12***	18		
	Vegetation control	−0.16 ± 0.10	1		
PC2: VegCov–Litter	Altitude	0.25 ± 0.09*	3	0.003	0.18
	Vegetation control	0.40 ± 0.14**	3		
	Farm area	−0.40 ± 0.21•	1		
PC3: CBBc–Soilst	Nitrogen content soil	−0.07 ± 0.25	3	0.16	0.03
	Fertilization management	0.47 ± 0.24•	7		
Coffee productivity	Soil K content	2250 ± 700 **	8	0.003	0.32
	Last pruning coffee	55 ± 21 *	6		
	Pest control index	2450 ± 1180 *	3		
	Altitude	2.7 ± 1.5•	2		
Coffee yield	Altitude	0.32 ± 0.12*	5	0.04	0.16
	Weed control	135 ± 87•	2		
	Last pruning coffee	3.4 ± 2.0	1		

farms with 'living fences' (15 ± 14 Mg C ha^{-1}, n = 12) and 'monoculture' farms (5.2 ± 4.2 Mg C ha^{-1}, n = 11), and 'alley' farms (22 ± 11 Mg C ha^{-1}, n = 12) also stored significantly more above-ground carbon than monocultures (F = 9.4, df = 58, P = 0.02; Fig. 4a and appendix Table A9). We also found that total carbon stocks increased over time since agroforestry was implemented in 'alley' farms (R^2 = 0.57, P = 0.003), and showed an increasing trend for farms with 'living fences' (R^2 = 0.22, P = 0.07), but no changes over time were found for 'dispersed' farms (appendix Table A9). Moreover, 'dispersed' farms stored 42% more total carbon than 'monoculture' farms, 120 Mg C ha^{-1} and 84 Mg C ha^{-1}, respectively. Also, 'dispersed' farms had 54% lower soil loss than 'monoculture' farms (F = 4.3, df = 41, P = 0.01; Fig. 4b). The diversity of butterflies was 39% higher in 'dispersed' farms than in 'monoculture' farms, and did not differ from the other tree arrangement groups (F = 4.3, df = 41, P = 0.01; Fig. 4c). We found that 'monoculture' farms had an average timber volume of 0.02 m^3 ha^{-1}, while 'dispersed' farms had 66 m^3 ha^{-1}, 'alley' farms 47 m^3 ha^{-1} and 'living fence' farms had 58 m^3 ha^{-1}. Finally, we found that the coffee yield of 'living fence' farms reduced over time since agroforestry was implemented (R^2 = 0.39, P = 0.02), and that the coffee quality in 'alley' farms increased over time (R^2 = 0.68, P = 0.004).

4. Discussion

We analyzed how the transition from a coffee monoculture system to an agroforestry system affects ecosystem service supply and interactions among ecosystem services, and what were the biotic and abiotic factors influencing this supply and interactions. We found that planting agroforestry trees on coffee farms improved the supply of multiple ecosystem services over time, mostly following an asymptotic relationship with a period of steep increase (0–10 y), then a period of little increase (11–20 y), and finally a stabilization period after 20 years (Fig. 2). The asymptotic shape best described the development of carbon stock, erosion control, habitat provisioning and pest control, while we found some support for a decreasing relationship for understory vegetation cover and coffee yields with time since implementation of agroforestry. We also found that interactions among ecosystem services during the first 10 years were different from those between 10–20 years, in particular only above-ground carbon and erosion control were consistently associated over the years. Canopy cover, and the farm's slope, altitude and vegetation control management were the factors that best explained ecosystem services bundles, especially the bundle with above-ground carbon, erosion control and epiphyte richness. Finally, tree arrangement also influenced ecosystem service supply, with particularly high supply if trees are dispersed over the farm, followed by farms with trees in alleys and farms with trees as living fences, and the lowest supply for monoculture farms. Coffee yields did not significantly differ between tree arrangement groups and monoculture farms.

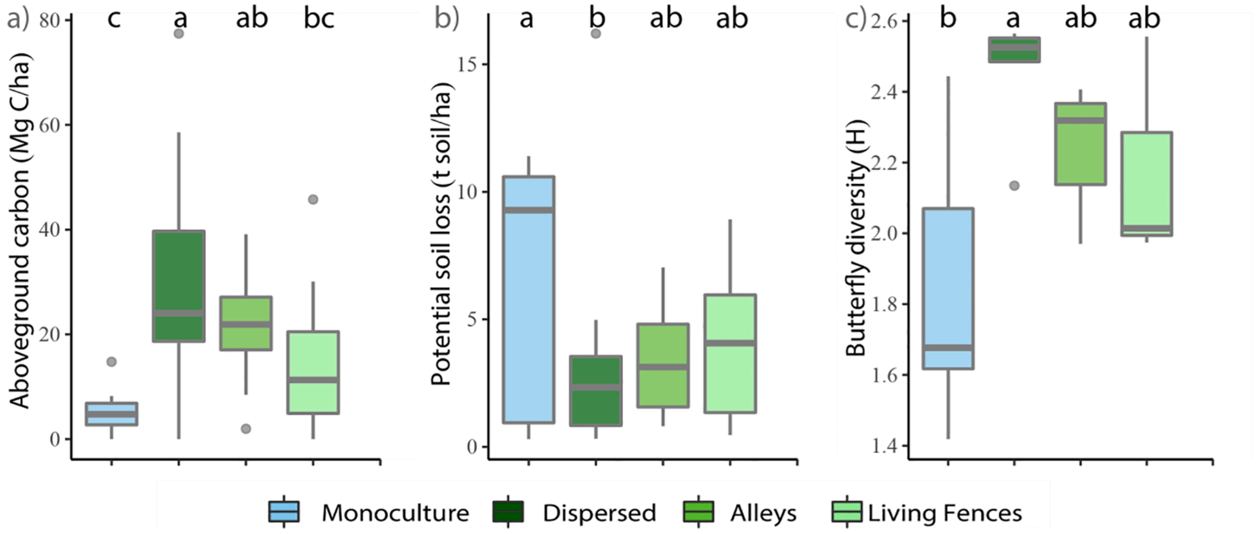

Fig. 4. Tree arrangement classes and a) above-ground carbon stock F = 4.3, df = 41, P = 0.01, b) potential soil loss F = 4.3, df = 41, P = 0.01, and c) butterfly diversity F = 4.6, df = 16, P = 0.02. Letters give the results of the Tukey test.

4.1. Ecosystem service trajectories

We found support for the hypothesis that ecosystem services trajectories are nonlinear and follow mostly an asymptotic relationship (Bullock et al., 2011). In other words, above-ground carbon stock, biodiversity proxies (butterflies and epiphytes), coffee quality and timber volume responded first rapidly and then slowly (Mills et al., 2019). We found that coffee quality, above-ground carbon, butterfly indicators, and epiphytes richness increased within the first 5 years after transition to agroforestry and a saturation point was reached after approximately 20 years. The initial fast response may have corresponded to carbon and biomass accumulation by the trees and the growing availability of habitat for butterflies and epiphytes (Mas and Dietsch, 2003). The trees, changed the micro-climatic conditions by buffering air temperatures and increasing air humidity (appendix Table A8), which may have resulted in the increased coffee quality (Muschler, 2001). Over time, the accumulation of biomass due to tree growth slows down (Turner, 2010), and therefore the increase in carbon stocks and habitat availability also slows down. These results are in line with our expectation that regulating ecosystem services would follow a trajectory similar to that of vegetation characteristics. Our results for the development of above-ground biomass according to an asymptote is in line with earlier findings in secondary tropical forests (Martin et al., 2013), and the restoration of butterfly communities in Ugandan forests was also found to follow an asymptotic shape (Nyafwono et al., 2014).

Coffee bean quality showed an increasing trend over time and coffee yields showed a decreasing trend over time. Both for coffee yield and coffee bean quality it has been demonstrated that they can be affected by shade trees, but the specific responses varied between studies (Jezeer et al., 2017). A previous study from Colombia showed that planting timber trees in coffee farms negatively affected coffee yields during the first five years after planting (Farfán-Valencia and Urrego, 2004). Our results are in line with this study, as coffee yield in the first 10 years after agroforestry negatively related to above-ground carbon stock ($r = -0.34$, $P = 0.03$; Table 3). On the other hand, provisioning of timber volume increased. Currently, a small number of farms marketed the timber, while there is still a large untapped potential to do this on a larger scale in a sustainable way.

We found that above-ground carbon strongly increased within the first 5 years after transition to agroforestry (half-time coefficient is 3.5 ± 2.7 y; Fig. 3; appendix Table A3). The magnitude of the above-ground carbon increase in our study (on average 0.75 tC y^{-1} for the first 20 years) was similar to what was reported for growing cocoa agroforests in Cameroon (0.72 tC y^{-1} over 80 years; Nijmeijer and Harmand, 2019). Belowground carbon dynamics are known to respond slower than above-ground carbon dynamics (Martin et al., 2013; Yang et al., 2019) and that may be a reason why we did not (yet) find an effect here. However, soil carbon content also depends on other factors, such as soil conditions and former or current land-use (Paul et al., 2002), which may have varied between our study locations. In developing cocoa agroforests in Cameroon the belowground carbon content (at 0–15 cm depth) increased over a period of 80 years after implementation (Nijmeijer and Harmand, 2019), which suggests that also belowground changes in carbon stock can be expected. Moreover, we found that canopy height was positively related to soil organic carbon (appendix Table A8), which also suggests that belowground carbon is related to above-ground biomass production and that this response has yet to occur.

We found that both butterflies and epiphytes responded rapidly. Butterflies are sensitive to changes in micro-climatic and habitat conditions and since they are mobile, they can rapidly respond to changes in these conditions (Meyer and Sisk, 2001). A study in Uganda showed that butterfly diversity rapidly increased (as of the first year) after forest restoration activities (Nyafwono et al., 2014). Epiphyte colonization speed depends on presence of woody vegetation to host on, and therefore the rehabilitation speed is slower than the growth of woody vegetation (Cruz-Angón and Greenberg, 2005). This is also reflected in our results as the epiphyte richness directly related to canopy cover (appendix Table A8). In a temporal analysis study in shaded coffee systems in Nicaragua, the authors found that shade tree densities declined over time, while epiphyte richness increased (Goodall et al., 2015). They suggested that for epiphytes the time to colonize and/or canopy height is more important than tree density (Goodall et al., 2015). The latter was also supported by our results as epiphytes were related to canopy closure and canopy height (woody vegetation development), but not to tree density or tree species richness (appendix Table A8). The presence of mature trees therefore seems to play a crucial role for epiphyte habitat provisioning.

Erosion control was found to be stable over time since implementation of agroforestry. This could mean that agroforestry does not affect this ecosystem service or that the speed of the response was either too fast or too slow to be captured in the study timeframe. We suspect that changes in erosion control were too fast to be captured in our study, as we found that the agroforestry systems had on average 48% lower potential soil losses than the monoculture coffee farms ($P = 0.008$; appendix Table A8), which suggests that implementation of agroforestry should play a role. Similar results were found in Nicaragua where coffee agroforestry had more soil covered with litter, reducing soil erosion (Blanco Sepúlveda and Aguilar Carrillo, 2015). We found that canopy cover significantly increased over time, while understory vegetation cover reduced over time, which can be explained by a limitation for light which reduces the growth of herbaceous vegetation (Soto-Pinto et al., 2002). Therefore, we expect that the opposite developments of understory cover against canopy cover and litter cover canceled out any changes in potential soil loss in the temporal analysis.

We also did not find differences in pest control with time since agroforestry in this study. This could be because our chosen method, space-for-time substitution, was not sensitive enough to detect changes in this service over time since agroforestry was implemented. We found that pest incidence was related to altitude, which in turn is related to temperature (appendix Table A8), and colder temperatures are known to suppress coffee berry borer incidence (Jaramillo et al., 2011). Therefore, we expect the environment in which the research site (farm) was embedded to have had a stronger influence on pest control than the *in situ* treatment.

4.2. Ecosystem service trade-off and bundle development

We found that most ecosystem service interactions are variable over time, since the positive relationship between erosion control and carbon stock was the only consistent relationship between time periods (Table 3). This is in line with earlier findings on historical dynamics of ecosystem services in mixed-use landscapes in Canada, where only 3 out of the 27 ecosystem service interactions were consistent cross time (Renard et al., 2015). The interaction between canopy cover, and their corresponding ecosystem services, and coffee yield remains a topic of debate. Shade trees have been found to negatively affect coffee yields (Campanha et al., 2005; Farfán-Valencia and Urrego, 2004), but also to not have an effect on coffee yields (Cerda et al., 2017; Clough et al., 2016; Jezeer et al., 2019). This variation in results is most probably caused by variation in local factors (i.e. soil conditions, rainfall patterns, solar radiations, etc.), which affects the trade-off relationship (Farfán and Jaramillo, 2009; Farfán, 2014). In this study we did not find significant differences in coffee yields between monoculture coffee farms and agroforestry farms (appendix Table A9), neither did we find a negative correlation between canopy cover and coffee yield (appendix Table A8), however, we did find a trade-off between coffee yield and above-ground carbon stocks in the first period (0–10 y) and we found that canopy height negatively related to coffee productivity (appendix Table A8). Further we also found that coffee yield significantly declined over time only for agroforestry farms that had trees planted in borders (appendix Table A10). These 'border' agroforestry farms had the highest timber tree density and the lowest tree species richness (appendix Table

A9). In our study *C. alliodora* was the most abundant timber tree, known to exert very strong effects on coffee yields (Farfán-Valencia and Urrego, 2004). Reducing the densities of *C. alliodora* and using more legume trees could remove these negative effects on coffee yield (Farfán-Valencia and Baute-Balcázar, 2010). Moreover, we found in the second period after transition (11–20 y) a synergy between erosion control and coffee yields, suggesting that soil loss on the long-term reduces coffee yields (Table 3). This could be caused by the loss of nutrients from the top layer of the soil due to erosion, which results in lower production potential of the soil (Pimentel et al., 1995).

4.3. *Factors explaining ecosystem service supply*

In the current study we found that tree layer characteristics (canopy cover), management intensity (weed and pest control management) and farm location characteristics (slope and altitude) explained ecosystem service supply. We also expected soil conditions to be related to ecosystem service supply, based on earlier findings (Méndez et al., 2009), but we did not find this. Canopy cover characteristics are widely reported to be related to ecosystem service supply in coffee systems, for example to pollination (Klein et al., 2003), habitat provisioning for butterflies and epiphytes (Jezeer et al., 2019; Mas and Dietsch, 2003), carbon stock (Jezeer et al., 2019) and erosion control (Cannavo et al., 2011). Farm management intensity also explained ecosystem supply, which is in line with previous findings in coffee systems in Costa Rica (Cerda et al., 2017). In our study more intensive pest control management related to higher coffee productivity and more weed control management related to more herb cover and less litter cover. The relation between pest control management and coffee production can be explained by the coffee berry borer, which was a sincere problem in this region (Escobar-Ramírez et al., 2019). Therefore, we expect that on farms where coffee plants where protected more actively, less coffee beans were lost due to infestation by berry borers. We expect that in farms where there was a faster growth of herbaceous plants, farmers applied more management to control this. Further, we found interaction among pruning of coffee plants, canopy cover and coffee production, since more recently pruned coffee plants had lower coffee production than more mature coffee plants, but agroforests with denser canopies tended to have older coffee plants (appendix Table A8).

5. Limitations

Space-for-time substitutions are less time consuming than repeated measurements over time, however, previous research has demonstrated that they are not sensitive enough to measure high level of details. A study comparing the two methods concludes that repeated measurements provide more precise information, but also that the strongest trends are found by space-for-time substitutions (Rácz et al., 2013). This can be explained by variation in biotic and abiotic conditions, such as local climatic conditions, slope, aspect, former land-use, and landscape configuration, which may influence ecological processes measured in space-for-time substitutions. Some of the indicators we used, such as butterfly communities, pest control, soil conditions and coffee production, are more sensitive to these confounding factors than others, such as above-ground carbon. A strength of the current study is that we were able to identify general development trajectories and the variation in interactions between ecosystem services over longer time periods ($\geq$10 years). However, it is not possible to use the results of this study to predict detailed changes in ecosystem service supply over time with a yearly resolution. We used a rapid ecosystem services assessment technique (Meyer et al., 2015) in which we assessed a wide range of ecosystem services to test the development of general ecosystem services performance over time. This enables us to find general trajectories of ecosystem services, but does not allow to fully understand the ecological processes that drive the trajectory in each single ecosystem service. We suggest that analyses based on the ecosystem service cascade approach could complement our results by adding insights into the underlying ecological dynamics that occur during the development of a single ecosystem service (Mace et al., 2012).

5.1. *Conclusion*

This study provides empirical support for a higher level of ecosystem services in agroforestry than in monocultures and that agroforestry can be used to catalyze the development of ecosystem services. Therefore we emphasize that agroforestry can indeed provide many restoration opportunities. This study showed that spatial arrangements of trees affects the rehabilitation potential and that trees dispersed over the farm provided more regulating and supporting ecosystem services compared to trees in living fences or in alleys. Further, we found that agroforestry provide, aside from coffee, also timber as a provisioning service. The use of this timber resources is currently under-utilized, therefore, we suggest sustainable forestry practices with conservation of some mature trees on the farm play an important role in habitat provisioning for epiphytes. Finally, we found more evidence that agroforestry may improve coffee bean quality, which should be considered by specialty coffee traders.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank the farmers who participated in this study for their assistance and hospitality, and for allowing us to work on their farms. We are grateful Norberto Rincón of the Comité Departamental de Cafeteros de Risaralda and to the National Federation of Coffee growers of Colombia (FNC), who helped with the organization of the fieldwork and the communication with the farmers. Specifically we thank Luz Betty, German, Nury, Maria Teresa and Myriam Christina who have been a great support in the field. This study was supported by funding from the graduate program 'Nature Conservation, Management and Restoration' of The Netherlands Organisation for Scientific Research (NWO) and the Commonland Foundation, which financially supported field data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2021.101246.

References

Arbeláez-Cortés, E., 2013. Knowledge of Colombian biodiversity: published and indexed. Biodivers. Conserv. 22, 2875–2906. https://doi.org/10.1007/s10531-013-0560-y.

Arifin, J., 2001. Estimasicadangan C pada berbagaisistem penggunaan lahan di Kecamatan Ngantang. Skripsi-S1. Unibraw, Malang.

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

Beer, J., Muschler, R., Kass, D., Somarriba, E., 1998. Shade management in coffee and cacao plantations. Agrofor. Syst. 38, 139–164.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x.

Blanco Sepúlveda, R., Aguilar Carrillo, A., 2015. Soil erosion and erosion thresholds in an agroforestry system of coffee (Coffea arabica) and mixed shade trees (Inga spp and Musa spp) in Northern Nicaragua. Agric. Ecosyst. Environ. 210, 25–35. https://doi.org/10.1016/j.agee.2015.04.032.

Bray, R.H., Kurtz, L.T., 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59, 39–46.

Bullock, J.M., Aronson, J., Newton, A.C., Pywell, R.F., Rey-Benayas, J.M., 2011. Restoration of ecosystem services and biodiversity: conflicts and opportunities. Trends Ecol. Evol. 26, 541–549. https://doi.org/10.1016/j.tree.2011.06.011.

Cairns, M.A., Brown, S., Helmer, E.H., Baumgardner, G.A., 1997. Root biomass allocation in the world' s upland forests. Oecologia 111, 1–11.

Caldas, A., Robbins, R.K., 2003. Modified Pollard transects for assessing tropical butterfly abundance and diversity 110, 211–219.

Campanha, M.M., Santos, R.H.S., de Freitas, G.B., Martinez, H.E.P., Garcia, S.L.R., Finger, F.L., 2005. Growth and yield of coffee plants in agroforestry and monoculture systems in Minas Gerais. Brazil. Agrofor. Syst. 63, 75–82. https://doi.org/10.1023/B:AGFO.0000049435.22512.2d.

Cannavo, P., Sansoulet, J., Harmand, J.-M., Siles, P., Dreyer, E., Vaast, P., 2011. Agroforestry associating coffee and Inga densiflora results in complementarity for water uptake and decreases deep drainage in Costa Rica. Agric. Ecosyst. Environ. 140, 1–13. https://doi.org/10.1016/j.agee.2010.11.005.

Cerda, R., Allinne, C., Gary, C., Tixier, P., Harvey, C.A., Krolczyk, L., Mathiot, C., Clément, E., Aubertot, J.-N., Avelino, J., 2017. Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. Eur. J. Agron. 82, 308–319.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Martínez-Yrízar, A., Mugasha, W.A., Muller-Landau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Ortiz-Malavassi, E., Pélissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J.G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob. Chang. Biol. 20, 3177–3190. https://doi.org/10.1111/gcb.2014.20.issue-1010.1111/gcb.12629.

Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T.C., Anshary, A., Buchori, D., Cicuzza, D., Darras, K., Putra, D.D., Erasmi, S., Pitopang, R., Schmidt, C., Schulze, C.H., Seidel, D., Steffan-Dewenter, I., Stenchly, K., Vidal, S., Weist, M., Wielgoss, A.C., Tscharntke, T., 2011. Combining high biodiversity with high yields in tropical agroforests. PNAS 108, 8311–8316. https://doi.org/10.1073/pnas.1016799108.

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

Collazos Quintana, L.F., 2004. Informe del estado de los recursos naturales y del medio ambiente. Pereira, Colombia.

Cruz-Angón, A., Greenberg, R., 2005. Are epiphytes important for birds in coffee plantations ? An experimental assessment. J. Appl 42, 150–159. https://doi.org/10.1111/j.1365-2664.2004.00983.x.

Escobar-Ramírez, S., Grass, I., Armbrecht, I., Tscharntke, T., 2019. Biological control of the coffee berry borer: Main natural enemies, control success, and landscape in fl uence. Biol. Control 136, 103992. https://doi.org/10.1016/j.biocontrol.2019.05.011.

Falk, D.A., Palmer, M.A., Zedler, J.B., 2006. Foundations of Restoration Ecology. Island Press.

FAOSTAT, 2020. FAOSTAT [WWW Document]. accessed 9.20.10. http://www.fao.org/faostat/en/#home.

Farfán-Valencia, F., Baute-Balcázar, J.E., 2010. Efecto de la distribución espacial del sombrío de especies leguminosas sobre la producción de café. Cenicafé 61, 35–45.

Farfán-Valencia, F., Urrego, J.B., 2004. Compartamiento de las especies forestales Cordia alliadora, Pinus oocarpa y Eucalyptus grandis como sombrío e influencia en la productividad del café. Cenicafe 55, 317–329.

Farfán, F., Jaramillo, Á., 2009. Sombrío para el cultivo del café según la nubosidad de la región. Av. Técnicos, 379 - Cenicafé FNC.

Farfán, V., F, 2014. Agroforestería y Sistemas Agroforestales con Café. Manizales, Caldas (Colombia).

FNC, 2011. Sustainability that matters 1927–2010. Bogota, Colombia.

Cenficafé, F.N.C.-, 2006. El Eucalipto - Guías silviculturales: para el manejo de especies forestales con miras a la producción de madera en la zona andina Colombiana. Chinchiná, Colombia.

FNC - Cenficafé, 1994. Disciplina de Química Agrícola. Inf. Anu.

Foley, J., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E. a, Kucharik, C.J., Monfreda, C., Patz, J. a, Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science (80-.). 309, 570–574. https://doi.org/10.1126/science.1111772.

Fremier, A.K., DeClerck, F.A.J., Bosque-Pérez, N.A., Estrada Carmona, N., Hill, R., Joyal, T., Klos, P.Z., Martínez-salinas, A., Niemeyer, R., Sanfiorenzo, A., Welsh, K., Wulfhorst, J.D., 2013. Understanding Spatiotemporal Lags in Ecosystem Services to Improve Incentives. Bioscience 63, 472–482. https://doi.org/10.1525/bio.2013.63.6.9.

Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J., Hua, F., Echeverría, C., Gonzales, E., Shaw, N., Decleer, K., Dixon, K.W., 2019. International principles and standards for the practice of ecological restoration. Second edition. Restor. Ecol. 27, 1–46.

Gilvear, D.J., Spray, C.J., Casas-Mulet, R., 2013. River rehabilitation for the delivery of multiple ecosystem services at the river network scale. J. Environ. Manage. 126, 30–43. https://doi.org/10.1016/j.jenvman.2013.03.026.

Goodall, K.E., Bacon, C.M., Mendez, V.E., 2015. Shade tree diversity, carbon sequestration, and epiphyte presence in coffee agroecosystems : A decade of smallholder management in San Ramón, Nicaragua. Agric. Ecosyst. Environ. 199, 200–206. https://doi.org/10.1016/j.agee.2014.09.002.

Guhl, A., 2002. Coffee Production Intensification and Landscape Change in Colombia , 1970-2002. In: Land Change Science in the Tropics: Changing Agricultural Landscapes.

Hairiah, K., Noordwijk, M. Van, Palm, C., 2001. Methods for sampling carbon stocks above and below ground. Bogor, Indonesia.

Hajian-forooshani, A.Z., Gonthier, D.J., Marin, L., Iverson, A.L., Perfecto, I., 2013. Arboreal spiders in coffee agroecosystems: Untangling the web of local and landscape influences driving diversity. PeerJPrePrints. https://doi.org/10.7287/peerj.preprints.151v1.

Heimann, M., Reichstein, M., 2008. Terrestrial ecosystem carbon dynamics and climate feedbacks. Nature 451, 289–292. https://doi.org/10.1038/nature06591.

ICRAF, 2019. Wood density database [WWW Document]. accessed 9.20.09. http://db.worldagroforestry.org/wd.

IPBES, 2019. The global assessment report on biodiversity and ecosystem services. Bonn, Germany.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories - Volume 4 Agriculture, Forestry and other Land Use. In: Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (Eds). Prepared by the National Greenhouse Gas Inventories Programme, IGES, Japan.

Jaramillo, Á., 2018. El Clima de la caficultura en Colombia. FNC - Cenicafé, Colombia.

Jaramillo, J., Muchugu, E., Vega, F.E., Davis, A., Borgemeister, C., Chabi-olaye, A., 2011. Some Like It Hot : The Influence and Implications of Climate Change on Coffee Berry Borer (Hypothenemus hampei) and Coffee Production in East Africa. PLoS One 6. https://doi.org/10.1371/journal.pone.0024528.

Jezeer, R.E., Santos, M.J., Verweij, P.A., Boot, R.G.A., Clough, Y., 2019. Benefits for multiple ecosystem services in Peruvian coffee agroforestry systems without reducing yield. Ecosyst. Serv. 40, 1–13. https://doi.org/10.1016/j.ecoser.2019.101033.

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

Jha, Shalene, Vandermeer, John H., 2009. Contrasting bee foraging in response to resource scale and local habitat management. Oikos 118, 1174–1180. https://doi.org/10.1111/oik.2009.118.issue-810.1111/j.1600-0706.2009.17523.x.

Johnson, M.D., Levy, N.J., Kellermann, J.L., Robinson, D.E., 2009. Effects of shade and bird exclusion on arthropods and leaf damage on coffee farms in Jamaica' s Blue Mountains. Agrofor. Syst. 76, 139–148. https://doi.org/10.1007/s10457-008-9198-2.

Kearney, S.P., Fonte, S.J., García, E., Siles, P., Chan, K.M.A., Smukler, S.M., 2017. Evaluating ecosystem service trade-offs and synergies from slash-and-mulch agroforestry systems in El Salvador. Ecol. Indic. 105, 264–278. https://doi.org/10.1016/j.ecolind.2017.08.032.

Klein, A.M., Steffan–Dewenter, I., Tscharntke, T., 2003. Fruit set of highland coffee increases with the diversity of pollinating bees. Proc. R. Soc. B Biol. Sci. 270, 955–961. https://doi.org/10.1098/rspb.2002.2306.

Korhonen, L., Korhonen, K.T., Rautiainen, M., Stenberg, P., 2006. Estimation of forest canopy cover: a comparison of field measurement techniques. Silva Fenn. 40, 577–588.

Locatelli, B., Lavorel, S., Sloan, S., Tappeiner, U., Geneletti, D., 2017. Characteristic trajectories of ecosystem services in mountains. Front. Ecol. Environ. 15, 150–159. https://doi.org/10.1002/fee.2017.15.issue-310.1002/fee.1470.

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

Mace, G.M., Norris, K., Fitter, A.H., 2012. Biodiversity and ecosystem services: a multilayered relationship. Trends Ecol. Evol. 27, 19–26. https://doi.org/10.1016/j.tree.2011.08.006.

Martin, P.A., Newton, A.C., Bullock, J.M., Martin, P.A., 2013. Carbon pools recover more quickly than plant biodiversity in tropical secondary forests. Proc. R. Soc. B 280, 1–8. https://doi.org/10.1098/rspb.2013.2236.

Mas, Alexandre H., Dietsch, Thomas V., 2003. An index of management intensity for coffee agroecosystems to evaluate butterfly species richness. Ecol. Appl. 13, 1491–1501.

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

Meyer, C.L., Sisk, T.D., 2001. Butterfly response to microclimatic conditions following ponderosa pine restoration. Restor. Ecol. 9, 453–461.

Meyer, S.T., Koch, C., Weisser, W.W., 2015. Towards a standardized Rapid Ecosystem Function Assessment (REFA). Trends Ecol. Evol. 30, 390–397. https://doi.org/10.1016/j.tree.2015.04.006.

Mills, M., Bode, M., Mascia, M.B., Weeks, R., Gelcich, S., Dudley, N., Govan, H., Archibald, C.L., Romero-de-Diego, C., Holden, M., Biggs, D., Glew, L., Naidoo, R., Possingham, H.P., 2019. How conservation initiatives go to scale. Nat. Sustain. 2, 935–940. https://doi.org/10.1038/s41893-019-0384-1.

Ministerio de Agricultura y Desarollo Rural, 2018. Datos abiertos. Gobierno Digital Colombia [WWW Document]. URL https://www.datos.gov.co/Agricultura-y-Desarrollo-Rural/Cadena-Productiva-Caf-Area-Producci-n-Y-Rendimient/mc73-h8xp (accessed 12.28.18).

Moguel, P., Toledo, V.M., 1999. Biodiversity traditional of Mexico. Conserv. Biol. 13, 11–21.

Muschler, R.G., 2001. Shade improves coffee quality in a sub-optimal coffee-zone of Costa Rica. Agrofor. Syst. 85, 131–139.

Nijmeijer, A., Harmand, L.J., 2019. Carbon dynamics in cocoa agroforestry systems in Central Cameroon: afforestation of savannah as a sequestration opportunity. Agrofor. Syst. 93, 851–868. https://doi.org/10.1007/s10457-017-0182-6.

Nyafwono, M., Valtonen, A., Nyeko, P., Roininen, H., 2014. Fruit-feeding butterfly communities as indicators of forest restoration in an Afro-tropical rainforest. Biol. Conserv. 174, 75–83. https://doi.org/10.1016/j.biocon.2014.03.022.

Paisaje Cultural Cafetero, 2020. Paisaje Cultural Cafetero [WWW Document]. URL http://paisajeculturalcafetero.org.co/.

Paul, K.I., Polglase, P.J., Nyakuengama, J.G., Khanna, P.K., 2002. Change in soil carbon following afforestation. For. Ecol. Manage. 168, 241–257.

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

Pickett, S.T.A., 1989. Space-for-time substitution. Long-Term Studies in Ecology 110–135. https://doi.org/10.1007/978-1-4615-7358-6.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., Blair, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science (80-) 267, 1117–1123. https://doi.org/10.1126/science:267.5201.1117.

Pribyl, D.W., 2010. A critical review of the conventional SOC to SOM conversion factor. Geoderma 156, 75–83. https://doi.org/10.1016/j.geoderma.2010.02.003.

R Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing.

Rácz, I.A., Eszter, D., Kisfali, M., Batiz, Z., Varga, K., Szabó, G., Lengyel, S., 2013. Early changes of orthopteran assemblages after grassland restoration : a comparison of space-for- time substitution versus repeated measures monitoring. Biodivers. Conserv. 22, 2321–2335. https://doi.org/10.1007/s10531-013-0466-8.

Rau, A., Wehrden, H.Von, Abson, D.J., 2018. Temporal dynamics of ecosystem services. Ecol. Econ. 151, 122–130. https://doi.org/10.1016/j.ecolecon.2018.05.009.

Renard, D., Rhemtulla, J.M., Bennett, E.M., 2015. Historical dynamics in ecosystem service bundles. Proc. Natl. Acad. Sci. 112, 13411–13416. https://doi.org/10.1073/pnas.1502565112.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.., Yoder, D.C., 1997. Prediciting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE).

Rey Benayas, J.M., Bullock, J.M., 2012. Restoration of biodiversity and ecosystem services on agricultural land. Ecosystems 15, 883–899. https://doi.org/10.1007/s10021-012-9552-0.

Schollenberger, C.J., Simon, R.H., 1945. Determination of exchange capacity and exchangable bases in soil-ammonium acetate method. Soil Sci. 59, 13–24.

Segura, M., Kanninen, M., Suárez, D., 2006. Allometric models for estimating aboveground biomass of shade trees and coffee bushes grown together. Agrofor. Syst. 68, 143–150. https://doi.org/10.1007/s10457-006-9005-x.

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

Soilgrids.org, 2019. Global Soil Map [WWW Document]. URL www.soilgrids.org (accessed 9.20.12).

Somarriba, E., Beer, J.W., 1987. Dimensions, volumes and growth of Cordia alliadora in agroforestry systems. Forest Ecol. Manag. 18, 113–126.

Soto-Pinto, L., Perfecto, I., Caballero-Nieto, J., 2002. Shade over coffee: Its effects on berry borer, leaf rust and spontaneous herbs in Chiapas. Mexico. Agrofor. Syst. 55, 37–45. https://doi.org/10.1023/A:1020266709570.

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

Spake, R., Lasseur, R., Crouzat, E., Bullock, J.M., Lavorel, S., Parks, K.E., Schaafsma, M., Bennett, E.M., Maes, J., Mulligan, M., Mouchet, M., Peterson, G.D., Schulp, C.J.E., Thuiller, W., Turner, M.G., Verburg, P.H., Eigenbrod, F., 2017. Unpacking ecosystem service bundles: Towards predictive mapping of synergies and trade-o ff s between ecosystem services. Glob. Environ. Change 47, 37–50. https://doi.org/10.1016/j.gloenvcha.2017.08.004.

Sutherland, I.J., Bennett, E.M., Gergel, S.E., 2016. Recovery trends for multiple ecosystem services reveal non-linear responses and long-term tradeoffs from temperate forest harvesting. For. Ecol. Manage. 374, 61–70. https://doi.org/10.1016/j.foreco.2016.04.037.

Tongway, D.J., Hindley, N.L., 2004. Landscape function analysis. Landscape 2614–2614. https://doi.org/10.1016/S0022-3913(12)00047-9.

Turner, M.G., 2010. Disturbances and landscape dynamics in a changing world. Ecology 91, 2833–2849.

UNESCO, 2020. Coffee Cultural Landscape of Colombia [WWW Document]. accessed 3.11.20. https://whc.unesco.org/en/list/1121/.

Walkley, A., Black, I.A., 1933. An examination of the degtjareff method for determining soil organic matter and proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.

Wunderle, J.M., Latta, S.C., 1996. Avian abundance in sun and shade coffee plantations and remnant pine forest in the Cordillera Central, Dominican Republic. Ornitol. Neotrop. 7, 19–34.

Yang, Y., Tilman, D., Furey, G., Lehman, C., 2019. Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nat. Commun. 10, 1–7. https://doi.org/10.1038/s41467-019-08636-w.