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Benefits for multiple ecosystem services in Peruvian coffee agroforestry systems without reducing yield

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ABSTRACT

Crop production often comes at the expense of losses in ecosystem services and biodiversity; however, this might not always be the case. Here we test the effects of shade gradients and agricultural inputs on trade-offs or synergies between coffee yield and ecosystem services and biodiversity data for smallholder coffee plantations of Arabica coffee in Peru. We collected data using surveys (n = 162 farmers) and field sampling (n = 62 farms) and modelled the relationship between coffee yield, butterfly species richness and carbon storage, accounting for soil fertility and yield losses to pests and diseases. We found that both carbon and forest butterfly species richness were higher in plantations with more shade, and with no reduction in coffee yields with increasing shade. There were no significant correlations between coffee yield, forest butterfly species richness and carbon storage. Use of agricultural inputs, especially fertilizers, was highest in sites with low coffee yield, but was not related with either forest butterfly species richness or carbon. The lack of trade-offs between yield, forest butterfly species richness and carbon, and their relationships with shade and agricultural inputs suggest that it is possible to manage coffee agroforests to simultaneously provide multiple ecosystem services without reducing coffee yields.

1. Introduction

Tropical agroforestry systems have been argued to be environmentally-friendly, reconciling biodiversity conservation, food production and the delivery of other ecosystem services (Schroth et al., 2004). The occurrence of multiple vegetation layers and different tree species provide habitat for a large number of species, making them valuable for nature conservation (Bhagwat et al., 2008; Bucheli and Bokelmann, 2017; Kay et al., 2019), but also offer multiple other benefits to people. Besides generating cash income from the main crop, they provide farmers with other products for sale or household use. Fruits, timber, firewood and other shade tree products such as rubber, medicine and forage (Moguel and Toledo, 1999) contribute to smallholders' livelihoods, diversify their income and increase food security (Souza et al., 2010). Maintaining shade trees is related to enhancing some ecosystem services such as improved soil fertility (Tscharntke et al., 2011), weed control (Staver et al., 2001), a lower need for agricultural inputs such as fertilizers, herbicides and pesticides (Vaast et al., 2006), buffering of micro-climate extremes (Lin, 2007), and pollination and natural pest control (Perfecto et al., 2004). Agroforestry systems make an important contribution to carbon storage on agricultural lands, both nationally and globally (Atangana et al., 2014; Zomer et al., 2016). The biodiversity and ecosystem service benefits of shaded agroforestry systems are often assumed to come at the cost of lower crop yields under shaded conditions compared to low shade and full sun conditions (Perfecto et al., 2005; Vaast et al., 2006). This is because it is assumed that shade trees compete with coffee plants for light, water and nutrients (Beer et al., 1998). The expectation of lower yields under shaded conditions has in many parts of the world driven the conversion of traditional agroforestry systems into simplified, low shade or full sun monocultures, to increase crop yields and farmer income (Meyfroidt et al., 2014; Perfecto and Vandermeer, 2015). At the same time, several studies report both high crop yields and high biodiversity for agroforestry systems (Clough et al., 2011; Gordon et al., 2007). More evidence is thus needed on the extent to which multiple ecosystem services can be provided simultaneously in coffee production

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systems, and on the trade-offs these systems face is critical. This is particularly important in a context of a growing world population, deforestation, climate change and commodity price volatility.

At the global level, the coffee sector is no exception to the world-wide intensification trend. In 2010, less than a quarter of the global coffee sector was managed as diverse agroforestry systems with multi-layered, multi-species shade, 35% with sparse shade, while the remaining 40% of coffee area lacked shade (Jha et al., 2014). About 20–25 million families are involved in global coffee production of which more than 70% are smallholders who farm on less than ten hectares (Jha et al., 2011). Coffee intensification is coupled to reduced shade, alongside with adopting new high-yielding varieties, higher coffee plant density and chemical inputs (Tscharntke et al., 2011). In Latin America, coffee intensification is accelerated by the perception that higher shade levels lead to increased incidence of coffee leaf rust (*Hemileia vastatrix*), a disease associated with a 10–70% reduction in coffee harvest in several countries during the latest outbreak in 2012–2013 (Avelino et al., 2015), especially in the Arabica variety, which represents over 60% of the global coffee market. Although increased coffee yields and income are important drivers behind intensification practices (Perfecto et al., 2005), evidence supporting the coupling of increased shade levels with decreased coffee yields is scarce (Jha et al., 2014).

Besides shade, there are other factors which jointly affect multiple ecosystem services, and potentially influence the observed trade-offs between yield and other ecosystem services. Incidence of pests and diseases and soil fertility may interact with the direct effects of shade or input management on coffee yields. High soil fertility may simultaneously benefit yields (Tittonell et al., 2005), biodiversity and carbon storage (Moguel and Toledo, 1999; Siebert, 2002). Increased frequency of management activities such as weeding and pruning, and increased use of organic and especially chemical inputs as fertilizers, insecticides and herbicides are expected to affect yields, but are reported to negatively affect multiple components of biodiversity in general (Lin et al., 2008; Tscharntke et al., 2005) and insect diversity in particular (Kremen and Miles, 2012; Potts et al., 2010). Pest and disease incidence have triggered farmers to change varieties and management regime (Jha et al., 2014), with potential consequences on yield.

As both input and shade management can affect yields, biodiversity and other ecosystem services, it is necessary to study the effect of both simultaneously (Hernández-Martínez et al., 2009), which is rarely done. Recent studies demonstrate that coffee agroforestry systems provide for enhanced ecosystem services compared to full sun systems in Central America (Allinne et al. (2016), Cerda et al. (2016) and Meylan et al. (2017)). At the same time these studies show complex interactions between environmental conditions, input and shade management, which emphasize the need for more research along gradients of elevation, shade and input management intensity in order to generalize findings.

Here, we investigated the positive (potential synergies) and negative relations (potential trade-offs) among Arabica coffee yield, butterfly species richness and carbon storage in Peruvian smallholder plantations under a range of shade and input practices. Butterflies (Lepidoptera) were chosen as a proxy for biodiversity due to their sensitivity to micro-climatic changes in e.g. temperature, air movement, air moisture and insolation (Bobo et al., 2006), thereby reflecting effects of shade cover, shade tree diversity; butterflies are also expected to be sensitive to pesticide use (Dolia et al., 2008). In this study we (i) assess the effects of shade and input management on coffee yield, butterfly species richness and carbon storage, while taking into account yield losses due to pests and diseases and variation in soil fertility; (ii) identify possible synergies or trade-offs between ecosystem services and discuss shade and input management implications for smallholder coffee farmers.

We expect that shade cover in coffee systems enhances biomass (Atangana et al., 2014), and increases habitat provisioning (Bhagwat et al., 2008), yet effects on coffee yields are difficult to predict (Jha et al., 2014). We also expect that agricultural inputs will improve coffee yield, due to improved soil fertility (Castro-Tanzi et al., 2012) and decreased losses due to pests and diseases (Cerda et al., 2016). We also expect that inputs might have negative effects on butterfly species richness (Scherr and McNeely, 2008).

2. Materials and methods

2.1. Study region

Following rapid expansion of coffee production over the past decades (Tulet, 2010), Peru now holds a 3.8% share in the global coffee sector (FAOSTAT, 2017). The study area was located in Peru within the department of San Martín, which together with the Amazonas region, accounts for almost 50% of the national coffee production (USDA, 2014). The study region was selected because of its importance for the Peruvian coffee sector, the presence of a wide variety in smallholder coffee systems, and large stretches of natural forests and national parks holding high biodiversity (Myers et al., 2000) and carbon stocks (Asner et al., 2014). At the same time, this region is experiencing high deforestation rates (> 20 000 hectares per year; Valqui et al., 2015), some of this deforestation due to the recent expansion of coffee plantations (Bax and Francesconi, 2018). The coffee plantations included in this study were spread over an area of approximately 2000 km^2 (Fig. 1a; 670–1500 m). Most plantations (n = 143 out of a total of 162) were situated in the provinces Moyobamba and Rioja, which together form the 'Alto Mayo', a tropical highland ranging from 850 to 1500 m in altitude. For these higher elevation plantations, the average rainfall is 1512 mm per year, and the mean temperature 22.8 °C. The remaining plantations (n = 19) were situated in the lowland province of Picota, with altitude ranging from 670 to 1000 m. The nearest weather station lies approximately 20 km from these plantations at an altitude of 218 m and reports a mean temperature of 26.5 °C and a mean annual rainfall of 937 mm. For both regions, the dry season occurs between May and September (Gobierno Regional de San Martín, 2008). For more information about the study region, see Appendix S1.

2.2. Site selection, sampling and surveying methods

In summary, data on coffee yield, aboveground carbon storage, butterfly species richness, soil fertility and micro-climate was recorded using both household surveys and field measurements, along with data on coffee management practices related to shade cover and input use. Plantations were selected to cover the gradient of agricultural input and shade management in the study area, from full sun monoculture coffee to diversified shaded plantations and from high agro-chemical to organic inputs or without inputs (Fig. 1; Table 1). The selection of the farms was based on information on farm shade level and input use. This information was collected by field technicians from extension services who provide advice to farmers and from local databases of farmers' organisations. Only plantations with coffee shrubs older than three years were selected because this is when Arabica shrubs start producing marketable beans (Perfecto et al., 1996).

We performed household surveys in 2014, and again in 2016 to collect specific information on shade tree species richness and density. Household surveys consisted of a semi-structured interviews to collect information on coffee yield, shade system characteristics and agricultural inputs as described below. Despite the potential for these surveys to represent perceptions on the system, we believe that the large sample size and our method to discard potential erroneous answers decrease the potential for biased results, and keep interpretations conditional on the original data collected. The interviewers were trained by the same person and surveys with plantation owners or tenants lasted 45–60 minutes per plantation. The interviewers assessed qualitatively if the farmers responded with confidence, and outliers

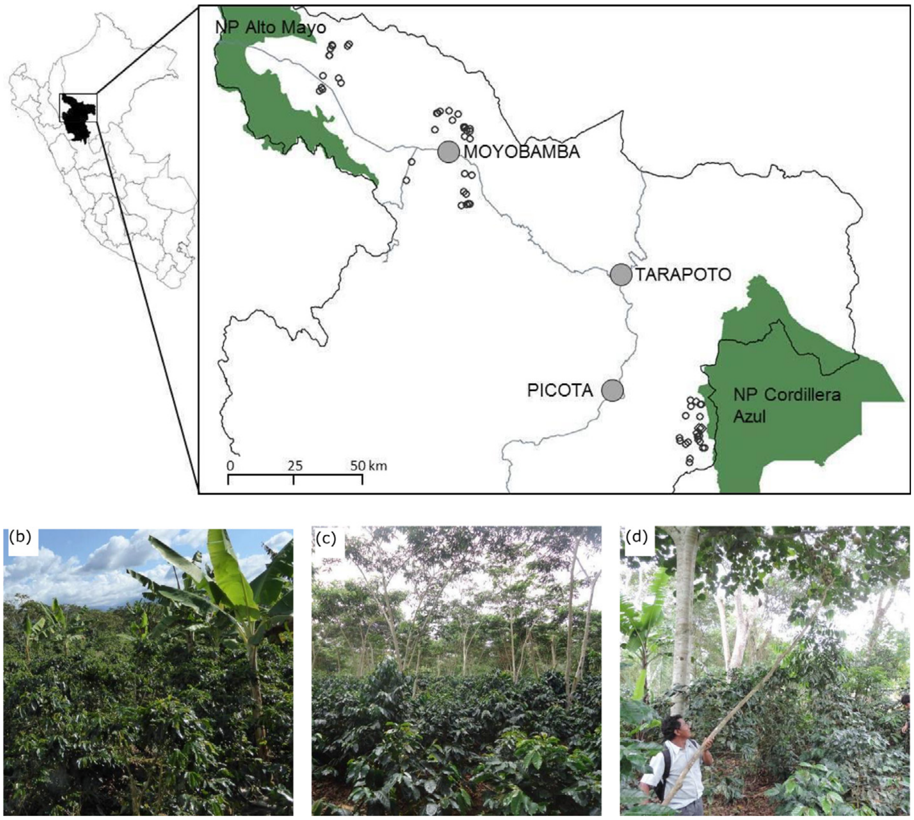

Fig. 1. Study area and management regimes. (a) Study area in the region of San Martín, Peru. Open circles represent the locations of the plantations were plot measurement where made, grey-filled circles represent important cities, grey lines depict major roads and the dark green areas depict national parks. Region 1 refers to the area near Moyobamba, all north of Tarapoto (altitude 850–1500 m), whereas region 2 refers to the area southeast of Picota, near the national park (NP) Cordillera Azul (altitude 670–1000 m); (b) full sun monoculture management regime, sometimes sparsely intercropped with bananas, (c) single-species shade management regime, (d) diversified shade management regime. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were double checked. In 2016, data was collected and recorded in a smartphone/tablet app developed for this study, using ODK software (ODK Collect, version 1.4.10). The app included fields for each question, which provided guidance for the surveyors to minimise interview bias.

To obtain more detailed information on shade management, butterfly species richness, carbon storage, soil fertility and microclimate, the dataset was complemented with plot measurements conducted in a subsample of 62 plantations (Fig. 2). These farms were selected so that they would reflect the gradient of shade cover and input management conditions in the study area. Plots of 10 × 10 m (Picota, n = 19) or 20 × 20 m (Alto Mayo, n = 43) were sampled and four additional plots (20 × 20 m) were set in the buffer zone of the national park Cordillera Azul to measure undisturbed forest as a reference. Field plots were sampled from May to August in 2014 and 2015, which corresponds to the dry season. We also recorded general farm characteristics (e.g., size (ha), coffee shrub planting density (shrubs ha^{-1}), elevation and coffee shrub age (y)). These variables were added in the modelling exercise as potential confounding factors (see description below). We analyzed two datasets: one consisting of only survey data, and the other consisting of survey data plus plot data. We refer to these two data sets as "*survey*" (n = 162) and "*survey + plot*" (n = 62) respectively (Fig. 2).

2.2.1. *Input management*

In 2014, the surveyed farmers were asked about their management practices related to input, cost of organic of chemical fertilizer, pesticides, and herbicides. Most inputs, especially fertilizers, are used in solid form as well as liquid concentrates, thus we transformed the inputs to their market value and report on the total value of used inputs (€ $ha^{-1}\,y^{-1}$) as a proxy for the amount of inputs used. This included inputs given to the farmers free of charge, for example by the farmer association or the government. We also distinguished between organic and chemical inputs, as we expected different effects of these types of inputs on biodiversity (Gomiero et al., 2011).

2.2.2. *Shade management*

Survey – Tree species richness was assessed in the 2016 survey by asking the farmers about the different types of trees and the number of shade trees present in their coffee farm. The farmers were also asked how difficult they thought it was to report the number and type of trees in their coffee farm (easy, medium or difficult). If they responded that they found this 'difficult' the answer was not included in the database. In addition, we used the field plot data on shade tree density, species richness, shade cover and height to compare shade estimates from field surveys and farmer interviews and assess the consistency across datasets (Fig. S2).

Plot – Within the sampling plot, all shade trees with a diameter at breast height > 5 cm were identified to species level if possible, and otherwise to genus level. Species identification was done using a field guide (Pennington et al., 2004), and knowledge from local experts and farmers. Three groups of trees that provide shade were distinguished as these are expected to show different relations with biodiversity and carbon (Philpott et al., 2008), namely: (i) banana plants, plantains and palm trees; (ii) planted leguminous trees, predominantly *Inga*; and (iii) other trees (hereafter referred to as timber trees, such as *Cedrela odorata* and *Mariosousa willardiana*), both naturally occurring and planted. Tree species falling under each of these categories are listed in the supplementary material (Table S1). Tree height was measured with a Nikon Forestry Hypsometer. Shade cover was determined visually by estimating canopy cover on a scale of 0% to 100% (Samnegård et al., 2014). We used visual estimates because they can be used when it is logistically difficult to collect canopy cover data above the tall coffee canopy using hemispheric lenses, and still accurately estimate shade levels (Bellow and Nair, 2003). We used highly trained observers for measuring shade cover, and the two trained observers cross-calibrated their estimates (Vittoz et al. 2010). Shade trees were rarely pruned and shade cover measurements were taken once per plantation from May to August. As shade trees are tropical evergreen trees, we expect shade cover not to vary much throughout the year.

Table 1
Descriptive statistics of all variables and model description. Variables were measured with data from surveys (n = 162), and field plots (n = 62). Variables were measured with data collected via farmer surveys, unless stated otherwise. As for some farms we could not obtain a measurement, we report the number of observations per variable. Only data from coffee plantations is reported here, not natural forest plots. Variables included in the models are marked with ●.

	unit	*mean* ± sd	*Min*-max	*n*	Model 1: Coffee yield	a) Survey: average '10–'14	b) Survey + plot : average '10–'14	Model 2: Butterfly diversity	a) Forest species richness (log)	b) Non-forest species richness (log)	Model 3: Carbon storage AGB carbon (log)	Model 4: Pests & diseases Estimated loss due to CLF; CBB; Ara; OdP	Model 5: Soil fertility N; OM; pH; CEC ; C:N
General farm characteristics													
Farm size	ha	6.4 ± 8.4	0.50–80	154									
Productive coffee area	ha	2.7 ± 1.9	0.50–13	154									
Elevation	m a.s.l.	1070 ± 172	673–1497	162		●	●		●		●	●	●
Coffee shrub age	year	8.8 ± 4.6	3–30	159		●	●		●		●	●	●
Region	[Alto Mayo]; [Picota]					●	●		●		●	●	●
Shade management													
Coffee shrub density	shrubs ha^{-1}	3935 ± 1140	1000–7000	154		●	●		●	●	●	●	●
Banana plant density (plot)	plant ha^{-1}	77 ± 231	0–1400	54		●	●		●	●	●		
Inga tree density	trees ha^{-1}	41 ± 72	0–550	154		●						●	
Inga tree density (plot)	trees ha^{-1}	127 ± 161	0–700	54			●		●		●		●
Timber-species tree density	trees ha^{-1}	27 ± 56	0–375	154		●						●	
Timber-species tree density (plot)	trees ha^{-1}	75 ± 94	0–375	54			●		●		●		●
Total tree density	trees ha^{-1}	71 ± 97	0–600	154			●						
Total tree density (plot)	trees ha^{-1}	194 ± 131	0–600	54			●		●	●			
Shade cover (plot)	%	36.8 ± 26.7	0–80	54			●		●	●	●		●
Maximum canopy height (plot)	m	12.4 ± 7.9	0–31.5	54			●		●	●	●		
Coffee variety	[sensitive];[resistant];[mixed]					●						●	
Input management													
Total	€ ha^{-1} y^{-1}	150 ± 197	0–1022	151					●	●		●	
Fertilizer (chemical/ organic)	€ ha^{-1} y^{-1}	124 ± 174	0–952	140		●	●		●	●		●	●
Pesticide	€ ha^{-1} y^{-1}	34 ± 77	0–468	128					●	●		●	
Herbicides	€ ha^{-1} y^{-1}	6.7 ± 26.2	0–250	138					●	●			
Landscape configuration													
Distance to natural forest (plot)	m	2532 ± 2122	0–7869	54					●				
Forested area in 1 km radius (ratio, 0–1) (plot)	%	0.41 ± 0.16	0.12–0.76	54					●				
Microclimate													
Air temperature (plot)	°C	26.5 ± 2.5	21.2–34.2	52			●		●			●	
Air humidity (plot)	%	77.4 ± 7.1	61.0–93.5	53			●		●			●	
Pests & Diseases-Estimated loss													
Total loss	%	74.11 ± 41.0	0–100	152		●	●						
Coffee leaf rust (*Hemileia vastatrix*, CLR)	%	46.2 ± 24.6	0–100	152		●	●						
Berry borer (*Hypothenemus hampei*, CBB)	%	9.6 ± 11.6	0–50	152		●	●						
Ojo de pollo (*Mycena citricolor*, OdP)	%	9.5 ± 14.1	0–60	152		●	●						
Arañero (*Pellicularia koleroga*, Ara)	%	8.5 ± 13.1	0–70	151		●	●						

(*continued on next page*)

Table 1 (*continued*)

	unit	*mean* ± sd	*Min-max*	*n*	Model 1: Coffee yield		Model 2: Butterfly diversity		Model 3: Carbon storage AGB carbon (log)	Model 4: Pests & diseases Estimated loss due to CLF; CBB; Ara; OdP	Model 5: Soil fertility N; OM; pH; CEC ; C:N
					a) Survey: average '10–14	b) Survey + plot : average '10–14	a) Forest species richness (log)	b) Non-forest species richness (log)			
Soil Quality (plot)											
Nitrogen (N)	%	0.2 ± 0.07	0.02–0.36	54		●			●		
Organic matter (OM)	%	4.8 ± 2.1	1.4–12.5	54		●			●		
pH		5.9 ± 1.0	4.3–7.8	54		●			●		
Cation exchange capacity (CEC)	Meq 100 g^{-1}	16.2 ± 12.5	2.3–60.7	54		●			●		
C:N	ratio	25.4 ± 22.3	11.9–127.2	35							
Yield											
Coffee yield	kg ha^{-1}	860 ± 526	112–2893	154							
Biodiversity											
Forest butterfly species richness	species transect^{-1}	5.2 ± 5.2	0–20	60							
Non-forest butterfly species richness	species transect^{-1}	4.8 ± 2.6	2–12	60							
Carbon storage											
Above ground carbon storage	Mg ha^{-1}	32.0 ± 81.7	0–538								

2.2.3. Coffee yield

To measure coffee production, we used coffee yield as a proxy. Farmers were asked to report their coffee yields in units of dried green coffee (known as café pergamino; 1 quintal = 56 kg) per year for 2010–2014, and the coffee varieties present on the plantation. Plantation averages were used for further analysis.

2.2.4. Butterfly species richness

Butterfly species richness was estimated using commonly used transect counts (Schulze et al., 2004). One transect with a total length of 300 m was walked by two observers per plantation at a pace of 12.5 m min^{-1} during 24 min, always between 9:30 and 15:30 h and without precipitation. All butterflies observed in a band of 3 m to each side of the transect were identified to species level based on wing characteristics by local butterfly specialists. When species identification was difficult, butterflies were netted and photographed for later identification. If species level identification was not possible, the lowest level taxon was recorded instead. All measurements were taken in the dry season to avoid inter-seasonal variation. Butterflies were classified as forest or non-forest species, based on preferred habitat type obtained from information of different sources, including peer reviewed articles, books and websites (details in Table S2). To account for weather variability, we recorded whether precipitation occurred before and after the sampling, and the day was sunny, medium-cloudy or cloudy. Simultaneously with the transect, we recorded air temperature (°C) and relative air humidity (%) at soil surface level over 30 minutes per plot using a thermo-hygrometer (TFA, Maxim II). Species accumulation curves (Chao et al., 2009) were calculated to determine sampling completeness and reliability (Fig. S1).

As the availability of source habitat in the surroundings may influence farm species diversity (Häger et al., 2014; Ricketts et al., 2001), we calculated the percentage cover of primary and secondary forest within circular buffers of 1000 m radius around the farm, as well as distance from the farm to the nearest primary forest. Farm location was recorded with a GPS (Garmin GPS 62 s). Maps with six land-use classes (urban areas, annual crop cultivation, perennial crops, pastures, primary forest and secondary forest) were derived from an automated land cover classification of Landsat data from 2011 (30 m, Proceja; https://www.gfa-group.de/projects/Agro-Environment_Program_Ceja_de_Selva_PROCEJA_3876974.html). The radius of 1000 m was chosen as this corresponds to typical butterfly dispersal distances (Tufto et al., 2012) and is comparable to areas analysed in previous research (e.g., Steffan-Dewenter et al., 2002). To check for potential effects of weather on butterfly species richness, we correlated precipitation and cloudiness on the day of the butterfly sampling with butterfly species richness.

2.2.5. Carbon storage

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

2.2.6. Pests and diseases

We asked farmers about coffee yield loss due to pests and diseases, estimated as percent yield lost to coffee leaf rust, “Ojo de Pollo” or “Ojo

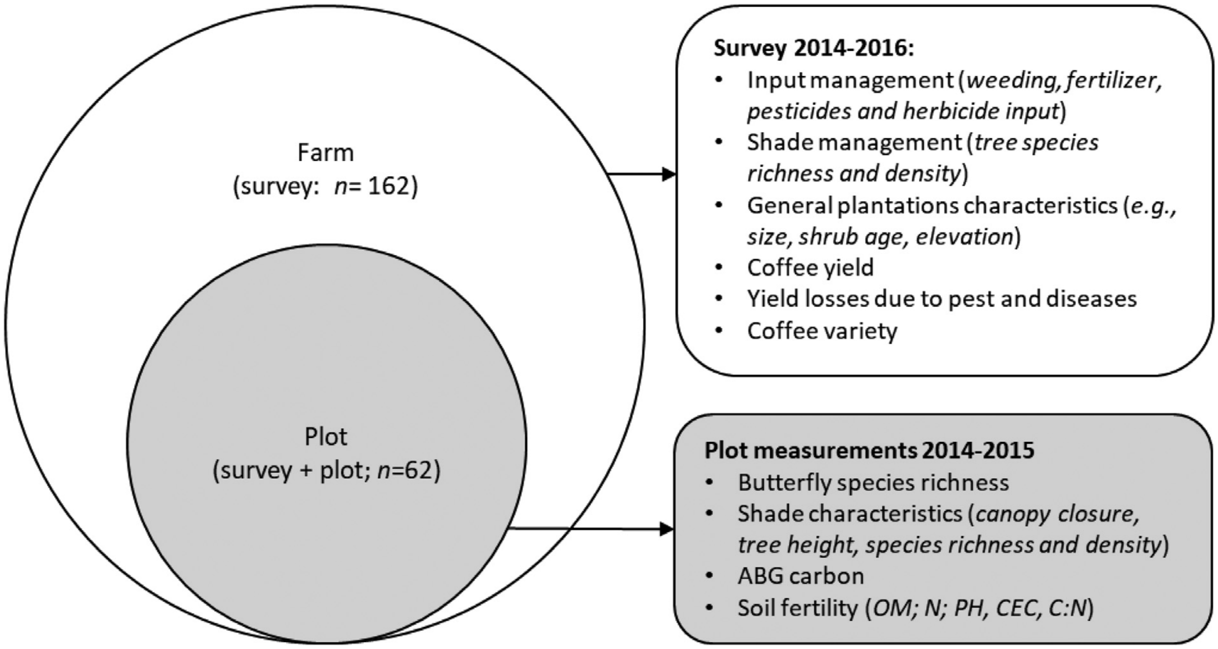

Fig. 2. Sampling design. Datasets, number of samples, and key variables collected per dataset.

de Gallo" (*Mycena citricolor,* OdP), "Arañero" (*Pellicularia koleroga,* Ara) and coffee berry borer (*Hypothenemus hampei*, CBB). We are aware that despite farmers' knowledge of the system, it is difficult for them to record precise % yield loss due to pests and diseases. Nonetheless, because this is such a widespread problem, we wanted to have an indication of the extent to which farmers perceive this loss. We reported % yield loss, included it as a potential confounding factor but refrained from over-extrapolating and drawing major conclusions. Although only Arabica coffee is grown in this region, a subset of widespread Arabica varieties is less prone to coffee leaf rust than others. Costa Rica 95 from the Catimor family and Iapar 59 were recognized as more coffee rust-tolerant varieties, and Pache, Caturra, Típica, Borbón, Catuaí and Nacional as varieties more sensitive to coffee rust (Arrieta et al., 2016). We recorded the variety mix within farm, and classified it as "*sensitive*", "*resistant*" or "*mixed*".

2.2.7. Soil fertility

As proxies of soil fertility, we measured soil organic matter (OM), nitrogen content (N), pH, cation exchange capacity (CEC) and C:N ratio in the field plots. For each plot, we took five random soil samples of 500 g from the top layer (0–15 cm). Samples were thoroughly mixed and for each plot (n = 57) a sub-sample of approximately one kg was sent for standard soil laboratory analyses (at the *Instituto de Cultivos Tropicales* in Tarapoto and the *Proyecto Especial Alto Mayo* in Nueva Cajamarca, both in Peru). See Appendix S2 for more detailed information on soil fertility measurements and Table S3 for lab procedures.

2.3. Data analyses

We used generalized linear models (GLM) to evaluate the effects of shade and input management on coffee yield, butterfly species richness, and carbon storage, while accounting for yield losses due to pests and diseases and soil fertility. We used coffee yield, butterfly species richness and above-ground carbon (AGC) as response variables and shade management, input use, micro-climate, yield loss due to pests and diseases, and soil fertility as predictor variables. We also included farm elevation, coffee shrub age, and region as fixed factors to account for potential confounding effects. We also included distance to primary forest and forest cover (% primary and secondary forest in the 1 km radius buffer around the farm) in butterfly species richness models. We tested pair-wise multicollinearity with Spearman's rank correlation, and excluded variables with $r > 0.50$ and mostly correlated with the response variable (Table S4).

For modelling coffee yields, we performed two sets of models, one based on the *survey* data only and one based on *survey + plot* data, where the latter allowed to use the more detailed data. All variables were tested for assumptions of homoscedasticity and normality of the residuals. Some variables failed to meet this assumption (above-ground carbon (AGC), butterfly species richness, input expenses) and were log-transformed (after adding the smallest value divided by two whenever observations included zero).

We used model selection procedures to select the best set of generalized linear models predicting each of the response variables with both the *survey* data only or the *survey + plot* data, using information criteria. Models were fit to a normal distribution and a generalized linear link function. Full models were checked for (i) homogeneity of variance by plotting the standardized residuals against fitted values, (ii) absence of skewness through a normal Q-Q plot, and (iii) absence of outliers by plotting Cook's distances against the standardized leverages. For each model set, candidate models with all valid combinations of the predictor variables were generated and Akaike Information Criterion (AIC) values and AIC weights computed. Maximum likelihood parameter estimates were then obtained by model averaging across the best set of models, including all models with $\Delta AIC < 2$ (Burnham and Anderson, 2002). We used the packages vegan (Oksanen et al., 2017) and MuMIn (Barton and Anderson, 2015) in R (version 3.0.2, R Core Team 2014). For more detailed information on the fitted models, see Table 1.

Finally, to identify possible synergies or trade-offs between ecosystem services, we correlated i) coffee yield and butterfly species richness; ii) butterfly species richness and carbon storage and; iii) coffee yield and carbon storage using the Spearman's correlation coefficient. To do this correlation analysis, in order to control for potentially confounding factors we used the model residuals of GLMs fitted for coffee yield, butterfly species richness and carbon storage, with altitude, coffee shrub age and region as explanatory variables.

3. Results

3.1. General plantation and management characteristics

The studied coffee plantations were small and covered gradients of agricultural input and shade cover, from full sun monoculture coffee to diversified shaded plantations and from high agro-chemical to organic inputs or without inputs. Average coffee plantation area was 2.7 ± 1.9 ha (Table 1), which is general for Peru as the largest share of coffee in San Martín is produced by smallholders (CENAGRO 2012). Most of the farmers were weeding manually, yet some farmers were weeding mechanically using a bush cutter, or chemically by applying herbicides. Majority of the farmers applied some type of fertilizer (organic and/or chemical) and harvesting was done manually over a period of four months per year. Most shade trees in the coffee plantations were planted after land clearing, especially trees of the genus *Inga*. A third of the 533 individual shade trees and plants observed was a mix of bananas and palm trees (32.6%) and another third were Inga trees (33.3%). The remaining 146 individual shade trees observed consisted of a mix of 39 tree species which were categorized as 'timber trees', leaving 6.5% of the trees unidentified to species level (6.5%; Table S1). For more information on plantation characteristics see Jezeer et al. (2018) and Table 1.

3.2. Coffee yield

Coffee yield was not significantly related to shade cover, yet we found a significant negative relation with chemical fertilizers. Coffee yield for the *survey* dataset was on average 860 ± 526 kg ha^{-1}. We found only non-significant trends for negative effects of yield loss to pests and disease, elevation and age (Tables 2 and S5). Models for the *survey + plot* dataset showed significant negative effects of chemical fertilizer expenses and coffee shrub age ($z = 2.36$; $p = 0.02$), and a trend of negative effect of shade tree density on coffee yield ($z = 1.72$; $p < 0.09$; Table 2).

3.3. Butterfly species richness

Forest butterfly species richness was not significantly related to either shade nor input variables, yet it varied significantly with region. We observed 2689 individuals; of which 92% could be identified to the species level. Altogether, 147 butterfly species from six different families were identified, comprising 40 non-forest species, and 107 forest species (see Table S2 for identified butterfly species and classification as forest and non-forest species). Unidentified morphospecies were included in species richness values. The observed butterfly species represented the total butterfly richness in the area sufficiently as the species accumulation curves reached an asymptote (Fig. S1). We did not observe a weather bias as precipitation and cloudiness were not related to forest butterfly species richness. We found a significant positive effect of region on forest butterfly species richness ($z = 3.81$; $p < 0.001$) and non-forest butterfly species richness ($z = 3.95$; $p < 0.001$), with higher values in Picota than in Alto Mayo (Table 2). We only found trends for positive effects of shade cover on forest butterfly species richness ($z = 1.68$; $p = 0.09$; Fig. 3b; Table 2), and negative effects of maximum canopy height on non-forest butterfly species richness ($z = 1.81$; $p = 0.07$), and no relationship with distance to native forest.

3.4. Carbon storage

Carbon storage was positively related to shade cover. Average above-ground carbon among plantations was 31 ± 81 Mg ha^{-1}, ranging from 0 to 538 Mg ha^{-1}. This large variation is possibly due to absence of trees or the presence of large trees in some of the plots. Only one model was selected, and it included a significant positive effect of coffee shrub age ($z = 2.92$; $p = 0.01$) and shade cover ($z = 7.49$; $p < 0.001$) on above-ground carbon (Table 2; Fig. 3c).

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

Coffee rust impact was higher in older plantations and plantations at higher elevation, and impact was lower for plantations with high input management. The *survey* data showed that most coffee yield loss was due to coffee rust (46.2 ± 24.6%), which was significantly higher on plantations with older coffee shrubs ($z = 2.50$; $p = 0.01$) and at higher altitudes ($z = 2.36$; $p = 0.02$). Coffee yield loss due to coffee leaf rust was significantly negatively correlated with input expenses ($p = 0.02$; Tables S4, S6). Yield losses to other pests and diseases amounted to 9.6 ± 11.6% for coffee borer, 9.5 ± 14.8% for Ojo de Pollo and 8.5 ± 13.1% for Arañero. Best models for both Ojo de Pollo and Arañero explained very little variance (< 1%) and were not included in final analyses (Table S5). Soil fertility indicators showed high variability, with N varying by a factor of 16, and CEC by a factor of 25 (Table 1). Both shade level and fertilizer expenses were related to soil fertility indicators, results are detailed in Appendix S3, Fig. S3 and Table S5).

3.6. Shade and input effects on ecosystem services

Higher shade cover was associated with higher above-ground carbon and butterfly species richness, while having no effect on coffee yield; the opposite was found for input. Inputs had no significant effect on butterfly species richness and above ground carbon storage, and had a negative effect on coffee yield (Fig. 3a-f). The correlations between measures of yield and above-ground carbon, yield and butterfly species richness, and above-ground carbon and butterfly species richness, adjusted for the effects of altitude, region and coffee shrub age, were not significant (Fig. 4a-c). The main findings are summarized in Fig. 5.

4. Discussion

Our analysis of the effects of input use and shade management on coffee yield and ecosystem services shows no evidence for trade-offs or synergies between coffee yield on one hand, and butterfly species richness and carbon storage on the other. Higher shade cover provided higher carbon storage and to some extent higher forest butterfly species. Importantly, variation in shade cover showed no negative effect on coffee yield. Contrary to expectations we found a negative relationship between chemical fertilizers and coffee yield. Amount and type of fertilizer and herbicide inputs showed no relation with carbon or butterfly species richness.

4.1. Effects of shade management

We did not find a significant relationship between coffee yield and shade cover, across a shade range of 0–80%, both when correcting for input use and yield losses due to coffee leaf rust. Previous research showed a diversity of relationships between coffee yield and shade, from being inversely correlated with shade (Beer et al., 1998; Perfecto et al., 2005; Vaast et al., 2006), highest at 35–50% shade cover (e.g., Mora et al., 1997; Soto-Pinto et al., 2000), or indifferent to shade cover (shade range of 0–30%; Cerda et al., 2016; Meylan et al., 2017). Thus these results suggest that we need further research to clarify the types of functional relationships in different coffee production regions. Part of the variability in the relationships between coffee yield and shade could be due to studies not accounting for factors, such as the variation in shade cover, its spatial distribution in the farm and the methods used to estimate it, the amount and type of inputs applied, and the age of the coffee plants. The range in shade cover measured in our study is comparable to that of other studies, e.g. Mexico (Romero-Alvarado et al., 2002; Soto-Pinto et al., 2000) and India (Boreux et al., 2016). However, the literature shows a wide variety of shaded coffee systems, and

Table 2
Ensemble model outcomes. Averaged parameter estimates of all variables included in the models with ΔAIC < 2 (Johnson and Omland, 2004) are weighed with the corresponding Akaike weight (see Table S5 for full lists of all best models that go into the ensemble). Coffee shrub age, elevation and region are included as fixed variables. Levels of significance are shown as: . < 0.10; *p < 0.05; **p < 0.01; ***p < 0.001. Units for the variables can be found in Table 1.

		Co-variate	models containing variable	Σ Weight	Estimate		z-value	SD
1. Yield	*a) Coffee yields (survey data; n = 126)*	*(Intercept)*			2008.155	***	4.48	445.12
		yield loss due to pests and diseases	6	0.570	−2.225	.	1.86	1.18
		chemical fertilizer expenses	5	0.430	−123.301		1.63	74.91
		total fertilizer expenses	4	0.340	−90.273		1.54	57.89
		yield loss due to coffee rust	3	0.230	−3.307		1.55	2.12
		coffee shrub density	2	0.120	−0.030		0.66	0.05
		timber shade tree density	1	0.060	−0.694		0.74	0.92
		coffee shrub age	*12*	1.000	*−21.076*	.	1.76	11.84
		elevation	*12*	1.000	*−0.655*	.	1.92	0.34
		region 2: Picota	*12*	1.000	*−5.413*		0.03	198.98
	b) Coffee yields (survey + plot data; n = 39)	*(Intercept)*			2389.757	***	4.10	560.49
		chemical fertilizer expenses	3	1.000	−279.001	*	2.36	113.49
		total shade tree density	2	0.630	−1.032	.	1.72	0.58
		soil OM	1	0.170	−52.015		1.02	48.89
		coffee shrub age	*3*	1.000	−43.976	*	2.28	18.53
		elevation	*3*	1.000	−0.488		0.90	0.52
		region 2: Picota	*3*	1.000	−322.001		1.50	206.25
2. Biodiversity	*a) Forest butterfly species richness (survey + plot data; n = 53)*	*(Intercept)*			0.203		0.69	0.29
		shade cover	2	0.320	0.003	.	1.68	0.00
		banana plant density	3	0.300	0.000		1.17	0.00
		Inga tree density	2	0.260	0.000		1.55	0.00
		total shade tree density	2	0.240	0.001		1.50	0.00
		coffee shrub age	*7*	1.000	0.011		0.99	0.01
		elevation	*7*	1.000	0.000		0.20	0.00
		region 2: Picota	*7*	1.000	0.487	***	3.81	0.12
	b) Non-forest butterfly species richness (survey + plot data; n = 51)	*(Intercept)*			0.790	*	2.23	0.35
		maximum canopy height	10	0.730	−0.008	.	1.81	0.00
		timber shade tree density	5	0.330	0.000		1.47	0.00
		air temperature	5	0.320	−0.016		1.31	0.01
		shade cover	4	0.240	0.001		1.30	0.00
		coffee shrub density	3	0.160	0.000		1.05	0.00
		banana plant density	1	0.060	0.000		1.17	0.00
		coffee shrub age	*14*	1.000	0.006		0.95	0.01
		elevation	*14*	1.000	0.000		0.28	0.00
		region 2: Picota	*14*	1.000	0.240	***	3.95	0.06
3. Carbon	*ABG carbon (survey + plot; n = 53)*	*(Intercept)*			0.436		1.11	0.39
		shade cover	1	1.000	0.017	***	7.49	0.00
		coffee shrub age	*1*	1.000	0.045	**	2.92	0.02
		elevation	*1*	1.000	0.000		−1.20	0.00
		region 2: Picota	*1*	1.000	−0.093		−0.62	0.15

further research is needed to better understand coffee yield along a gradient of shade cover. The visual estimation method we used to estimate shade cover could introduce bias; however, it has been successfully used by Bellow and Nair (2003), in particular when using trained observers as we did (Vittoz et al., 2010), and the strong positive relation between shade tree density and average shade tree height we found (Table S4, Fig. S2) suggests that the visual estimates of shade cover were reliable. While all the coffee investigated was in a productive age, which is considered to be up to 30–40 years (Wang et al., 2015), we found a significant negative effect of coffee shrub age on yield, in accordance with other studies, as the number of unproductive trees increases with age (Wang et al. 2015). We also found that higher elevation farms tend to be those with higher shade cover and lower yield. Both these factors were controlled for, in addition to region, when assessing the relationships between yield, biodiversity and ecosystem services, thus minimizing the risks for confounding effects.

Previous research presented evidence that coffee plantations with higher shade cover support higher levels of biodiversity (e.g., Bhagwat et al., 2008; Mas and Dietsch, 2003; Perfecto et al., 2005); however we only found a positive trend between shade cover and forest butterfly species richness. This could be because our sampling method for forest butterfly species might have underestimated canopy dwelling butterfly species. In line with Perfecto et al. (2003), we found no effect of distance to a natural forest on butterfly diversity. This is a positive finding, with no decrease in biodiversity values even in farms that are farther away from the forest, which could mean that some of the characteristics of the farm are providing habitat to these butterflies likely due to the diversity of shade trees.

Above-ground carbon of plantations with high shade cover (> 50%) was comparable to that of the natural forest, which ranged between 90–145 Mg ha^{-1} (n = 4; Fig. 3c) and was more than 15 times higher than plantations with shade levels < 30%. With ~55 Mg ha^{-1}, above-ground carbon of plantations with shade cover > 40% was comparable with shaded coffee plantations in Peru (Ehrenbergerová et al., 2016), in Latin America (Haggar et al., 2013; Soto-Pinto et al., 2010), and other continents (van Noordwijk et al., 2002). Our results confirm that shaded coffee systems can significantly contribute to above-ground carbon (Kay et al., 2019). Small plot sizes add uncertainty to the estimates of above-ground carbon, and in some plots individual large trees resulted in extreme carbon values when extrapolating to hectare. However, our sample size was large, which reduced the effect of such outliers on the results.

4.2. Effects of input management

Input use was not related to either butterfly species richness or

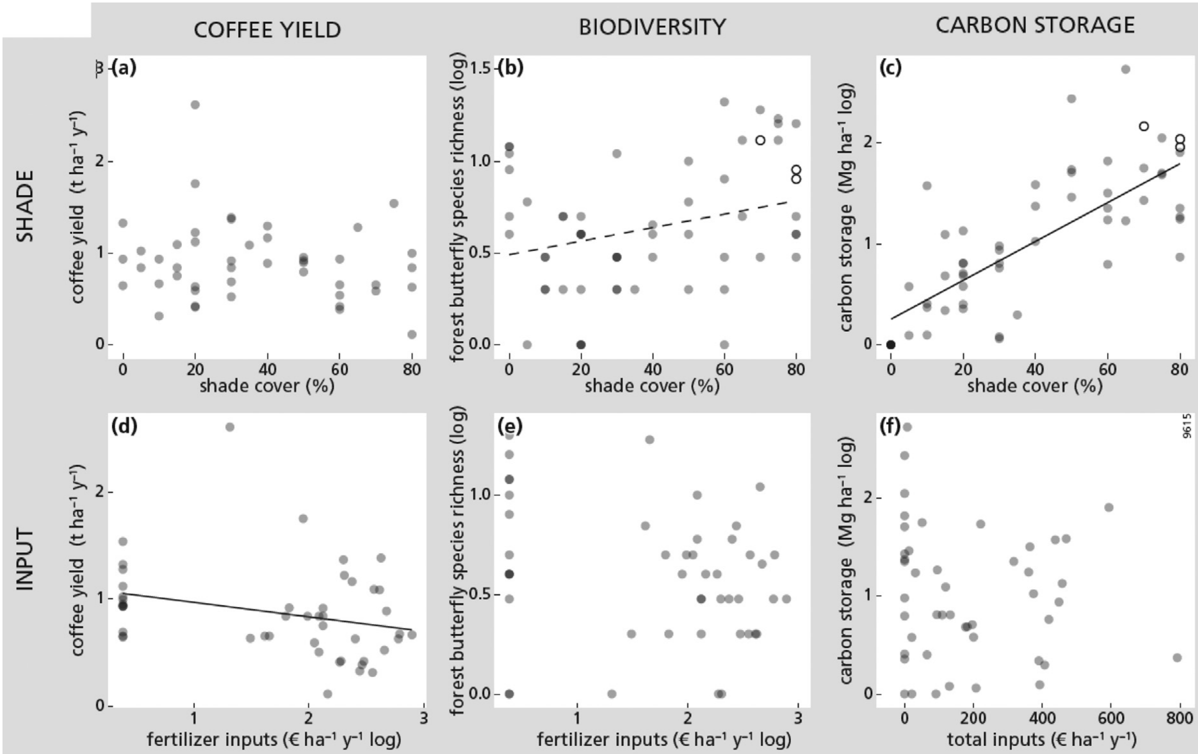

Fig. 3. Effects of shade and input management on ecosystem services. Relation of management variables shade (first row) and input expenses (second row) are shown for: coffee yields (a, d), forest butterfly species richness (b, e) and aboveground carbon storage (c, f) with closed circles. Open circles represent observed forest butterfly species richness (b) and carbon storage (c) in natural forests as reference. Black lines represent a significant relation ($p < 0.05$; solid line) or a trend ($p < 0.1$; dotted line).

above-ground carbon. While the latter was not to be expected, the former finding contrasts previously reported detrimental effects of agrochemicals on butterfly, bee and plant diversity (e.g., Potts et al., 2010; Gomiero et al. 2011). The difference may be in part due to butterflies not being directly exposed to pesticide applications either at the adult or the larval stage, so results cannot be extrapolated to other species groups that are more active in the coffee canopy.

Coffee yield was negatively related to fertilizer and pesticide applications, as input management is often a strategy to mitigate yield losses during pest outbreaks (Boudrot et al., 2016). The average coffee yield we report ($854 \pm 514\,kg\,ha^{-1}\,y^{-1}$) is comparable to average Arabica smallholder coffee yields in Peru (Bean and Nolte, 2017; Nelson et al., 2016) and in Latin America (Panhuysen and Pierrot, 2014), including Mexico (Soto-Pinto et al., 2000) and Costa Rica (ICO, 2016). However, our data on pest and diseases, yields and inputs have some uncertainty. Measuring pest and disease impact and coffee yield in an experimental setting over a representative period is costly and time consuming, so we opted for a survey rather than field-measurements as this is a relatively cost-effective and easy way to obtain data. Estimates of coffee yields were obtained through farmer surveys as in other studies (Beuchelt and Zeller, 2011; Haggar et al., 2017), and we acknowledge this can be a source of error since reporting yield for consecutive years relies on memory and annotations of the farmers. However, we expect that even if a few reported yields are erroneous they will have little effect on average values because of our large sample size. For input use, using costs of inputs as proxy for fertilizer use and not the actual concentration of active substances in those fertilizers is a relative indicator of the actual differences in the field.

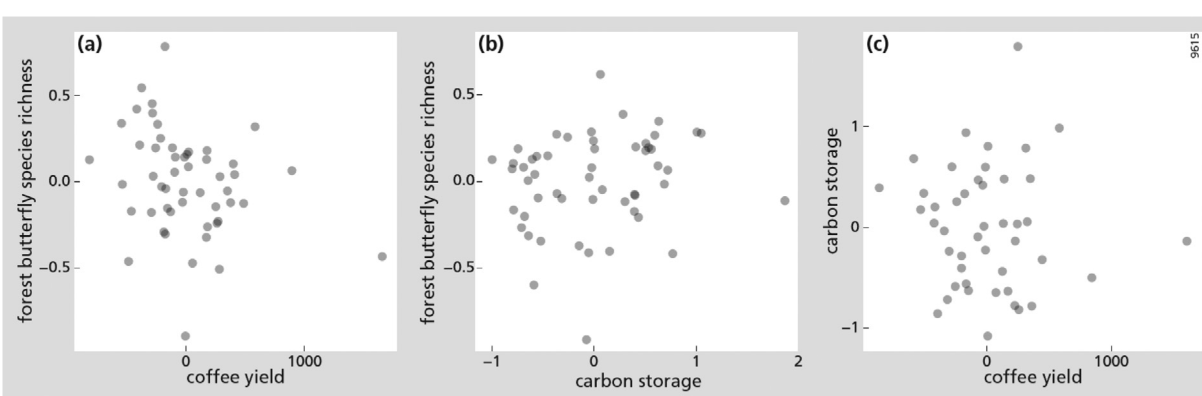

Fig. 4. Relationships between the three ecosystem services. (a) coffee yields and forest butterfly species richness, (b) carbon storage and forest butterfly species richness, (i) and coffee yields and carbon storage of linear regression analysis are presented (all $R^2 < 0.1$). X and Y-axis show coffee yield, biodiversity and carbon model residuals corrected for altitude, coffee shrub age and region.

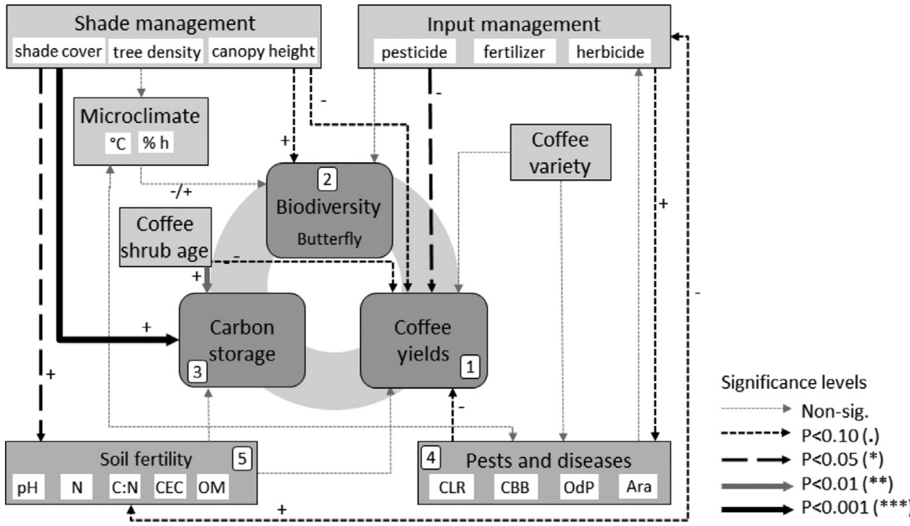

Fig. 5. Conceptual diagram depicting observed relations. Width and type of arrows indicates significance level. CLR = Coffee leaf rust; CBB = Coffee berry borer; OdP = Ojo de Pollo; Ara = Arañero.

4.3. Implications

We found average yields (~850 kg ha^{-1} y^{-1}) less than half of those observed for the most intensive, unshaded production systems in Brazil and Colombia (Capa et al., 2015). In line with other recent studies (e.g., Cerda et al., 2016; Charbonnier et al., 2017; Meylan et al., 2017; Rahn et al., 2018), the relations between shade and input management and coffee yields are complex and location specific. Growing coffee under shade might be the favoured or required system in some coffee areas, whilst in other areas lower shade levels or full sun systems may be favourable. For example, in areas with high annual cloud cover, higher shade levels further reduce incoming sunlight, which leads to a decrease in coffee yields (Farfán-Valencia and Sánchez Arciniégas, 2007). As a first step, it is important to acknowledge this complexity. Secondly, there is a need for more research spanning a wider range in elevation, climatic and soil conditions, while addressing both shade and input management.

In this study, these shaded coffee systems supported forest butterfly species richness and above ground carbon, without reduction in yield. In general, the major coffee producing regions in Peru are highly biodiverse and the majority of the coffee farms are currently managed with relatively low levels of agrochemical inputs (Bean and Nolte, 2017) and relatively high levels of shade (Jha et al., 2014). Thus there is still large potential to safeguard ecosystem services while increasing income and improving livelihoods. To enhance these double benefits, more knowledge on suitability of shade trees to be intercropped with coffee is needed, taking nutrient competition, management requirements and local market prices of timber and fruits, and site-specific conditions into consideration. Importantly, technical interventions should not only take scientific information on agroforestry practices into account, but also the knowledge of local farmers and local experts to identify suitable tree species and guide future research (Rigal et al., 2018).

In our area, a large fraction of the yield was lost due to pests and diseases. Application of fungicides is reported to effectively control coffee rust (Avelino et al., 2006), but may reduce natural pest control (Vandermeer et al., 2009). Allinne et al. (2016) recommended to adapt pest and disease management to the physical conditions of the plantation, such as climate and soil. Thus, in our case, short term development and establishment of rust-resistant coffee cultivars could be an important strategy to improve and stabilize yields, particularly for farmers at lower altitudes where the disease is more severe (Ribeyre and Avelino, 2012). This could also address the coffee shrub age effects we found.

Extension services such as trainings and agricultural inputs, given by farmer organisations, companies or local governments, could provide farmers with advice on the necessary skills and information to deal with pests and diseases, support farmers with the choice of shade tree species, and improved tree management that accounts for nutrient competition, and local market prices of timber and fruits. This could be in tandem with environmental certification schemes (e.g., Rainforest Alliance and Bird Friendly), which could steer the production of coffee towards more sustainable directions. The price premiums coupled to certification can increase smallholders' net income (Lyngbæk et al., 2001), as long as their requirements are aligned with farmers' goals. Importantly, local and national governance should favour and promote biodiversity friendly management; i.e., intercropping of coffee with shade trees – whilst taking local conditions into account and using sustainable intensifying management practices.

5. Conclusions

The lack of relationship between shade cover and Arabica coffee yields supports the adoption of agroforestry practices. Thus, this study highlights that it is possible to manage shade and input in smallholder coffee farms in a way that supports forest butterfly species richness and above-ground carbon storage and produce similar amounts of coffee as more intensified systems. However, the relations between shade and input management and coffee yields are complex and location specific. Furthermore, contrary to expectations we found a negative relationship between chemical fertilizers and coffee yield, which points at the need to consider farmers' decisions. Amount and type of fertilizer and herbicide inputs showed no relation with carbon or butterfly species richness. The results of this study are promising and challenge previous notion that crop production often comes at the expense of losses in ecosystem services and biodiversity. Nonetheless, many of the relationships are not very strong so more studies may be needed to settle the directionality and nuances of the drivers leading to these conclusions. Importantly, future studies should also take knowledge of local farmers and local experts into account. Overall, this study suggests that maintaining important ecosystem services that sustain livelihoods while maintaining coffee production is possible.

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.

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Author contributions

RJ, MJS, PV, RB and YC provided substantial contributions to conception and design; RJ collected data; RJ, MJS, PV and YC performed the analysis; RJ drafted the paper. RJ, MJS, PV and YC contributed critically to the drafts and all authors gave final approval for publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2019.101033.

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