G Model
EURAGR-25595; No. of Pages 12
ARTICLE IN PRESS
Europ. J. Agronomy xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
European Journal of Agronomy
journal homepage: www.elsevier.com/locate/eja

Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems

Rolando Cerda[a,b,*], Clémentine Allinne[a,b], Christian Gary[c], Philippe Tixier[b,d], Celia A. Harvey[e], Louise Krolczyk[f,g], Charlie Mathiot[b,f], Eugénie Clément[g,h], Jean-Noel Aubertot[i], Jacques Avelino[b,g,j]

[a] CIRAD, UMR System, 2 place Pierre Viala, 34060 Montpellier, France
[b] CATIE, Program of Sustainable Agriculture and Agroforestry, 7170 Turrialba, Costa Rica
[c] INRA, UMR System, 2 place Pierre Viala, 34060 Montpellier, France
[d] CIRAD, UPR GECO, TA B-26/PS4, Boulevard de la Lironde, 34398 Montpellier, France
[e] Conservation International, 2011 Crystal Drive Suite 500, Arlington, VA, USA
[f] AgroParisTech, F-75231 Paris, France
[g] CIRAD, UR Bioagresseurs, TA A-106, Avenue Agropolis, 34398, Montpellier, France
[h] INSA, Toulouse 135, Avenue de Rangueil, 31077 Toulouse, France
[i] INRA, UMR Agir, 31326 Castanet Tolosan Cedex, Toulouse, France
[j] IICA, AP 55, 2200 Coronado, San José, Costa Rica

ARTICLE INFO

Article history:
Received 19 January 2016
Received in revised form
18 September 2016
Accepted 29 September 2016
Available online xxx

Keywords:
Agroforestry
Carbon sequestration
Coffee yields
Disservices
Incomes
Pests and diseases
Soil fertility
Trade-offs

ABSTRACT

Agroforestry systems provide diverse ecosystem services that contribute to farmer livelihoods and the conservation of natural resources. Despite these known benefits, there is still limited understanding on how shade trees affect the provision of multiple ecosystem services at the same time and the potential trade-offs or synergies among them. To fill this knowledge gap, we quantified four major ecosystem services (regulation of pests and diseases; provisioning of agroforestry products; maintenance of soil fertility; and carbon sequestration) in 69 coffee agroecosystems belonging to smallholder farmers under a range of altitudes (as representative of environmental conditions) and management conditions, in the region of Turrialba, Costa Rica. We first analyzed the individual effects of altitude, types of shade and management intensity and their interactions on the provision of ecosystem services. In order to identify potential trade-offs and synergies, we then analyzed bivariate relationships between different ecosystem services, and between individual ecosystem services and plant biodiversity. We also explored which types of shade provided better levels of ecosystem services. The effectiveness of different types of shade in providing ecosystem services depended on their interactions with altitude and coffee management, with different ecosystem services responding differently to these factors. No trade-offs were found among the different ecosystem services studied or between ecosystem services and biodiversity, suggesting that it is possible to increase the provision of multiple ecosystem services at the same time. Overall, both low and highly diversified coffee agroforestry systems had better ability to provide ecosystem services than coffee monocultures in full sun. Based on our findings, we suggest that coffee agroforestry systems should be designed with diversified, productive shade canopies and managed with a medium intensity of cropping practices, with the aim of ensuring the continued provision of multiple ecosystem services.
© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Agroforestry systems in tropical landscapes provide a series of ecosystem services that help sustain crop production, improve farmersí livelihoods and conserve biodiversity (Jose, 2009; Tscharntke et al., 2011). Shade trees and other companion plants in agroforestry systems can produce fruits (Rice, 2011; Cerda et al., 2014), timber, firewood and other products for sale or household use (Somarriba et al., 2014), thereby diversifying the sources of income for farmers and contributing to food security. The roots and leaf litter of shade trees, especially leguminous trees, improve nutrient recycling and soil quality (Beer et al., 1998) and can help reduce soil erosion (Gómez-Delgado et al., 2011). Shade trees are

* Corresponding author at: CATIE, Program of Sustainable Agriculture and Agroforestry, 7170 Turrialba, Costa Rica.
E-mail address: rcerda@catie.ac.cr (R. Cerda).

http://dx.doi.org/10.1016/j.eja.2016.09.019
1161-0301/© 2016 Elsevier B.V. All rights reserved.

also useful for protecting crops from strong winds, high temperatures and extended dry periods (Schroth et al., 2009; Jha et al., 2014). Shade trees and other woody perennials contribute to the conservation of animal and plant biodiversity, and sequester carbon from the atmosphere, thereby contributing to climate mitigation (Jha et al., 2011; Somarriba et al., 2013; Deheuvels et al., 2014).

Yet agroforestry systems can also result in disservices and antagonistic effects (Zhang et al., 2007; Power, 2010). A known drawback of agroforestry systems is that the yields of the main crop are often lower than those in full sun systems (López-Bravo et al., 2012), at least in the short term. With increasing shade cover, the relative yield of the main crop tends to decrease (Zuidema et al., 2005) due to greater competition for light, water and nutrients in soil between trees and the main crop. Another potential drawback of agroforestry systems is the higher labor requirements to manage trees and other plants. Agroforestry systems can favor or disfavor the attack of pathogens and insects depending on the composition, structure and management of the shade canopies (Staver et al., 2001; Avelino et al., 2006; Cheatham et al., 2009; Pumariño et al., 2015).

Despite the recognition that agroforestry systems can potentially provide diverse ecosystem services, there is still limited understanding on how shade trees affect the provision of multiple ecosystem services and about the potential trade-offs or synergies among them. Most studies in agroforestry systems have focused on a single ecosystem service (Jose, 2009), and have not examined relationships among various ecosystem services. In addition, most studies have only considered the individual effect of shade on ecosystem services, underestimating other factors, such as management practices and environmental conditions, which may interact with shade to provide ecosystem services (Staver et al., 2001; Avelino et al., 2006). However, a good understanding of different factors, including their interactions, affecting the provision of ecosystem services, and the analysis of relationships (trade-offs or synergies) among ecosystem services, are needed to design high performing agroforestry systems (Rapidel et al., 2015).

Understanding the provision of ecosystem services by agroforestry systems is particularly important for the coffee sector in Central America which is currently under severe stress. A chain of events, including decreasing coffee prices, increasing production costs, and an outbreak of coffee leaf rust (*Hemileia vastarix* Berkeley and Broome) since 2012, has significantly reduced coffee production. Following the coffee rust outbreak, farmers were forced to stump their impacted coffee plantations to rejuvenate coffee trees or to renew them with new coffee varieties, or even to replace them with new crops (Baker, 2014; Avelino et al., 2015; McCook and Vandermeer, 2015). For instance, 50% of coffee areas have disappeared in the Volcan Central Talamanca Biological Corridor in Costa Rica between 2000 and 2009 (Bosselmann, 2012), and 35% of the coffee areas in southern Guatemala between 2000 and 2004 (Haggar et al., 2013). The conversion of coffee plantations to other land uses results in the loss of shade trees and other vegetation and negatively affects plant biodiversity (Zhang et al., 2007; De Beenhouwer et al., 2013). Information on the potential benefits provided by shade trees associated with coffee plantations could encourage decision makers, technicians, and farmers to maintain and/or increase land uses under coffee agroforestry systems, and stem the ongoing loss of these systems (Cheatham et al., 2009; Jose, 2009).

The objectives of this study were i) to assess the effectiveness of different types of shade of coffee agroecosystems in providing multiple ecosystem services under different environmental and management gradients, and ii) to understand the relationships (trade-offs or synergies) across different ecosystem services and plant biodiversity. We quantified indicators of four major ecosystem services: 1) regulation of pests and diseases; 2) provisioning of agroforestry products (coffee, bananas, other fruits, timber); 3) maintenance of soil fertility; and 4) carbon sequestration, in coffee agroecosystems belonging to smallholder farmers under a range of altitudes (as representative of environmental conditions), management practices and types of shade. We hypothesized that the effectiveness of different types of shade in providing ecosystem services depends on their interaction with coffee management and altitude where coffee is grown, and that trade-offs or synergies could occur among certain ecosystem services. Based on our findings, we highlighted key aspects that should be considered for the design and management of coffee agroecosystems to ensure the continued provision of multiple ecosystem services.

2. Materials and methods

2.1. Coffee plot network and experimental design

A coffee plot network (69 plots) was established in the canton of Turrialba, Costa Rica. Turrialba is located in a premontane wet forest life zone, with an mean annual rainfall of 2781 mm and a mean annual temperature of 22.2 °C (averages of the last 10 years), with small variations among months. In this area, coffee is grown from 600 to 1400 m.a.s.l. (meters above sea level). Farms in higher elevations experience slightly wetter and cooler temperatures compared to farms at lower elevations.

The plot sampling strategy had the objective to select coffee plots of different types of shade across altitudinal and management intensity gradients. Plots were selected with contrasting characteristics in the botanical composition and structure of shade canopies (in terms of species richness, abundances and trunk basal areas), with contrasting coffee cropping practices (in terms of different types of practices and frequency of applications), and at different altitudes. However, in order to limit variations and avoid confounding effects of different factors (Clermont-Dauphin et al., 2004), we chose coffee plots that shared three main characteristics: i) they were owned by smallholder farmers, ii) had coffee plants (*Coffea arabica* L.) of the dwarf variety *Caturra* as the unique or dominant variety, which is the most common variety in Costa Rica and in other countries of Central and South America (McCook and Vandermeer, 2015), and iii) were located on soils belonging to the order Inceptisols, suborder Udepts. These soils in Turrialba are considered to have moderate fertility but with problems of acidity (CIA, 2016).

In each coffee plot of the network, an experimental subplot composed of eight coffee rows with 15 plants each was demarcated in a representative place of the plot. Eight coffee plants (and three branches per plant) were marked, one plant per row, inside the experimental subplot. These eight plants were used for measurements of pests and diseases and coffee yields, and for sampling soil subsamples near them. For the measurement of characteristics of the shade canopy, a circular area of 1000 m^2 was established in the center of the experimental subplot (17.8 m radius).

2.2. Measurements and calculations of the factors studied

2.2.1. Altitude

The altitude of each coffee plot was measured with a GPS. The mean altitude ± standard deviation of all coffee plots was 877 ± 126 m.a.s.l., ranging from 646 to 1107 m.a.s.l.

2.2.2. Management intensity index

Data on the management were obtained through semi structured interviews with farmers. A management intensity index was calculated for each coffee plot. The calculations were based on existing indices of management intensity used in coffee studies (Mas and Dietch, 2003; Philpott et al., 2006). In the present study, the calculations included 11 cropping practices commonly applied in

Table 1
Management descriptors of coffee agroecosystems in the coffee plot network (n = 69 plots) in Turrialba, Costa Rica.

Cropping practices	Mean	SD	Minimum	Maximum	Median
Distance between coffee rows (cm)	173.0	23.5	100.2	233.5	174.3
Distance between coffee plants (cm)	119.7	17.7	76.6	168.8	118.9
Pruning of coffee plants (number yr^{-1})	0.8	0.4	0	1	1
Machete weedings (number yr^{-1})	1.3	1.3	0	5	1
Shovel weedings[a] (number yr^{-1})	0.4	0.7	0	3	0
Applications of fertilizers (number yr^{-1})	1.4	0.9	0	3	1
Applications of fungicides (number yr^{-1})	2.1	1.8	0	6	2
Applications of herbicides (number yr^{-1})	1.8	1.3	0	5	2
Harvest rounds of coffee (number yr^{-1})	10.3	2.4	5	14	11
Diversity of practices	5.2	1.1	3	7	5
Overall (number of practices yr^{-1})	18.1	4.3	8	26	18
Management intensity index[b]	5.0	1.3	2.1	7.7	5.1

SD: standard deviation;Diversity of practices: number of different practices applied per year.
[a] Shovel weedings are done with a shovel, scraping at the ground level trying to better eliminate the weeds.
[b] See text in Section 2.2.2 for calculation of management intensity index.

Turrialba (Table 1). First, for each cropping practice, the number of times per year that this practice was applied was transformed to a value *IH* or *IL* between 0 and 1 reflecting the practice intensity, the higher the value, the higher the intensity:

$$IH = \frac{value - minimum}{maximum - minimum} \quad IL = 1 - \frac{value - minimum}{maximun - minimum}$$

where IH is the transformed value for cropping practices for which a higher number of applications denotes a higher management intensity (e.g. number of weedings, application of fertilizers, fungicides, etc.) and IL is the transformed value for cropping practices for which a lower value denotes a higher management intensity (distances between coffee rows and between coffee plants); value was the annual number of applications of a given cropping practice for a given plot; and minimum and maximum were the minimum and maximum values registered for that cropping practice in the data set, respectively. Then, the transformed values obtained for all cropping practices were summed to obtain the management intensity index of each coffee plot (maximum possible = 11, since we had 11 cropping practices); the higher the index, the higher the management intensity.

2.2.3. Types of shade

In the circular area of 1000 m^2, the shade canopy was characterized by identifying and measuring all plants >2.5 m in height. Plants were classified as: *Musaceae* (bananas and plantains), service trees (i.e., nitrogen fixing trees), fruit trees or timber trees. The trunk diameters and *Musaceae* stems were measured at 1.3 m from ground (breast height); fruit tree diameters were measured at 0.30 m. For service trees, such as *Erythrina poeppigiana,* which are pollarded once or twice a year, the height of the main trunk was also measured. In addition, the trunk diameters of the eight marked coffee plants were measured at 0.15 m from the ground. Shade cover (%) was measured with a spherical densiometer in the four corners and in the center of the experimental subplot, and then averaged. Finally, basal areas of tree trunks and the Shannon diversity index were calculated.

These variables were analyzed by using cluster analysis (Ward method and Euclidean distance) which classified coffee plots in three types of shade: i) Coffee monocultures in full sun (CFS); ii) Coffee agroforestry systems with low diversification (CLD), where the shade canopy was dominated by *Erythrina poeppigiana*, a leguminous tree; and iii) Coffee agroforestry systems with high diversification (CHD), where the shade canopy included a mix of service trees, bananas, fruit trees, timber trees and other plants (Table 2). These systems were equally distributed in the range of altitude, and were not related to the age of the plantation, the planted area, nor the management intensity index; that is why the means and standard deviations of these data were similar across the types of shade (Table 2).

2.3. Measurements and calculations of ecosystem service indicators (response variables)

The choice of ecosystem service indicators must meet several conditions in order to ensure that they are relevant. It should take into account the following criteria: i) be easily measured; ii) be sensitive to changes in the system; iii) respond to change in a predictable manner; iv) be anticipatory (be an early warning indicator); v) predict changes that can be averted by management actions; vi) be integrative (able to reflect the features of the system along with other indicators; vii) have known variability in response (Dale and Polasky, 2007). Each one of the indicators used in this study (see Table 3 for description and measurements) is considered to meet at least the majority of these criteria. In the following paragraphs, a brief overview and justification for the selection of indicators is provided.

The regulation of pests and diseases was represented by the area under the disease progress curve (AUDPC) of each pest or disease and the number of dead branches. The AUDPC was deduced from the incidences which were measured five times, and then standardized (sAUDPC) by the total number of days of observation. The attack of pests and diseases can cause the defoliation of branches leading to their death; dead branches therefore can be an overall reflection of such attack (Avelino et al., 2015).

For the provisioning services, the indicators were coffee yield and economic indicators such as the gross income, net income, cash flow and family benefit. This information was obtained through semi structured interviews with farmers. Economic indicators included coffee income and also incomes and/or the value of the domestic consumption of other agroforestry products (bananas and other fruits, timber). Including several agroforestry products and not only the product of the main crop is an appropriate way to reflect the real overall contribution of the coffee system to the provisioning of agroforestry products to farmer families (Rice, 2011; Cerda et al., 2014).

Coffee yields were estimated for the 69 coffee plots through an empirical model. This model was calibrated from the data obtained by harvesting a subsample of three coffee plants in 20 out of the 69 coffee subplots. Out of the 20 harvested subplots, 8 were of the type CHD, 8 of CLD and 4 of CFS. Based on these data, a general linear model was developed to estimate coffee yields in all plots, including the 49 non-harvested plots. The model was initialized with coffee yield per plant as a function of coffee yield components (number of productive stems per plant; number of productive branches; number of fruiting nodes per plant; number of fruits per node),

Table 2
Structure and plant diversity, age, planted area, management intensity and altitude of the three types of shade (CFS: Coffee monocultures in full sun; CLD: Coffee agroforestry systems with low diversification; CHD: Coffee agroforestry systems with high diversification) in the coffee plot network, Turrialba, Costa Rica.

	Variable	CFS (n = 13) Mean ± SD	CLD (n = 27) Mean ± SD	CHD (n = 29) Mean ± SD
Structure and plant diversity	Density of coffee plants (Ind ha^{-1})	4864 ± 612	4868 ± 978	5286 ± 1367
	Density of fruit trees (Ind ha^{-1})	N/A	12 ± 27	59 ± 80
	Density of timber trees (Ind ha^{-1})	N/A	18 ± 29	63 ± 69
	Density of *Musaceae* plants (Ind ha^{-1})	N/A	98 ± 123	401 ± 340
	Density of service trees (Ind ha^{-1})	N/A	265 ± 136	173 ± 136
	Total density of shade canopy (Ind ha^{-1})	N/A	392 ± 180	695 ± 367
	Basal area of coffee plants (m^2 ha^{-1})	47.9 ± 32.1	52.0 ± 25.5	43.9 ± 25.7
	Basal area of fruit trees (m^2 ha^{-1})	N/A	0.1 ± 0.3	0.9 ± 1.1
	Basal area of timber trees (m^2 ha^{-1})	N/A	0.5 ± 0.9	3.4 ± 3.2
	Basal area of *Musaceae* plants (m^2 ha^{-1})	N/A	1.6 ± 2.2	6.5 ± 5.9
	Basal area of service trees (m^2 ha^{-1})	N/A	8.2 ± 5.3	5.0 ± 4.0
	Total basal area of shade canopy (m^2 ha^{-1})	N/A	10.4 ± 5.8	15.7 ± 6.7
	Total species richness (number)	N/A	4 ± 2	7 ± 3
	Shannon diversity index	N/A	0.7 ± 0.4	1.2 ± 0.4
	Shade cover (%)	N/A	14 ± 9	29 ± 10
Other data	Age of the cropping system (years)	15 ± 9	20 ± 10	15 ± 9
	Planted area (ha)	1.5 ± 1.0	1.0 ± 1.0	1 ± 0.9
	Management intensity index	5.4 ± 1.0	4.9 ± 1.3	5.0 ± 1.3
	Altitude (m.a.s.l.)	873 ± 109	885 ± 129	872 ± 133

SD: standard deviation; Musaceae: includes mainly bananas but also plantains; Citrus: includes mainly oranges (Citrus sinensis) and mandarin lemons (Citrus aurantifolia); Other fruits: includes mainly avocados (Persea americana), cas (Psidium friedrichsthalium), arazá (Eugenia stipitata) and peach palm (Bactris gasipaes); Service trees: includes mainly poro trees (Erythrina poeppigiana); Timber trees: includes mainly Cordia alliodora and Cedrela odorata.

sAUDPC of pests and diseases, and number of dead branches after harvest as fixed effects. Plots were considered as random effects. The model, including only significant variables ($p < 0.05$) to estimate the coffee yield, is shown in Table 3, and a figure showing the regression between predicted and observed (harvested) yield, and other indicators (R^2, mean of residues, mean absolute error, root-mean-squared error, relative root-mean-squared error, modeling efficiency, index of agreement) to support the model reliability, are shown in a Supplementary material.

For the maintenance of soil fertility service, the indicators used were soil acidity, C, N, P and K contents. These are also considered as key indicators of soil quality and soil fertility and are key elements for crop growth (Beer et al., 1998; Swinton et al., 2007).

For the carbon sequestration service, the main indicator was the total carbon stored in the aboveground biomass. However, the amounts of carbon stored per type of plant or tree were also considered, in order to show the particular contribution of different types of shade to carbon sequestration. This indicator is useful to compare the carbon storage (sequestered) among different types of agroecosystems. It is also helpful to guide better management practices to increase the carbon sequestration (Somarriba et al., 2013).

2.4. Statistical data analyses

2.4.1. Analysis of the effects of shade, altitude and management on indicators of ecosystem services

A linear model was used to estimate the effects of altitude, management intensity (quantitative data for both variables), type of shade (qualitative data), and their interactions on each specific ecosystem service indicator. Ecosystem service indicators were first checked for normality. Then, model selection procedure for each indicator was run several times. Each time, non-significant factors or interactions were removed from the model. Factors retained in the final model were those that were considered to have effects on the specific ecosystem service indicator. Analysis of variance and Fisher's LSD test ($p < 0.05$) were also used to compare the effects of types of shade on ecosystem service indicators. Significant effects of double and triple interactions among the factors on ecosystem service indicators were represented graphically.

2.4.2. Analysis of relationships between ecosystem services and biodiversity

Bivariate linear regressions were performed between indicators of the four ecosystem services studied, and between indicators of ecosystem services and plant biodiversity. Significant negative relationships denote trade-offs, while significant positive relationships denote synergies (Rapidel et al., 2015).

For simplification and in order to highlight only the most important relationships between ecosystem service indicators, only one indicator which better represents each ecosystem service was used in the bivariate linear regressions. The number of dead branches was chosen as representative of the regulation of pest and disease service, given that it is considered as a general indicator of the plant illness. Coffee yield was used as the indicator of provisioning services since this indicator is of interest both to smallholder farmers (looking for diversification of incomes, but always with coffee as the main source of revenue) and to medium or big farmers (with coffee as their unique product of interest). Soil acidity was chosen as representative of the maintenance of soil fertility service, considering that soil acidity is a general problem in tropical areas, and reducing acidity involves high extra costs (labor and inputs) for farmers. Total aboveground biomass carbon was used to represent carbon sequestration. Finally, the Shannon index of plant diversity was used as an indicator of biodiversity.

Regressions were performed with all the observations as a whole, and also per type of shade, with the aim of verifying if ecosystem services are related to a particular type of shade. The regressions were represented with figures, where a "desirable area" was demarcated. The "desirable area" was defined as the area where the best values of the ecosystem service indicators could be found (Rapidel et al., 2015); this area was demarcated to identify which type of shade achieved those values. This type of approach and analysis has been demonstrated to be useful to evaluate and design agroecosystems (Groot et al., 2012; Rapidel et al., 2015).

The procedure to demarcate the "desirable area" was: 1) outlier points were removed from the figures for not taking into account very uncommon observations that could difficult the demarcation of "desirable areas"; 2) the cloud of points was divided into four quadrants based on the values of the mid-point in each axis (same distance to zero and to the maximum value, outliers excluded); and 3) the best quadrant, representing the "desirable area", was

Table 3
List of indicators of ecosystem services (ES) and the methods used for measuring them in the coffee plot network, Turrialba, Costa Rica.

ES	Indicators of ES	Methods/Formulas	Data sources/times of measurement
Regulation of pests and diseases	sAUDPC of pests and diseases (%)	$AUDPC = \sum_{i=1}^{n-1} \frac{I_i + I_{i+1}}{2} \times (t_{i+1} - t_i) \quad sAUDPC = \frac{AUDPC}{Nd}$ where *AUDPC*: area under the disease progress curve; I_i: incidence of a given pest or disease at the *i*th measurement; t_i: time (in days) of the *i*th measurement; n: total number of measurements *sAUDPC*: standardized AUDPC; *Nd*: total number of days in which the plants were measured (from the first to the last measurement) Source: (Simko and Piepho, 2012)	Incidences where measured five times: 1st Fruit formation (slightly dry period); 2nd Beginning of fruit ripening (beginning of rainy period); 3rd Just before the harvest (rainy period); 4th During the peak of harvest (slightly dry period); 5th End of coffee harvest period (highest rainy period)
	Dead branches (Number MS^{-1})	The number of dead branches in the main stem (MS) of the marked coffee plants was counted	End of the coffee harvest period
Provisioning of agroforestry products	Coffee yield (kg fresh coffee cherries ha^{-1} yr^{-1})	$Coffee\ yield = (8.58 + 3.88 \times NPS + 1.95 \times NFNode + 0.03 \times NFNPlant - 0.18\ DeadB)^2$ where *NPS*: number of productive stems per plant; *NFNode*: number of fruits per node; *NFNPlant*: number of fruiting nodes per plant; *DeadB*: number of dead branches in the main stem per plant. $R^2 = 0.78$ The model estimates the yield expressed in grams of fresh coffee cherries per plant; estimated yield in kg per hectare was deduced by using the coffee plant density of each coffee plot	Coffee yield components were counted in three coffee plants in 20 subplots, during the period of fruit formation
	Gross income (USD ha^{-1} yr^{-1}) Cash flow (USD ha^{-1} yr^{-1}) Family benefit (USD ha^{-1} yr^{-1})	$GI = AS \times MP$ $CF = GI - CC$ $VDC = ADC \times MP$ $FB = CF + VDC$ where: *GI*: gross income from sale of agroforestry products; *AS*: amount of agroforestry products for sales; *MP*: market price; *CF*: cash flow; *CC*: cash costs; *VDC*: value of domestic consumption; *ADC*: amount of agroforestry products for domestic consumption; *FB*: family benefit Sources: (Ambrose-Oji, 2003; Cerda et al., 2014)	Data on management practices of coffee plots, costs of labor and inputs, and agroforestry production (fruits, bananas, plantains, etc.) were obtained through semi-structured interviews with the owners of the coffee plots, at the end of the coffee harvest period
Maintenance of soil fertility	Soil acidity (mg kg^{-1}) Phosphorus (mg kg^{-1}) Potassium (mg kg^{-1}) Carbon (%) Nitrogen (%)	Acidity was obtained with chemical titration with standardized solution of NaOH 0.01 Normal. The extraction of P and K was done with the method of Olsen modified; the quantification of P was done with the colorimetric method and K was determined by spectroscopy with atomic absorption C and N were determined with the method of combustion in auto-analyzer equipment Sources: (Briceño and Pacheco, 1984)	Eight subsamples of soil at a depth of 0–20 cm were taken near the trunk of eight coffee plants (at 50 cm approximately) in each experimental subplot, during the peak of harvest (slightly dry period). The subsamples were mixed to obtain a composite sample for the chemical analyses
Carbon sequestration	Aboveground biomass carbon (Mg ha^{-1})	Allometric equations for the estimation of biomasses: *Coffea arabica:* $B = 10\hat{(}-1.113 + 1.578 * Log_{10}(d_{15}) + 0.581 * Log_{10}(h))$ (Segura et al., 2006) *Cordia alliodora:* $B = 10\hat{(}-0.755 + 2.072 * Log_{10}(dbh))$ (Segura et al., 2006) *Inga spp.:* $B = 10\hat{(}-0.559 + 2.067 * Log_{10}(dbh))$ (Segura et al., 2006) *Bactris gasipaes:* $B = 0.74 * h^2$ (Szott et al., 1993) Fruit trees: $B = 10\hat{(}-1.11 + 2.64 * Log_{10}(dbh))$ (Andrade et al., 2008) Other trees: $B = (21.3 - 6.95 *(dbh) + 0.74*(dbh^2))$ (Brown and Iverson, 1992) *Musaceae*: $B = 0.030 * dbh^{2.13}$ (van Noordwijk et al., 2002) where *B*: biomass (kg); Log_{10}: Logarithm base 10; d_{15}: trunk diameter (cm) at 15 cm from soil; *dbh*: trunk diameter (cm) at breast height (1.3 m from soil); *h*: height of the plant The biomass was multiplied by a 0.47 fraction to obtain the carbon content	The trunk diameters were measured as described in section 2.2.3, during the coffee fruit formation (slightly dry period) Note: for *E. poeppigiana* trees, given that they are pollarded once or twice a year, only the volume of the trunk was used for C sequestration assessment to avoid overestimations; the trunk was considered as a cylinder; the volume was then multiplied by 0.00045 kg cm^{-3} (density of the wood) to obtain the biomass

demarcated. In order to compare the abundance of different types of coffee plots in the "desirable areas", the percentage of coffee plots per type of shade in the "desirable areas" was calculated.

Statistical analysis were performed with the software R version 3.1.1 (R_Core_Team, 2014).

3. Results

3.1. Effects of altitude, shade and management intensity on indicators of ecosystem services

The factors affecting the provision of ecosystem services varied across services. In some cases, individual factors (i.e., type of shade, management intensity or altitude) had significant single effects, while in others the double or triple interactions between these factors were important (Table 4). We first explored the impacts of individual factors, then explained the significant double interactions and triple interactions. We have broken down the triple interactions into two double interactions *altitude* × *type of shade* and *type* of *shade* × *management intensity* to make it easier for the reader to understand the results.

3.1.1. Effects of altitude, shade and management on regulation of pest and diseases

The most common pests and diseases found in Turrialba included coffee leaf rust (*Hemileia vastatrix* Berkeley and Broome),

Table 4
General statistical measures and effects of altitude (A), type of shade (S) and management intensity (M) on indicators of four ecosystem services provided by coffee agroecosystems in Turrialba, Costa Rica (n = 69 plots).

Ecosystem service	Indicators	General statistical measures			Effects of altitude, type of shade and management intensity						
		Mean ± SD	Min	Max	Single effects			Interactive effects			
					A *p*	S *p*	M *p*	A x S *p*	A x M *p*	S x M *p*	A x S x M *p*
Regulation of pests and diseases	sAUDPC Rust (%)	60.8 ± 14.3	12.8	88.2				*Fig. 1A			
	sAUDPC Cerc (%)	4.9 ± 3.3	0.7	13.8	**(+)		*(+)				
	sAUDPC Antra (%)	1.6 ± 1.2	0.0	5.3							
	sAUDPC Miner (%)	1.1 ± 0.9	0.0	4.7	**(+)		*(+)				
	Dead Branches (number MS^{-1})	8.4 ± 6.9	0.1	35.4							*Fig. 1B1,B2
Provision of agroforestry products	Coffee Yield (kg ha^{-1} yr^{-1})[†]	6407 ± 4132	259	22864			**(+)				
	Gross Income (USD ha^{-1} yr^{-1})	3206 ± 1969	123	10828							*Fig. 2B1,B2
	Cash Costs (USD ha^{-1} yr^{-1})	858 ± 772	12	3572						*Fig. 2A	
	Cash Flow (USD ha^{-1} yr^{-1})	2348 ± 1808	−680	9229			*(+)				
	Family Benefit (USD ha^{-1} yr^{-1})	2469 ± 1798	−680	9229			*(+)				
Maintenance of soil fertility	Soil Acidity (mg kg^{-1})	169.3 ± 125.6	9.0	577.8		*Fig. 3A					
	Soil Carbon (%)	4.8 ± 2.8	2.1	14.1							**Fig. 4A1,A2
	Soil Nitrogen (%)	0.4 ± 0.2	0.2	1.2							*Fig. 4A1,A2
	Soil Phosphorus (mg kg^{-1})	7.0 ± 6.4	1.5	26.8							
	Soil Potassium (mg kg^{-1})	77.6 ± 64.8	23.4	347.1		*Fig. 3B					
Carbon sequestration	TAGB Carbon (Mg ha^{-1})	20.2 ± 10.5	2.8	51.1				*Fig. 5			

sAUDPC: standardized area under the disease progress curve; Rust: coffee leaf rust; Cerc: brown eye spot; Antra: anthracnosis; Miner: leaf miner insect; #: number; MS: main stem of coffee plants; †Fresh coffee cherries; TAGB Carbon: total aboveground biomass carbon. SD: standard deviation; Min: minimum; Max: maximum. *p*-values: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$; (+) indicates that the effect was positive: with increasing value of the factor, the value of the response also increased; Fig: indicates that the effect was significant and the reader is directed to the indicated figure to appreciate the effect on the indicator.

the brown eye spot (*Cercospora coffeicola* Berk. and Curtis), anthracnosis (*Colletotrichum spp.*) and leaf miner (*Leucoptera coffeella* Guérin-Mèneville). Coffee leaf rust was the most important disease in terms of the mean sAUDPC; the sAUDPC of other pests and diseases did not exceed 5% on average (Table 4). Dead branches were useful to reflect the attack of pests and diseases, especially for its positive significant relationship with the sAUDPC of coffee leaf rust ($p = 0.0005$; $R^2 = 0.17$).

The effects of shade, altitude and management on pest and disease regulation were variable across different pests and diseases. Both altitude and management intensity had significant single positive effects on leaf miner insect and brown eye spot, with attack levels increasing with increasing altitudes and management intensities, irrespective of the shade type (Table 4). In contrast, neither altitude nor management nor shade had any effect on the prevalence of Anthracnosis. The most important disease, coffee leaf rust, was affected significantly by the double interaction *altitude* × *type of shade*, and was not affected in any form by management intensity. With increasing altitudes (meaning increasing rainfall and decreasing temperatures), the sAUDPC of coffee leaf rust decreased in CFS and CHD, but was not affected in CLD. These results suggest that coffee leaf rust responded more to environmental conditions than to management intensities under different types of shade (Fig. 1A). Interestingly, the disease behaved the same in the two most contrasting systems (full sun versus highly diversified agroforestry system). The triple interaction *altitude* × *type of shade* × *management intensity* was significant for dead branches: the number of dead branches was lower in higher altitudes (Fig. 1B1), and increased with increasing management intensity in CFS only, while remaining practically stable in CLD and slightly decreasing in CHD (Fig. 1B2).

3.1.2. *Effects of altitude, shade and management on indicators of provisioning of agroforestry products*

Interestingly, neither the type of shade nor the altitude affected coffee yields. Coffee yields were only positively affected by management intensity. Management intensity also had positive significant effects on cash flow and family benefits (Table 4). However, there was a significant double interaction effect of *type of shade* × *management* on cash costs, and a significant triple interaction effect on gross income. The increasing management intensity strongly increased the cash costs for CFS and slightly for CHD, but did not have any effect on the costs of CLD (Fig. 2A), Gross income was always higher in coffee plots with greater management intensity (Fig. 2B2); but with increasing altitudes, it increased in CFS and decreased in CLD (Fig. 2B1). These results suggest that the costs of increasing management intensity (and therefore increasing coffee yield, cash flow and family benefits) were clearly higher in monocultures than in agroforestry systems, independent of the altitude of the plot.

3.1.3. *Effects of altitude, shade and management on indicators of maintenance of soil fertility*

The types of shade had significant single effects on soil acidity and K; whereas there was a significant triple interaction effect of *altitude* × *type of shade* × *management intensity* on soil C and N. With increasing complexity of the shade canopy (from CSF, passing through CLD, until CHD) the acidity was lower (Fig. 3A) and the soil K content was higher (Fig. 3A). Soil C was always higher at higher altitudes (Fig. 4A1), but with increasing management intensity, soil C was higher in CHD than in CFS and CLD (Fig. 4A2). The effects on soil N were practically the same as on soil C. So, agroforestry systems maintained less acidity than monocultures in full sun conditions independent on the management intensity and altitude; highly diversified agroforestry systems had more soil K, and soil C and N contents were not affected by management intensity, in comparison to the other types of shade.

3.1.4. *Effects of altitude, shade and management on indicators of carbon sequestration*

There was a significant double interaction *altitude* × *type of shade* effect on carbon sequestration. At higher altitudes the total aboveground biomass carbon increased in CFS and CLD compared to lower altitudes while the opposite occurred in CHD. However, in this case, it is more relevant to show that agroforestry systems on average had more than the twice the carbon stock than CFS, due to

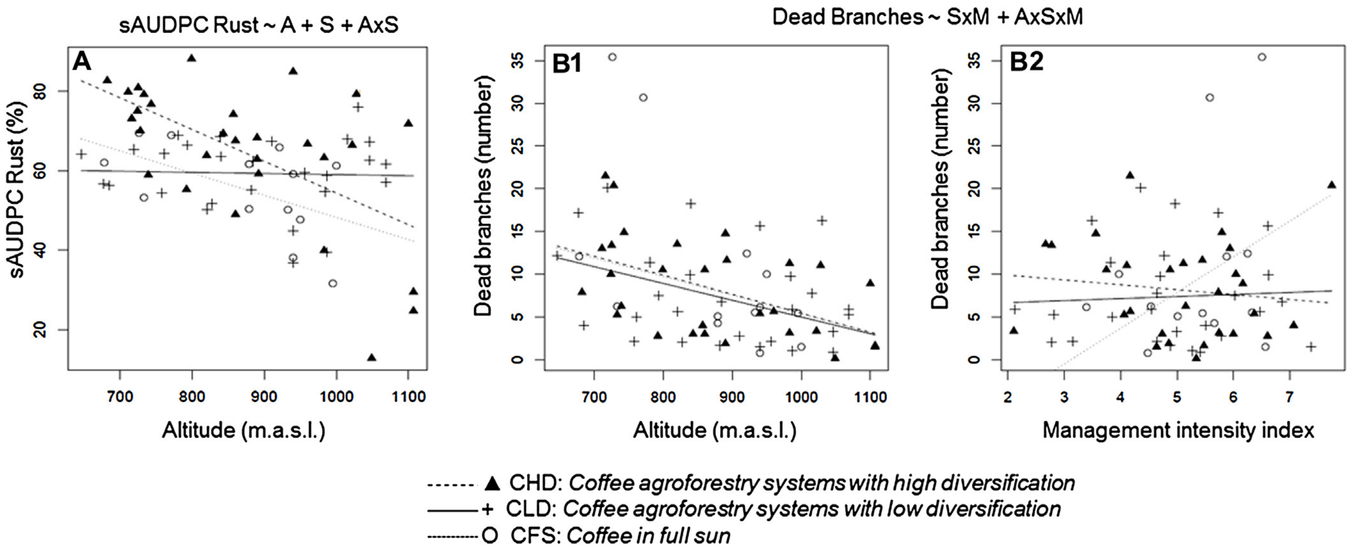

Fig. 1. Effects of the double interaction *altitude* × *type of shade* on the sAUDPC of coffee leaf rust (A), and of the triple interaction *altitude* × *type of shade x management intensity* on the number of dead branches (B1 and B2). The two double interactions *altitude* × *type of shade* (B1) and *shade* × *management intensity* (B2) are represented for simplification.

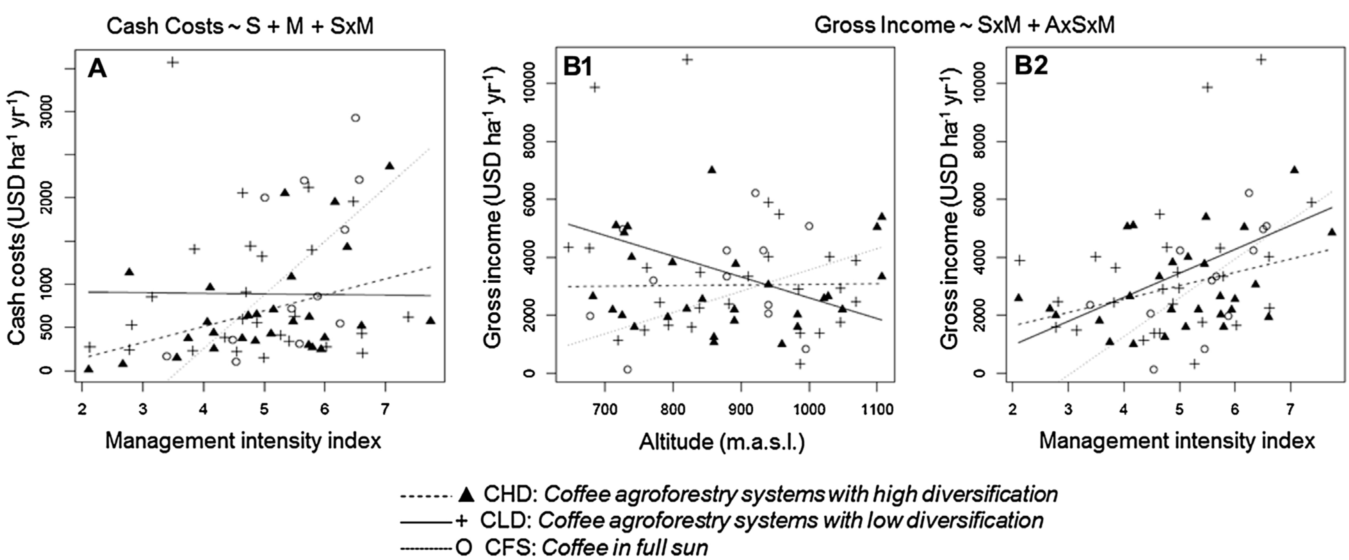

Fig. 2. Effects of the double interaction *type of shade* × *management intensity* on cash costs (A), and of the triple interaction *altitude* × *type of shade* × *management intensity* on gross income (B1 and B2). The two double interactions *altitude* × *type of shade* (B1) and *shade* × *management intensity* (B2) are represented for simplification.

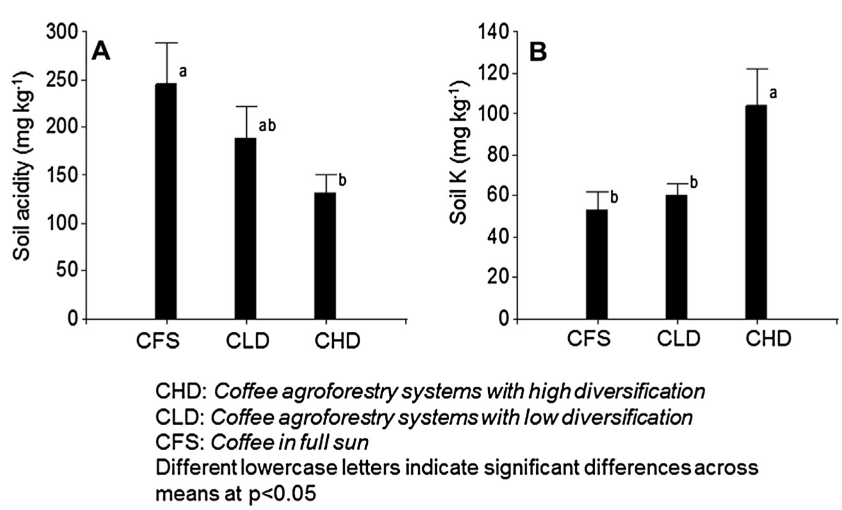

Fig. 3. Single effects of type of shade on soil acidity (A) and soil K (B).

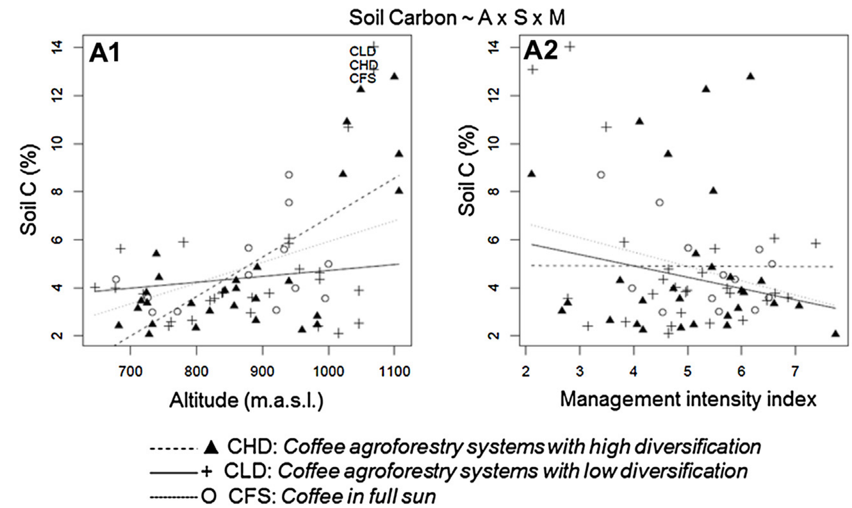

Fig. 4. Effects of the triple interaction *altitude* × *type of shade* × *management intensity* on soil C. The two double interactions *altitude* × *type of shade* (A1) and *shade* × *management intensity* (A2) are represented for simplification.

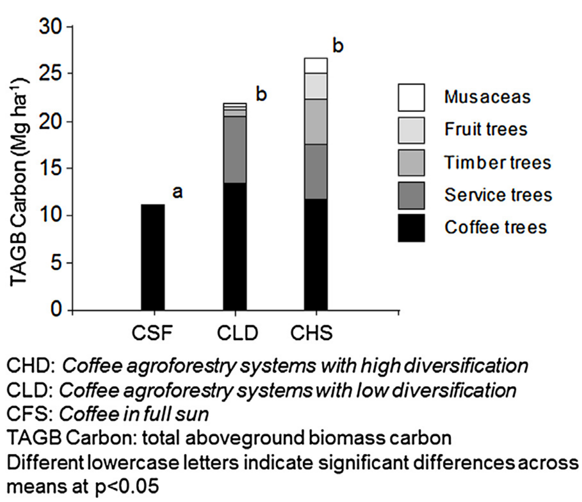

Fig. 5. Effects of the types of shade on the total aboveground biomass carbon.

the carbon of the fruit trees, timber trees and service trees present in their shade canopies (Fig. 5).

3.2. Relationships between ecosystem services, and with biodiversity

The pairwise comparisons of different ecosystem services provided by different types of shade systems showed no clear trade-offs across the provision of different ecosystem services; i.e. there were no clear patterns where the provision of one service came at the expense of another. Similarly, pairwise comparisons of the provision of different ecosystem services relative to the biodiversity present in the coffee plots showed no clear trade-offs (Fig. 6). Only in the case of CHD, one synergy ($p = 0.012$; $R^2 = 0.22$) was found between biodiversity and carbon sequestration; i.e. as biodiversity of the system increased, so did the amount of carbon stored in aboveground biomass (Fig. 6).

The graphs showing 'desirable' levels of ecosystem services indicate that plots of agroforestry systems (CLD and CHD) were more likely to be located in the 'desirable' quadrants than CFS (Fig. 6). Coffee plots of the type CHD were present in all the desirable areas, and with more plots of this type than CLD and CFS. CLD plots were present in almost all the desirable areas (except one); while CFS plots were present only in three desirable areas (Fig. 6).

4. Discussion

In our study, the indicators of each type of ecosystem service (e.g., regulation of pests and diseases, provisioning of agroforestry products, soil fertility, and carbon sequestration) responded differently to the effects of altitude, shade and management. In addition, there were no clear trade-offs among different ecosystem services or across ecosystem services and biodiversity. The fact that at least one indicator of three major ecosystem services was affected by the triple interaction *altitude* × *type of shade* × *management intensity* indicates that the combination of these three factors should be always considered in studies aiming to understand the provision of ecosystem services by the cropping systems under study.

4.1. Effects of types of shade on the provision of ecosystem services

The combined knowledge of single and/or interactive effects of shade with altitude and management intensity on ecosystem services is useful for understanding how to manage coffee agroecosystems to obtain the ecosystem services of interest. For instance, coffee leaf rust, the most important disease in our study, was affected by the interaction *types of shade* × *altitude*, but not by management intensity. This suggests that efforts to manage coffee leaf rust need to consider both the type of shade and the altitude which determines environmental and microclimatic conditions (Avelino et al., 2006). Highly diversified coffee systems will be better at reducing coffee leaf rust incidences in higher altitudes; whereas in lower altitudes less diversified agroforestry systems will be more suitable. We hypothesize that the less diversified canopies maintain low moisture in lower altitudes, while in higher altitudes the highly diversified canopies maintain low temperature; both effects could reduce the development of the pathogen.

We did not find any effect of types of shade on coffee yields. That means that agroforestry systems, besides providing several ecosystem services, did not reduce coffee yields within the studied range of shade cover (<30%). In addition, under shade, yields are more stable over time, ensuring also more stable incomes to coffee farmers (DaMatta, 2004). In contrast, coffee plantations in full sun had more dead branches, especially with high management intensities. Consequently, reduction and higher variability in yields in

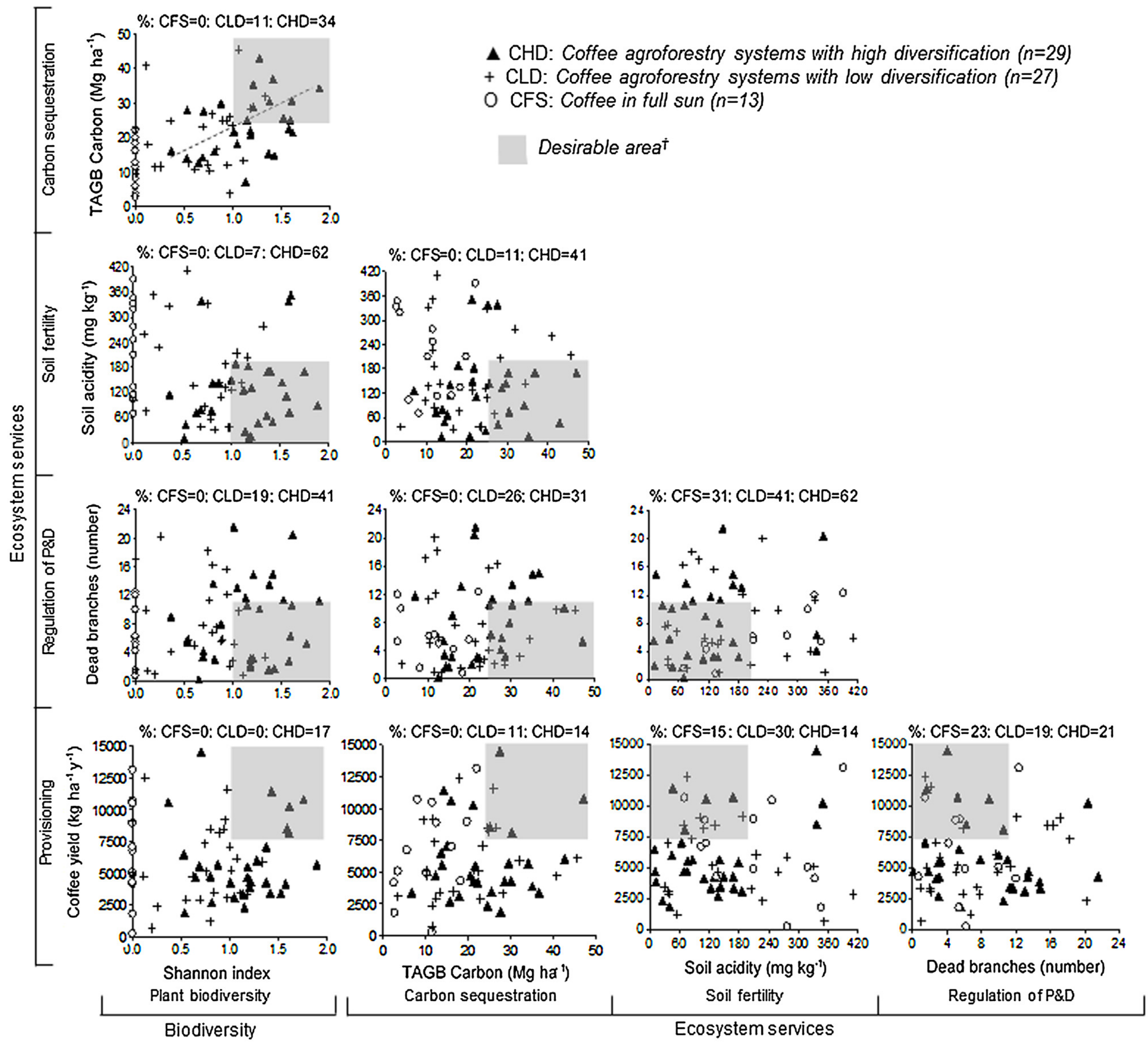

Fig. 6. Relationships between ecosystem services and biodiversity; and percentage of different types of coffee plots achieving the most desirable values of ecosystem services. TAGB Carbon: total aboveground biomass carbon; P&D: pests and diseases.
†The Desirable area is the quadrant in the figure where the most desirable values of both indicators can be found. Examples: in the combination of carbon sequestration and plant biodiversity, the desirable area is the quadrant in the upper right corner of the figure, because this was the quadrant with higher TAGB Carbon and higher Shannon index; in the combination of provision and regulation of P&D, the desirable area is the quadrant in the upper left corner of the figure, because plots in this quadrant had higher coffee yields but fewer dead branches.
Percentages (%) above each figure: represent the number of coffee plots of a given type of shade in the desirable area with respect to the total coffee plots of that type of shade. For instance, in the figure of carbon sequestration vs biodiversity, 10 coffee plots of the type CHD were identified in the desirable area, representing ~34% of the total of 29 CHD coffee plots.
The only one significant relationship (a synergy) was found between biodiversity and carbon sequestration for CHD plots.

subsequent years can be expected (Avelino et al., 2015). The reduction of yields, i.e. yield losses, is also considered as a key indicator of the regulation of pests and diseases; therefore, it should be explicitly quantified to reinforce the assessment of this ecosystem service in further studies (Avelino et al., 2011; Allinne et al., 2016).

We found that agroforestry systems can have lower cash costs than full sun systems. This indicates that the management intensity of these agroforestry systems can still be increased without incurring necessarily high cash costs. The shade canopy management would not mean more costs either. For instance, the cutting of banana leaves, pruning of trees and the harvesting of fruits are usually done by family members and together with operations applied to coffee plants (pruning of coffee plants, weedings, coffee harvests, etc.); that way, those activities do not imply to hire external workers nor many extra labor.

Contrary to what was expected, no interaction was found between types of shade and management on cash flow and family benefit. This reflects that coffee farmers in Turrialba rarely harvest agroforestry products (such bananas, other fruits and timber) either for sale or home consumption. In other regions where socioeconomic conditions are worse, the contribution of agroforestry products is more important to farmers. For instance, Guatemalan coffee farmers harvest fruits for sale, and Peruvian farmers use fruits for home consumption (Rice, 2011). In remote areas of different countries of Central America, the agroforestry products contribute significantly more than the main crop (cocoa) to family benefit (Cerda et al., 2014). Other studies demonstrate that sustainable high timber harvest ratio (>4 m^3 ha^{-1} $year^{-1}$ ~ 265 USD ha^{-1} $year^{-1}$) in agroforestry systems is possible (Somarriba et al., 2014). The important point is that plants and trees that are present in the coffee agroforestry systems can be harvested when farmers need products for consumption or for sale, which is not possible in coffee in full sun. This is especially important during crises of low coffee prices or low coffee production (Rice, 2008).

In our study, coffee agroforestry systems (~25 Mg C ha^{-1}) had more than twice the amount of aboveground carbon than coffee in full sun. In other parts of the world, coffee agroforestry systems can store even more carbon due to their more diverse and denser shade canopies. For instance, the stock of aboveground biomass can reach ~40 Mg ha^{-1} in Guatemalan, Nicaraguan and Mexican coffee agroforestry systems (Soto-Pinto et al., 2010; Haggar et al., 2013; Rahn et al., 2013), ~43 Mg ha^{-1} in Indonesia (van Noordwijk et al., 2002), and ~67 Mg ha^{-1} in Togo (Dossa et al., 2008). Carbon sequestration within the coffee agroforestry systems could be enhanced by the establishment and management of trees with tall and coarse trunks, which can store high amounts of carbon vertically, also increasing the shade canopy production without reducing the yields of the main crop (Somarriba et al., 2013).

Agroforestry systems had better soil fertility than coffee in full sun, considering single effects of types of shade or in interaction with management intensity. Other studies have also documented the importance of shade for soil fertility in coffee agroecosystems. More trees means less loss of nitrogen (Tully et al., 2012). The use of bananas can help improve the cation exchange capacity (Tully et al., 2013). In our study, shade was important for reducing acidity and increasing K independently of the other factors, and was capable of maintaining higher soil C and N levels with increasing management intensity (especially in CHD plots). The use of shade trees and bananas can reduce the need for nitrogen fertilizers and amendments for correcting the soil acidity, and thus, reduce both soil contamination and production costs. In addition, although soil physical indicators that are also important for soil fertility were not measured, it is known that soil C is closely related to organic matter and better soil physical conditions (Swinton et al., 2007).

In summary, overall, agroforestry systems have proven to be more effective than full sun coffee for the provision of ecosystem services, and consequently for improving farmersí livelihoods. Furthermore, the delivery of multiple ecosystem services can considerably increase the economic value of the land (Dale and Polasky, 2007; Pert et al., 2013), which is important for both current and future generations.

4.2. Relationships between ecosystem services and biodiversity

We did not observe trade-offs between ecosystem services or between individual ecosystem services and biodiversity. Trade-offs reported in the scientific literature on agroforestry systems such as the ones between yields and carbon sequestration, yields and biodiversity (Wade et al., 2010), and yields and regulation of diseases (López-Bravo et al., 2012) were expected, but did not happen. The lack of trade-offs among the studied ecosystem services is a novel result. This can be explained by the fact that the provision of ecosystem services is the consequence of both the composition and the management of the system (Rapidel et al., 2015), i.e. of the interaction between these factors. Thus, highly diversified systems should be able to produce high levels of ecosystem services without trade-offs with the appropriate management. Several studies have documented that management of the system can strongly affect coffee pollination and production (Boreux et al., 2013), provision of other tree products (Ango et al., 2014), regulation of diseases (Avelino et al., 2006), soil fertility (Méndez et al., 2009) and carbon sequestration (Häger, 2012). In Turrialba, many different combinations of types of shade and cropping practices can be found, with varying responses in terms of ecosystem services provision. Some coffee plots had low values of an ecosystem service and other coffee plots of the same type of shade had high values of the same ecosystem service; that is why no trade-offs between ecosystem services were found.

On the other hand, not all the synergistic relationships between ecosystem services and plant biodiversity reported in the literature were observed. The well-known synergy between carbon sequestration and plant biodiversity (Häger, 2012; Richards and Mendez, 2014) was also confirmed in our study, but only for CHD plots. There are recent studies in other crops that report synergies between plant biodiversity and economic indicators, which were not found in our study, apparently because coffee farmers in Turrialba did not take advantage of agroforestry products as mentioned earlier. Such studies demonstrate that synergies are found in multistrata agroforestry systems with a notable presence of productive species in the shade canopy and adequate management, including frequent harvests of agroforestry products (Cerda et al., 2014; Cardozo et al., 2015). Although we did not find significant synergies between ecosystem services, the fact that most of coffee systems that achieved high levels of ecosystem services were highly diversified agroforestry systems (desirable areas in Fig. 6), indicates that the use of shade trees and other plants in combination with the coffee crop is essential for providing multiple ecosystem services simultaneously. These specific agroforestry systems should be studied in more detail to identify the specific set of practices which makes these systems more successful (Rapidel et al., 2015).

4.3. Important caveats on the results of ecosystem service indicators

There are several important caveats related to our results. First, we have used a specific set of indicators (Table 3) to measure ecosystem services. While these indicators were carefully selected and have been used in other studies on ecosystem services, it is possible that the use of other ecosystem service indicators might lead to different results. As more research on the provision of multiple ecosystem services by coffee systems becomes available, the extent to which our results can be generalized across ecosystem services will become clear. Second, we used a specific method to identify the desirable levels of ecosystem services and to explore which systems were more likely to provide these desirable levels (Rapidel et al., 2015). While this method has been proven to be useful in identifying systems with different levels of ecosystem service provision, the boundaries of the desirable area are subjective and the use of different boundaries or thresholds for desirability could lead to slightly different results. Finally, our results are applicable only to the range of altitudes, shade cover and management intensity that we studied (Tables 1 and 2). In other regions where coffee is grown at much higher elevations or with higher shade, the relationships between altitude, management practices, shade type, and ecosystem services could vary.

4.4. Key aspects for the design and management of coffee agroforestry systems

We have shown that agroforestry systems with low or high diversification allow the delivery of multiple ecosystem services without compromising coffee yields in smallholder farms. Therefore, smallholder farmers should be able to design and manage shade trees without undermining their productive and economic objectives, and at the same time ensure the delivery of other ecosystem services.

Key aspects that should be considered in the design and management of coffee agroecosystems are described below.

Efforts to ensure that coffee systems deliver ecosystem services need to consider not only the type of shade, but also the altitude where the plantation occurs and the management practices implemented, as demonstrated in the present and in other studies (Boreux et al., 2013). The altitude must be especially considered regarding pests and diseases (Allinne et al., 2016); the decision on the type of shade and management practices to implement at a given altitude, must be in accordance with the expected pest or pathogen and their responses to environment conditions. In case that various altitudes also involve types of soil with different characteristics, the types of shade and management practices should aim at controlling soil fertility.

Farmers manage trees mainly according to their objectives and socioeconomic conditions, in order to obtain the most beneficial services and avoid the most problematic disservices (Haggar et al., 2013; Ango et al., 2014). When designing new coffee systems, farmers should integrate tree and plant species that have good prices in the local market and require little management. The inclusion of bananas, plantains and productive (fruit and timber) tree species can help ensure products for farmer households as well as providing other services (e.g. shade, protection, N fixation, etc.). The decision on how many trees and which tree species to use, must also consider the soil fertility, because higher tree densities than those shown in this study (CHD in Table 2) could cause disservices such as cost increments and competition for soil water and nutrients (Dale and Polasky, 2007; Zhang et al., 2007). High tree densities are associated with less N, K and soil C; in contrast, tree species richness was positively related to soil pH, CEC, Ca, and Mg (Méndez et al., 2009; Tully et al., 2013). In areas with low rainfall and well-marked dry periods, the densities of trees and plants in the shade canopy should be lower than those in Turrialba where water availability is not limiting.

The significant effects of management intensity on indicators of provisioning service, reported in this and in other recent studies (Cerda et al., 2014; Cardozo et al., 2015), suggest that both low and highly diversified shade canopies require specific management strategies to deliver multiple ecosystem services (Power, 2010). In areas where severe attacks of diseases occur, such as coffee leaf rust, and where soils are considered of medium fertility (like in Turrialba), we suggest that the best option for smallholder farmers is to use medium management intensity under shade. We define this management as two fungicide sprays per year against diseases, at least one soil fertilization, at least one coffee plant pruning, the necessary controls of weeds (hopefully manual weedings), the necessary labors of harvest according to the ripening of coffee fruits, and maintaining the shade cover around 30% during the year. Such management should also include resistant coffee varieties to pests and diseases (Avelino et al., 2015), avoid unnecessary excessive quantities of inputs (McCook and Vandermeer, 2015) and use family labor to reduce cash costs. In order to avoid or reduce disservices like poisoning of the family members, death of non-target organisms, contamination of soil and emissions of greenhouse gases (Dale and Polasky, 2007; Zhang et al., 2007; Power, 2010), farmers should try to use low toxic preventive fungicides and traps for insects instead of chemical insecticides. When possible, organic fertilizers (composts, manures) should be applied with the aim to also improve soil physical characteristics.

Agricultural extension and training of farmers, as well as adequate certifications, market based incentives and payment of ecosystem services, can help promote the adoption of well-designed, sustainable coffee agroforestry systems that provide both economic and ecological benefits. There is a lack of agroforestry education and extension to farmers (Lasco et al., 2015), which can be attended through trainings with participatory methodologies (Tscharntke et al., 2011). Certifications and market based incentives to increase prices (Williams-Guillén and Otterstrom, 2014), the economic valuation of ecosystem services (Zhang et al., 2007; Avelino et al., 2011), and payment of ecosystem services (Le Coq et al., 2011) are needed to encourage better management of agroforestry systems in general.

5. Conclusions

The effectiveness of different types of shade to provide major ecosystem services in coffee plantations depends both on the altitude where the coffee is grown and how the system is managed. In our study, no trade-offs were found between different ecosystem services, and between ecosystem services and biodiversity. This indicates that it is possible to increase the provision of ecosystem services without decreasing the provision of other ecosystem services (at least under the types of coffee shade, management and altitudes studied here). More ecosystem services are provided by coffee agroforestry systems than by coffee systems in full sun. Coffee agroforestry systems should be designed with diversified, productive shade canopies and managed with a medium intensity of cropping practices, in order to ensure the continued provision of multiple ecosystem services.

Acknowledgements

This research was supported by CASCADE project "Ecosystem-based Adaptation for Smallholder Subsistence and Coffee Farming Communities in Central America", funded by the International Climate Initiative (ICI). The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) supports this initiative on the basis of a decision adopted by the German Bundestag.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eja.2016.09.019.

References

Allinne, C., Savary, S., Avelino, J., 2016. Delicate balance between pest and disease injuries yield performance, and other ecosystem services in the complex coffee-based systems of Costa Rica. Agric. Ecosyst. Environ. 222, 1–12.
Ambrose-Oji, B., 2003. The contribution of NTFPs to the livelihoods of the 'forest poor': evidence from the tropical forest zone of south-west Cameroon. Int. For. Rev. 5, 106–117.
Andrade, H.J., Segura, M., Somarriba, E., Villalobos, M., 2008. Valoración biofísica y financiera de la fijación de carbono por uso del suelo en fincas cacaoteras indígenas de Talamanca. Costa Rica Agroforestería en las Américas, 45–50.
Ango, T.G., Börjeson, L., Senbeta, F., Hylander, K., 2014. Balancing Ecosystem Services and Disservices: Smallholder Farmers' Use and Management of Forest and Trees in an Agricultural Landscape in Southwestern Ethiopia Ecology and Society 19, 30.
Avelino, J., Zelaya, H., Merlo, A., Pineda, A., Ordoñez, M., Savary, S., 2006. The intensity of a coffee rust epidemic is dependent on production situations. Ecol. Modell. 197, 431–447.
Avelino, J., Ten Hoopen, M., DeClerck, F., 2011. Ecological mechanisms for pest and disease control in coffee and cacao agroecosystems of the neotropics. In: Rapidel, B., DeClerck, F., Le Coq, J.F., Beer, J. (Eds.), Ecosystem Services from Agriculture and Agroforestry Measurement and Payment. Earthscan, pp. 91–117.
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.
Baker, P., 2014. The 'Big Rust': an update on the coffee leaf rust situation. Dis. Pest Control C&CI, 37–39.
Beer, J., Muschler, R., Kass, D., Somarriba, E., 1998. Shade management in coffee and cacao plantations. Agrofor. Syst. 38, 139–164.
Boreux, V., Kushalappa, C.G., Vaast, P., Ghazoul, J., 2013. Interactive effects among ecosystem services and management practices on crop production: pollination in coffee agroforestry systems. In: Proceedings of the National Academy of Sciences of the United States of America, United States, pp. 8387–8392.
Bosselmann, A.S., 2012. Mediating factors of land use change among coffee farmers in a biological corridor. Ecol. Econ. 80, 79–88.

Briceño, J., Pacheco, R., 1984. Métodos Analíticos Para El Estudio De Suelos Y Plantas. UCR, San José, Costa Rica (41 p).
Brown, S., Iverson, L.R., 1992. Biomass estimates for tropical forest. World Res. Rev. 4, 366–383.
CIA, 2016. Mapa digital de suelos de Costa Rica. In: Centro De Investigaciones Agronómicas. Universidad de Costa Rica http://www.cia.ucr.ac.cr/?page_id=139.
Cardozo, E.G., Muchavisoy, H.M., Silva, H.R., Zelarayán, M.L.C., Leite, M.F.A., Rousseau, G.X., Gehring, C., 2015. Species richness increases income in agroforestry systems of eastern Amazonia. Agrofor. Syst. 89, 901–916.
Cerda, R., Deheuvels, O., Calvache, D., Niehaus, L., Saenz, Y., Kent, J., Vilchez, S., Villota, A., Martinez, C., Somarriba, E., 2014. Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. Agrofor. Syst. 88, 957–981.
Cheatham, M.R., Rouse, M.N., Esker, P.D., Ignacio, S., Pradel, W., Raymundo, R., Sparks, A.H., Forbes, G.A., Gordon, T.R., Garrett, K.A., 2009. Beyond yield: plant disease in the context of ecosystem services. Phytopathology 99, 1228–1236.
Clermont-Dauphin, C., Cabidoche, Y.M., Meynard, J.M., 2004. Effects of intensive monocropping of bananas on properties of volcanic soils in the uplands of the French West Indies. Soil Use Manage. 20, 105–113.
DaMatta, F.M., 2004. Ecophysiological constraints on the production of shaded and unshaded coffee: a review. Field Crops Res. 86, 99–114.
Dale, V.H., Polasky, S., 2007. Measures of the effects of agricultural practices on ecosystem services. Ecol. Econ. 64, 286–296.
De Beenhouwer, M., Aerts, R., Honnay, O., 2013. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. Agric. Ecosyst. Environ. 175, 1–7.
Deheuvels, O., Rousseau, G.X., Soto Quiroga, G., Decker Franco, M., Cerda, R., Vílchez Mendoza, S.J., Somarriba, E., 2014. Biodiversity is affected by changes in management intensity of cocoa-based agroforests. Agrofor. Syst. 88 (6), 1081–1099.
Dossa, E.L., Fernandez, E.C.M., Reid, W.S., Ezui, K., 2008. Above- and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation. Agrofor. Syst. 72, 103–115.
Gómez-Delgado, F., Roupsard, O., le Maire, G., Taugourdeau, S., Pérez, A., van Oijen, M., Vaast, P., Rapidel, B., Harmand, J.M., Voltz, M., Bonnefond, J.M., Imbach, P., Moussa, R., 2011. Modelling the hydrological behaviour of a coffee agroforestry basin in Costa Rica. Hydrol. Earth Syst. Sci. 15, 369–392.
Groot, J.C.J., Oomen, G.J.M., Rossing, W.A.H., 2012. Multi-objective optimization and design of farming systems. Agric. Syst. 110, 63–77.
Häger, A., 2012. The effects of management and plant diversity on carbon storage in coffee agroforestry systems in Costa Rica. Agrofor. Syst. 86, 159–174.
Haggar, J., Medina, B., Aguilar, R.M., Munoz, C., 2013. Land use change on coffee farms in southern Guatemala and its environmental consequences. Environ. Manage. 51, 811–823.
Jha, S., Bacon, C.M., Philpott, S.M., Rice, R.A., Méndez, V.E., Läderach, P., 2011. A review of ecosystem services, farmer livelihoods, and value chains in shade coffee agroecosystems. In: Campbell, W.B., Lopez Ortiz, S. (Eds.), Integrating Agriculture, Conservation and Ecotourism: Examples from the Field. Springer, Netherlands, pp. 141–208.
Jha, S., Bacon, C.M., Philpott, S.M., Ernesto Mendez, V., Laderach, P., Rice, R.A., 2014. Shade coffee: update on a disappearing refuge for biodiversity. Bioscience 64, 416–428.
Jose, S., 2009. Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor. Syst. 76, 1–10.
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.
Lasco, R.D., Espaldon, M.L.O., Habito, C.M.D., 2015. Smallholder farmers' perceptions of climate change and the roles of trees and agroforestry in climate risk adaptation: evidence from Bohol, Philippines. Agrofor. Syst. 90 (3), 521–540.
Le Coq, J., Soto, G., González Hernández, C., 2011. PES and Eco-Label. A comparative analysis of 629 their limits and opportunities to foster environmental services provision. In: Rapidel, B., DeClerck, F.A.J., Le Coq, J., Beer, J. (Eds.), Ecosystem Services from Agriculture and Agroforestry 631 Measurement and Payment. Earthscan.
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.
Mas, A., Dietch, T., 2003. An index of management intensity for coffee agroecosystems to evaluate butterfly species richness. Ecol. Appl. 13, 1491–1501.
McCook, S., Vandermeer, J., 2015. The big rust and the red queen: long-term perspectives on coffee rust research. Phytopathology 105, 1164–1173.
Pert, P.L., Boelee, E., Jarvis, D.I., Coates, D., Bindraban, P., Barron, J., Tharme, R.E., Herrero, M., 2013. Challenges to agroecosystem management. In: Boelee, E. (Ed.), Managing Water and Agroecosystems for Food Security. CAB International, pp. 42–52.
Philpott, S.M., Perfecto, I., Vandermeer, J., 2006. Effects of management intensity and season on arboreal ant diversity and abundance in coffee agroecosystems. Biodivers. Conserv. 15, 139–155.
Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. London B Biol. Sci. Engl., 2959–2971.
Pumariño, L., Sileshi, G.W., Gripenberg, S., Kaartinen, R., Barrios, E., Muchane, M.N., Midega, C., Jonsson, M., 2015. Effects of agroforestry on pest, disease and weed control: a meta-analysis. Basic Appl. Ecol. 16, 573–582.
R_Core_Team, 2014. R: A language and environment for statistical computing. In: R Foundation for Statistical Computing. R_Core_Team, Vienna, Austria http://www.R-project.org/.
Rahn, E., Läderach, P., Baca, M., Cressy, C., Schroth, G., Malin, D., van Rikxoort, H., Shriver, J., 2013. Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? Mitig. Adapt. Strat. Glob. Change, 1–19.
Rapidel, B., Ripoche, A., Allinne, C., Metay, A., Deheuvels, O., Lamanda, N., Blazy, J.-M., Valdés-Gómez, H., Gary, C., 2015. Analysis of ecosystem services trade-offs to design agroecosystems with perennial crops. Agron. Sustainable Dev. 35, 1373–1390.
Rice, R.A., 2008. Agricultural intensification within agroforestry: the case of coffee and wood products. Agric. Ecosyst. Environ. 128, 212–218.
Rice, R.A., 2011. Fruits from shade trees in coffee: how important are they? Agrofor. Syst. 83, 41–49.
Richards, M.B., Mendez, V.E., 2014. Interactions between carbon sequestration and shade tree diversity in a smallholder coffee cooperative in El Salvador. Conserv. biol. J. Soc. Conserv. Biol. 28, 489–497.
Schroth, G., Laderach, P., Dempewolf, J., Philpott, S., Haggar, J., Eakin, H., Castillejos, T., Garcia Moreno, J., Soto Pinto, L., Hernandez, R., Eitzinger, A., Ramirez-Villegas, J., 2009. Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. Mitig. Adapt. Strategies Glob. Change 14, 605–625.
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.
Simko, I., Piepho, H.P., 2012. The area under the disease progress stairs: calculation, advantage, and application. Phytopathology 102, 381–389.
Somarriba, E., Cerda, R., Orozco, L., Cifuentes, M., Dávila, H., Espin, T., Mavisoy, H., Ávila, G., Alvarado, E., Poveda, V., Astorga, C., Say, E., Deheuvels, O., 2013. Carbon stocks and cocoa yields in agroforestry systems of Central America. Agric. Ecosyst. Environ. 173, 46–57.
Somarriba, E., Suárez-Islas, A., Calero-Borge, W., Villota, A., Castillo, C., Vílchez, S., Deheuvels, O., Cerda, R., 2014. Cocoa–timber agroforestry systems: theobroma cacao–Cordia alliodora in Central America. Agrofor. Syst. 88, 1001–1019.
Soto-Pinto, L., Anzueto, M., Mendoza, J., Ferrer, G., Jong, B., 2010. Carbon sequestration through agroforestry in indigenous communities of Chiapas. Mexico Agrofor. Syst. 78, 39–51.
Staver, C., Guharay, F., Monterroso, D., Muschler, R., 2001. Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. Agrofor. Syst. 53, 151–170.
Swinton, S.M., Lupi, F., Robertson, G.P., Hamilton, S.K., 2007. Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits. Ecol. Econ. 64, 245–252.
Szott, L., Arévalo-López, L., Pérez, J., 1993. Allometric relationships in pijuayo (Bactris gasipaes H.B.K.). In: Mora-Urpí, J., Szott, L., Murillo, M., Patiño, V. (Eds.), Congreso Internacional Sobre Biología. Agronomía e Industrialización del Pijuayo San José, Costa Rica, pp. 91–114.
Tscharntke, T., Clough, Y., Bhagwat, S.A., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., Wanger, T.C., 2011. Multifunctional shade-tree management in tropical agroforestry landscapes – a review. J. Appl. Ecol. 48, 619–629.
Tully, K.L., Lawrence, D., Scanlon, T.M., 2012. More trees less loss: nitrogen leaching losses decrease with increasing biomass in coffee agroforests. Agric. Ecosyst. Environ. 161, 137–144.
Tully, K.L., Lawrence, D., Wood, S.A., 2013. Organically managed coffee agroforests have larger soil phosphorus but smaller soil nitrogen pools than conventionally managed agroforests. Biogeochemistry 115, 385–397.
Wade, A.S.I., Asase, A., Hadley, P., Mason, J., Ofori-Frimpong, K., Preece, D., Spring, N., Norris, K., 2010. Management strategies for maximizing carbon storage and tree species diversity in cocoa-growing landscapes. Agric. Ecosyst. Environ. 138, 324–334.
Williams-Guillén, K., Otterstrom, S., 2014. Market-based incentives for the conservation of ecosystem services in agricultural landscapes: examples from coffee cultivation in latin America. Encycl. Agric. Food Syst. 4, 172–185.
Zhang, W., Ricketts, T.H., Kremen, C., Carney, K., Swinton, S.M., 2007. Ecosystem services and dis-services to agriculture. Ecol. Econ. 64, 253–260.
Zuidema, P.A., Leffelaar, P.A., Gerritsma, W., Mommer, L., Anten, N.P.R., 2005. A physiological production model for cocoa (Theobroma cacao): model presentation, validation and application. Agric. Syst. 84, 195–225.
van Noordwijk, M., Rahayu, S., Hairiah, K., Wulan, Y.C., Farida, A., Verbist, B., 2002. Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung: indonesia): from allometric equations to land use change analysis. Sci. China Ser. C Life Sci. 45, 75–86.

Please cite this article in press as: Cerda, R., et al., Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. Eur. J. Agron. (2016), http://dx.doi.org/10.1016/j.eja.2016.09.019