Agricultural Systems 162 (2018) 179–190

Contents lists available at ScienceDirect

Agricultural Systems

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

Effects of shade and input management on economic performance of small-scale Peruvian coffee systems

Rosalien E. Jezeer[a,c,*], Maria J. Santos[a], René G.A. Boot[b,c], Martin Junginger[a], Pita A. Verweij[a]

[a] Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Heidelberglaan 2, 3584, CS, Utrecht, The Netherlands
[b] Section of Ecology & Biodiversity, Institute of Environmental Biology, Utrecht University, Padualaan 8, 3584, CH, Utrecht, The Netherlands
[c] Tropenbos International, Lawickse Allee 11, 6701, AN, Wageningen, The Netherlands

ARTICLE INFO

Keywords:
Agroforestry systems
Arabica coffee
Benefit-cost ratio
Net income
Smallholders

ABSTRACT

Tropical agroforestry systems provide a number of ecosystem services that might help sustain the production of multiple crops, improve farmers' livelihoods and conserve biodiversity. A major drawback of agroforestry coffee systems is the perceived lower economic performance compared to high-input monoculture coffee systems, which is driving worldwide intensification practices of coffee systems. However, comprehensive cost-benefit analyses of small-scale coffee plantations are scarce. Consequently, there is a need to improve our understanding of the economic performance of coffee systems under different shade and input management practices. We provide a comprehensive economic analysis of Arabica coffee farming practices where we compare productivity, costs, net income and benefit-cost ratio (BCR) of 162 small-scale, Peruvian coffee plantations under different shade and input management practices along an elevation gradient. By using a cluster analysis, three shade and three input classes (low, medium and high) were defined. We found similar economic performance for all shade classes, but reduced net income and BCR in the High-Input class. More specifically, there was no difference in net income or BCR between low, medium and high shade classes. The High-Input class had significantly lower net income and BCR, mainly due to increased costs of (hired) labour, land, and fertilizer and fungicides; costs which were not fully compensated for by higher coffee yields. Coffee yield decreased with elevation, whereas gate coffee price and quality, as well as shade levels, increased with elevation. Additional revenues from timber could increase farmers' income and overall economic performance of shaded plantations in the future. Our analysis provides evidence that for small-scale coffee production, agroforestry systems perform equally well or better than unshaded plantations with high input levels, reinforcing the theory that good economic performance can coincide with conservation of biodiversity and associated ecosystem services. Additional comprehensive and transparent economic analyses for other geographic regions are needed to be able to draw generalizable conclusions for smallholder coffee farming worldwide. We advise that future economic performance studies simultaneously address the effects of shade and input management on economic performance indicators and take biophysical variation into account.

1. Introduction

Millions of smallholder farmers in the humid tropics depend on tree crops such as cocoa, coffee, oil palm and rubber for their livelihoods (Schroth et al., 2014). In 2011, the annual retail value of coffee was approximately US$ 90 billion, making it the world's most valued tropical export crop (Jaramillo et al., 2011). An estimated 25 million farmers are growing coffee on over 11 million ha in > 60 countries (Waller et al., 2007), predominantly by smallholders who account for approximately 70% of worldwide coffee production (Bacon, 2005). In recent decades, there has been a transformation of coffee farming systems worldwide to more intensified systems by eliminating shade trees, increasing agro-chemical inputs and selecting genotypes (Bosselmann, 2012; Jha et al., 2014; Perfecto et al., 1996). Consequently, a large share of coffee production area worldwide is currently being managed without shade, and only less than a quarter of coffee plantations has multi-layered, diversified shade (Jha et al., 2014; Perfecto et al., 1996). This transformation is driven by the perceived higher economic performance of intensified systems, aiming to increase short term income (Clough et al., 2011; Siebert, 2002). Economic performance indicators such as yield, costs and profitability are important determinants for decision making of small-scale coffee farmers (Bravo-

---

[*] Corresponding author at: Copernicus Institute of Sustainable Development, Utrecht University, Heidelberglaan 2, 3584, CS, Utrecht, The Netherlands.
E-mail addresses: R.E.Jezeer@uu.nl (R.E. Jezeer), M.J.FerreiraDosSantos@uu.nl (M.J. Santos), rene.boot@tropenbos.org (R.G.A. Boot), H.M.Junginger@uu.nl (M. Junginger), P.A.Verweij@uu.nl (P.A. Verweij).

https://doi.org/10.1016/j.agsy.2018.01.014
Received 8 July 2017; Received in revised form 17 January 2018; Accepted 17 January 2018

Monroy et al., 2016). This intensification trend, however, appears to come at the expense of long-term maintenance of ecosystem services relevant for agricultural production (Foley et al., 2011), as intensified farming systems are known to cause environmental problems, such as loss of biodiversity and increased soil erosion (Perfecto and Vandermeer, 2015).

Fluctuating (global) market prices and increased incidence of pest and disease are putting pressure on smallholder coffee farmers, and climate change is expected to exacerbate their vulnerability (Morton, 2007). In the face of current and future challenges, it is important to identify farming practices that meet both economic and environmental goals while being resilient to current and future changes. Tropical agroforestry systems have been proposed as farming systems which can reconcile economic and environmental goals (e.g., Schroth et al., 2004; Steffan-Dewenter et al., 2007). Ample research has shown that agroforestry systems can sustain high biodiversity levels (e.g., De Beenhouwer et al., 2013). The shade trees planted with coffee can provide other important ecosystem services such as enhanced soil fertility (Tscharntke et al., 2011) and stabilized microclimate (Lin, 2007), which are expected to reduce the vulnerability of farms to climate change (Perfecto and Vandermeer, 2015). However, because agroforestry is perceived to have lower economic performance, it is questionable whether it decreases farmers' vulnerability in face of fluctuating market prices.

In a recent review article on economic performance of shaded coffee and cocoa systems, we concluded that the general perception of lower economic performance of agroforestry systems is often based on incomplete economic analyses (Jezeer et al., 2017). Firstly, coffee yield is often used as the sole indicator of economic performance. Multiple studies have shown a negative relation between coffee yield and shade (Jaramillo-Botero et al., 2010; Vaast et al., 2006), yet this assumption is challenged by several recent studies showing that shade had no effect on coffee productivity (Cerda et al., 2016; Meylan et al., 2017). Also, despite lower coffee productivity, higher coffee prices due to improved quality or certification premiums have been linked to higher levels of shade (Muschler, 2001; Vaast et al., 2006). Secondly, the costs associated with producing coffee are not always taken into account and it is debated whether these production costs of agroforestry systems are higher than those of more intensified systems (Cerda et al., 2016) or the opposite (Lyngbæk et al., 2001). Thirdly, benefits derived from shade-tree products like fruits and firewood are frequently overlooked, underestimating potential income from agroforestry plantations. The studies that include these benefits show that shade tree products can significantly contribute to farmers' income (Cerda et al., 2014; Gobbi, 2000; Wulan et al., 2008). Overall, outcomes of previous studies suggest that it is important to not only consider coffee yield but also production costs and other revenues to evaluate economic performance because these indicators are likely to influence economic performance. To be able to compare economic performance across studies and draw generalizable lessons, more comprehensive analyses are needed that include multiple economic performance indicators.

The transformation towards more intensified coffee systems (which we define as increased use of input and lower levels of shade) has resulted in a broad spectrum of coffee plantation management practices, ranging from low-input shaded plantations to high-input full-sun plantations. For agroforestry systems, both the forestry (shade tree) and the agricultural components (e.g., input use, pruning or weeding practices) are expected to affect the productivity and economic performance of the coffee plantation and studies should reflect both simultaneously. A recent study by Cerda et al. (2016) observed an interaction between shade and input management, confirming the need to include both dimensions in comprehensive economic analyses. Additionally, it is important to take specific biophysical conditions into account, which may have a large effect on coffee productivity, bean quality and the management/productivity relation, as the coffee crop is very sensitive to changes in for example temperature, precipitation and insolation (Avelino et al., 2006; Perfecto and Vandermeer, 2015). Comparing the effect of shade and input management on performance of coffee plantations without looking into the biophysical conditions may therefore result in an incomplete or incorrect picture. In general, we expect coffee management practices to be adjusted to variation in biophysical conditions, which will in turn affect economic performance.

We aim to address the following research questions: (i) what is the economic performance of small scale coffee systems under different shade and input levels? and (ii) what are the options to enhance the economic performance of coffee agroforestry systems? We hypothesize that the benefits of high shade low input systems are at least similar to unshaded, high input coffee plantations. To this regard, we analyse the economic performance of Peruvian coffee farming practices in the department of San Martín, which is one of the major coffee producing regions of the country (Valqui et al., 2015). Here we compare productivity, costs, net income and benefit-cost ratio of small-scale coffee plantations and link this to shade and input management practices. The information compiled in this study can be useful to enhance the economic performance of smallholder coffee agroforestry systems, especially in the face of current and future challenges posed on smallholder coffee farmers worldwide.

2. Methods

2.1. Study region

The study was conducted in the department of San Martín, Peru, distributed over an area of approximately 2000 km^2 with an average altitude of 1066 m (Fig. 1a; 673–1497 m). Most plantations ($n = 143$) were situated in the provinces of Moyobamba and Rioja, which together form the 'Alto Mayo', a tropical highland with an average altitude of 1101 m (range 850–1497 m). The average rainfall is 1512 mm per year, the mean temperature 22.8 °C. The remaining 19 plantations were situated in the lowland province of Picota, with an average altitude of 861 m (range 673–1001 m.). The nearest weather station lies approximately 20 km from each of 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. The dry season occurs from May to September (Gobierno Regional de San Martín, 2008).

2.2. Sampling and surveying method

Household surveys were conducted with 162 coffee to characterise coffee management practices both on shade management (e.g. canopy closure, tree species richness) and on input management (e.g. application of fertilizer and pesticides), and used these to classify coffee systems in terms of shade and input. Plantations were selected to cover the range of shade and input intensity found in the study area, from full sun monoculture coffee to multi-layered shaded plantations, and from high agro-chemical input, use of organic inputs or without inputs. We chose coffee plantations older than three years and producing coffee berries with marketable beans, which were owned by smallholder farmers. Plantation elevation was measured with a GPS (Garmin GPS 62 s).

We performed household surveys twice; the first time in 2014 and the second time in 2016. This was necessary because the sample from 2014 did not include information on coffee bean quality and thus we collected additional information on 2016 (see below and Fig. S1 for hierarchy of collected data). On both cases we performed household surveys using a semi-structured questionnaire and we collected data on (i) farm characteristics (e.g., size (ha), age (y)), (ii) shade tree species and approximate density (2014; trees ha^{-1}), (iii) harvested coffee yield (2010–2016; kg ha^{-1} y^{-1}), (iv) costs of inputs, labour and land (2014; € ha^{-1} y^{-1}), (v) coffee price (2010–2016; € kg^{-1}), (vi) coffee quality of dry green beans (2014–2016; at the farm gate, local scale from 0 to 100), and (vii) benefits derived from other products (firewood, fruit, livestock; 2014; € ha^{-1} y^{-1}). Data for coffee yield, price and quality for

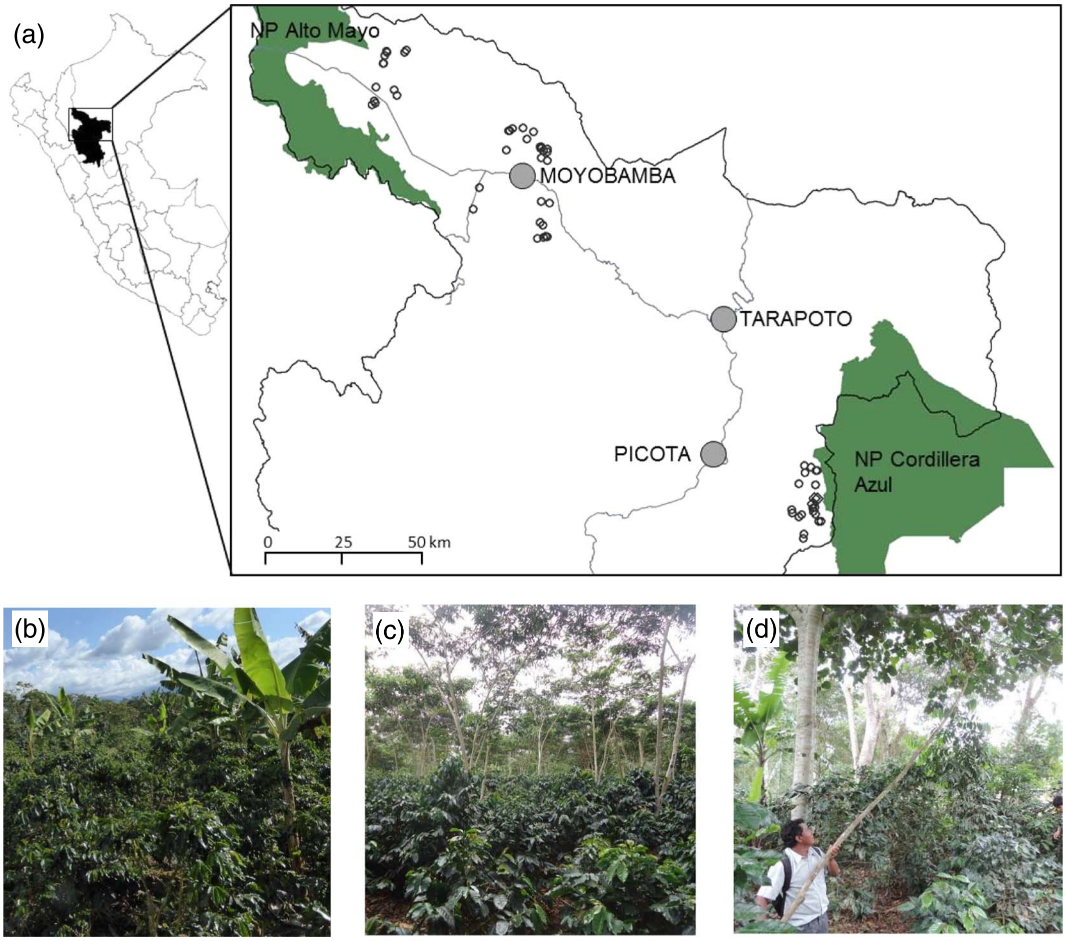

Fig. 1. Study area and management regimes. (a) Study area in the region of San Martín, Peru. Open circles represent the locations of the plantations were plot measurement where made, grey-filled circles represent important cities, grey lines depict major roads and the dark green areas depict national parks. Region 1 refers to the area near Moyobamba, all north of Tarapoto, whereas region 2 refers to the area southeast of Picota, near the national park (NP) Cordillera Azul; (b) full sun monoculture management regime, sometimes sparsely intercropped with bananas during the first years, (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.)

consecutive years was included for those years that the farmer could report values from 2010 to 2016. Coffee yield and price were obtained by both the 2014 and the 2016 surveys. Costs of input, labour, land and equipment, as well as income from other products were obtained for 2014 only. Tree species richness was assessed with the survey in 2016 by questioning the farmers about the different types of trees present at their coffee farms and by estimating the number of trees present at their coffee farm. Subsequently, the farmers were asked how difficult they thought it was to report the number and type of trees present at their coffee farm (easy, medium or difficult). If they responded that they found this ‘difficult’ then the answer was not included in the database. The interviewers were trained by the same person and surveys lasted between 45 and 60 min per farmer. The interviewers assessed qualitatively if the farmers responded with confidence, and outliers 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.

More detailed information on plot level was obtained in 2014 using field measurements for a subset of the farms (n = 62), to complement the information obtained from the household surveys (see Fig. S1); it was only possible to collect such complete and detailed field data for a smaller number of farms. These were chosen to reflect the same range in shade and input management practices as that observed for all the plantations. Data collected on plot level included for example, basal area, shade level, timber tree species and timber tree values. To collect this data, we established plots of 10 × 10 m (n = 19) or 20 × 20 m (n = 43) in representative areas of the farm, for a subset of 62 coffee plantations. All shade trees with diameter at breast height > 5 cm within the plots were identified to species level if possible and otherwise to genus level, using a field guide (Pennington et al., 2004), and knowledge from local experts and farmers. Shade tree density and tree basal area were estimated on a plot basis and extrapolated to hectare and were reported in trees ha^{-1} and $m^2 ha^{-1}$ respectively. Tree height was measured with a Nikon Forestry Hypsometer. Level of shade (hereafter referred to as shade cover) was determined visually by estimating canopy cover on a scale of 0% to 100% (Samnegård et al., 2014). Visual estimation techniques have potential for accurately estimating shade levels (Bellow and Nair, 2003) and are recommended when it is logistically difficult to collect canopy cover data above the tall coffee canopy, using hemispheric lenses. Following Vittoz et al. (2010), who concluded that only the use of highly trained observers could improve the power for detecting changes in cover, we used at least two trained observers whom practiced until their estimated aligned before setting out to estimate shade cover for data collection. Shade trees were rarely pruned and the shade measurements were taken once per plantation from May to August in 2014 and 2015, which corresponds to the dry season. As these are predominantly tropical evergreen trees, we have no reason to expect a large variation of shade cover during the year.

Table 1

List of economic performance indicators and methods, formulas and assumptions used. Exchange rate of Peruvian Sol (S/.) to Euro (€) = 0.27 was applied (November 1st 2014, www.oanda.com). Values are presented on a € per hectare per year basis (€ ha^{-1} y^{-1}). (width: 1.0 columns).

Indicators of economic performance	Methods, formulas and assumptions
Coffee yield (kg ha^{-1} y^{-1})	Harvested dry green coffee beans[a] from 2010 to 2016, average
Coffee price (€ kg^{-1})	Farm gate price from 2010 to 2016, average
Coffee gate quality (0 − 100)	Quality of coffee beans at the farm gate, from 2014 to 2016, average
Gross coffee income (€ ha^{-1} y^{-1})	[Yield] ∗ [Price]
Other income (€ ha^{-1} y^{-1})	Value of firewood, other crops and livestock, estimated by the farm gate price either for sale or domestic consumption. Timber value was analysed separately
Costs (€ ha^{-1} y^{-1})	Production costs in terms of [Fixed costs] + [Flexible costs]
Net coffee income (€ ha^{-1} y^{-1})	[Gross coffee income] − [Costs]
Farm income (€ ha^{-1} y^{-1})	[Net coffee income] + [Other income]
Benefit-cost ratio (BCR)	[Net coffee income] / [Costs], with or without costs of family labour included

[a] 1 quintal (qq) of dried green coffee known as café pergamino = 56 kg.

2.3. Economic performance indicators

To compare the economic performance of coffee farms with different shade and input management practices, we evaluated a set of economic performance indicators including coffee productivity, costs, gross income, net income and benefit-cost ratio (BCR; Table 1). This set of indicators was chosen because their combination allows for a comprehensive economic performance analysis. All data was derived from farmer surveys, except for the current value of standing timber volume of shade trees that was estimated by a combination of field measurements and survey data.

2.3.1. Yields and revenues

Coffee yields (kg ha^{-1} y^{-1}) were reported by farmers as harvested dry coffee beans from 2010 to 2016. Coffee bean quality was surveyed for 2014, 2015 and 2016 and average value was used in further analysis. This measure of coffee quality is expressed on a scale from 0 to 100 and the rank value is given to the coffee beans by the buyer when the coffee is being purchased. This is known as ‘rendimiento físico’ of dry green beans and is an integrated measure of bean moisture content, size, colour, smell and percentage of defect beans (Rosero et al., 2015). We will refer to this variable as ‘gate quality’ from here onwards. Shade species were classified as: *Musaceae* (bananas and plantains), guavas (from the leguminous genus *Inga*), fruit trees (e.g., lemon and orange) or timber trees (all other trees). Benefits of livestock, trees and crops were estimated by taking substitution costs using the respective market prices of these products, irrespective of whether the products were sold or used for domestic consumption. The estimated prices for the most relevant agroforestry products between as reported in 2014 were €1.60 per bunch of bananas, €2.70 per bundle of firewood and €6.75 per 50 kg of cassava (*Manihot esculenta*) as reported by farmers in 2014. Standing timber value was analysed separately. Cubic volume of sawn wood (m^3 ha^{-1}) was estimated for the trees that could provide timber by first calculating the volume of round wood. In absence of local equations, we used the generic equation from the Food and Agriculture Organization (FAO, n.d), which estimates commercial wood volume per tree trunk as $v = 0.42 * B * H$, where B is basal area at 1.30 m above ground level, H tree height in m, and 0.42 is the generic correction factor for tapered stems. Secondly, 1 m^3 roundwood was assumed to convert to 0.52 m^3 sawn wood in Peru (Gobierno Regional de San Martín, 2012). Using local species-specific export prices for sawnwood, the monetary value of standing tree stock per plot was estimated. Third, these values were extrapolated to hectare and annuitized according to a 30 y harvest cycle as this is the average lifespan of a coffee plantation (Wintgens, 2012). A 10% discount rate was applied which is commonly used for tropical countries and is assumed to match local conditions of the banking system (Rahman et al., 2007). As these are values estimated for currently standing trees, they represent potential rather than actual income and costs, and costs for felling, sawing and transport are not included; therefore, we chose to report all economic performance indicators without income from timber, unless specified.

2.3.2. Costs

2.3.2.1. Fixed costs

2.3.2.1.1. Land and equipment costs. Price of land and investment costs of equipment were obtained by farmer surveys. The majority of farmers own their land and we asked the purchase price to include in the analysis. There were also farmers who rent the land for periods of six or seven years. Equipment costs include the purchase of e.g., fruit pulp machines, machetes and brush cutters. All costs were annuitized assuming a 30 year's coffee cycle and applying a 10% discount rate.

2.3.2.2. Flexible costs

2.3.2.2.1. Labour. Labour days per management activity were recorded for establishment, pruning, weeding, fertilizing, pest and disease control, harvest and post-harvest activities. A distinction was made between hired labour and family labour. Plantation specific wages per day were used to calculate labour costs per plantation. As costs for family labour are not actually incurred costs, we hereafter refer to labour costs excluding family labour, unless specified otherwise.

2.3.2.3. Flexible costs

2.3.2.3.1. Input. Costs of all material used for fertilization, pest and disease control and weeding were calculated in euro per hectare per year and are referred to as inputs. Differentiation was made between (i) organic and chemical substances, and (ii) type of input in terms of herbicides, pesticides, fertilizer or fungicides.

2.4. Input and shade indices

2.4.1. Input index

Using the survey data, an input index was calculated for each coffee plantation, similar to indices used in other coffee studies (Cerda et al., 2016; Hernández-Martínez et al., 2009; Mas and Dietsch, 2003). In this study, the input index is an aggregate of five management variables that describe fertilizing, weeding and pest and disease control activities (Table 3), which are important management practices in the region as verified based on the survey. These input management variables were transformed to range between 0 and 1. For the continuous variables (pesticide quantity and fertilizer quantity; € ha^{-1} y^{-1}), a value between 0 and 1 was obtained by $index\,value = \frac{value - minimum}{maximum - minimum}$. For the categorical variables, values of 0, 0.5 or 1 were assigned based on applied type of fertilizer, pest and disease control and weeding (Table 3). The final index value corresponds to the sum of the ranks for the five variables of each farm. These farm-specific values were subsequently re-scaled to values between 0 and 1, with zero representing the lowest input and one the highest.

2.4.2. Shade index

Two separate, yet complementary, shade indices were calculated, one based on field data and the other on survey data. The index based on survey data used information on shade tree density and shade tree species richness. For the farms for which we collected data in 2016, we used this data because this was considered more accurate, but if only survey 2014 data was collected, we used survey 2014 data. Consequently, there is only one shade clustering based on survey data. The index based on plot data included information on shade tree density and species richness, and also shade cover and basal area, all collected by field measurements on plot level. All variables were continuous and standardized to range between 0 and 1, as described above for input. Farm-specific totals were rescaled, with zero representing the absence of shade and one representing high shade.

2.4.3. Using input and shade indices for farm classification

Farm profiles were classified according to their input and shade management characteristics. To identify clusters of farms that had similar levels of shade and input management, i.e. different farm profiles, we used a Principal Component Analysis (PCA). Subsequently, we used a hierarchical cluster analysis with Euclidean distances and the Ward minimum variance method to define homogeneous groups. Analysis of variance was used to test for significant differences between farm profiles in terms of shade and input levels. For non-normally distributed data without homogeneity of variance, the non-parametric Kruskal-Wallis test was used. Data were tested for normality with Shapiro-Wilk test and for homogeneity of variances with Levene's test. More information on the cluster analysis can be found in Appendix S2 in supporting information.

2.5. Statistical analysis

To assess if there was a relation between input and shade management and cost and benefits, we checked for correlations between general plantations characteristics, input and shade management variables and cost and benefit indicators with Pearson correlation coefficient for normally distributed variables. Spearman's rank correlation was used for data which did not meet assumptions of normality. To assess whether economic performance differed between input classes and shade classes we used Kruskal–Wallis test and Tukey's post-hoc test with Chi-square distance. We checked for correlations between the explanatory variables with Spearman's rank correlation (Table S3), which was also used to check the robustness of the data obtained, in particular the visually estimated shade cover (Fig. S4). Significance level was set at α = 0.05. Statistical analyses were performed with R (version 3.0.2, R Core Team, 2014), using the 'mclust' (Fraley et al., 2017) and 'car' (Fox et al., 2016) packages.

3. Results

3.1. General plantation characteristics

Average coffee plantation area was 2.74 ± 1.96 ha (Table 2), which is general for Peru as the largest share of coffee in San Martín is produced by smallholders (CENAGRO 2012). The majority of the farmers were migrants (90%) and farmers had on average 14 ± 8 years of experience of cultivating coffee. Only Arabica coffee (*Coffea arabica L.*), is grown in this region, of which 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). In total, 533 individual shade trees and plants were observed, the majority of which was identified to species level (92.5%). A third of observed trees and plants was a mix of bananas and palm trees (32.6%) and the other third were Inga trees (33.3%). Of the remaining shade trees, 146 individual trees were identified to species level (27.4%), which consisted of a mix of 39 tree species. The remaining shade trees could not be identified to species level (6.5%). The shade index was significantly higher for plantations at higher elevations (see Table S3 in supporting information). For more information on study region and plantation characteristics see Table 2 and Appendix S5.

Table 2
Descriptive statistics of general plantation characteristics and shade and input practices. Data was collected using farmer surveys, unless indicated otherwise. (width = 2 columns).

	Unit	Mean	± SD	Min	Max	n
General farm characteristics						
Farm size	ha	6.38	8.42	0.50	80.00	154
Productive coffee area	ha	2.74	1.96	0.50	13.00	154
Elevation	m a.s.l.	1066.36	171.74	673.00	1497.00	162
Coffee shrub age	year	8.75	4.56	3.00	30.00	159
Coffee shrub density	shrubs ha^{-1}	3934.63	1139.65	1000.00	7000.00	154
Shade management						
Shade tree density	trees ha^{-1}	71.34	105.33	0.00	700.00	154
Shade tree density (plot)	trees ha^{-1}	222.22	183.75	0.00	700.00	54
Shade tree species richness	species per farm a^{-1}	4.24	3.6	0.00	22.00	161
Shade tree species richness (plot)	species per plot	2.31	1.72	0.00	7.00	54
Shade cover (plot)	%	36.76	26.74	0.00	80.00	54
Basal area (plot)	$m^2 ha^{-1}$	8.84	15.91	0.00	101.42	54
Input management						
Total	€ $ha^{-1} y^{-1}$	149.74	196.90	0.00	1021.80	151
Fertilizer	€ $ha^{-1} y^{-1}$	123.93	174.29	0.00	951.60	140
Pesticide	€ $ha^{-1} y^{-1}$	34.07	77.25	0.00	468.00	128
Herbicides	€ $ha^{-1} y^{-1}$	6.67	26.21	0.00	249.60	138

3.2. Input and shade indices

Three shade classes were distinguished for the field and the survey data (Low-, Medium- and High-Shade) that differed significantly for all shade variables (Fig. 2, Table 3). The Low-Shade class derived from the field-subset (n = 8) corresponded to a mean shade cover of 1.2 ± 2.3% and on average 13 ± 23 shade trees ha^{-1}, on average from a single tree species. The Medium-Shade plantations (n = 27) corresponded to a mean level of shade of 28 ± 16% and an average of 157 ± 65 shade trees ha^{-1}, on average with two species. High-Shade plantations (n = 19) were characterized by a mean shade cover of 64 ± 17% and an average of 403 ± 181 shade trees ha^{-1}, which consisted of three different shade tree species on average. For more details on the cluster analysis see Appendix S2.

Three input classes (Low-, Medium- and High-Input) were significantly different for variables describing the fertilizing, weeding and pest and disease control management (Fig. 2, Table 3). Low-Input plantations (n = 23) were characterized by absence of pest and disease control activities and fertilizer application and all weeding was done manually. Medium-Input plantations corresponded to the largest group of farmers (n = 50) and who spent on average € 124 $ha^{-1} y^{-1}$ on predominantly organic fertilizers. Also, some of these farmers applied pest and disease control (40%), largely using organic inputs (72%). Although the majority of the farmers were weeding manually, some farmers were weeding mechanically by using a bush cutter. High-Input plantations (n = 37) corresponded to plantations where weeding was mostly mechanical, yet some were applying herbicides. The majority of these farmers applied chemical fertilizers with a cost of € 220 $ha^{-1} y^{-1}$ and applied chemicals (pesticides and/or fungicides) to control pests and diseases. Overall, applied fertilizer, weed and pest management intensities were higher on plantations at lower elevations, as the Input Index was negatively related to elevation (see Table S3). The values obtained by the survey and by field work shows strong correlation for

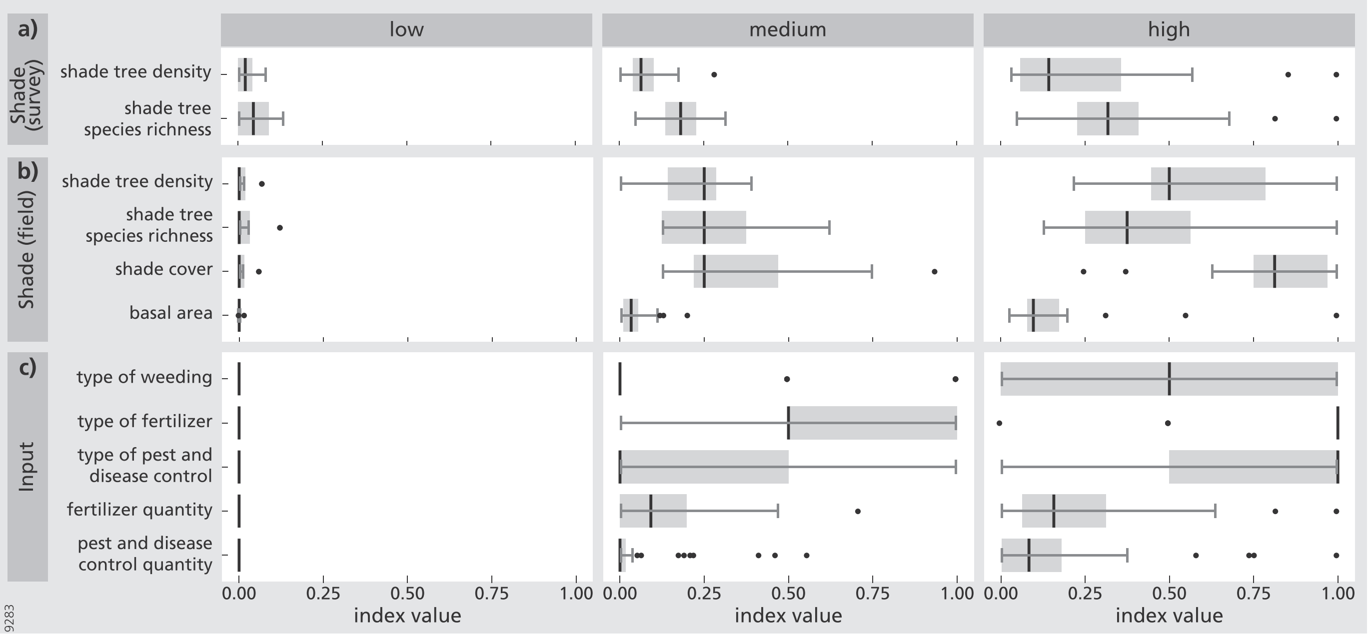

Fig. 2. Representation of profiles obtained from a hierarchical cluster analysis of variables describing; a) Shade practices (survey data); b) Shade practices (field data) and c) Input practices. Shade practices variables included are: shade tree density, shade tree species richness, level of shade and basal area. Input practices variables included are: type of weeding (0 = by hand, machete; 0.5 = mechanical, brush cutter; 1 = herbicide), fertilizer type (0 = none, 0.5 = organic; 1 = chemical), pest control type (0 = none, 0.5 = organic; 1 = chemical), fertilizer quantity (fertilizer costs, € ha^{-1} y^{-1}) and pest and disease control quantity (costs of e.g., pesticides and fungicides, € ha^{-1} y^{-1}). Boxplots indicate the lower quartile, median and upper quartile, with whiskers extending to the most extreme data point that is no > 1.5 times the interquartile range from the edge of the box.

Table 3
List of selected variables to obtain Input and Shade Indices and description of coffee plantation management practices. Results are obtained from a k-means cluster analysis for Shade Index (survey), Shade Index (field) and Input Index separate. For each group, mean and standard deviation (SD) are summarized for all variables. Significant differences between groups were evaluated using an ANOVA performed on a linear model for data with a Normal distribution (a) or with a Kruskal–Wallis non-parametric test (b). Significance level of $p < 0.001$ is indicated with ***. (Width: 2 columns).

		Low (n = 45)	Medium (n = 56)	High (n = 51)	Sig.
		Mean ± SD	Mean ± SD	Mean ± SD	
Shade index (survey)	Shade tree density (trees ha^{-1})	19.0 ± 20.0	52.0 ± 35.0	153.0 ± 149.0	***$^{(b)}$
	Shade tree species richness (per farm)	1.0 ± 1.0	3.9 ± 1.4	7.5 ± 4.1	***$^{(b)}$
	Shade index	0.0 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	***$^{(b)}$
		Low (n = 8)	Medium (n = 27)	High (n = 19)	Sig.
		Mean ± SD	Mean ± SD	Mean ± SD	
Shade index (field)	Shade tree density (trees ha^{-1})	12.0 ± 23.0	157.0 ± 65.0	403.0 ± 181.0	*** $^{(b)}$
	Shade tree species richness (per plot)	0.3 ± 0.5	2.1 ± 1.2	3.5 ± 1.8	*** $^{(b)}$
	Shade cover (%)	1.2 ± 2.3	28.3 ± 16.3	63.7 ± 16.9	*** $^{(b)}$
	Basal area (m^2 ha^{-1})	0.3 ± 0.7	4.6 ± 4.8	18.6 ± 23.5	*** $^{(b)}$
	Shade index	*0.0 ± 0.0*	*0.2 ± 0.1*	*0.5 ± 0.1*	*** $^{(a)}$
		Low (n = 23)	Medium (n = 50)	High (n = 37)	Sig.
		Mean ± SD	Mean ± SD	Mean ± SD	
Input index	Pesticide quantity [a] (€ ha^{-1} y^{-1})	0.0 ± 0.0	25.0 ± 58.0	80.0 ± 114.0	*** $^{(b)}$
	Fertilizer quantity [a] (€ ha^{-1} y^{-1})	0.0 ± 0.0	124.0 ± 146.0	220.0 ± 222.0	*** $^{(b)}$
	Type of pest and disease control (0 = none, 0.5 = organic; 1 = chemical)	0.0 ± 0.0	0.3 ± 0.4	0.7 ± 0.4	*** $^{(b)}$
	Type of fertilizer (0 = none, 0.5 = organic; 1 = chemical)	0.0 ± 0.0	0.5 ± 0.4	0.9 ± 0.2	*** $^{(b)}$
	Type of weeding (0 = by hand; 0.5 = mechanical; 1 = chemical)	0.0 ± 0.0	0.2 ± 0.4	0.5 ± 0.4	*** $^{(b)}$
	Input Index	0.0 ± 0.0	0.2 ± 0.1	0.5 ± 0.1	*** $^{(b)}$

[a] Input such as fertilizer or pesticides are partly used as concentrates, we therefore considered the total value of the applied herbicides in the analyses, assuming a positive correlation between the concentration of active substances and price.

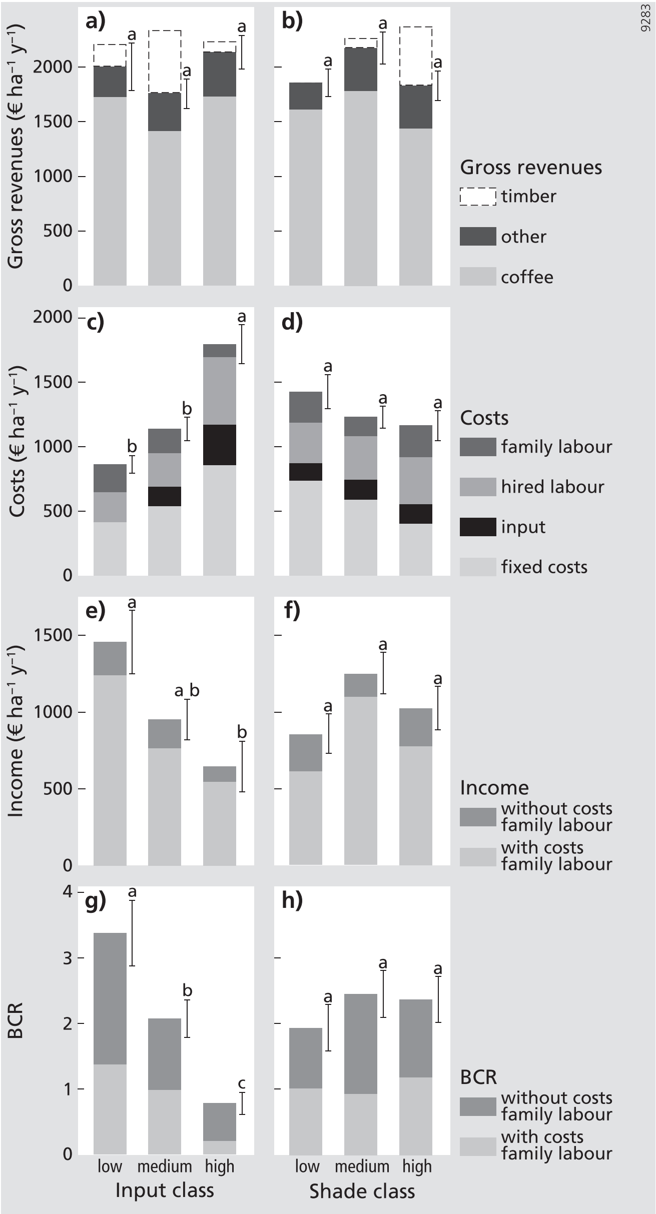

Fig. 3. Revenues (a–b), costs (c–d), net income (e–f) and BCR (g–h) are presented for input (left column) and shade (right column) practices classified as low, medium and high. Bars sharing the same letter are not significantly different ($p \leq 0.05$) among mean values between classes. For more details on descriptive statistics and Kruskal-Wallis tests see Table S6.

species richness ($R^2 = 0.55$; $p < 0.001$) and shade tree density ($R^2 = 0.78$; $p < 0.001$).

3.3. Economic performance

Here we present the results from the analysis of the effects of shade and input practices on economic performance indicators, while taking the effect of elevation into account. We first present results on the benefits derived from coffee and other products, and secondly the costs of coffee production. Finally, we present the results on net income and BCR of coffee plantations under different shade and input management practices.

3.3.1. Gross revenues of coffee, other farm products and timber

Gross coffee revenues averaged (± SD) 1585 ± 917 € ha^{-1} y^{-1} and ranged between 204 and 5080 € ha^{-1} y^{-1}. Following these large differences, there was a significant difference in gross coffee revenues between shade classes, with higher gross revenues for Medium-Shade than for High-Shade (Fig. 3a–b; see Table S6 for detailed numbers). Additionally, we found a trend of lower gross coffee revenues for Medium-Input compared to High-Input. The large variation in gross coffee revenues can partially be explained by the large variation in coffee yield, which ranged between 112 and 2893 kg ha^{-1} y^{-1} (854 ± 514 kg ha^{-1} y^{-1}). Coffee yield was also highly variable over the years as average yields in 2014 were roughly half of those in 2011, respectively 1162 and 514 kg ha^{-1} y^{-1} (Fig. S7). Coffee yields were significantly lower for High-Shade plantations compared to Medium-Shade and there was a negative relation between the shade index derived from the survey data (n = 162) and coffee yields (Fig. 4, Table S6). This relation was not found for the Shade classes based on field measurements (n = 62; Table S6). Also, coffee yields were higher in plantations with higher costs ($R^2 = 0.39$; p-value < 0.001), i.e., costs for the land and equipment ($R^2 = 0.33$; p-value < 0.001), chemical inputs ($R^2 = 0.15$; p-value < 0.05) and hired labour ($R^2 = 0.35$; p-value < 0.001). There was a large variability in the price that farmers received for their coffee beans (1.87 ± 0.26 € kg^{-1}), which ranged between 1.21 and 2.74 € kg^{-1} (Fig.S7). Coffee bean price significantly increased with gate quality ($R^2 = 0.38$) and fluctuated over the years (Fig. S7). We found no relation between gate quality and shade or input practices, yet gate quality was significantly higher on plantations situated at higher elevations (Fig. 4).

On top of gross coffee revenues, farmers were estimated to receive an additional 345 ± 314 € ha^{-1} y^{-1} from firewood, livestock and other crops combined, either by selling these products or use them for their own livelihoods. Though no difference in revenue from other products was observed between input classes, there was a difference in revenues between shade classes obtained by farmer surveys. Even without including potential timber income, farmers with Medium- and High-Shade plantations gained approximately 60% more income from other products compared to Low-Shade plantations (Table S6). Timber value was highly variable (238 ± 852 € ha^{-1} y^{-1}) and potential income from timber was significantly higher for High-Shade compared to Low-Shade plantations. When gross revenues for coffee and other products were combined (with or without potential timber income), no differences in gross revenues were observed between input classes or between shade classes. Gross coffee revenues decreased significantly with increasing elevation, reflecting the negative relation between elevation and coffee yield (Fig. 4).

3.3.2. Costs of coffee production

Total costs of coffee production were variable (1378 ± 905 € ha^{-1} y^{-1}) and ranged between 103 and 5745 € ha^{-1} y^{-1}. The largest share of these costs were associated with land (44%), followed by labour costs (38%). Input only accounted for an average of 11% of all costs, of which fertilizer was the most important (83%; Fig. 3c, d). Not surprisingly, costs of fertilizer, pesticide and herbicide input were significantly different between all input classes as these variables were used to cluster input profiles (Fig. 3c, d; Table S6). Land costs were twice as high for High-Input compared to Low-Input and were higher for plantations at lower elevations. Total labour costs showed no difference between input classes, yet separate analysis of costs for hired and family labour showed contrasting results. Family labour costs showed a trend of being more than twice as high for Low-Input compared to High-Input, whereas costs of hired labour of High-Input were significantly higher and double of those of Medium-Input. Total production costs associated with High-Input plantations were approximately twice the costs associated with Medium- and Low-Input plantations (Fig. 3c), both with and without costs of family labour, land costs and/or input costs. Despite a significant reduction in land costs for High-Shade plantations, no significant difference was detected in total production costs between shade groups (Fig. 3d). Costs of organic input and family labour increased with elevation, while the

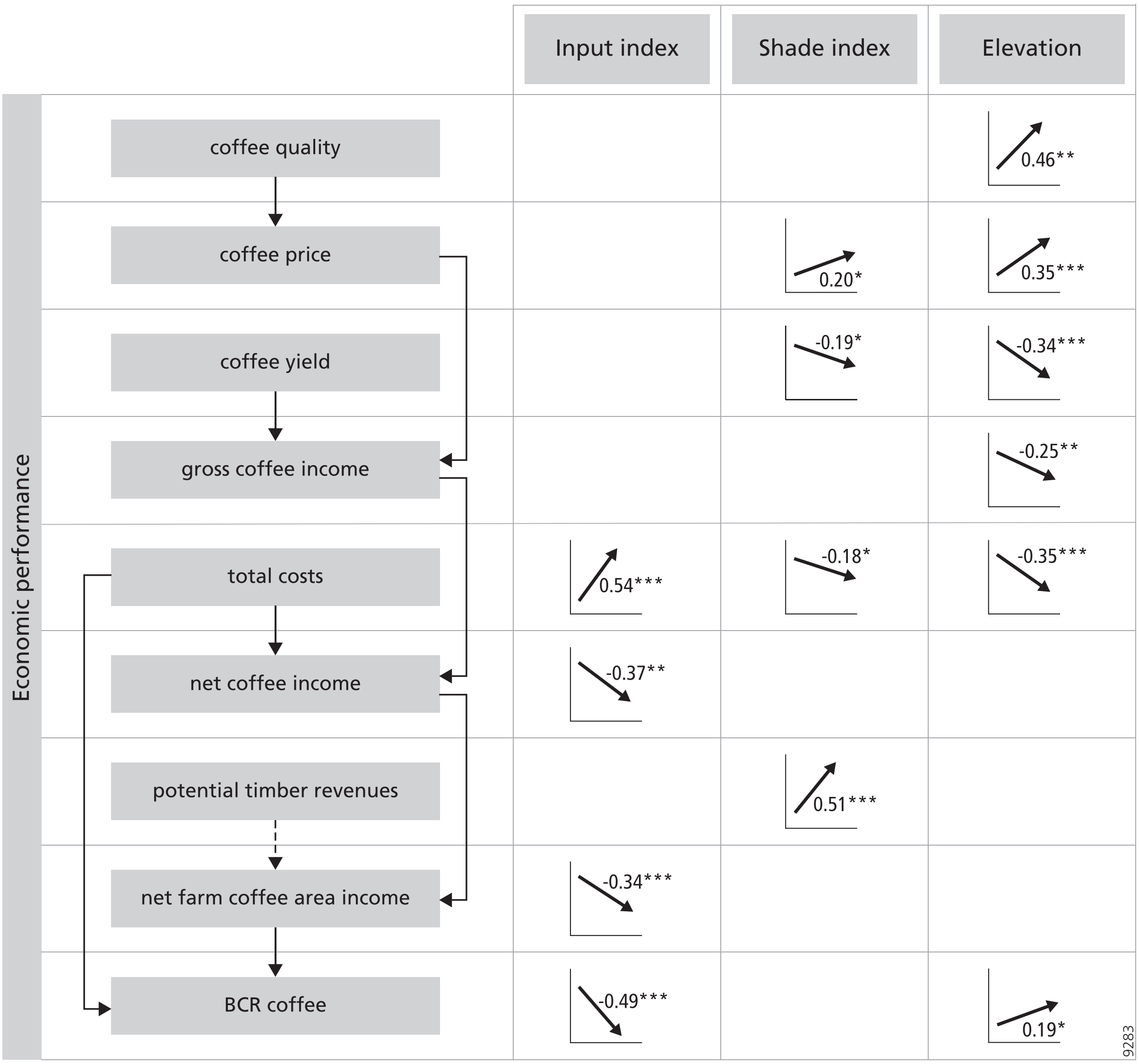

Fig. 4. Correlation matrix between economic performance indicators (y-axis) and Input Index (left column); Shade Index (middle column) and elevation (right column). Spearman rank correlation coefficients are shown. The level of significance is indicated with [empty] at $p > 0.5$; $*p < 0.05$; $**p < 0.01$; $***p < 0.001$. For a more detailed correlation matrix see Table S3.

opposite was the case for costs of chemical input and hired labour, as these were lower at higher elevations (Table S3). Costs were significantly lower for plantations at higher elevations (Fig. 4).

3.3.3. Net income and BCR

Similar to costs and benefits, net income was highly variable with an average income of 1047 ± 949 € ha^{-1} y^{-1}, ranging from −1480 to 4303 € ha^{-1} y^{-1}, which includes benefits from other products except timber revenues. With an average value of 345 ± 314 € ha^{-1} y^{-1}, benefits from firewood, other crops and fruits and livestock add 49% to the average net farmer income obtained from coffee alone. Net income was significantly lower for High-Input compared to Low-Input, irrespective of whether also costs of family labour were included (Fig. 3e). No difference in income was detected between shade groups (Fig.3f), nor was there a difference in net income for plantations at different elevations (Fig. 4). BCR showed a high variability, with an average of 2.6 ± 3.1 and a range of −0.85 and 13.63. BCR was highest for Low-Input, followed by Medium-Input (Fig. 3g). These results suggest that the majority of the farming strategies were profitable as the break-even point of 1.0 was surpassed by 63% of the farmers. Although 14% of the farmers had five times higher returns than their investment costs, 37% of the farmers were experiencing losses, as their BCRs were < 1.0. In particular, BCR of plantations with highest input levels was on average 0.78 ± 1.05. No significant difference in net income or BCR was found between shade classes (Fig. 3f, h) and for each shade class, average BCR was > 1.0 (Fig. 3h; Table S6). BCR was significantly higher for plantations at higher elevations (Fig. 4).

4. Discussion

This case study provides evidence that the economic performance of coffee agroforestry systems is equally good or better than that of unshaded plantations and/or with higher input levels The novelty of this study is that the effects of shade and input practices on net income and BCR are taken into account, as well as costs and benefits of coffee production and benefits of other products, making this a comprehensive economic performance analysis. We find that while shade showed no relation with either net income or BCR, input was negatively related to economic performance. At the same time, these relations were elevation dependent likely due to differences in biophysical conditions. In the following sections, we discuss how the economic performance in terms of net income and benefit-cost ratio was affected by shade and input management, and what the implications are for smallholder coffee farmers.

4.1. Net income and benefit-cost ratio

The results of this study suggest that there is no difference in economic performance between small-scale coffee plantations with different shade levels as there were no differences between net income and BCR for plantations with different shade management practices. Rather, we observed a difference in economic performance between plantations with different levels of input as net income and BCR were lower for plantations with higher input practices. With an average net coffee income of 702 ± 961 € $\text{ha}^{-1}\,\text{y}^{-1}$, the results of this study are in line with a recent study of Nelson et al. (2016), where net income of Peruvian coffee farmers in the department of San Martín was estimated to be 836 € ha^{-1} in 2011. These observed average BCR values (2.6 ± 3.1) are in line with findings of a recent meta-analysis, where an average BCR value of 1.9 was obtained from thirteen shaded coffee systems located in six different countries (Jezeer et al., 2017). About a third of the farmers were experiencing losses, which are likely related to recent outbreaks of coffee leaf rust (*Hemileia vastatrix*) and the high costs of production, as explained in more detail below. Including the costs of family labour further reduced the BCR of these farmers. For all shade classes, average BCR was > 1.0, indicating that the average farmer was gaining income from their plantations. This is likely because of reduced average labour costs and lower average input costs across different shade levels, and (when taken into consideration) added benefits from firewood, livestock and other crops. In the next sections, we will elaborate on the benefits and costs associated with shade and input practices, as well as the effect of diversification, i.e., mixed cropping systems, on economic performance.

4.2. Benefits

With an average of 854 ± 514 kg $\text{ha}^{-1}\,\text{y}^{-1}$, coffee yield was comparable to average Arabica smallholder coffee plantations yields in Peru (Bean and Nolte, 2017; Nelson et al., 2016) and elsewhere in Latin American countries (Panhuysen and Pierrot, 2014; Soto-Pinto et al., 2000). An explanation for the large variation observed in coffee yields could be found in the recent outbreak of coffee leaf rust. This outbreak peaked in 2013/2014 in Peru (Avelino et al., 2015) and has been estimated to drop yields of Peruvian farmers on average by half (Nelson et al., 2016). Estimates of coffee yields were obtained from farmer surveys, similar to other studies (Beuchelt and Zeller, 2011; Haggar et al., 2017). This can be a source of error, since reporting yield for consecutive years relies on memory and annotations of the farmers. Unfortunately we do not have field data to verify these estimates, yet we expect that even if a few reportings of yield are erroneous they will have little effect on average values because of our large sample size. The general consensus is that yield decreases with increased levels of shade (Beer et al., 1998; Perfecto et al., 2005; Vaast et al., 2006). Our results support this as we observed lower coffee yields at higher shade tree densities, resulting in a negative relationship between coffee yield and shade index obtained from farmer survey data. No negative relation was observed between the shade index obtained from plot data and coffee yields, suggesting that the relationship depends on the methods used for measurements of shade. Though there is a possible bias of shade cover estimates as a result of visual estimation, this method was reported to be accurate (Bellow and Nair, 2003) in particular when using trained observers as we did (Vittoz et al., 2010). Also, our shade cover results showed strong correlation with shade tree density and mean shade tree height measured in the coffee farms (Table S3, Fig. S4) and importantly, shade cover was only used in combination with other variables (shade index) and therefore we expect that even if generally biased, its effect on our overall results and conclusions is limited.

In recent years, farmers gained stronger interest in high quality coffee as demand for specialty coffees increased rapidly; sustainable coffee sales (often certified) in terms of volume increased by > 400% between 2004 and 2009 and is only expected to increase further (Vellema et al., 2015). Fluctuating coffee prices are a major issue for smallholder coffee farmers, and it has been shown that in times of low world coffee prices the prices of certified coffee did not drop as low as overall market prices in Peru (Nelson et al., 2016). Although this was not observed, we saw that coffee prices were higher if gate quality was higher. A study in Mexican coffee systems shows that the dominant shift in this country to non-coffee activities was attributed to the low and variable coffee prices (Padrón and Burger, 2015), which suggests that changes in coffee price lead to diversification. As demonstrated for coffee production in Latin America, elevation and shade were expected to improve coffee quality (Muschler, 2001; Vaast et al., 2006). The relation with elevation was confirmed in this study, but we found no relationship between shade index and gate quality. These results are in line with a study of Bosselmann et al. (2009) in Colombia, where the relation between shade and quality was more complex as it depended on elevation. Although similar, the measure we used for bean quality is different from the measure of bean quality used by Vaast et al. (2006) and Bosselmann et al. (2009), which could have affected this observation.

4.3. Costs

With an average 1032 ± 783 € $\text{ha}^{-1}\,\text{y}^{-1}$, costs estimated in this study were comparable to those of a recent study which reported expenditures of approximately 1068 € $\text{ha}^{-1}\,\text{y}^{-1}$ for coffee production in the department of San Martín, Peru, and between 800 and 1300 € $\text{ha}^{-1}\,\text{y}^{-1}$ for coffee production in El Salvador and Colombia (Nelson et al., 2016). Costs of intensified systems were higher, both for flexible (input and labour) and fixed costs (land and equipment), while an opposite relation with shade was observed as costs were lower for plantations with higher shade levels. These dynamics are not just seen in Peru but also in other coffee producing countries. For example Gobbi (2000) demonstrated that in El Salvador, the capital requirements for shaded coffee systems were low and that these requirements increased with a reduction in shade levels. Land costs in particular were high in this study as they accounted on average for 44% of the total costs. These high land costs can be partially explained by the recommended 10% discount rate (Rahman et al., 2007). However, it was clear that High-Input plantations were associated with higher land costs in general, irrespective of this applied discount rate. This could indicate that if land costs are higher, farmers are more likely to resort to high intensity practices (high input – low shade) expecting that this will increase net benefits. More generally, our study results corroborate the understanding that intensive management is related to higher yields, as higher yields were positively correlated with amount of hired labour and costs. Importantly, increase in coffee yields was not correlated with net income for these farmers. This corroborates the findings of our recent review on the economic performance of shaded coffee and cocoa plantations where we found that in general yield alone is not a good indicator of economic performance of these production systems, and more comprehensive economic assessments are needed.

More generally, a steep increase in production costs was observed in major Latin American coffee producing countries in recent years (ICO, 2016), linked to increasing labour costs and to rising prices of agrochemical inputs. Indeed, as a response to the coffee leaf rust outbreaks, many of the farmers in the region have invested in their plantations by switching to more coffee rust resilient varieties to minimise future coffee rust induced yield losses. It appeared that farmers with high-input practices reported lower yield losses due to coffee rust (personal observation), but this was not translated into better economic performance. It has indeed been demonstrated that a reduction and misuse of inputs such as fertilizers and fungicides were important factors in the variability of the impact of the coffee rust epidemic (Avelino et al., 2015). Training of farmers to apply fertilizers and fungicides more effectively is therefore recommended. As small-scale farmers often have limited access to resources and capital, which is no different for Peru (USDA, 2014), the lower costs associated with high shade practices may be a more attractive option for many coffee farmers.

4.4. Diversification

Benefits derived from other products can greatly contribute to the income of small-scale farmers (Rice, 2008). In our case, income from other products accounted for an average of 32% of total farm income, excluding potential income from timber, and was lowest for plantations with high input levels and low shade levels. If the potential income from timber would be realized, the total yearly income could increase by a third in High-Shade plantations. Similar results were also found in Costa Rica and Guatemala, where income from timber and firewood accounted for > 70% of the income derived from shaded coffee plantations (Martínez Acosta, 2005; Mehta and Leuschner, 1997). Souza et al. (2010) found similar results, as income derived from other products (mainly fruits) added more than a third to the income of coffee farmers in Brazil. There is some uncertainty in our estimates of timber values due to small plot sizes and the occurrence of some large trees and highly valuable tree species, which resulted in high timber values when extrapolating to hectare. However, our sample size was large enough and we took care in avoiding such data points overly influencing the results. Our estimate of timber values combined sawn-mill prices with current standing stock, without including costs for e.g., felling and transport. The former two were likely overestimated as they did not reflect the price farmers could receive for the harvested round wood based in commercial tree height, while the later did not consider economic effects over a 30-year cycle. Overall, it is clear that benefits from fruit trees, timber or firewood are significant and may result in a better financial performance than would occur in plantations without shade trees or with a low amount of Inga trees (Beer et al., 1998). There are, however, important ecological and economic challenges that need to be overcome, such as market access and improving the management of shade trees. If these barriers are overcome, the benefits derived from shade trees can provide important contributions to farmers' livelihoods, especially in times of low coffee prices or productivity, thereby increasing farmers' economic resilience. Although the focus of this article is on economic performance, the assumption that environmental performance is higher with higher levels of shade or lower levels of input is important to make a case for farming systems that can reconcile economic and environmental goals.

Small-scale farmers are very sensitive to changes in coffee prices and declining coffee yields, as coffee often provides their main source of income. The farmers in San Martín are no exception, as coffee provided for > 50% of farmers' income (excluding potential timber revenues). Due to diversification, fluctuations in coffee prices will have a lower impact on total income (Gordon et al., 2007) as income from other products can be retrieved in times of low prices or failure of the coffee production. Also, environmental benefits provided by shade trees such as erosion control or nutrient cycling are less frequently included in these calculations, further underestimating potential benefits from agroforestry plantations. Compared with other Latin American coffee producing countries, intensification of shade practices in Peru is lower and only 2% of the total production was estimated to take place under full sun conditions in 2010 (Jha et al., 2014). Although this suggests that there is great potential for small scale coffee farmers in Peru to reconcile ecological and economic needs, more insight about the economic performance of coffee plantations under different management practices is needed in order to deviate from the global trend towards intensification of coffee systems.

5. Conclusions

Our results suggest that intercropping coffee with shade trees shows no negative relation with economic performance of smallholder coffee systems. Rather, income from other products, including income from timber, can provide these farmers with an extra source of income which is an opportunity to increase their economic resilience. As we find that economic performance shows no relation with shade management, our results suggest that conservation of biodiversity and associated ecosystem services can coincide with local development. This article therefore provides important evidence in the support of a transition towards economically and ecologically sustainable systems, which is not only needed to provide farmers with sustainable livelihoods, but also to decrease landscape degradation.

Economic performance is expected to be an important driver of farmer decision making. The most common argument against agroforestry practices is that the economic performance is relatively low in comparison to more intensive and/or unshaded plantations, thereby driving intensification practices which consequently result in environmental degradation. Extension services should support farmers with the choice of shade tree species and improved tree management, taking local market prices of timber and fruits into consideration. Furthermore, training of farmers to apply fertilizers and fungicides more effectively is highly recommended, keeping in mind that pest and disease control should be adapted to physical conditions of the plantation such as climate and soil. Such extension services seem to be increasingly important in response to the fluctuating coffee prices, rising production costs and increased pest and disease pressure.

In order to reconcile economic and ecological goals in coffee systems, comprehensive economic analyses are needed to be able to draw generalizable conclusions and gain insight in trade-offs between economic and environmental performance. To this regard, future economic performance studies should simultaneously address the effects of shade and input management on multiple economic performance indicators and take variation in biophysical variation into account.

Acknowledgements

We are grateful for the valuable support received by staff members of the local Solidaridad office in Moyobamba and Luis Sánchez Celis. We thank Vincent de Leijster, Claudia Rieswijk, Steffie Rijpkema and Rutger Baar for field data collection and two anonymous reviewers for their help with the manuscript. We thank all coffee farmers who welcomed us to their farms and shared experiences, knowledge and views on their farming practices. Data collection and data analysis were funded by the Business for Biodiversity project of Hivos, while Tropenbos International also supported data analysis and writing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.01.014.

References

Arrieta, N., Anzueto, F., Echeverria, F., McCook, G., Schuller Petzold, S., Obin, D., Pineda, J.A., Ramos, O., Rodríguez, C.M., Zamarripa, A., 2016. Las variedades de café de Mesoamérica y el Caribe. US, College Station.

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. Model. 197, 431–447. http://dx.doi.org/10.1016/j.ecolmodel.2006.03.013.

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. http://dx.doi.org/10.1007/s12571-015-0446-9.

Bacon, C., 2005. Confronting the coffee crisis: can fair trade, organic, and specialty coffees reduce small-scale farmer vulnerability in northern Nicaragua? World Dev. 33, 497–511. http://dx.doi.org/10.1016/j.worlddev.2004.10.002.

Bean, C., Nolte, G.E., 2017. Peru- coffee annual- peruvian coffee production bouncing back. In: USDA Foreign Agricultural Services. Global Agricultural Information Network.

Beer, J., Muschler, R., Kass, D., Somarriba, E., 1998. Shade management in coffee and cacao plantations. Agrofor. Syst. 38, 139–164. http://dx.doi.org/10.1023/A:100595652.

Bellow, J.G., Nair, P.K.R., 2003. Comparing common methods for assessing understorey light availability in shaded-perennial agroforestry systems. Agric. For. Meteorol. 114, 197–211. http://dx.doi.org/10.1016/S0168-1923(02)00173-9.

Beuchelt, T.D., Zeller, M., 2011. Profits and poverty: certification's troubled link for Nicaragua's organic and fairtrade coffee producers. Ecol. Econ. 70, 1316–1324. http://dx.doi.org/10.1016/j.ecolecon.2011.01.005.

Bosselmann, A.S., 2012. Mediating factors of land use change among coffee farmers in a biological corridor. Ecol. Econ. 80, 79–88. http://dx.doi.org/10.1016/j.ecolecon.2012.05.007.

Bosselmann, A.S., Dons, K., Oberthur, T., Olsen, C.S., Ræbild, A., Usma, H., 2009. The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia. Agric. Ecosyst. Environ. 129, 253–260. http://dx.doi.org/10.1016/j.agee.2008.09.004.

Bravo-Monroy, L., Potts, S.G., Tzanopoulos, J., 2016. Drivers influencing farmer decisions for adopting organic or conventional coffee management practices. Food Policy 58, 49–61. http://dx.doi.org/10.1016/j.foodpol.2015.11.003.

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. http://dx.doi.org/10.1007/s10457-014-9691-8.

Cerda, R., Allinne, C., Gary, C., Tixier, P., Harvey, C.A., Krolczyk, L., Mathiot, C., Clément, E., Aubertot, J.-N., Avelino, J., 2016. Effects of shade, altitude and management on multiple ecosystem services in coffee agroecosystems. Eur. J. Agron. 82, 308–319. http://dx.doi.org/10.1016/j.eja.2016.09.019.

Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T.C., Anshary, A., Buchori, D., Cicuzza, D., Darras, K., Putra, D.D., Erasmi, S., Pitopang, R., Schmidt, C., Schulze, C.H., Seidel, D., Steffan-Dewenter, I., Stenchly, K., Vidal, S., Weist, M., Wielgoss, A.C., Tscharntke, T., 2011. Combining high biodiversity with high yields in tropical agroforests. Proc. Natl. Acad. Sci. U. S. A. 2, 5–8. http://dx.doi.org/10.1073/pnas.1201800109.

R Core Team, 2014. A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, In.

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. http://dx.doi.org/10.1016/j.agee.2013.05.003.

FAO, n.d. Volume estimation [WWW Document]. URL http://www.fao.org/forestry/17109/en/ (accessed 6.12.17).

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. http://dx.doi.org/10.1038/nature10452.

Fox, J., Weisberg, S., Adler, D., Bates, D., Baud-Bovy, G., Ellison, S., Firth, D., Friendly, M., Gorjanc, G., Graves, S., Heiberger, R., Laboissiere, R., Monette, G., Murdoch, D., Nilsson, H., Ogle, D., Ripley, B., Venables, W., Winsemium, D., Zeileis, A., R-Core, 2016. An R Companian to Applied Regression.

Fraley, C., Raftery, A.E., Scrucca, L., Murphy, T.B., Fop, M., 2017. Mclust -Gaussian Mixture Modelling for Model-Based Clustering, Classification and Density Estimation.

Gobbi, J.A., 2000. Is biodiversity-friendly coffee financially viable? An analysis of five different coffee production systems in western El Salvador. Ecol. Econ. 33, 267–281. http://dx.doi.org/10.1016/S0921-8009(99)00147-0.

Gordon, C., Manson, R., Sundberg, J., Cruz-Angón, A., 2007. Biodiversity, profitability, and vegetation structure in a Mexican coffee agroecosystem. Agric. Ecosyst. Environ. 118, 256–266. http://dx.doi.org/10.1016/j.agee.2006.05.023.

Haggar, J., Soto, G., Casanoves, F., Virginio, E. de M., 2017. Environmental-economic benefits and trade-offs on sustainably certified coffee farms. Ecol. Indic. 79, 330–337. http://dx.doi.org/10.1016/j.ecolind.2017.04.023.

Hernández-Martínez, G., Manson, R.H., Hernández, A.C., 2009. Quantitative classification of coffee agroecosystems spanning a range of production intensities in central Veracruz, Mexico. Agric. Ecosyst. Environ. 134, 89–98. http://dx.doi.org/10.1016/j.agee.2009.05.020.

ICO, 2016. Assesing the Economic Sustainability of Coffee Growing, in: International Coffee Council. United Kingdom, London.

Jaramillo, J., Muchugu, E., Vega, F.E., Davis, A., Borgemeister, C., Chabi-Olaye, A., 2011. Some like it hot: the influence and implications of climate change on coffee berry borer (Hypothenemus hampei) and coffee production in East Africa. PLoS One 6, e24528. http://dx.doi.org/10.1371/journal.pone.0024528.

Jaramillo-Botero, C., Santos, R.H.S., Martinez, H.E.P., Cecon, P.R., Fardin, M.P., 2010. Production and vegetative growth of coffee trees under fertilization and shade levels. Sci. Agric. 67, 639–645. http://dx.doi.org/10.1590/S0103-90162010000600004.

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

Jha, S., Bacon, C.M., Philpot, S.M., Ernesto Mendez, V., Laderach, P., Rice, R.A., 2014. Shade coffee: update on a disappearing refuge for biodiversity. Bioscience 64, 416–428. http://dx.doi.org/10.1093/biosci/biu038.

Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agric. For. Meteorol. 144, 85–94. http://dx.doi.org/10.1016/j.agrformet.2006.12.009.

Lyngbæk, A.E., Muschler, R.G., Sinclair, F.L., 2001. Productivity and profitability of multistrata organic versus conventional coffee farms in Costa Rica. Agrofor. Syst. 53, 205–213. http://dx.doi.org/10.1023/A:1013332722014.

Martínez Acosta, M.H., 2005. Contribución económica del componente forestal en diferentes tipos de fincas cafetaleras en la bocacosta pacifica de Guatamala. CATIE, Turrialba, Costa Rica.

Mas, A., Dietsch, T., 2003. An index of management intensity for coffee agroecosystems to evaluate butterfly species richness. Ecol. Appl. 13, 1491–1501. http://dx.doi.org/10.1890/01-5229.

Mehta, N.G., Leuschner, W.A., 1997. Financial and economic analyses of agroforestry systems and a commercial timber plantation in the la Amistad biosphere reserve, Costa Rica. Agrofor. Syst. 37, 175–185. http://dx.doi.org/10.1023/A:100584052.

Meylan, L., Gary, C., Allinne, C., Ortiz, J., Jackson, L., Rapidel, B., 2017. Evaluating the effect of shade trees on provision of ecosystem services in intensively managed coffee plantations. Agric. Ecosyst. Environ. 245, 32–42. http://dx.doi.org/10.1016/j.agee.2017.05.005.

Morton, J.F., 2007. The impact of climate change on smallholder and subsistence agriculture. Proc. Natl. Acad. Sci. 104, 19680–19685. http://dx.doi.org/10.1073/pnas.0701855104.

Muschler, R.G., 2001. Shade improves coffee quality in a sub-optimal coffee zone of Costa Rica. Agrofor. Syst. 85, 131–139. http://dx.doi.org/10.1023/A:101060332.

Nelson, V., Haggar, J., Martin, A., Donovan, J., Borasino, E., Hasyim, W., Mhando, N., Senga, M., Mgumia, E., Quintanar Guadarrama, E., Kendar, Z., Valdez, J., Morales, D., 2016. Fairtrade Coffee: A Study to Assess the Impact of Fairtrade for Coffee Smallholders and Producer Organisations in Indonesia, Mexico, Peru and Tanzania. Chatham, United Kingdom.

Padrón, B.R., Burger, K., 2015. Diversification and labor market effects of the Mexican coffee crisis. World Dev. 68, 19–29. http://dx.doi.org/10.1016/j.worlddev.2014.11.005.

Panhuysen, S., Pierrot, J., 2014. Coffee Barometer 2014. Hivos, The Hague.

Pennington, T.D., Reynel, C., Daza, A., 2004. Illustrated Guide to the Trees of Peru. DH Books, Sherborne, England.

Perfecto, I., Vandermeer, J., 2015. Coffee Agroecology- a New Approach to Understanding Agricultural Biodiversity, Ecosystem Services and Sustainable Development. Routledge. US, New York.

Perfecto, I., Rice, R.A., Greenberg, R., van der Voort, M.E., 1996. Shade coffee: a disappearing refuge for biodiversity. Bioscience 46, 598–608.

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

Rahman, S.., Rahman, M.., Codilan, A.., Farhana, K.., 2007. Analysis of the economic benefits from systematic improvements to shifting cultivation and its evolution towards stable continuous agroforestry in the upland of eastern Bangladesh. Int. For. Rev. 9, 536–547. http://dx.doi.org/10.1505/ifor.9.1.536.

Rice, R.A., 2008. Agricultural intensification within agroforestry: the case of coffee and wood products. Agric. Ecosyst. Environ. 128, 212–218. http://dx.doi.org/10.1016/j.agee.2008.06.007.

Rosero, P.Y.G., Sánchez, S.A.M., Narváez, I.E.P., 2015. Caracterización Física De Café Especial (Coffea Arabica) En El Municipio De Chachagüí (Nariño, Colombia). Rev. Lasallista Investig. 12, 90–98.

Samnegård, U., Hambäck, P.A., Nemomissa, S., Hylander, K., 2014. Dominance of the semi-wild honeybee as coffee pollinator across a gradient of shade-tree structure in Ethiopia. J. Trop. Ecol. 30, 401–408. http://dx.doi.org/10.1017/S0266467414000327.

Gobierno Regional de San Martín, 2008. Climate data San Martín [WWW Document]. Perú. URL http://es.climate-data.org/ (accessed 2.3.17).

Gobierno Regional de San Martín, 2012. San Martín Forestal en Números, Año 2012. Boletin Semestral I-2012.

Schroth, G., da Fonseca, G.A.B., Harvey, C.A., Gascon, C., Vasconcelos, H.L., Izac, A.N., 2004. Agroforestry and Biodiversity Conservation in Tropical Landscapes. Island Press, Washington, DC.

Schroth, G., Jeusset, A., Gomes, A.D.S., Florence, C.T., Coelho, N.A.P., Faria, D., Läderach, P., 2014. Climate friendliness of cocoa agroforests is compatible with productivity increase. Mitig. Adapt. Strateg. Glob. Chang. 21, 67–80. http://dx.doi.org/10.1007/s11027-014-9570-7.

Siebert, S.F., 2002. From shade- to sun-grown perennial crops in Sulawesi, Indonesia: implications for biodiversity conservation and soil fertility. Biodivers. Conserv. 11, 1889–1902. http://dx.doi.org/10.1023/A:102080461.

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

Souza, H.N., Cardoso, I.M., Fernandes, J.M., Garcia, F.C.P., Bonfim, V.R., Santos, A.C., Carvalho, A.F., Mendonça, E.S., 2010. Selection of native trees for intercropping with coffee in the Atlantic rainforest biome. Agrofor. Syst. 80, 1–16. http://dx.doi.org/10.1007/s10457-010-9340-9.

Steffan-Dewenter, I., Kessler, M., Barkmann, J., Bos, M.M., Buchori, D., Erasmi, S., Faust, H., Gerold, G., Glenk, K., Gradstein, S.R., Guhardja, E., Harteveld, M., Hertel, D., Hohn, P., Kappas, M., Kohler, S., Leuschner, C., Maertens, M., Marggraf, R., Migge-Kleian, S., Mogea, J., Pitopang, R., Schaefer, M., Schwarze, S., Sporn, S.G., Steingrebe, A., Tjitrosoedirdjo, S.S., Tjitrosoemito, S., Twele, A., Weber, R., Woltmann, L., Zeller, M., Tscharntke, T., 2007. Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. Proc. Natl. Acad. Sci. 104, 4973–4978. http://dx.doi.org/10.1073/pnas.0608409104.

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. http://dx.doi.org/10.1111/j.1365-2664.2010.01939.x.

USDA, 2014. Annual Global Agricultural Information Network (GAIN) Report on Green Coffee. Production, Peru Targets Expanded Coffee.

Vaast, P., Bertrand, B., Perriot, J.J., Guyot, B., Génard, M., 2006. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (Coffea Arabica L.) under optimal conditions. J. Sci. Food Agric. 86, 197–204. http://dx.doi.org/10.1002/jsfa.2338.

Valqui, M., Feather, C., Llanos, R.E., 2015. Revealing the Hidden - Indigenous Perspectives on Deforestation in the Peruvian Amazone; the Causes and Solutions. Lima, Perú.

Vellema, W., Buritica Casanova, A., Gonzalez, C., D'Haese, M., 2015. The effect of specialty coffee certification on household livelihood strategies and specialisation. Food Policy 57, 13–25. http://dx.doi.org/10.1016/j.foodpol.2015.07.003.

Vittoz, P., Bayfield, N., Brooker, R., Elston, D.A., Duff, E.I., Theurillat, J.P., Guisan, A., 2010. Reproducibility of species lists, visual cover estimates and frequency methods for recording high-mountain vegetation. J. Veg. Sci. 21, 1035–1047. http://dx.doi.org/10.1111/j.1654-1103.2010.01216.x.

Waller, J.M., Bigger, M., Hillocks, R.J., 2007. World coffee production. In: Pests, Coffee (Ed.), Diseases and Their Management. CABI, Egham, Surrey, UK, pp. 17–33. http://dx.doi.org/10.1079/9781845931292.0000.

Wintgens, J.N., 2012. In: 2nd, revised edition (Ed.), Coffee: Growing, Processing, Sustainable Production - A Guidebook for Growers, Processors, Traders, and Researchers. Wiley, Weinheim. http://dx.doi.org/10.1002/9783527619627.

Wulan, Y.C., Budidarsono, S., Joshi, L., 2008. Economic Analysis of Improved Smallholder Rubber Agroforestry Systems in West Kalimantan, Indonesia - Implications for Rubber Development. In: Sustainable Sloping Lands and Watershed Management Conference, pp. 431–444.