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The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia

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ABSTRACT

Production of coffee, especially by small holders, is often associated with various forms of shade management. To analyse the effects of shade on physical coffee quality and on sensorial cup quality of *Coffea arabica* L. cv. Caturra KMC, a study was carried out with 94 plots on 16 farms in two municipalities, Timaná and Oporapa, located at elevations from 1272 to 1730 masl. in Huila, Colombia. The study was designed with emphasis on shade cover variation within each of the two study areas, while minimizing the variability of environment, agronomic management other than shade, and post-harvest processing. 46 samples of shade coffee and 46 samples of sun coffee were evaluated for physical and sensorial attributes using three professional coffee cuppers (assessors). A principal component analysis including all quality and environmental variables showed that sensory attributes were influenced negatively by shade, and that physical attributes were influenced positively by altitude. A mixed linear model, with coffee cupper and farm as random variables, revealed different shade effects on coffee quality in the two areas. In Oporapa, situated at high altitudes, shade had a negative effect on fragrance, acidity, body, sweetness and preference of the beverage, while no effect was found on the physical quality. In Timaná, situated at lower altitudes, shade did not have a significant effect on sensorial attributes, but significantly reduced the number of small beans. At high altitudes with low temperatures and no nutrient or water deficits, shade trees may thus have a partly adverse effect on *C. arabica* cv. Caturra resulting in reduced sensory quality. The occurrence of berry borer (*Hypothenemus hampei*) was lower at high altitudes and higher under shade. Future studies on shade and coffee quality should focus on the interaction between physical and chemical characteristics of beans.

1. Introduction

Coffee is one of the most important commodities worldwide, at times only surpassed by oil (Ponte, 2002). Even so, the price paid to coffee producers in 2001 was the lowest in real terms in 100 years and below production costs in many parts of the tropical America (ICO, 2002; Varangis et al., 2003). Small coffee producers struggle to secure satisfactory economic returns on a volatile world market, where climatic events and few large companies influence prices significantly (Ponte, 2002; Muradian and Pelupessy, 2005). One possibility for small holder farmers to gain increased market shares and to reduce their vulnerability to fluctuating prices is to differentiate their coffee product through certification schemes such as fair trade, organic or Bird Friendly® coffee. However, it has been demonstrated that certification is not enough to ensure increased market shares and an added value to coffee (Kilian et al., 2006). Despite a growing demand for certified coffee, producer prices for fair trade and organic coffee is predicted to decrease in the future as supply of these coffees increases faster than demand (Giovannucci, 2001, 2003). Another and perhaps more viable differentiation strategy focus on specialty or gourmet coffee of high quality.

Production of high quality Arabica coffee depends on three main factors: the genetic resource, environmental conditions, and management (both agronomic and post-harvest management). For most coffee producers the environmental conditions, e.g. topography and climate, are given, while the genetic resource depends on choice of coffee variety and provenance. Besides use of fertilizer and pesticides, pruning of coffee trees, etc., agronomic management also involves shade management. Though not a prerequisite,

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production of certified organic and specialty gourmet coffees are often associated with various forms of agronomic management of shade trees. Shade management ranges from coffee systems under natural untouched forest cover over scattered multipurpose trees to highly controlled shade in commercial agroforestry systems (Vaast and Harmand, 2002; Perfecto et al., 2005). Some work has been done to document the relationship between shade and coffee yield, e.g. Beer (1987) and DaMatta (2004) find positive effects in suboptimal locations, whereas Soto-Pinto et al. (2000) find negative effects when shade density is above 50%. The effects on physical and in particular on cup quality are less documented. At low altitudes where the climate is warmer than what is considered optimal for coffee, shade is found to improve physical quality and organoleptic attributes of the brew of some Arabica varieties (Muschler, 2001; Vaast et al., 2005). The benefits of shade are explained primarily by a reduction of heat-induced stress in the plant and a lengthening of the maturation period of coffee berries (Muschler, 2001; Vaast et al., 2006). However, shade effects are site specific and there is a need for studying the relations between shade and cup quality along environmental gradients (Beer et al., 1998; Muschler, 2001). Especially at higher altitudes with lower temperatures, the effects of shade on cup quality are unclear (Guyot et al., 1996; Avelino et al., 2005).

The objective of this study was to test the hypothesis, derived from the above studies, that shade improves the beverage and physical qualities of coffee grown under favourable conditions. We also investigated the importance of altitude in these conditions. The study was conducted in fields of *Coffea arabica* L. cv. Caturra KMC with irregularly distributed shade trees.

2. Materials and methods

2.1. Research site

The study was carried out at 16 small-scale coffee producing farms (<2.5 ha) in two neighbouring municipalities, Oporapa and Timaná in Huila in the Southern part of Colombia, from October to November 2006. Until the 1980s, the area was characterized by densely shaded coffee fields, but after the introduction of new coffee varieties the area was converted into more open coffee fields with large variations in shade levels between farms. The most common shade trees are the leguminous tree genera *Inga* spp., which is frequent in Timaná, and *Erythrina* spp. which is frequent in Oporapa. Other shade species in the areas include Citrus trees, banana (*Musa* spp.), fig trees (*Ficus* spp.) and Laural (*Cordia* spp.).

The two municipalities are situated at different altitudes on the south face of each of two parallel mountain ridges in the central mountain range in Huila. Farms in Timaná are situated at 1°56′N, 75°57–58′W, at 1270–1630 masl. with average annual temperature at 19.8 °C, while farms in Oporapa are distributed at 2°2′N, 75°58′W, in altitudes of 1590–1730 masl., with an annual temperature of 18.6 °C. Mean annual rainfall in both areas is 1600 mm. All the farms in both municipalities are located on slopes with inclinations between 20° and 45° and orientations between 100° and 160°. Soil samples taken from a depth of 40 cm from the study sites show that soil textures are predominantly clay and clay loam.

Mean annual temperatures and rainfall at farm level were obtained from the global WorldClim 1.4 climate model of 1 km^2 resolution. The WorldClim consists of a set of data layers generated through interpolation of average monthly climate data from weather stations and climate databases supported by the SRTM Digital Elevation Model (Hijmans et al., 2005).

Due to abundant and continuous rainfall there is no irrigation and water treatment on the fields. Furthermore, coffee trees flower all year. Some farmers harvest throughout the year while others only harvest in the main and minor harvest seasons, October–December and February–March. During the main harvest season, farmers carry out 2–6 harvests. Main coffee varieties in the two areas are *C. arabica* cv. Caturra and to a lesser degree cv. Colombia. Farmers process the coffee on their farms and sell the coffee as dry beans with husk either to local buyers or to farmers' coffee associations.

2.2. Selection of sample areas, farms and plots

The municipalities for this study were chosen because of their high final grades in the national competition 'Cup of Excellence®' (COE, 2007). In both municipalities, the hill side with south-east orientation was chosen as sampling area due to topographic and climatic homogeneity. Sampling was carried out to keep agronomic management and environmental factors, besides shade cover, within defined ranges (Table 1). The ranges were defined and farms were selected during a preliminary survey, where (i) shade systems, aspects and inclinations of the hill sides were recorded by use of binoculars, compass and inclinometer, (ii) potential farms were visited, and characteristics of the coffee fields, such as variety, plant height and soil conditions were visually assessed, and (iii) short semi-structured interviews were held with owners of potential farms to establish main agronomic practices. Farms that fell outside the predefined ranges were omitted. Before, during and after harvest, some farms were taken out of the study due to practical difficulties such as changes in harvest dates or uncertainties regarding ownership and user rights as well as boundaries of certain fields. The final selection included 16 farms out of approximately 200 in the study areas.

The selected farms had coffee agroforestry systems with irregularly distributed shade trees. Shade plots of 10 m × 10 m were placed beneath the larger shade trees. Next to each shaded plot and within the same field an unshaded plot was marked, thereby creating pairs of plots with maximum difference in shade percentage, but with same inclination, aspect, management and age of coffee plants. In sun plots there was no shade canopy directly above the coffee trees, but lower degrees of shade was provided from trees in the perimeter of some plots.

2.3. Shade percentage

Shade percentage was measured by analysis of hemispheric photos taken with a Nikon Coolpix 4500 digital camera with a FC-E8 fish eye lens with a field of view of 180° including all shade trees directly above the coffee plants and in the horizon. The camera was placed on a gyroscope that maintained the camera in a constant

Table 1
Parameters used in farm selection; ranges determined during a preliminary survey in the two study areas.

Parameters	Requirements/ranges
Shade system	Shade and sun coffee within the same field
Inclination of slope	20–45°
Aspect of slope	100–160°
Arabica variety	Caturra
Coffee trees per hectare	Coffee plant distances > 2 m
Height of coffee trees	>1.3 m
Age of coffee trees	>3 years from planting
Soil texture	Soils without high sand or gravel content
Chemical fertilizer	N–P–K mix, between 500 and 2000 kg ha^{-1} $year^{-1}$
Organic fertilizer	No
Use of insecticides	No
Pruning of coffee trees	Yes
Pruning of shade trees	No

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vertical position. In each plot, four pictures were taken in the middle of a transect from the centre of the plot to each corner. The photos were analyzed individually in WinSCANOPY 2005 (Regent Instruments Inc., 2005), where image pixels were classified into two categories, sky or canopy. WinSCANOPY calculates the gap fraction (GF) as the number of sky pixels over total number of pixels for the complete hemisphere of 180°, where hill side and coffee trees have been manually masked away in WinSCANOPY. The shade percentage was then found as (1-GF)*100 and the average of the four photos were calculated for each plot.

2.4. Agronomic data

In each plot, the average distance between coffee plants, height of the coffee plants and local names of the shade trees were recorded. Specimens of shade trees were preserved for later determination of scientific names of family and genera. Soil organic matter (SOM) content and soil pH were measured in soil samples taken from the centre of each plot, whereas soil texture analysis was done for one sample from each farm taken in-between all plots. All samples were dried and ground where after soil texture was found by use of the hydrometer method (Bouyoucos, 1927). Soil pH was found by potentiometer in a 1:1 relation with water, and SOM was determined using the Walkley–Black method (Walkley and Black, 1932).

2.5. Coffee sampling and post-harvest processing

Harvest and post-harvest procedures were kept constant by uniform procedures. All coffee samples were harvested within 10 days in the peak harvest period in October 2006. From each plot, marked with coloured tape and plot identification, approximately 5 kg of coffee berries were harvested by two teams, each consisting of farm workers and researchers. Only fully ripe berries were harvested, determined by the bright red colour. In order to ensure uniformity, all coffee samples were evaluated by the same person and any unripe or over mature berries were discarded. Every day before 2 p.m. samples were depulped and demucilaged in a mobile processing machine (J.M. Estrada Model 100 unit). The largest and smallest beans (an estimated 3% per sample) were discarded in the process due to technical limitations of the processor. The samples were left to ferment in separate 10 l buckets for 5 h, before they were washed manually and then dried in a mobile gas heated oven at 40–50 °C until a humidity level between 9 and 12% was reached. The dry samples of approximately 1 kg of parchment beans (with husks) were stored in perforated plastic bags under identical conditions for a minimum of 15 days prior to the first sensorial evaluation.

2.6. Evaluation of coffee quality

The coffee samples were evaluated during two cupping sessions. The first session took place in Huila, Colombia, November 2006, and the second session took place in Copenhagen, Denmark, March 2007. Before the cupping sessions, the parchment (endocarp) was removed by a de-husking machine designed for test samples and an evaluation of the physical quality of the green beans was carried out. Beans attacked by coffee berry borer (*Hypothenemus hampei* Ferrari) were visually detected, discarded and registered by weight for each sample. The beans were passed through a series of sieves, whereby being divided into classes of small, medium sized, and large beans corresponding to bean diameters of ≤6.35, ≤6.75 and >6.75 mm (corresponding to screen sizes 16 and 17).

Prior to each cupping beans with visual defects were removed by hand. At the first cupping session, samples of 120 g were roasted according to a predefined roasting curve to ensure identical roasting of all samples. The roasting curve dictates the exact temperature in the roaster for each minute of the roasting procedure. Samples that deviated from the curve with more than 2 °C in at least one of the 9 min of roasting were discarded, and another batch from the same sample was then roasted. Identical roasting procedures were also followed in the second cupping, where a luminance measurement (colour of finely ground beans) of the roasted samples was used as an indicator of the degree of roasting. At both cupping sessions, coffee samples were roasted 48 h prior to assessment.

Both cupping sessions followed the CIAT protocol, which are developed from the procedures and formats of the Specialty Coffee Association of America (SCAA) and Cup of Excellence® (Lingle, 2001; COE, 2007). The coffee assessment was done by three professional SCAA-certified cuppers who regularly work with specialty coffee quality control. Two assessors made the first cupping, whereas the third assessor made the second cupping. The evaluated organoleptic attributes were fragrance, aroma, aftertaste, acidity, sweetness, bitterness, body, and preference. All attributes were rated from 1 (very poor) to 10 (outstanding), except bitterness, which was rated from 1 (imperceptible, best) to 10 (intense, adverse). In order to avoid bias, the presentation of samples was randomized and identities of the samples were not known to the cuppers. Bitterness was evaluated by the third cupper only.

2.7. Descriptive analysis

In order to acquire an overview, summary statistics were made for all numerical data. A principal component analysis (PCA) of sensorial scores from each cupper was carried out as described by Kermit and Lengard (2005) and confirmed that the cuppers generally agreed, which meant that an average of the three cuppers' scores could be used in subsequent analyses. PCA was also used for a descriptive analysis in order to find groupings of and relationships between quality attributes and plot factors. The analyses were carried out in Unscrambler version 9.2 by CAMO process AS, Oslo and all variables were auto-scaled with the purpose of reducing the non-systematic variation in the data.

2.8. Statistical analyses

In order to analyze the relation between quality and plot factors, as well as differences between shade and sun plots as prompted by the sampling of paired plots, two statistical approaches were chosen for data analysis; a mixed linear model and a paired *t*-test. The mixed linear model was used to find significant effects of plot factors on coffee quality attributes. The model uses multiple regressions to analyze the variance of one-dependent variable by several fixed and random independent variables. The variables included in the analysis are listed in Table 2.

Data from plots at the same farm, as well as the scores given by the same cupper, were correlated. These correlations are represented in the model by including the two categorical variables farm and cupper as random variables. The scores from the three cuppers were analyzed together, which meant that there were $n = 282$ observations for each sensory attribute (3 cuppers × 94 plots) minus possible missing scores. The following equation shows the mixed linear model:

$$Y_i = \alpha + \beta_1 X_{i1}, \ldots, \beta_5 X_{i5} + \lambda(S_i) + \gamma(C_i) + \delta(F_i) + \varepsilon_i,$$
$$\gamma(1), \ldots, \gamma(3) \sim N(0, \sigma_1^2), \delta(1), \ldots, \delta(16) \sim N(0, \sigma_2^2),$$
$$\varepsilon_i \sim N(0, \sigma^2), i = 1, \ldots 282, \quad (1)$$

where Y_i is the ith observation of the dependent variable, i.e. a quality attribute, X_{1-5} are the fixed independent variables (shade

Table 2
List of dependent and independent variables used in data analysis. Soil texture, cupper and farm are categorical variables.

Dependent variables[a]		Independent variables	
Small beans percentage, <6.35 mm	Aftertaste score	Shade cover percentage	Soil pH
Large beans percentage, >7.14 mm	Acidity score	Soil organic matter (SOM)	Cupper (random)
Berry borer defects	Sweetness score	Coffee trees per hectare	Farm (random)
Fragrance score	Body score	Height of coffee trees	Altitude[b]
Aroma score	Preference score	Soil texture	

[a] Bitterness is not included in the mixed linear model as only one cupper evaluated the samples for this attribute.
[b] Altitude is only included in the analysis of each separate area.

percentage, soil organic matter, coffee trees per hectare, height of coffee trees and soil pH), S is the fixed variable soil texture, C and F are the two random variables cupper and farm, α is the general intercept, β_{1-5} and λ are the parameters for the fixed variables, γ and δ are parameters for the random variables, and ε_i are the errors of the model. γ, δ and ε_i are assumed to be independent and normally distributed with means 0 and variance $\sigma_1^2, \sigma_2^2, \sigma^2$. The variance for the ith observation is Var $Y_i = \sigma^2 + \sigma_1^2 + \sigma_2^2$. Residual plots were made in order to assess the model and generally showed that the model described the data well. Except shade cover, which was the main factor of interest, other independent variables were eliminated from the model if they were not significant ($p < 0.05$) using a stepwise elimination. The two areas were analyzed jointly as well as separately. The analyses were performed in SAS version 9.2 by SAS Institute Inc. New York. Covariance parameters were found by the restrictive maximum likelihood estimation, while the Kenward–Rogers method was used for approximation of the denominator degrees of freedom for the test of significant fixed effects as recommended by Spike et al. (2004) and Piepho et al. (2003).

In order to analyze the differences between shade and sun plots with shade as the only source of variation, pairs of shade and sun plots with identical plot factors were analyzed with a paired t-test. This secured that all environmental factors other than shade are controlled within each pair of plots.

A correlation analysis of quality attributes and luminance was done in order to assess if the roasting degree affected sensorial attributes or was affected by bean size.

3. Results

With the exception of shade cover, there were no significant differences in management attributes between shade and sun plots. This was expected from the study design, which emphasized shade cover variability and minimized differences in other factors (Table 3). Shade cover ranged from 3 to 67%, while the average difference in shade cover between pairs of shade and sun plots was 33% points, with a minimum difference of 10 and a maximum of 53% points.

3.1. Principal component analysis

A PCA was performed for all quality attributes and independent variables. Fig. 1 shows the first two principal components (PC1 and PC2), which accounted for a total of 42% of the variation in the original data. The two principal components provide an overview of the covariation between variables. The immediate findings support the average values reported in Table 4. PC1 is based on the variation in sensory attributes, which are divided into two groups of olfaction (smell) and gustation (taste) attributes that both appear to covary negatively with shade percentage due to their location opposite of the centre (0,0) relative to shade. Other plot factors exhibit less covariation with sensory attributes. PC2 is based on the variation in altitude and bean sizes. It appears that altitude covaries positively with height of coffee trees and large bean percentage, and negatively with small bean percentage. Berry borer occurrence is located opposite altitude and to a lesser degree

Table 3
Means and standard deviations (S.D.) of all numeric variables. The data is organized into four groups: Oporapa, Timaná, sun and shade plots. Quality attribute means are adjusted for the effect of the variable farm and in the case of sensory attributes also cupper. Small and large beans percentages are determined after de-pulping. Soil samples were taken at a depth of 40 cm. The categorical variables farm and cupper are not included in the table.

Variables		Oporapa (n = 40)		Timaná (n = 54)		Sun plots (n = 47)		Shade plots (n = 47)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Plot factors	Altitude (masl.)	1629	48.4	1439	84	1521	119	1518	119
	Shade cover (%)	26.3	18.7	29.2	19.1	11.5	6.1	44.5	11.2
	Height of coffee (m)	2.1	0.3	1.9	0.4	1.9	0.3	2.1	0.4
	Coffee trees/ha	5317	1300	5132	998	5190	1129	5231	1148
	Soil pH	4.7	0.6	4.9	0.6	4.9	0.7	4.7	0.6
	SOM (%)	5.2	2.3	5.0	2.0	5.1	2.3	5.1	2.0
	Soil clay[a] (%)	44	10	47	10	n.a.		n.a.	
	Soil silt[a] (%)	17	6	26	11	n.a.		n.a.	
	Soil sand[a] (%)	39	11	27	13	n.a.		n.a.	
Physical quality attributes	Small beans (%)	1.4	0.34	2.2	0.26	2.2	0.25	1.7	0.24
	Large beans (%)	87	2.0	85	1.5	84	1.3	86	1.3
	Berry borer (%)	0.15	0.13	0.35	0.10	0.22	0.08	0.32	0.08
Sensory quality attributes	Fragrance	6.81	0.13	6.91	0.10	7.05	0.10	6.68	0.10
	Aroma	6.85	0.10	6.97	0.08	7.06	0.09	6.77	0.09
	Aftertaste	6.80	0.15	6.74	0.12	6.86	0.12	6.66	0.12
	Acidity	6.80	0.20	6.88	0.16	7.04	0.14	6.66	0.13
	Body	7.07	0.14	7.21	0.11	7.23	0.10	7.04	0.10
	Sweetness	6.96	0.14	6.95	0.11	7.14	0.11	6.77	0.11
	Bitterness	2.60	0.14	2.85	0.12	2.78	0.13	2.72	0.13
	Preference	6.91	0.20	6.91	0.15	7.10	0.14	6.72	0.14

[a] In the analyses, soil clay, silt, and sand are replaced by soil texture classes, which are based on the proportions of the three components.

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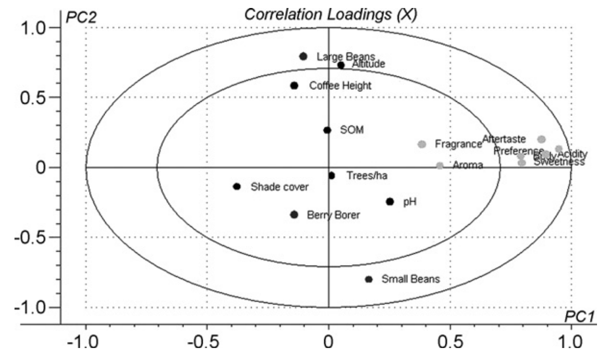

Fig. 1. PCA loading plot of plot factors (black dots), physical attributes (dark grey) and sensory attributes (light grey), excluding bitterness. As a categorical variable soil texture cannot be included in the loading plot. Sensory attributes are average scores of the three cuppers. PC 1 and 2 explain 27 and 15% of the variance in the data, respectively. The factors clustered to the right in the figure are preference, acidity, body and sweetness.

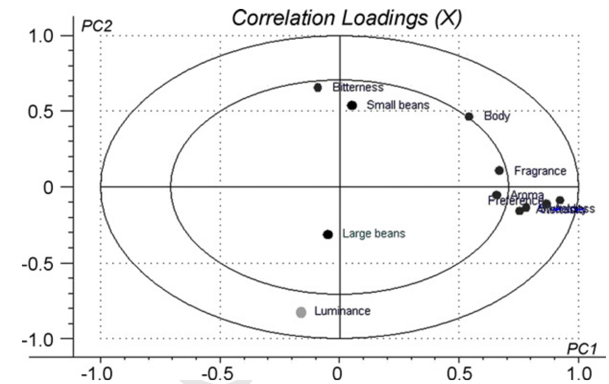

Fig. 2. Loading plot of sensory attributes (grey dots), small- and large-bean percentages (dark grey) and luminance (light grey) of the roasted beans. All variables are auto-scaled. Large bean percentage is passive, i.e. do not contribute variation to the two PCs. PC 1 and 2 explain 39 and 17% of the variance in the data. The factors clustered to the right are aroma, preference, acidity, aftertaste and sweetness.

Table 4
Q2 Pearson correlation coefficients (r) between luminance and body, bitterness and bean size percentages and associated probabilities under H0: no correlation. The other quality attributes did not covary significantly with luminance.

Regressor	Luminance	
	r	$Pr > \|r\|$
Body	−0.34	0.001***
Bitterness	−0.31	0.009**
Small beans	−0.38	0.002**
Large beans	0.22	0.060 ns

$^{*}p < 0.05$.
$^{**}p < 0.01$.
$^{***}p < 0.001$.

in the same direction as shade. Generally, sensory attributes appear to be influenced by shade cover, while physical attributes appear to be influenced by altitude.

Bitterness was omitted in the PCA in Fig. 1, because it was found that this particular attribute was predominantly influenced by the degree of roasting. Fig. 2 shows a loading plot from a PCA with data from the second cupping including all sensory attributes, bean sizes and luminance, which is an indicator for the roast degree. Lighter roasts have higher luminance. Lighter roasts were less bitter as indicated by the position of bitterness which is placed opposite luminance relative to PC2. Body was also influenced by roasting, but not exclusively as bitterness, which can be seen by the positions of the variables in Fig. 2. Other quality attributes showed no covariation with luminance. Luminance was affected by bean size with small beans resulting in a darker roast than large beans. This was confirmed in a test of linear correlation between luminance and bean size (Table 4). The positive relation between bitterness and small beans observed along PC2 in Fig. 2 could not be verified.

3.2. The influence of shade on sensorial quality

The results of the mixed linear model confirm the findings in Fig. 1. When coffee samples from both areas were analyzed jointly fragrance, acidity, body, sweetness and preference were negatively influenced by shade cover ($p < 0.05$, Table 5). The same was found when samples from Oporapa were analyzed separately. When samples from Timaná were analyzed alone, no significant effects of shade cover on any of the seven sensory attributes were found. In samples from Oporapa, fragrance was significantly affected by altitude with better fragrance found at higher altitudes. Similarly, aroma was found to be influenced by pH and after taste was influenced by trees per hectare, though not significantly. These were the only cases where a plot factor other than shade was eliminated from the mixed linear model later than shade.

The findings from the mixed linear model were supported by similar results from a paired t-test. However, not only were scores for fragrance, acidity, body, sweetness and preference significantly higher in sun plots than in shade plots when both areas were analyzed jointly, so was scores for aroma and aftertaste, i.e. all seven sensory attributes (Table 7).

3.3. The influence of shade on bean size and berry borer occurrence

The proportion of small beans significantly decreased with increasing shade level in Timaná and when both areas were

Table 5
Q2 Results of tests of shade cover by the mixed linear model. The parameter estimates indicate the difference in the attribute value to a change in shade percentage.

Attribute	Both areas		Oporapa		Timaná	
	Parameter estimate	$Pr > F$	Parameter estimate	$Pr > F$	Parameter estimate	$Pr > F$
Fragrance	−0.011	0.015*	−0.014	0.008**	−0.008	0.057 ns
Aroma	−0.005	0.087 ns	−0.008	0.106 ns	−0.004	0.296 ns
Aftertaste	−0.003	0.425 ns	−0.009	0.124 ns	0.001	0.898 ns
Acidity	−0.011	0.005**	−0.016	0.006**	−0.008	0.123 ns
Body	−0.007	0.015*	−0.010	0.036*	−0.006	0.124 ns
Sweetness	−0.011	0.006**	−0.013	0.011*	−0.009	0.093 ns
Preference	−0.011	0.006**	−0.018	0.003**	−0.005	0.280 ns

The level of significance: ns at $p > 0.05$. $^{***}p < 0.001$.
$^{*}p < 0.05$.
$^{**}p < 0.01$.

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Table 6
Q5 Results of tests of shade cover by the mixed linear model.

Attribute percentages	Both areas		Oporapa		Timaná	
	Parameter estimate	$Pr > F$	Parameter estimate	$Pr > F$	Parameter estimate	$Pr > F$
Small beans	−0.012	0.028*	−0.003	0.618 ns	−0.019	0.024*
Large beans	0.035	0.130 ns	0.031	0.310 ns	0.038	0.070 ns
Berry borer	0.002	0.069 ns	0.001	0.609 ns	0.003	0.254 ns

The level of significance: ns at $p > 0.05$. ** $p < 0.01$; *** $p < 0.001$.
* $p < 0.05$.

Table 7
Q5 Comparison of quality attributes between sun and shade plots in each area. Means are adjusted for the effect of farm and cupper (the latter only for sensorial attributes).

Variables	Both areas			Oporapa			Timaná		
	Sun	Shade	Pr[a]	Sun	Shade	Pr	Sun	Shade	Pr
Fragrance	7.05	6.68	0.023*	6.98	6.62	0.092*	7.10	6.73	0.138 ns
Aroma	7.06	6.77	0.049*	7.00	6.70	0.221 ns	7.11	6.82	0.119 ns
Aftertaste	6.86	6.66	0.032*	6.97	6.64	0.052 ns	6.79	6.68	0.280 ns
Acidity	7.04	6.66	0.005**	7.13	6.57	0.010*	7.00	6.76	0.125 ns
Body	7.23	7.04	0.007**	7.27	6.92	0.008**	7.29	7.13	0.187 ns
Sweetness	7.14	6.77	0.015*	7.22	6.71	0.012*	7.09	6.83	0.201 ns
Preference	7.10	6.72	0.006**	7.26	6.61	0.008**	7.01	6.81	0.183 ns
Small beans (%)	2.2	1.7	0.121 ns	1.4	1.4	0.708 ns	2.7	1.9	0.030*
Large beans (%)	84	86	0.696 ns	86	88	0.751 ns	83	85	0.737 ns
Berry borer (%)	0.22	0.32	0.056 ns	0.14	0.12	0.655 ns	0.25	0.46	0.024*

The level of significance: ns at $p > 0.05$; *** at $p < 0.001$.
* $p < 0.05$.
** $p < 0.01$.
[a] Based on paired *t*-test.

analyzed jointly (Table 6). The proportion of large beans was not significantly affected by shade in any area, though there was a tendency for large beans to be positively affected by shade in Timaná. No significant effect of shade on the occurrence of berry borer was found in the mixed linear model, although there was a trend toward higher occurrence under shade. The paired *t*-test did find a significantly higher occurrence of berry borer in shade plots compared with sun plots in Timaná. The paired *t*-tests were otherwise similar to the results of the mixed linear model regarding bean sizes (Table 7).

Table 8 shows a comparison of bean sizes and occurrence of berry borer in the two areas. Coffee samples from Oporapa had a significantly higher proportion of large beans and a significantly lower proportion of small beans compared with Timaná. Samples from Oporapa were also significantly less attacked by berry borer.

4. Discussion

4.1. The influence of shade and area on sensory quality

The difference in shade cover percentages between sun and shade plots was relatively low (33% points on average) compared with other studies (e.g. Muschler, 2001). One reason is that the analysis of the 180° hemispherical images includes shade from distant trees in the horizon that have limited impact on the coffee plants in the plot due to atmospheric attenuation of solar radiance at near horizontal angels. Another reason is the focus on single shade trees contrary to earlier studies that analyzed dense shade tree canopies. Thus, in plots that were covered by shade trees, lower shade percentages were registered due to open sky from the horizon under the canopy.

The cuppings were carried out for beans smaller than 7.54 mm (sieve plate number 19). Even small variations in bean size can affect a number of sensorial attributes, e.g. through different responses to roasting. This implies that an indirect shade effect on cup quality, stemming from the shade effect on bean size, was reduced.

The analyses revealed differences in shade effects on beverage quality between Oporapa and Timaná. Shade was found to be more influential on the sensorial quality than other factors which differed between the two areas, e.g. altitude and temperature. The different shade effects on coffee quality in the two areas indicate that site conditions need to be taken into consideration when shade effects on coffee quality are studied. Farmers' choice of shade trees in the two areas also indicates differences in site conditions.

The higher quality of sun coffee in Oporapa compared to Timaná supports studies by Guyot et al. (1996) and Vaast et al. (2005) who found that high elevations had a positive impact on coffee quality, possibly due to reduced temperatures. The high sensorial quality of sun coffee compared to shade coffee in Oporapa is analogous to results by Avelino et al. (2005), who found that, at high altitudes, sensorial quality increased on slopes facing east, possibly due to more sun hours.

The lack of a significant shade effect on sensorial quality in Timaná supports findings by Guyot et al. (1996), who concluded that shade cover at high altitudes had no effect on acidity, body, astringency or aroma. The main differences between the areas are altitude, temperature, soil characteristics and shade tree species. The significant negative effect of shade on sensorial attributes in Oporapa, contrary to the minor effect in Timaná, may be a result of

Table 8
Q5 Comparison of bean size percentages and berry borer occurrence between areas. Means are adjusted for the effect of farm.

Characteristic of beans	Oporapa	Timana	$Pr > \|t\|$[a]
Small sizes	1.49	2.25	<0.001***
Large sizes	86.3	83.1	0.008**
Berry borer occurrence	0.15	0.57	<0.001***

Level of significance: ns at $p > 0.05$; * at $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.
[a] Student's *t*-test.

the temperature being in the lower end of the optimal temperature range for which the lower threshold has been found to be 18 °C (DaMatta, 2004). Shade trees lower temperatures under the canopy (Vaast et al., 2006). It is therefore possible that the temperature for shaded coffee in Oporapa is below the optimal range, while coffee trees in open sun are still within the optimal temperature range. Studies in warm climates, generally considered sub-optimal coffee sites, show that coffee quality was improved under shade. This is possibly because shade trees improve the microclimate for the coffee trees, reducing the temperature to a more optimal range (Muschler, 2001; Vaast et al., 2005). In the open fields in Oporapa the temperature is lower because of the high elevation, and shade trees may reduce the temperature to below the optimal range. Since no water or nutrient deficits were observed in the study area and because of the present climatic conditions, it is possible that reduced solar radiation and low temperatures, induced by shade trees, become stress factors for the coffee trees. This would be in agreement with Avelino et al. (2005), who found improved sensorial quality at high altitudes when coffee was grown on slopes facing east where they have longer sun exposure. In the present study however, it cannot be excluded that other factors, such as soil characteristics and shade tree species, could explain the differences in reaction between sites.

The results from the paired *t*-test support the results found by the mixed linear model. However, when data from both areas are analyzed with the *t*-test, results for aroma and aftertaste are also significant. The reason is the *t*-test's comparison of scores in pair wise plots, disregarding other variables which are similar within the pairs, while the mixed linear model is analyzing variations of scores and shade percentages, disregarding the paired plots. Furthermore, only in the case of aroma and aftertaste did other variables (pH and tree density) influence the attributes more than shade percentage.

4.2. The effect of shade on bean sizes

In Timaná, the percentage of small beans in coffee samples was significantly reduced by shade, while shade had no significant effect on bean sizes in Oporapa. However, bean size was significantly influenced by site, as beans were generally larger in Oporapa compared to Timaná. The temperature decreases with altitude and under shade. It is likely, that the lower temperature in Oporapa facilitates a longer maturation period allowing for increased grain filling. Conversely, the higher temperature in Timaná may explain why a significant difference in bean size between shade and sun plots is found here. Vaast et al. (2006) and Guyot et al. (1996) found similar positive effects of shade and altitude on bean size.

In addition to decreased temperatures, shade also influences the number of beans on each plant. Floral initiation is light dependent and fewer flowers are developed in shade, allowing more assimilates for each individual bean on the plant (Cannell, 1985). Other studies find more pronounced differences in bean size between shade and sun plots (Guyot et al., 1996; Muschler, 2001; Vaast et al., 2006). However, these studies were conducted in areas with higher temperatures or in more dense shade.

4.3. The relation between shade and bitterness

A PCA revealed that bitterness was influenced by the degree of roasting (indicated by luminance), even though all samples underwent identical roasting procedures. These findings support previous chemical studies where *bitterness* and astringency were found to be related to the degree of roasting (Farah and Donangelo, 2006). Decazy et al. (2003) also found higher bitterness in darker roasted coffees. In the study of Guyot et al. (1996), bitterness was the only sensorial attribute affected by shade at high altitudes, i.e. shade coffee was less bitter. The same study also found beans from shade coffee to be significantly larger. The present study found a significant effect of bean size on the roasting degree, with large beans resulting in a lighter roast and small beans resulting in a darker roast. This relation was clear despite the alignment of bean sizes and the identical roasting procedures which reduced variations considerably. Therefore, the relation between shade and bitterness is not exclusively characterised by improved chemical composition, but is also indirectly promoted by larger bean sizes and the subsequent lighter degree of roasting. Future studies on the effect of shade on the relation between sensorial quality and chemical constituents in beans at various size classes would help clarify this issue.

4.4. Occurrence of berry borer in relation to shade and site

Though only significant in the comparison of sun and shade plots in Timaná, there was a tendency for higher occurrence of berry borer under shade. This supports an earlier study where berry borers were found to be favoured by shade (Staver et al., 2001). The level of occurrences might be underestimated as the quantification of berry borer attacks was found by weighing the inflicted beans and then comparing it to the weight of total beans in a sample, thereby not considering the material removed by the borer. The biological control agents often found in dense shade are likely not present in the moderate shade from the solitary trees in Timaná (Beer et al., 1998). The occurrence of berry borer was significantly higher in Timaná compared to Oporapa. This may be explained by farms being generally located at higher altitudes in Oporapa, in agreement with similar to findings by Soto-Pinto et al. (2002).

4.5. Implications for the farmers

Farmers' incentives for planting shade trees are diverse and include a number of other considerations than physical and sensorial quality of coffee. In Oporapa and Timaná farmers are not separating shade and sun coffee, but harvest and sell a blend of both. At highest elevations farmers could increase the sensorial quality by focusing on sun coffee, but at lower elevations bean size might be reduced. However, while the influence of shade was found to be significant in this study, the actual differences in sensory scores between sun and shade plots are small. Even minor differences may be important in the specialty coffee market, but local quality assessment of specialty coffee may also include an assessment of size class distribution, proportion of physical defects and absence of off-tastes related to post-harvest processing. Depending on the local quality assessment, it is beneficial for the farmers to consider both pre- and post-harvest management as well as potential reduction in yields under shade.

Households may depend on shade trees for a range of products, such as fruit, firewood and timber that can either be sold or used and consumed within the household. In addition to the effect of shade on physical and sensorial qualities, the farmers decision to plant shade trees may also depend on a number of factors, such as certification opportunities (e.g. Rainforest Alliance, 2005), management considerations related to agronomic inputs and the need for alternative products from shade trees. Farmers have to weigh the shade effects on sensorial and physical quality against the multiple products and services provided by shade trees.

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5. Conclusion

The study demonstrates that shade trees should not be planted with the purpose of improving beverage quality of *C. arabica* cv. Caturra at the two sites. Shade had a negative effect on a number of sensory quality attributes, and we hypothesise that, at high altitudes, shade trees restrict the sensorial quality because temperature and radiation are reduced under shade trees. Since at lower elevations, previously studies have shown that shade has a positive impact on coffee quality, optimal agronomic shade management for coffee quality is related to site conditions, and recommendations regarding shade management should be targeted site-specific climatic and other environmental conditions.

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