Effects of slope exposure, altitude and yield on coffee quality in two altitude terroirs of Costa Rica, Orosi and Santa María de Dota

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Abstract: This study assessed the effects of slope exposure, altitude and yield on several cup quality criteria of coffees from two altitude terroirs of Costa Rica, Orosi (between 1020 and 1250 m above sea level) and Santa María de Dota (between 1550 and 1780 m above sea level). East-facing slopes gave beverages with generally superior attributes, probably owing to better exposure to morning sunlight. These beverages were mainly more acid: at Orosi an acidity score of 2.73 out of 5 was obtained (3.64 for Santa María de Dota) for eastern exposures, as opposed to 2.36 on average (3.28 for Santa María de Dota) for other exposures. In addition, a positive relation was found between altitude and taster preferences in both terroirs. A negative relation was also found between yield and beverage acidity at Santa María de Dota, where some coffee trees produced up to 13 kg of coffee cherry. Coffees from Orosi were characterised by a floral flavour, which depended on slope exposure, whilst coffees from Santa María de Dota displayed a chocolate taste, which was more marked at high altitude. In both terroirs the caffeine, trigonelline, fat, sucrose and chlorogenic acid contents were not well correlated with the sensory characteristics.

Keywords: Coffea arabica; cup quality; topography; fruit load; caffeine; trigonelline; fat; sucrose; chlorogenic acids

INTRODUCTION

Coffee is going through a surplus production crisis, which has caused prices to slump to record lows. Gourmet coffees are resisting the crisis better. Indeed, their taste characteristics, or simply the production methods used, make them original products that fetch a better price, as they are sought after by roasters and consumers. The emergence of these quality coffees on the market explains why coffee—producing countries are showing an increasing interest in environmental factors and local techniques that affect quality, ie terroir effects.1–3 The environmental factors most frequently mentioned are altitude (positive effect on coffee quality) and rainfall (negative effect).4–7 Among local techniques, the varieties cultivated, harvesting quality and postharvest processing play a predominant role in obtaining a quality coffee.4–13 A negative effect of high yields on coffee quality has also been reported.6 Moreover, shade provided by trees intercropped with coffee, through its effects on light intensity and yield, has been reported as a factor favouring coffee quality.5–7,12 Light intensity depends on shade trees. It also depends on the exposure of the slope on which coffee trees are grown. For some cultivated plants the effects of slope exposure on end-product quality have long been known. Such is the case with the grapevine, grapes and wine.1,14,15 However, the way slope exposure affects coffee quality has yet to be studied. The main purpose of this study was therefore to assess for the first time how slope exposure affects the quality of the coffee produced. We also examined how altitude and yield affect quality in each terroir. In addition, the relations between sensory criteria and certain chemical characteristics of coffees were investigated to try and gain a clearer understanding of the effects of the factors studied.

MATERIAL AND METHODS

Description of the Orosi and Santa María de Dota terroirs

The two terroirs studied were close to each other (under 25 km apart), but separated by a mountain range, the Cordillera de Talamanca (Fig 1), which determined the type of oceanic influence, Orosi being under an Atlantic influence (very wet zone with a somewhat indistinct dry season) and Santa María de Dota under a Pacific influence (relatively low rainfall with a marked...
dry season). The two terroirs also differed in altitude. The coffee plantings were mostly located between 1000 and 1300 m above sea level at Orosi, whilst they were mostly between 1500 and 1800 m above sea level at Santa María de Dota.

**Sampling principle**

The study was based on coffee sampling from 17 plots at Orosi and 18 plots at Santa María de Dota. The altitude ranges covered by the sampling procedure were 1020–1250 m for Orosi and 1550–1780 m for Santa María de Dota (Table 1). Some plots, located in valley bottoms, were flat. Others were on hillsides (slopes over 15%). For Orosi, four slope exposure categories were established corresponding to the four cardinal points. For Santa María de Dota, only two categories were established, as plots were concentrated according to two exposures: east and northwest (Table 1). Two samples were taken from low-yielding plants and two from high-yielding plants in each plot. A total of 68 and 72 coffee samples were therefore collected in the Orosi and Santa María de Dota terroirs respectively.

The differences in crop management patterns in each terroir were minimised by only taking coffee from vigorous coffee trees exposed to sunlight (far from shade trees), with a similar architecture (three to five productive stems). In addition, samples were only taken from plots planted with Caturra or Catuai varieties, which give similar, good quality coffees in Costa Rica.

**Harvesting and postharvest processing**

Coffee was harvested at the harvest peak for each plot (between 12/12/2002 and 10/01/2003 for the Orosi plots and between 13/01/2003 and 05/03/2003 for the Santa María de Dota plots), when the coffee was of better quality. All the cherries were harvested, including unripe cherries, in order to evaluate the total yield of the harvested plants. Subsequently, only just-ripe cherries were processed. They were pulped immediately after harvest, then transported to the processing factory of the Costa Rica Coffee Institute (ICAFE) in Heredia, at 1190 m above sea level (Fig 1). Mucilage anaerobic fermentation began during transport and was complete once the samples felt rough to the touch at the processing factory site (about 24h duration). The samples were then washed and dried in the sun until their moisture content reached 12%. They were stored in plastic bags. Parchment was removed between 10 and 14/03/2003 for the Orosi samples and between 21 and 25/04/2003 for the Santa María de Dota samples. After parchment removal the coffee was sorted. Chemical analysis and roasting were carried out on beans retained in a size 16 screen (larger than 16/64 in).

**Roasting, grinding and brewing**

Roasting and the tasting tests began on 18/03/2003 for the Orosi samples and on 06/05/2003 for the Santa María de Dota samples, ie more than 2 months after the harvest ended.

Coffee (150 g per sample) was placed in a Probat BRZ2 laboratory roaster (Emmerich, Germany) at 180 °C. Roasting was halted once the coffee was close to a medium roast (reference colour No 55 in the Agtron/SCAA roasted coffee classification system). The colour and luminance of the roasted coffee were checked on a Minolta Tristimulus CR 310 colorimeter.
(Osaka, Japan). The coffee beverage was prepared by decocting 10 g of medium-ground coffee (Ditting coffee mill; Bachenbülach, Switzerland) per 150 ml cup for 2 min.

**Tasting**

A group of 10 trained tasters took part in the tasting sessions. An initial group tasting session was used to typify samples from Orosi and Santa María de Dota. A floral flavour was detected for the Orosi coffees, whilst a chocolate taste was identified in the Santa María de Dota coffees. These typicalities, or distinctive characters, were sought in the subsequent tasting sessions.

Each sample was roasted and tasted twice (except for eight Orosi samples from plots on flat land which were only tasted once). Cup quality was assessed using five criteria: aroma, body, acidity, bitterness and typicity (floral or chocolate depending on origin). Scoring was on an intensity scale of 0–5, where 0 = nil, 1 = very light, 2 = light, 3 = medium, 4 = strong and 5 = very strong. An additional preference score, a hedonic criterion, was used ranging from 0 to 5, where 0 = unacceptable, 1 = bad, 2 = regular, 3 = good, 4 = very good and 5 = excellent. For the statistical tests the means of the values attributed by all the tasters were used.

**Chemical analyses**

Fat, sucrose, caffeine, trigonelline and chlorogenic acid contents were determined on green coffee (50 g) by reflectance near infrared spectroscopy (6500 model, NIRSyste, Silver Spring, MD, USA) and by comparing with calibration curves established for each constituent through reference analytical methods. These constituents, particularly sucrose, were considered as coffee flavour precursors. Condensation and sucrose degradation during roasting play a major role in flavour formation through Maillard reactions.

**Statistical analyses**

The way altitude and yield, which were quantitative variables, affected the sensory variables was examined through linear correlations. The relations between those variables and the chemical composition of the beans were studied by principal component analyses.

On the other hand, the slope exposure variable was qualitative (Table 1). The way the combined effects of altitude, yield and slope exposure affected the sensory variables was therefore analysed by an analysis of covariance, using the general linear model, where altitude and yield were covariables and slope exposure was the factor. In order to correct the exposure effects for any effects of interaction they might have with altitude and yield, we examined the results of the Henderson 3 model. Adjusted means, ie corrected for the effects of the two covariables, were compared by the Bonferroni test.

**RESULTS AND DISCUSSION**

**Sensory profiles of coffees from Orosi and Santa María de Dota**

The Orosi coffees had a floral flavour. The Santa María de Dota coffees had a chocolate taste. These coffees did not only differ through those typicalities. Significant differences between the two terroirs were found for all the criteria except for bitterness according to the t-test (*p* < 0.05) (Fig 2). In particular, the Santa María de Dota coffees were more acid (mean = 3.34, standard deviation = 0.56) than the Orosi coffees (mean = 2.42, standard deviation = 0.54). The Santa María de Dota coffees had average scores for body of 2.86 (standard deviation = 0.53) and for aroma of 3.64 (standard deviation = 0.51), slightly higher than those for the Orosi coffees, at 2.60 (standard deviation = 0.30) and 3.42 (standard deviation = 0.37) respectively. All these differences explain why the tasters attributed higher preference scores to the Santa María de Dota coffees (mean = 3.22, standard deviation = 0.62) than to the Orosi coffees (mean = 2.59, standard deviation = 0.54) (Fig 2). The higher altitude and less abundant rainfall at Santa María de Dota were probably responsible for the differences in acidity and preference found.

**Chemical constitution of beans from Orosi and Santa María de Dota**

Table 2 gives the average caffeine, trigonelline, fat, sucrose and chlorogenic acid contents for the Orosi and Santa María de Dota samples. These contents were within the range determined for Arabica coffees produced in Central America (Guyot B, personal communication). Some values reported in the literature are shown in Table 2. The caffeine and fat contents were similar to those reported for Catuai and Caturra.
samples taken at the Costa Rica Coffee Institute site at Heredia. However, the sucrose and chlorogenic acid contents were higher and the trigonelline contents were lower in our samples. Intra-regional variations for these chemical compounds were low in all cases. Significant differences between the two terroirs were found for all the chemical compound contents we quantified except for fat according to the t-test (p < 0.05) (Table 2). The caffeine, trigonelline and chlorogenic acid contents of Santa María de Dota coffees were higher than those of Orosi coffees, probably because of the higher altitude of the first origin. On the contrary, the sucrose contents of Santa María de Dota coffees were lower than those of Orosi coffees. The differences between the beans from Orosi and Santa María de Dota in caffeine, trigonelline, chlorogenic acid and sucrose contents suggested deep differences in chemical constitution for these two origins, which could explain their distinct sensory characteristics.

**Relations between altitude and sensory characteristics in each terroir**

Despite the limited amplitude of the altitudes sampled at both Orosi and Santa María de Dota (230 m in both cases), there was a positive altitude–acidity relation in both regions (Table 3). The relation was significant at Orosi. It was only a tendency at Santa María de Dota, probably owing to the higher altitudes of the sampled plots in that terroir. These results tally with those found in Honduras, where a wider range of altitudes was studied (some below 750 m and others over 1100 m). At Santa María de Dota, altitude was also positively linked to body (Table 3). A similar tendency was found at Orosi. In work carried out in Honduras, when low-altitude plots were included in the analyses, body was in an inverse relation to altitude. Body is a sensory perception of the beverage heaviness on the tongue. Thus the altitude–body relation could vary depending on the nature of the heaviness. A high body score may also be perceived as a defect in some cases, notably for coffees from very-low-altitude plots, and as a quality in other cases. For Santa María de Dota and Orosi the body evaluated was generally pleasant to the palate according to our tasters. At Santa María de Dota, altitude was also positively linked to the chocolate taste. Lastly, the high-altitude coffees from Orosi and Santa María de Dota were preferred by the tasters (Table 3). Their acidity characteristics at

<table>
<thead>
<tr>
<th>Table 2. Chemical characteristics of coffees from Orosi and Santa María de Dota compared with those reported for other Central American coffees (means)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin</td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Orosi</td>
</tr>
<tr>
<td>Santa María de Dota</td>
</tr>
<tr>
<td>Heredia, Costa Ricaa</td>
</tr>
<tr>
<td>Cuilapa, Guatemalab</td>
</tr>
<tr>
<td>Hondurasb</td>
</tr>
</tbody>
</table>

Standard deviations are given in parentheses.

* Significant differences between Orosi and Santa María de Dota terroirs according to t-test (p < 0.05).

a Caturra and Catuai varieties, 1200 m above sea level.

b Catuai, variety, 1100 and 1400 m above sea level.

c Caturra, Catuai, Pacas and Villasarchi varieties, from 600 to 1200 m above sea level.

<table>
<thead>
<tr>
<th>Table 3. Partial correlation coefficients (r) between altitude/coffee tree yield and sensory criteria and associated probabilities (p) at Orosi and Santa María de Dota</th>
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<tbody>
<tr>
<td>Terroir</td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Orosi (1020–1250 m)</td>
</tr>
<tr>
<td>Yield (1.00–6.94 kg coffee cherry per tree)</td>
</tr>
<tr>
<td>Santa María de Dota (1550–1780 m)</td>
</tr>
<tr>
<td>Yield (1.90–13.00 kg coffee cherry per tree)</td>
</tr>
</tbody>
</table>

a Floral for Orosi, chocolate for Santa María de Dota.

b Corresponding to 60 samples roasted and tasted twice and eight samples tasted once.

c Corresponding to 72 samples roasted and tasted twice.

r values in bold are significant (p < 0.05).
Orosi and their body and typicity characteristics at Santa Maria de Dota were responsible for the high preference scores. This altitude–preference relation was also mentioned in Honduras.6,7 In all cases, altitude did not seem to affect the sensory criteria to any great extent (Fig 3), probably because of the limited amplitude of the altitudes sampled in both terroirs.

**Relations between yield and sensory characteristics in each terroir**

Yield was found to have a negative effect on beverage acidity at Santa Maria de Dota (Table 3), which tallied with the results obtained in Honduras.6 However, this effect seemed to be a minor one: as an illustration of this minor effect, the acidity of the 36 samples from trees with less than 5 kg of coffee cherry (roasted and tasted twice) reached an average value of 3.40 (standard deviation = 0.50), whilst the acidity of the 36 samples from trees with more than 5 kg of coffee cherry (roasted and tasted twice) reached an average value of 3.28 (standard deviation = 0.60). That negative relation was not found at Orosi, probably because the yields studied were not as large as those at Santa Maria de Dota (Table 3). Indeed, in Honduras the effect of yield on beverage quality was only visible when yields were very high or even excessive.6 That was the case for some plots at Santa Maria de Dota, where yields of 13 kg of coffee cherry per tree were recorded (Table 3). In addition, flowering and ripening were more concentrated at Santa Maria de Dota, where the dry season is very marked, than at Orosi, where the dry season is not particularly marked. In general, producers at Santa Maria de Dota do not carry out more than three harvesting rounds. In our samples taken at the harvest peak, 74.1% of the coffee harvested was ripe on average (standard deviation = 19.5). The coffee trees therefore bore a large number of fruits at the same stage of development and were exposed to strong nutritional demand in a short period,27 which might have affected product quality. Producers at Orosi rarely carry out fewer than six harvesting rounds. In our samples, only 62.7% of the coffee harvested was ripe on average (standard deviation = 11.4). Nutritional demand was therefore probably staggered in time, which might have helped to reduce the effect of yield on quality.

**Relations between chemical constitution of beans, sensory characteristics, altitude and yield in each terroir**

At Santa Maria de Dota, altitude was positively linked to fat content (Fig 4), which tallied with what was found in Honduras.7 However, this relation did not explain the chocolate taste of high-altitude coffees from this terroir, as the fat contents, just like the other chemical characteristics that we assessed, were largely independent of the sensory characteristics. Indeed, the sensory characteristics were clearly represented along axis 1 of the principal component analysis, whilst the chemical characteristics were along axis 2 (Fig 4). For Orosi there was similar independence (Fig 4). These results mainly indicate that the chemical compounds we quantified cannot explain by themselves the cup quality criteria we evaluated. Other compounds such as free amino acids, peptides and proteins probably needed to be quantified, as they are also required for the development of coffee flavour.28

Variable yield was poorly represented along the first two axes of the principal component analyses carried out on the data from Santa Maria de Dota and Orosi (Fig 4). However, opposition was seen for both Santa Maria de Dota and Orosi between yield and sucrose, which had already been observed in Honduras.7 The sucrose content of beans was generally positively associated with beverage acidity.7,9,13 Our results did not show that relation, probably because the
sucrose contents of our samples were higher than those reported in the other works (Table 2).

**Effect of slope exposure on sensory characteristics in each *terroir***

Although it was possible to detect significant correlations between altitude and yield on the one hand and the sensory characteristics of the coffee on the other hand, the correlations were weak, probably because measurement of sensory variables usually lacks precision. In addition, other sources of variation may have affected the quality of the correlations, particularly slope exposure. Table 4, which gives the results of the covariance analyses, shows that slope exposure did indeed play a role in most of the sensory characteristics of the coffees. At Orosi the body, acidity and typicity of the beverages depended on slope exposure. A similar tendency was found for aroma, bitterness and preference. At Santa Maria de Dota this factor affected aroma, body, acidity and preference. It should be noted that in these analyses the effects of altitude and yield on the sensory variables were not generally significant, except for altitude which explained part of the variation in beverage acidity at Orosi. That was because the range of variations of the covariables, altitude and yield, was reduced by excluding flat plots that had no particular exposure. These plots were located at the lowest altitudes.

Table 4. Analyses of covariance on sensory variables for Orosi and Santa Maria de Dota: Fisher test values ($F$) and associated probabilities ($p$)

<table>
<thead>
<tr>
<th>Terroir</th>
<th>Factor and covariables</th>
<th>Aroma</th>
<th>Body</th>
<th>Acidity</th>
<th>Bitterness</th>
<th>Typicity</th>
<th>Preference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F$</td>
<td>$p$</td>
<td>$F$</td>
<td>$p$</td>
<td>$F$</td>
<td>$p$</td>
</tr>
<tr>
<td>Orosi</td>
<td>Slope exposure (factor)</td>
<td>2.04</td>
<td>0.11</td>
<td>3.24</td>
<td>0.02</td>
<td>2.98</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Altitude (covariable)</td>
<td>1.24</td>
<td>0.27</td>
<td>1.64</td>
<td>0.20</td>
<td>5.63</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>Coffee yield per plant (covariable)</td>
<td>1.11</td>
<td>0.29</td>
<td>0.91</td>
<td>0.34</td>
<td>0.65</td>
<td>0.42</td>
</tr>
<tr>
<td>Santa Maria de Dota</td>
<td>Slope exposure (factor)</td>
<td>5.03</td>
<td>0.03</td>
<td>4.18</td>
<td>0.04</td>
<td>11.60</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>Altitude (covariable)</td>
<td>1.72</td>
<td>0.19</td>
<td>1.32</td>
<td>0.25</td>
<td>1.10</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Coffee yield per plant (covariable)</td>
<td>0.77</td>
<td>0.38</td>
<td>0.30</td>
<td>0.99</td>
<td>1.20</td>
<td>0.28</td>
</tr>
</tbody>
</table>

$a$ Floral for Orosi, chocolate for Santa Maria de Dota.

$F$ values in bold are significant ($p < 0.05$).
and gave the highest yields at Santa María de Dota (Table 1).

Table 5 shows that the east-facing slopes gave beverages which were generally preferred by our tasters. At Orosi the beverages that received the highest body, acidity and typicity scores came mainly from coffees harvested in east-facing plots. At Santa María de Dota the beverages that received the highest aroma, body, acidity and preference scores also came from coffees harvested in east-facing plots. In a tropical climate during the rainy season, which can last from 8 to 10 months, east-facing slopes benefit from longer exposure to sunshine, because the morning climate is generally sunny. Banks of cloud only form late in the morning or early in the afternoon. On the other hand, the other slopes, particularly west-facing slopes, are exposed to sunlight for shorter periods owing to cloud cover. These sunlight effects on beverage quality may seem to be in contradiction to the generally accepted beneficial effects of shading on quality. In fact, such effects have been described for low- to medium-altitude zones or even for suboptimal coffee trees.27

Our results are similar to those reported for grape quality in cool climates.1,14,15 In northern grape-growing areas, sun availability, which affects temperature, has an important influence on must density. In those regions, southern exposure generally provides the best conditions for sun availability and thus for grape quality. In the case of high-altitude coffees, as we did not find any good relations between cup quality and the chemical compounds of the beans we quantified, it is difficult to understand why coffees from east-facing slopes are of better quality. We think that slope exposure cannot affect coffee quality through cherry ripening, as ripening generally takes place at the end of the rainy season, especially at Santa María de Dota. Consequently, it might be assumed that slope exposure affects the stages before ripening, ie endosperm formation and bean dry matter accumulation.27

CONCLUSION
This study suggested that coffee quality depends on the terroir, ie mainly on the macroclimate, which determines sensory characteristics, including typicalities, and chemical contents of the beans. However, quality also depends on altitude and slope exposure, ie on the mesoclimate. This mesoclimate introduces nuances in the sensory characteristics of coffees within the same terroir. Beverage quality is therefore partly determined by environmental factors, which are similar to those that influence wine quality.1,14,15 These results open up the way for more authentic coffees whose specificities would be linked to the origin of the beans and not only to the postharvest processes including roasting. These are arguments in favour of protecting coffee with a geographical indication, a sign which benefits today from international recognition and which is applied to products which, like wine, have qualities associated with their origin.1–3

ACKNOWLEDGEMENTS
We should like to thank the staff at ICAFE involved in this study, particularly L Zamora, manager of the technical department, M Alpízar, GIS manager, JM Alpízar, manager of the processing factory, JC Selva, manager of the tasting laboratory, JJ Obando, manager of the San Marcos office, and G Ramirez, manager of the Turrialba office.

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