Control of the Coffee Fermentation Process and Quality of Resulting Roasted Coffee: Studies in the Field Laboratory and on Small Farms in Nicaragua During the 2005-06 Harvest.

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Summary

This paper describes a field study conducted during the 2005-06 Nicaraguan coffee harvest investigating the relationship between scientific control of the coffee fermentation process and the quality of the resulting roasted coffee. In phase one of the study, small-scale, well-controlled laboratory fermentation was carried out on eleven batches of coffee at the farm La Canavalia in Matagalpa, Nicaragua. With otherwise identical treatment, fermentation of the small samples was halted by washing when the pH of the fermenting mass decreased to approximately 4.6, 4.3, or 3.9. After drying and roasting, these samples were individually evaluated by two certified cupping laboratories. The results indicate a weak positive correlation between pH at washing and subsequent roasted coffee quality.

In phase two of this study, 100 small-holder coffee producers were asked to characterize their customary procedures using standard pH paper and then to "optimize" the fermentation times. Generally, this required somewhat shortening fermentation times, with termination at higher pH. The coffee from the "usual" and "optimized" procedures was dried, roasted, and evaluated by two cupping laboratories. The results indicated that the coffee producers were very successful in optimizing the fermentation process, but that the roasted coffee quality did not reflect these changes, possibly due to a general decrease in the quality of the crop at the end of the harvest.

Resumen

Este escrito describe un estudio en el campo de la cosecha cafetalera Nicaragüense llevado a cabo durante los años 2005 y 2006, en el cual se investiga la relación entre el control científico del progreso de fermentación del café y la calidad del café tostado resultante. La primera fase de estudio, en escala pequeña y en un laboratorio de fermentación muy bien controlado, se llevó a cabo en 11 lotes de café de la finca La Canavalia en Matagalpa, Nicaragua. Asimismo y con tratamiento idéntico, se interrumpió la fermentación de muestras pequeñas a través del lavado cuando el pH de la masa en fermentación decrecía aproximadamente a 4.6, 4.3, o 3.9. Después que estas muestras fueron secadas y tostadas, se evaluaron individualmente por dos laboratorios de catación debidamente certificados. Los resultados indican una débil correlación positiva entre el pH del café en el lavado y la calidad subsiguiente del café tostado.

En la segunda fase de este estudio, se solicitó a 100 pequeños productores de café caracterizar sus procedimientos tradicionales usando papel pH estándar y luego optimizar el tiempo de fermentación. Generalmente, esto requirió de un tiempo corto de fermentación para finalizar con un alto valor del pH. Tanto el café ¨habitual¨ como el ¨optimizado¨ fueron sometidos a procedimientos de secado, tostado y evaluado por laboratorios de catación. Los resultados indicaron que el café de los productores fue muy exitoso en la optimización del proceso de fermentación, pero la calidad del café no reflejó cambio, posiblemente debido a un decrecimiento en la calidad del café al final de la cosecha.

Introduction

While the global coffee crisis has somewhat eased since the lowest market prices were reached in 2001, the effects remain significant among the impoverished coffee producers in developing countries. In Nicaragua where 42% of rural labor is employed in coffee, over 120,000 jobs were lost during the hardest years of the coffee crisis, with continuing social and environmental consequences (ICO 2003). Nicaraguan small-holder coffee producers have responded by strengthening their cooperative organizations and seeking certification that can give access to specialty (organic and Fair Trade) markets (Bacon 2005). International development and relief organizations, such as Catholic Relief Services (CRS), have come to the aid of coffee producers by assisting in certification efforts, coffee quality improvement, and access to markets in developed countries (CRS/NI 2005, p10). The United States Agency for International Development (USAID 2003, p5) has contributed through projects designed to aid small-holder coffee producers in assessing and improving their coffee quality.

In this project, initiated in 2003, an international group of faculty and student chemists works in Nicaragua with coffee producer cooperatives and CRS to contribute scientific expertise with appropriate technology in order to put simple methods into the hands of producers for improvement of coffee quality, certification, and market access.

After a series of discussions with coffee producers and the staffs of CRS and USAID, it was decided to focus first on over-fermentation, a major concern of coffee producers. Processing methods had been known to be important for coffee quality (Wootton 1966; Puerta-Quintero 1999), and over-fermentation was generally considered detrimental to coffee quality (Lopez and others 1989). A field study conducted in 2004 on small-holder farms resulted in the characterization of chemical changes during fermentation and in particular the decrease in pH that is associated with the liquification of the coffee mucilage, allowing the coffee to be washed clean (Jackels and Jackels 2005). It was determined under a wide range of conditions on various farms that the batches of fermenting coffee could be washed clean when the pH fell from approximately 5.5 to 4.6. Upon receiving this finding, the coffee producers wanted to know if pH measurement could be used to improve and control fermentation on the farm, resulting in coffee quality improvement.

The primary goals of this study were: (1) to determine if a relationship exists between coffee quality, as evaluated in the cupping laboratory, and the pH when fermentation is terminated by washing; and (2) to determine the feasibility of producers themselves using pH measurements to improve coffee quality through a “fermentation optimiza-

tion" method. These two questions were investigated simultaneously in December 2005 – March 2006. In phase one, small-scale, well-controlled laboratory fermentation was carried out on eleven batches of coffee processed on a Nicaraguan farm. With otherwise identical treatment, fermentation of the small samples was halted by washing when the pH of the fermenting mass decreased to approximately 4.6, 4.3, or 3.9. After drying and roasting, these samples were individually evaluated and rated by two certified cupping laboratories. In phase two, approximately 100 small-holder coffee producers were asked to characterize their customary procedures using standard pH paper and then to "optimize" the fermentation times. Generally, this required shortening fermentation times, with termination at higher pH. The coffee from the "usual" and modified procedures was dried, roasted, and evaluated by two cupping laboratories.

Materials and Methods

Controlled Fermentation (Field) Experiments

Small-scale controlled fermentation (field) experiments were conducted at La Canavalia, the experimental and model farm of the Association for Agricultural Diversification and Development (ADDAC), located in Yasika Sur near the village of San Ramón, Matagalpa, Nicaragua. At 750 m altitude, the farm receives 200 - 240 cm of precipitation annually and has a temperature range of 20 – 26^{o}C. Typically, ripe coffee cherries (*coffea arabica,* var. caturra) were harvested in the morning hours and were washed and selected by density, retaining only those that did not float. After being mechanically pulped in the wet mill building in late afternoon, they were placed in a cement tank with a drain (no water added) for natural fermentation, which typically required approximately 15 hours. For the field experiments, about 30 kg of freshly pulped coffee was divided among six fermentation buckets, which were constructed to mimic the process in the large tank. A five-gallon outer bucket served to collect the drain liquid, while a three-gallon inner bucket with a drain platform and holes contained the coffee (Figure 1). The apparatus was jacketed with high efficiency insulation and covered with mosquito net. The six buckets remained in a covered location where fermentation proceeded under ambient conditions.

Figure 1. Apparatus for controlled fermentation of coffee.

Each bucket of fermenting coffee was monitored by time, temperature, and pH. The pH readings were measured both semi-quantitatively (short range paper, EMD Chemicals, Inc. colorpHast^{TM}, two ranges, 4-7 and 2.5-4.5) and quantitatively (Reflectoquant, RQflex2^{TM}, Merck, Darmstadt, Germany, range 4 – 7). Sample preparation is described below in "Measurement of pH in Fermenting Coffee Batches." The fermentation process was terminated by washing the coffee when it reached the desired pH, denoted herein as pH_{term}. Washing consisted of

transferring the coffee to a five gallon washing bucket that had several hundred small holes in the sides and bottom. The washing bucket was placed inside another five gallon bucket without holes. Approximately 3 gallons of clean water were added, and the coffee was stirred vigorously for approximately 5 minutes. Debris was skimmed, and the coffee was drained by pulling the inner bucket out of the water. The "dirty" water was discarded, and the washing process repeated five more times. The washed coffee was sorted and partially sun-dried in racks, before being transported to a commercial processing service (Sol Café) in the valley, where it was placed on a patio in the sun and dried to 10 – 12% moisture.

Each field experiment consisted of six buckets derived from a common batch of beans harvested on the day of the experiment. The fermentation was terminated so that approximately duplicate samples were created from coffee with pH_{term} 4.5 – 4.8 (Range 1), 4.1 – 4.4 (Range 2), and 3.6 - 4.0 (Range 3). Fermentation was always "complete" in Range 1, with Ranges 2 and 3 representing over-fermentation by 1.5 and 4 h (medians) respectively. Experiments were conducted over a three-week period, after which, the samples were roasted and their quality evaluated by cupping in two independent laboratories (see below).

Fermentation Optimization by Coffee Producers

Since it was not feasible to travel to each of the 100 project farms in order to train the coffee producers in the process of fermentation optimization, the technical staff of the cooperatives serving them was given hands-on training in the methods of the project, including pH measurements, and provided with kits of materials to deliver to each farm. The technicians trained the producers at the time of kit delivery and returned a few weeks later to answer any questions.

Each farm was asked to complete a questionnaire giving the following information: location, cooperative membership, altitude, coffee cultivation area, and traditional practice of wet processing, including batch size, time of initiating fermentation, and its usual duration. Each farm was provided a kit with the necessary materials: cups, sampling and stirring spoons, thermometer (digital), watch (digital), pH strips (EMD Chemicals, Inc. colorpHast™, two ranges, 4-7 and 2.5-4.5) and color charts, instructions and data sheets, pen, clipboard, and container. The instructions were for a three step process: 1) document the regularly practiced process (Step A), 2) make changes to the process (Step B), and 3) document the optimized process (Step C).

On the farm, coffee was typically picked in the morning, sorted and pulped in the early afternoon, and put in the fermentation tanks in late afternoon. In Step A of the procedure, the producer was asked to maintain the traditional schedule for three days, recording pH, temperature of coffee, and time of initiation of fermentation. The same data were to be recorded for the fermenting coffee early the next morning and again at the time of its washing. In Step B, the producer was asked to note the typical pH_{term} value at the time of washing (from Step A) and make changes in fermentation time if necessary. If pH_{term} was < 4.0, the time of fermentation during the next day was reduced by two hours. If the pH was between 4.0 and 4.2, the time of fermentation was reduced by one hour. If the pH was between 4.2 and 4.6, no change was made in fermentation time. In Step C, the same data were collected for a batch using the

optimized fermentation process. The producers were asked to wash, sort and partially dry the parchment coffee from each batch, following their usual procedure. Samples of partially dried parchment coffee, about 1 kg from each of steps A and C, were collected from each farm, were dried to approximately 12% moisture in the sun using the usual procedure, and were sent to two laboratories for husking, roasting and cupping.

Measurement of pH in Fermenting Coffee Batches

The following instructions were provided to coffee producers along with a pictorial representation of each step. First, the date and time were noted on a data sheet provided. A reminder was given to start with clean, dry cups and spoons. The cups for coffee and water were marked with levels for filling. Approximately 50 mL volume of coffee (30 g) with its associated mucilage was taken from a hole about 10 cm deep in the mass of coffee and was mixed with 50 mL of fresh, pure water. The mixture was stirred for 15 seconds. Then the pH strip was dipped into the water and the color was immediately matched with the manufacturer's chart to determine the pH. The data were recorded to the nearest tenth of a pH unit.

Quality Evaluation by Cupping Laboratories

All coffee samples, from both the field experiments and the producer optimization steps, were evaluated by roasting and cupping at certified cupping laboratories. The coffee was mechanically husked, brought to a medium roast in a small roaster, and then cupped in the Sol Café laboratory, a facility of CECOCAFEN, a second-tier cooperative well known in Nicaragua and internationally. The same roasted sample was then cupped in the laboratory of CECOSEMAC, a second-tier cooperative organized by Cáritas Matagalpa and directly serving the 100 coffee farms that participated in this project. In each cupping evaluation, the same procedure was followed. A 12 g sample of medium roasted coffee was finely ground and placed in a glass cup. The aroma of the ground coffee was sniffed and then the brew was made by adding freshly boiled water (Fuente Puro, heated in an aluminum kettle). The aroma of the crust and broken crust were sampled. Following crust removal with stainless steel spoons, the coffee was tasted by aspiration into the mouth and nose. Numerical scores were recorded for aroma, body, acidity, flavor, after-taste and balance. The total scores were tabulated on a 100 point scale where 90 – 100 is excellent, 80 – 90, very good; 70 – 80, commercial grade, and below 70, poor or damaged.

Statistics

Statistical analyses were carried out using SPSS version 14.0 for Windows™ (2005).

Results

Comparison of Cupping Results for Equivalent Samples

A number of samples (both field and producer) were created under such similar conditions as to be considered "equivalent." A comparison of the results from a single laboratory for these "equivalent" sets gives an indication of the reproducibility of both the processes in the field and at the cupping laboratories. For the thirty-one such comparisons possible among the samples cupped at Sol Café the correlation coefficients are: $r_{Pearson} = 0.453$ ($p=0.010$) and $\rho_{Spearman} = 0.564$ ($p=0.001$). The twenty-six comparisons in the Cáritas laboratory yielded $r_{Pearson} = 0.436$ ($p=0.026$) and

$\rho_{Spearman}$ = 0.0.396 (p=0.045). Linear fits to these data sets account for only 15-30% (r^2)of the total variance.

Controlled Fermentation Experiments

Buckets were assigned to pH_{term} ranges (see above), with both instrumental and test-strip pH values being considered. In two batches, all six buckets were placed in Ranges 2 and 3 because fermentation had progressed beyond Range 1 at first measurement. After categorization of the 66 buckets from 11 batches, the three ranges contained 18, 25, and 23 samples, respectively. All samples were evaluated by Sol Café laboratory, and 59 of them were also evaluated at the Cáritas laboratory. After censoring scores below 70 ("damaged" coffee), there were 60 values from the Sol Café data and 50 from Cáritas. In the Sol Café data, nine of the eleven batches were represented in all three ranges, and the Cáritas data set had six such batches. Approximately 20% of the data points in these sets were single values rather than the average of "equivalent" buckets.

"Common knowledge" among producers is that over-fermentation degrades coffee quality. Since it has been shown that pH drops throughout the fermentation process, the working hypothesis of this study was that the quality of coffee as determined by cupping laboratories *decreases* as pH_{term} *decreases*. The null hypothesis is that coffee quality and pH_{term} are unrelated.

Average cupping scores for the three ranges could not be compared directly because of variation in coffee quality between single-day batches. The differences between batches would be expected to be larger than the differences between ranges within any batch, as was confirmed by ANOVA calculations. Accordingly, the data was analyzed using pair wise t-tests to compare data in Range 1 with data from the same batch in Ranges 2 and 3. In Table 1 are presented average cupping scores for the three ranges and the changes from Range 1 to Ranges 2 and 3. One-tail probabilities are appropriate here for the paired t-tests because the over-fermentation in going beyond Range 1 can only result in degradation of coffee quality. If, as in some instances, the evaluation rises, this change is assigned to random variation in the field and laboratory processing.

Table 1. Average Cupping Scores and Changes for Field Experiments

	Range 1[a]	**Range 2[a]**	**Range 3[a]**	**Change (1→2)[b]**	**Change (1→3)[b]**
Sol Café Results	80.26 (2.9; 9)	79.14 (3.1; 9)	78.76 (3.2; 9)	-1.1 (t=1.41; p=0.10)	-1.5 (t=2.00; p=0.04)
Cáritas Results	82.46 (4.0; 6)	82.38 (2.9; 6)	81.17 (3.7; 6)	-0.1 (t=0.05; p=0.48)	-1.3 (t=0.81; p=0.23)

[a] Reported as: mean (standard deviation; number of batches)

[b] Reported as: change in mean (pair wise t-statistic; one-tail p-value)

Although the changes reported in Table 1 are statistically significant ($p < 0.05$) in only one case, the overall set of negative changes is suggestive of a decrease in coffee quality with decreasing pH_{term} (over-fermentation). It is noted that the only case with a significant decrease in quality corresponded to the broadest pH range (1→3) and the more extensive of the two data sets (Sol Café).

In Figure 2 it is shown that the cupping score change (Sol Café) for individual batches increases in only one case from Range 1 to Range 2 and in only two cases from Range 1 to Range 3. Nonparametric analysis of this data using the Wilcoxon Signed Rank test indicated a marginally significant difference ($Z=-1.718$, $p_{1\text{-tail}}=0.043$) for Range 1 to Range 2 and a marginally insignificant one ($Z=-1.599$, $p_{1\text{-tail}}=0.055$) for Range 1- Range 3. The dominant trend is clearly a decrease in cupping score with a decrease in pH_{term}, with the decreases between ranges being close to the p=5% significance level in both parametric and nonparametric tests. It is suggestive that with more repetitions and larger data sets, this relationship would become more significant with decreased variance of the data and increased statistical power of the study.

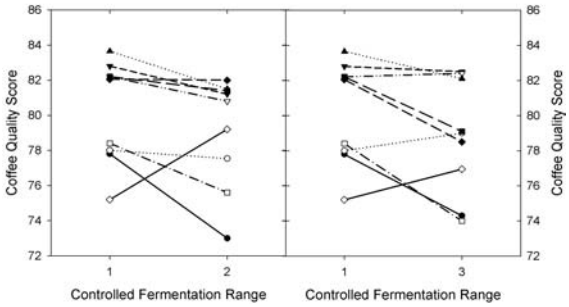

Figure 2. Coffee Quality vs Fermentation Range

Producer Data (fermentation optimization)
Seventy-seven producers returned data, of which sixty-nine had both fermentation times and pH_{term} values noted for each of Steps A and C. To determine if *on the average* the producers followed the protocol, comparison was made between fermentation times and pH_{term} values for Steps A and C. From Step A to Step C, the average fermentation time decreased from 18.0 h to 16.3 h ($n=69$, $t=3.32$, $p_{2\text{-tail}}=0.0014$). From Step A to Step C, the average pH measured at the termination of fermentation increased from 3.97 to 4.28 ($n=69$, $t=-4.70$, $p_{2\text{-tail}}=1.3\times10^{-5}$). In going from Step A to Step C, the producers clearly shortened the fermentation time, resulting in higher pH_{term}. The two changes are significantly correlated, with $r_{Pearson}=-0.319$ ($p_{2\text{-tail}}=0.008$) and $\rho_{Spearman}=-0.341$ ($p_{2\text{-tail}}=0.004$).

The hypothesis to be tested is that the changes in process from Step A to C resulted in higher coffee quality. The average cupping scores (Sol Café) for 67 producers changed insignificantly from 81.7 to 81.8. After limiting the analysis to those producers who also reported valid pH measurements for both steps (N=50), the average scores were unchanged (81.8). Further limiting analysis to those cases (N=33) where the change in pH_{term} was greater than zero, in accord with the experimental design, the mean score changed from 82.0 to 81.8, an insignificant (p=0.35) decline in quality. The correlation coefficients between change in quality and change in pH_{term} were negative, but statistically insignificant: $r_{Pearson}=-0.16$ ($p=0.37$) and $\rho_{Spearman}=-0.23$ ($p=0.19$). A subset (N=43) of samples were also evaluated by Cáritas and similarly displayed only small and insignificant changes in quality.

Discussion and Conclusions

Previous work had shown that pH measurements could be used in the field to track the fermentation process of pulped coffee cherries (Jackels and Jackels 2005). Two further questions were addressed in the present study: 1) Does coffee quality as

determined in cupping laboratories correlate with the pH of the fermentation mass at time of washing? and 2) Can producers themselves use pH test paper to effect change in their fermentation process and consequently in their coffee quality?

The first question was addressed by the controlled fermentation experiments carried out in our field laboratory. The results show a weak relationship in which a decrease in coffee quality accompanies a decrease in pH_{term}, corresponding to over-fermentation. This relationship is statistically significant only for the case of the largest pH difference (Range 1 to Range 3) considered and for evaluation at the more professional and experienced laboratory (Sol Café). This change is a decrease of 1.5 quality points (out of an average of 80) with a pH decrease of at least 0.5 units. The changes from Range 1 to Range 2, while even less significant, are still suggestive of this relationship.

Cupping laboratory data are semiquantitative in nature and inherently possess relatively large variance. It is expected that with increasing sample and cupping replication, the variances would decrease and that the correlations suggested here would become significant. Although the change in cupping score suggested by these results is modest, it would be important in the effort to improve and maintain coffee quality.

The question addressed in the producer study is complicated. First, it was necessary to determine whether or not pH could be measured and could be used to control fermentation time by producers with training from their cooperative technical staff*s*. Producers were clearly successful in raising the average pH_{term} of their fermentation process by shortening the fermentation time. Fermentation times decreased, and pH_{term} increased at a very significant level from Step A to Step C, with the two changes being significantly correlated. Our conclusion is that, on the average, the producers accomplished the desired changes in their fermentation processes.

There is no indication, however, of coffee quality improvement being effected by the process changes. In fact, the suggested correlation between the changes in pH_{term} and in coffee quality is an *inverse one.* Although the pH changes accomplished by the producers were smaller than those observed in the controlled field experiments, an additional uncontrolled factor is more likely dominant. The producer experiments were conducted during from December 20, 2005 through January 30, 2006. The 2005-06 coffee harvest in Matagalpa was earlier than expected and was approaching completion by January 1. It is well known to producers that the coffee quality declines markedly toward the end of the season. Since Step C typically occurred 2-3 weeks after Step A, Step C used coffee that may have been generally inferior to that in Step A. The experimental protocol assumed that the quality would be unchanged between steps, which was clearly not the case. This is very likely the underlying cause of the suggested decline in quality from Step A to C.

The overall conclusion is that under controlled conditions, the pH of washing shows a weak correlation with coffee quality, which is very likely to be strengthened with a statistically more powerful experimental design. The question of whether producers can use pH measurements on their farms to improve the quality of their coffee is unanswered. While the producers can clearly utilize the technology to control their processes, it is unknown if that control can result in practical improvement.

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