FACTORS INFLUENCING CUP QUALITY IN COFFEE

Photo Courtesy of SPREAD, Rwanda

Prepared for the Global Coffee Quality Research Initiative
Brian Howard

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Introduction

Photo Courtesy SPREAD Rwanda

Cup quality in coffee is affected by a great number of factors; agronomic, genetic and production related. In this review the author seeks to summarize the major findings of the research that has been conducted that is specifically related to cup quality and how it is affected by the environment in which the coffee tree is grown, the genetic makeup of the coffee plant itself and the manner in which coffee is prepared for consumption. More than 800 aromatic compounds combine to give acidity, body and aroma to a cup of coffee. These three descriptors will serve as the parameters around which cup quality is described in this document.

The quality of coffee is extensive in its definition. Leroy et al, 2006 defines coffee quality on a number of levels. At the exporter or importer level coffee quality is linked to bean size, number of defects, regularity of provisioning, tonnage available, and physical characteristics. At the roaster level coffee quality depends on moisture content, characteristic stability, origin, organoleptic (taste and smell) qualities and biochemical compounds. At the consumer level coffee quality is about taste and flavor, effects on health and alertness, geographical origin, and environmental and sociological considerations. At every link in the supply chain there is the consideration of price. In 2004 the International Organization for Standardization (IOS) defined a standard for green coffee quality which entails defects, moisture content, size, and some chemical compounds of beans as well as standardization of preparation of a sample from which to perform cup tasting. According to Bertrand, Arabica coffee production makes up 70% of the world total. Consequently this review will deal mainly with C. Arabica with a few notable exceptions in the sections on genetics and crossbreeding for disease resistance.

Agronomy:

Soil Nutrition

Coffee can be cultivated on a wide variety of soil types, provided these are at least 2 meters deep, free-draining loams with a good water retention capacity and a pH of 5-6, fertile and contain no less than 2% organic matter. High quality, acidic Arabica coffees tend to be produced on soils of volcanic origin.

Van Der Vossen, 2005 expresses concern that, “to sustain economically viable yield levels, 1 ton green coffee per hectare (4.5

acres) per year, large additional amounts of composted organic matter will have to come from external sources to meet nutrient requirements, especially nitrogen & potassium. The majority of small land holders will not be able to acquire the necessary quantities and will be confronted with declining yields. Organic farming does not necessarily prevent disease or pests below economically harmful thresholds and the humid conditions of heavily shaded coffee may actually stimulate the outbreak of others.

Vaast et al, 1998 found that total uptake of nitrate ($N0_3$) and ammonium (NH_4), key nutrients for plant growth and development and the limiting nutrient in Arabica Coffee, at any ratio was higher than that of plants fed solely with nitrate or ammonium alone. Anaerobic, lack of oxygen, soil conditions reduced nitrate and ammonium uptake by 50% and 30% respectively and the presence of dinitrophenol almost completely inhibited N uptake in any form. Vaast suggests that these results indicate that Arabica coffee is well adapted to acidic soil conditions and can effectively utilize the seasonally available forms of inorganic nitrogen (N). These observations can help to optimize coffee nitrogen nutrition by suggesting agricultural practices that maintain root systems in the temperature range that is optimum for both ammonium and nitrate uptake. Vaast found that both nitrate and ammonium uptake peaked when root systems were maintained at 34 degrees Celsius. Below this temperature plant color indicated a loss of vigor. Therefore both nitrate and nitrite availability in soi, as well as the coffee trees capacity for uptake through ideal temperature regimes, can be maximized. Van Der Vossen, 2009 notes that excessive calcium and potassium in soils produce a hard and bitter tasting liquor.

Fertilizer

Organic vs Inorganic Fertilizer

Organic production of coffee is often thought preferable due to the strong potential of negative environmental impacts from fertilizer leaching into surface waters and groundwater. However, any production crop significantly depletes its soils ability to replenish key nutrients and humic matter taken from it in the form of produce. Inorganic fertilizer is often applied at rates approaching 100 to 300 kilograms per hectare at significant expense to producers. (Carvajal, 1959) Because of the preference for organically produced produce, especially in the specialty coffee market, solutions for such a deficit must be found and implemented in regionally appropriate ways.

In the shaded Indian coffee terrior of Karnataka, India Nagaraj et al., 2006 found that the addition of inorganic potassium in the form of muriat of potash and sulphate of potash had the effect of increased coffee yields over the period of four years at a rate of approximately 15%. The difference between the two treatment methods outlined by Nagaraj not being statistically significant. It should be noted that the soils in which this coffee were planted were receiving approximately 40 to 60 kg of potassium per hectare per year in leaf fall. The study indicated that no consistent trend could be observed in the cup evaluation report for three years. Cup quality of Arabica coffee was found to be similar in both MOP and SOP treated plots but that there was a modest improvement in the cup quality of robusta coffee in the sulphate potash

treated plots compared to muriate of potash applications in the second and third years. It should be noted that there has not been any evidence of changes occurring in the flavour compounds due to agronomic use of sulphur or otherwise. (Krishnamurthy Rao, 1989) Studies conducted in Kenya by (Njoroge and Mwakha, 1985) did not note any difference in liquor quality of coffee between NPK fertilized plots and control treatment over eleven years of research.

Cup quality differences have been found in studies contrasting organic and inorganic fertilization. In a 2008 study undertaken by Malta, et al. no significant differences were observed on the cup quality among beans from conventional and organic plants in the first year. However in the second year, cup quality of some organic treated plants was superior when compared to conventionally treated plants. A positive effect on sensorial attributes was observed using cattle manure, either alone or associated with coffee straw and green manure.

In Hawaii, Youkhana & Idol, 2009 found that the addition of mulch from shade tree pruning significantly offset net nitrogen and carbon losses from coffee cultivation. Improved carbon and nitrogen sequestration in soil was measured over two years and it was found that soil bulk density did not decline in mulched plots as opposed to significant changes in bulk density for unmulched plots.

Grossman et al., 2006 found that organic production standards are being met while available Nitrogen in soil is supplemented by nitrogen fixing shade trees. Biological Nitrogen Fixation is facilitated through the use of leguminous shade trees in the genus Inga with the most significant results found in 1 to 3 year old plots of C. Arabica and I. oerstediana. In these young plots it was found that coffee trees were deriving approximately 20% of their nitrogen from the biological nitrogen fixation occurring via symbiosis with I. oerstediana. No estimate could be derived for plots between 5 and 7 years. It is a reasonable assumption to make that greater availability and uptake of soil nitrogen has a strong positive correlation to cup quality via plant health and bean size.

Environmental Factors

Shade vs Sun

It has been shown that on the most appropriate sites, with intensive management, self-shading coffee monocultures can give 2 and 3 fold increases over more traditional shaded systems. (Beer, 1987) Shade tends to reduce photosynthesis, rates of transpiration, plant metabolism and thus demand on soil nutrients. Due to lower nutrient needs a crop could potentially be obtained on more marginal soils with lower fertility. In areas where regular fertilization cannot be guaranteed it is recommended that some shading trees be retained as a hedge against uncertain future soil inputs. Dr. John Beer of CATIE stresses, “The fundamental question, when planning the renovation or establishment of a coffee and cacao plantation is whether the owner has the site, education and resources to maintain the crops without shade. Coffee under shade will survive setbacks far better than monocultures of the crop.” (Beer, 1987) As important as the question “could improvements in coffee quality through shade be made” in a given location, the question of whether a farmer “should” seek to use

shade in his plantation becomes equally important. Dr. Beer suggests a number of possible advantages and disadvantages of such a decision.

Advantages of Shading Include:

(1) The Suppression of Weed Growth
(2) Potential for Product Diversification such as fruits and timber alongside coffee
(3) Greater control over crop phenology such as fruit setting and maturation
(4) Potential improvement of crop quality
(5) Reduction of evapotranspiration rate of the shaded crop
(6) Removal of excess soil moisture by transpiration of a heavy shade tree cover
(7) Potential for increased moisture input through horizontal interception of mist or clouds
(8) Extension of the productive life of the crop
(9) Reduction of temperature extremes
(10) Reduction of damage caused by hail or heavy rain and winds
(11) Better soil drainage and aeriation
(12) The provision of soil mulch from tree throughfall
(13) Reduction of erosion on slopes, ie soil conservation
(14) Recycling of nutrients not accessible to the crop
(15) Nitrogen fixation by shade trees

Disadvantages of Shading Include:

(1) Throughfall damage to understory crop
(2) Sudden defoliation of shade trees could cause a shock to the crop
(3) Additional labor necessary to maintain the same acreage
(4) Mechanization of the crop may be hindered
(5) Erosion control structures like terracing would be hampered once shade trees are planted
(6) New crop varieties are often bred for monocultural conditions
(7) Reduced air movement and humidity may encourage fungal growth
(8) Shade trees can be other potential hosts for pests and diseases
(9) Reduction of photosynthetically available sunlight
(10) Shade tree root competition of nutrients
(11) Rainfall redistribution could cause spot erosion or reduce overall soil moisture
(12) Harvesting of wood or fruit from shade trees is an additional drain of soil nutrients

Desirable Characteristics for Shade Trees Include:

(1) The ability to fix nitrogen from the atmosphere
(2) Compatibility with the crop in terms of facilitating minimal competition for water, nutrients and growing space
(3) Strong rooting systems as shade trees are more exposed to adverse climatic conditions
(4) Ability to extract soil nutrients which are not trapped by the crop
(5) A light crown that provides regular mottled shade rather than uniform shadow and poor light quality
(6) Flexible branches and stems
(7) High biomass productivity of recycled material in soil
(8) Absence of major disease susceptibility that could lead to rapid defoliation
(9) Small leaves to reduce rain drop coalescence
(10) Not an alternative host for insects or pathogens which could endanger the crop

Bosselmann et al., 2009 in Huila, Colombia found that sensory attributes were influ-

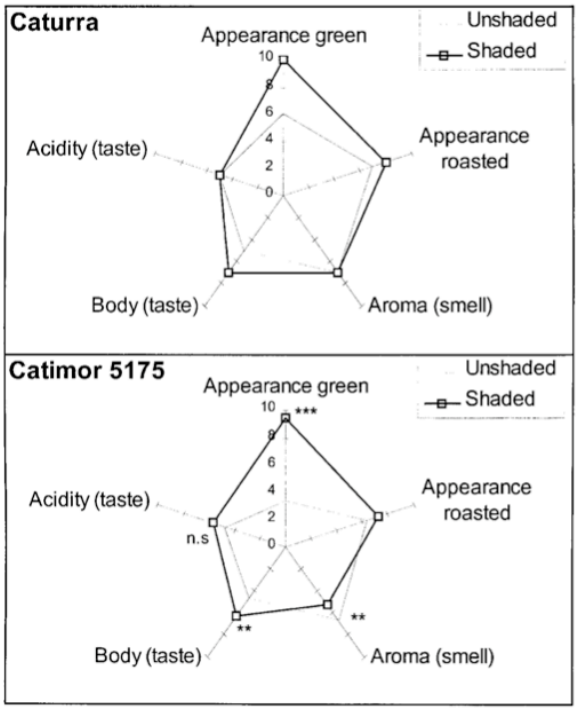
enced negatively by shade, and that physical attributes were influenced positively by altitude. In higher altitudes (approximately 1700 meters above sea level) shade had a negative effect on fragrance, acidity, body, sweetness and preference of the beverage, while no effect was found on the physical quality of the bean. 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 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. Bosselman goes on to suggest that future studies on shade and coffee quality should focus on the interaction between physical and chemical characteristics of beans.

A study was done in Costa Rica by Vaast et al., 2005 contrasting light regimes and optimal coffee growing conditions on dwarf coffee, Coffea Arabica. Shade was found to decrease coffee tree productivity by 18% but reduced alternate bearing. Shade also positively affected bean size and composition as well as cup quality due to a delay in berry flesh ripening by up to a month. Higher levels of sucrose, chlorogenic acid and trigonelline in sun grown beans indicated incomplete bean maturation and resulted in higher bitterness and astringency in cup quality. Higher fruit loads, which can be mitigated through branch thinning, reduced bean size owing to carbohydrate competition among berries during bean filling. Higher taste preferences were linked to lower fruit load. Shade was also found to mitigate negative attributes in coffee quality like bitterness and astringency while positive attributes like acidity were found to be significantly higher in shade grown beans. A noteworthy aspect of this study was that the overall beverage quality, higher acidity, lower astringency and higher preference, was found to be higher in the year 2000 when production was around 30% lower than in 1999.

Geromel et al, 2008 builds his study on the effects of shade on the development and sugar metabolism of Coffea Arabica L. on the premise that coffee fruits grown in shade are characterized by larger bean size than those grown under full sun conditions. Bean size, as noted, is a strong contributor to cup quality. He found that shade led to a significant reduction in sucrose content and to an increase in reducing sugars. In pericarp and perisperm tissues, higher activities of sucrose synthase and sucrose phosphate synthase were detected at maturation in the shade compared with full sun and that both enzymes also had higher peaks of activities in developing endosperm under shade than in full sun. Geromel went on to suggest that metabolic pathways for sucrose needed further study for identification. Van Der Vossen concurs that shade has a positive effect on coffee quality, particularly at medium altitudes but also reduces yields. He also found that at altitudes above 1800 meters shade did not improve cup quality.

Muschler, 2001 found across the board improvement in organoliptic parameters as shading increased. A blind tasting experiment showed highly consistent shade induced improvements in both green and roasted coffee. Improvements were made in both the acidity and body of the beverage for both Caturra and Catimor arabicas. The one mildly negative effect of shade was found to be on the aroma of the beverage for Catimor. It is thought that in the suboptimal coffee zone that was studied, the shade promoted slower and more balanced

filling and more uniform ripening of berries that yielded a better cup quality than the unshaded coffee plants. (Muschler, 2001)



Above: Quality attributes of green beans of two varieties of Coffea arabica grown without shade and with dense shade (80% shade) of *Erythrina poeppigiana* at a low elevation. Beans were harvested at full maturity. (This figure courtesy of CATIE)

Rainfall & Irrigation

Van Der Vossen states that rainfall requirements for Arabica coffee production are at least 1200mm per year with a maximum of 2500mm. He contends that coffee plants grow and yield better if exposed to alternate cycles of wet and dry seasons and that a period of water deficit is helpful in synchronizing flower bud differentiation. Areas with precipitation in excess of 2500mm have the tendency to produce lower quality coffee due to irregular cherry ripening and poor bean drying conditions after harvesting. On the other end of the spectrum in drought years shoot dieback and premature ripening of the berries can result in light beans producing a liquor with immature and astringent notes.

Da Silva et al, 2005 investigated the influence of environmental conditions and irrigation on the chemical composition of green coffee beans and the relationships of those parameters to the quality of the beverage according to both sensorial and electronic analysis. He found that irrigation was not a major factor affecting chemical composition since there were few differences in relation to non irrigated coffee plants. He found the production site temperature differentials to be the main influencing factor on biochemical composition. The study was undertaken near Sao Paulo, Brazil and the major finding was that cup quality decreased as air temperature rose to about 3.5 degrees above the optimum limit for coffee cultivation at 18 to 21 degrees Celsius. Similar findings are reported by Decazi et al., 2003 in Argentina.

In a study done in Australia between 2000-2002 by David Peasley of Rural Industries Research, irrigation was found to significantly increase bean yield as well as produce the following results under internationally recognized SCAA cupping forms. The non irrigated control crop scored a 69 with the description of "low acidity and mild smoky flavour and thin body." The low water stressed irrigated treatment scored 73 with the description of "dull bakey aroma, nice acidity, sour, green apple flavor." The medium water stressed irrigated treatment scored 75.5 with the description of "faint but sweet aroma, juicy, citrus flavour, OK body." Each of the three areas received 1634mm of rainfall with the low water stressed irrigated area having 2100mm of irrigation applied to it and the

highly water stressed irrigated area having 647mm of irrigation applied to it.

Temperature & Altitude

Decazy et al, 2003 found that Honduran coffees of superior quality came from high altitudes, above 1000m, where rainfall remains relatively low, that is to say below 1500mm per year. It was found that a strong inverse relation between rainfall and fat content exists and that this relation needs to be considered in relation to altitude because in the sampled regions in Honduras, rainfall and altitude were found to be inversely correlated. High altitude green coffee beans had a higher fat content than lower altitude beans and gave a better cup quality. Van Der Vassen stresses that high altitudes are critical for the successful production of high quality Arabica coffees in equatorial regions. Lower temperatures, and their longer daily amplitudes, tend to induce slower growth and more uniform ripening of the berries, and produce larger and denser beans. Bean size and density is often correlated to aroma, flavor and superior beverage quality. Altitude also tends to have a positive effect on acidity while reducing bitterness.

While for traditional cultivars elevation has tended to play a significant role in bean biochemistry and organoleptic qualities, with chlorogenic acid and fat concentration increasing with increasing elevation, this is not necessarily the case with Arabica hybrid cultivars like the Caturra. For Arabica hybrids little correlation is found in variation in chorogenic acid concentration and none of the variation in fat can be correlated to elevation.. However, Arabica hybrids were found to have 10-20% higher fat concentrations than traditional carieties at low elevations and similar fat concentrations at high elevations. The analysis confirmed homeostasis of the hybrids for which bean biochemical composition was only slightly affected by elevation than that of traditional varieties. The cupping performed on samples originating from high elevations showed no significant differences between Arabica hybrids and traditional lines. (Bertrand et al., 2006)

Slope

East facing slopes were found by Avelino et al., 2005 to yield beverages with generally superior attributes, probably because of superior exposure to morning sunlight. The beverages from east facing slopes were mainly more acid, with a score of 2.73 out of 5, in the higher quality terriors, as opposed to 2.36 out of 5 for other exposures. In addition a positive relation was found between altitude and taster preferences.

Laderach & Vaast et al. in their "Geographical Analyses to Explore Interactions between Inherent Coffee Quality and Production Environment" state that increasing slope negatively influenced the final score of cup quality from terriores on two test sites in Columbia and Nicaragua.

Genetics:

With total economic damage to coffee crops mounting to an estimated US $2-2.5 billion annually, coffee leaf rust and coffee berry disease affect a significant portion of the supply chain. In addition to increased scarcity due to disease and fungus significant environmental hazards exist due to the copper based fungicides used to fight Coffee Berry Disease and Coffee Leaf Rust chemically. (Van Der Vossen, 2009) Ac-

cording to Walyaro, 1997 the aim of most genetic improvement programs is disease resistance and quality. Determination of berry and bean characteristics using plant breeding is relatively simple, aroma and flavor attributes present significantly greater difficulties due to their chemical complexity and susceptibility to agronomic variability. Walyaro goes on to postulate that the development of reliable lab procedures which relate individual chemical compounds to cup quality could have important bearing on genetic improvement of cup quality in coffee. It has been shown that resistance to disease and nematodes can be increased through genetic exchange between C. Arabic and C. canephora. (Bertrand et al., 2005, Dessalegn et al., 2008, Leroy et al., 2006)

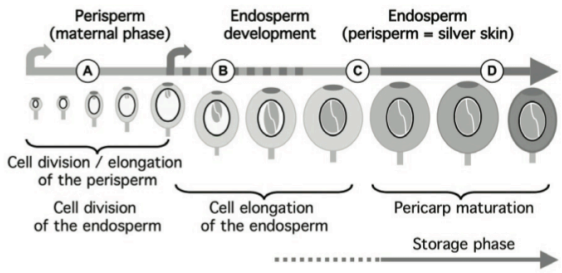
The *Coffea* genus encompasses about 100 different species. Within those species, C. Arabica and C. Canephora make up approximatley 70 and 30% of the total coffee market. At a genetic level, Arabica is a tetraploid (2n=4x=44 chromosomes), which have their origin in a natural cross between the species C. Canephora and C. Eugenoides according to Lashermes et al., 1999, 2000. Arabica is a self pollinating species which partially explains its narrow genetic base and the ensuing difficulty with incorporating new traits. Robusta, however, is diploid (2n=22 chromosomes) and is not self compatible because of a gametophytic system of incompatibility controlled by a single gene with multiple S-alleles which explains the higher genetic diversity within the species and ensuing ease of genetic improvement by conventional breeding techniques. Castro et al., 2006)

<u>Coffee Fruit Development</u>

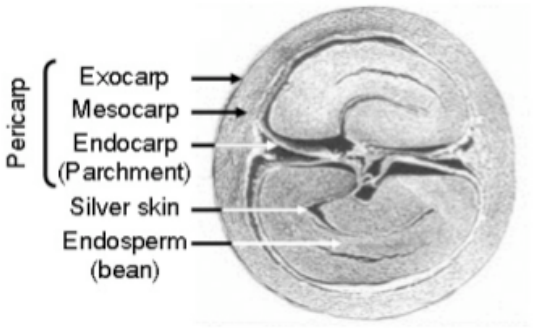
In C. Arabica and C. Canephora bean development is a long process that is characterized by fundamental shifts in the makeup of the beans' tissue. For economically viable species ,C. Arabica & C. Canephora, 6 to 8 months and 9-11 months are respectively required for beans to reach maturity. Fruit development does not occur at the same time with varying proportions of different fruit sizes occuring on the same plant. Despite variation in fruit growth timing and the differences in the length of each species reproductive cycle, the primary steps of seed development are thought to be identical between commercial species. (De Castro et al., 2006)

After fertilization and up to mid development the fruit is primarily made up of pericarp and perisperm tissue. In the latter phases of development the perisperm gradually disappears and is replaced by the endosperm, also known as the "true seed" which was initially present in a liquid state. The endosperm hardens as it ripens during the maturation phase due to accumulation of storage proteins, sucrose and complex polysaccharides which represent the seeds primary energy reserves. The final phase of bean maturation is the dehydration of the endosperm and the color change of the pericarp to a dark red color. Key changes accompany the development of the coffee cherry which require both quantitave and qualitative description in order to fully describe the growth and development of the bean in relation to it's eventual cup quality. (De Castro et al., 2006)

Below: Phases of coffee fruit development (Taken from De Castro et al., 2006):



Schematic representation of the tissues present at the mature stage (220-250 days after fertilization). Photo Courtesy of Nestle Inc.



A: 0-60 days after flowering: Ovary after anthesis. The growing perispern tissue, the integuments and the young embryo sac that will further develop in the endosperm are visible.

B: 60 – 120 days after flowering: The pericarp and liquid endosperm tissue or "true seed" which grows by absorbing the inner perisperm tissue, become clearly visible in crossection.

C: 120-150 days after flowering: The remaining folded outer perisperm layer is enclosing the completely milky endosperm.

D: 230 – 240 days after flowering: A mature cherry fruit has been formed showing two developed mature seeds enclosing one cotyledonary mature embryo inside of the solid endosperm. (Decastro, 2006)

Plant Resistance

According to De Nardi et al., Coffee plants fight off pathogenic infections through a number of strategies, including the strengthening of cell walls, activating or synthesizing antimicrobial compounds (antibiotics) and expressing defense-associated proteins like pathogenesis related (PR) proteins. Often, plants will activate a hypersensitive response that is characterized by the rejection and death of infected cells as shown by Greenburg, 1997. A localized response can trigger longer standing systemic responses known as SAR - systematic acquired resistance. This response prepares the plant for resistance against a large spectrum of pathogens. Plants express large arrays of resistance genes (R genes) that guard against pathogens. These genes encode putative receptors that respond to the products of avirulence genes expressed by pathogens during the infection of a plant. The recognition of avirulence genes initiates a downstream signaling that can render the attempted infection unsuccessful. Systematic acquired resistance (SAR) inducing chemicals provide a unique opportunity to view induced resistance mechanisms in plants in the absence of a biological model system. Specifically, 2 chemicals, 2,6-dichloroisonicotinic acid (INA) and benzo (1,2,3)thiadiazole-7-carbothionic acid s-methyl ester (BTH), have been demon-

strated to be effective inducers of systematic acquired resistance in a variety of plants. These compounds work to protect plants from pathogenic infections without having direct microbial activity. Despite acting downstream of salicylic acid in SAR signaling, they activate the SAR signal transduction pathway through the same signaling cascade thus imitating an infection and improving the plant's natural defenses, making it more resistant to infection in the future. De Nardi went on to confirm C arabica showed typical SAR responses to BTH treatment. Both roots and leaves responded with a shift in metabolism from normal housekeeping activity defensive activity. Unexpectedly, the root reaction was found to be different than the leaf reaction. The primary response in the leaf was an increase in physical and chemical barriers, along with repression of the genes involved in photosynthesis and normal metabolic pathways. The enhancement of cell walls appeared to be the main response in root systems and the normal anti-microbial peptides, in the form of chitinases and peroxidases, were not observed. It is propounded by De Nardi that this approach for mimicking a plant disease or a pest attack is an approach that can be applied to the problem of producing quality coffee without the use of microbicides, insecticides and fungicides while safeguarding crops from pests and diseases. (Di Nardi et al., 2006)

The greater debate and perhaps of more importance to the topic of cup quality is whether this genetic resistance will lower overall cup quality by necessity and in the end decrease consumer experience.

Major Diseases:

Coffee leaf rust (CLR) is caused by a pathogen of the leaf called Hemileia vastarix and is characterized by orange rust postules on the under side of the leaf. This pathogen causes significant losses as a result of loss of leaf area and the corresponding loss of photosynthesis and leaf drop. Coffee leaf rust has now spread through all Arabica coffee producing countries in the world making it a significant issue for the coffee industry as a whole in terms of supply susceptibility.

Coffee berry disease (CBD) is caused by Colletotrichum kahawae and is a fungus that causes dark lesions on the green and ripening berries. CBD is unique in that crop losses due to the fungus can be severe. According to the Coffee Research Foundation' s annual report for 1987-1988 in Africa as a whole losses can range between 30% and 50% during very high precipitation years even with chemical treatment.

Fusarium (Giberella) stilboides (Fusarium bark disease) is a pathogen that causes bark lesions which are a result of damage to the vascular system. Vascular wilt often results in the death of the entire tree. Fusarium is reported to have almost killed the entire coffee industry in Malawi in the late 1970's according to Siddiqi, 1980.

Root Knot Nematode (Meloidogyne exigua) has been shown to be a huge threat to Arabica growing areas in Latin America. *Coffea Arabicas'* resistance to M. exigua is controlled by an single inherited major gene, Mex-1. Alipzar et al., compared resistant and susceptible pure line cultivars with clones of hybrid cultivars derived from crosses between resistant and susceptible lines. The results show that reproduction of the nematode was significantly higher on the hybrid cultivars than on resistant pure line cultivars, however

resistance was much lower than on a susceptible pure line cultivar. Individual galls on the root systems of hybrid cultivars were found to be much smaller than on susceptible cultivars. After a 4 year monitoring period Alpizar et al. reports that M. exigua populations in a test field were multiplied by a factor of 14 on susceptible plants buy only by a factor of 1.9 on hybrid cultivars. They come to the conclusion that Mex-1 could have incomplete dominant expression that allowed nematode penetration, but inhibited the durable reproduction of the namatode. (Alpizar et al., 2006)

Genetic modifications have in some cases affected cup quality adversely but in many cases have not adversely affected cup quality and increased genetic resistance to coffee leaf rust and M. exigua by introducing genetic material into the Arabica plant from C Canephora via the Timor hybrid. (Leroy et al., 2006) There are regional variations in resistance to disease that can be exploited while maintaining or improving beverage quality as is noted by Anzueto et al., 2001. Anzueto remarks that Ethiopian origins provide resistance to nematodes and partial resistance to leaf rust and likely improve beverage quality.

In higher quality C. Arabica stocks the main goal seems to be in the area of improvement of resistances to pathogens and an increasing of yield. LeRoy et al., contends that introgression of alien genetic material, material from C. canephora, does not seem to be linked directly to variation in cup quality. (Leroy et al., 2006) Bertrand et al., 2003 came to similar conclusions when he stated that selection can avoid accompanying the introgression of resistance genes with a drop in beverage quality due to positive results in approximately half of the trials that he carried out dealing with taste characteristics such as sucrose content and beverage acidity.

Introgression processes that began in the 1980's to combat the spread of coffee leaf rust and root nematodes was not restricted to resistance traits but also included genes that coffee producers widely contend affected cup quality. Most coffee buyers claim that new introgressed varieties have a poorer cup quality than the standard varieties, this finding was confirmed by Bertrand et al., 2003 in the same study in which he showed that some introgressed lines were similar to the control and that cup quality was not necessarily related to the amount of introgressed genome of Robusta. Since the late 1990's, CIRAD and partners have worked to develop a generation of F1 hybrid varieties that are crosses F_1 hybrids of C. Arabica with 7 to 22% genetic material from C. canephora have been shown by Bertrand et al., 2006 to produce good cup quality under ideal conditions and in about half of the tested strains.

In order to avoid damage to roots from nematodes, C. Arabica is commonly intergrafted onto C canephora. The performance of such grafts was evaluated over 5 years in Costa Rica by Bertrand et al., 2001. The grafting did not have an appreciable effect on caffeine, fat and sucrose contents. However the C. Liberica rootstocks did significantly reduce aroma and the size of the bean produced. These deficiencies were partially explained however by tissue incompatibility at the graft level.

With approximately a 10% market share of the total coffee consumed world wide, decaffeinated coffee is being considered as a genetic trait. Consideration of genetic diversity and the correlation of caffeine content in relation to cup quality was looked at specifically by Dessalegn et al., 2008. Des-

salegn found that Ethiopian genotypes of low caffeine content typically showed a lower cup quality but that there were notable exceptions. Consequently he concludes that simultaneous selection for low caffeine content and good cup quality is possible given that there are sources of desirable genes in terms of cup quality with relatively low caffeine content that can be utilized for resistance breeding.

Bertrand et al., 2006 in Central America found homeostasis, stable equilibrium, in taste characteristics of Arabica hybrids for which bean biochemical composition was less affected by elevation than that of the traditional varieties. The organoleptic evaluation of hybrids, which was performed on samples originating from high elevation, showed no significant differences between Arabica hybrids and traditional cultivars. Bertrand goes on to note that "new hybrid varieties with high beverage quality and productivity potential should act as a catalyst in increasing the economic viability of coffee agroforestry systems being developed in Central America.

Van Der Vossen, 2009 points out that traditional cultivars of Arabica coffee are susceptible to coffee leaf rust and coffee berry disease. CLR being of worldwide importance while CBD remains restricted to Africa. Van Der Vossen contends that there is a mounting volume of scientific evidence accumulated over many years showing that, given optimum environmental factors, disease resistant cultivars can in fact produce coffee of equal quality to those from the best traditional varieties.

Etienne et al., 2001 states that the molecular phylogeny of Coffea species has been established using DNA sequencing. Molecular markers were found that reveal an extremely reduced genetic diversity in Coffea Arabica L. in comparison to C Canephora. Wild accessions found in Ethiopia seem to constitute a key gene reservoir for Arabica stocks. The use of Molecular Assisted Selection in coffee breeding promises to drastically increase the efficiency of breeding programs as a complete genetic linkage map of C. Canephora was reported and additional linkage maps are under construction for C. arabica. Economically crucial genes related to the caffeine biosynthetic pathway or genes encoding for seed storage proteins have been isolated. The high performance already achieved in the in vitro propagation process by somatic embryogenesis offers the possibility to mass propagate superior hybrids in different regions for both C arabica and C. Canephora. (Etienne et al., 2001) Initial production by somatic embryogenesis is now permitting preparation for direct commercial application. Seed cryopreservation enables a routine use for long-term conservation of coffee genetic resources.

Bertrand et al., in his study of C. Arabica hybrid performance isolated three key quality indicators; yield, fertility and weight and sought to improve plant performance. This was done by breeding F1 hybrids derived from South American and wild Sudanese - Ethiopian stock. The African stock is thought to improve genetic diversity. Sudan-Ethiopian genetic material carries significant resistance to root nematodes and leaf rust and possibly even brings better beverage quality to the table. Bertrand's main objective was to increase bean quality, plant productivity and to introduce more variation into a very narrow genetic base. His study found that hybrid populations yielded 22-47% more than the maternal lines but that hybrids showed significantly more sterility than parental control lines. Selection in the hybrid popu-

lations using the aforementioned traits resulted in significant genetic gain for yield and dry weight of 100 beans with insignificant gains in fertility. When selected on the basis of fertility alone, increase in yield and 100-bean weight were not obtained within the hybrid populations. By applying selection on yield and 100-bean weight, the hybrids produced 11-47% higher yields than the best line with significantly higher or identical 100-bean weight and the same fertility rates.

Pautigny et al., 2010 propounds the idea that comparative genomics provides the opportunity to leverage genetic information between species using comparative genetic mapping. He goes on to state that pholgenetically, the model species most closely related to coffee, for which significant genetics and genomic resources are available, is the tomato. Both coffee and tomato belong to the Euasterid I clade of flowering plants and are likely descended from a single ancestral species with a haploid number of x=11 or 12. They go on to produce the first comparative map for coffee and link it to the genetic and genomic resources available on tomato and other Solanaceae species.


Photo Courtesy of SREAD, Rwanda

Quality Evaluation Methods

The successful integration of genetic traits, which add positive taste characteristics as well as contribute to robustness against disease and pests, can yield significant results in terms of supply chain security and cup quality. DNA introgression of alien genetic material is being carried out world wide with varying and highly disputed results. Discussion of various quality evaluation methods to determine the extent of gene introgression success is a key component of genetic research. Coffee identification and classification serves as a means to avoid coffee adulteration. This is essential due to the high variability of sale prices which are largely dependent on coffee origin and variety. Prices of pure Arabica achieve prices upwards of 25% over robusta coffees taken as a whole and prices for the finest specialty coffees can soar to upwards of $50 per kilo green for rarities like the Panamanian Esmerelda.

Near Infrared Reflectance

Near Infrared Reflectance (NIRS) is based on the absorption of electromagnetic radiation by matter. This method of analysis allows for the extraction of a large amount of information concerning biochemical composition and is used extensively in a number of crops. The ability to quickly extract a great deal of information makes NIR a highly cost effective source of information for researchers, coffee buyers and roasters.

In today's marketplace coffee identification and classification is as crucial to cup quality as it is to consumer requirement for origin and species specification. In order to obtain top market prices, methods of ef-

ficient, inexpensive, and highly accurate identification of coffee origins and characteristics are paramount.

NIRS is the method that Bertrand et al., 2005 & Posada et al., 2009 have shown to be efficient for determining whether a green coffee comes from an Arabica tree that has been introgressed with C. Canephora genes. Spectra taken from near-infrared reflectance of green coffee were capable, by principal component and factorial discrimination, of correctly classifying beans into categories of introgressed or non-introgressed with degrees of accuracy from 92.3% to 94.87%. This type of analysis can serve coffee buyers or roasters as they seek to distinguish between non introgressed Arabicas and genotypes carrying chromosome fragments of C. Canephora genetic material which could produce negative affects on cup quality. Posada et al., 2009 concurs that a near infrared spectroscopy signature that has been acquired over a set of harvests can in fact effectively characterize a coffee variety. Posada hypothesizes that the spectral signature is affected by annual environmental factors but that through multiple harvest calibration data can be made useful for practical application to breeding.

The Science of Taste

Chemical composition in relation to pre-established cup quality:

Attributes of green coffee beans, both bean density and volume, were higher for softer tasting samples as opposed to the rio off flavored samples according to a study done by Franca et al., 2004. The rio sample presented lower lipid contents, most likely associated with the presence of defective beans. Acidity increased and pH levels decreased as cup quality decreased likely due to the effect of defective beans which had undergone fermentation. After roasting, the rio sample presented higher density trigonelline levels, indicating that it had not roasted to the same degree as the other samples tested.

"Each of the main reserve compounds of the bean (parietal polysaccharids, lipids, proteins, sucrose) as well as secondary metabolites (chlorogenic acids, caffein, trigoneline) play a central role in chemical reactions during roasting. We believe that deciphering the correspondent metabolic pathways are the key to better understanding quality and the use of biomarkers for breeding. On the other hand, volatile components, mainly from phenylpropanoids and isopropenoids, are synthesized during bean maturation. Even very low quantities (nano-mole) might strongly influence cup quality. We have two ongoing preliminary works (to be published) in which we have been studying the influence of environment and genetics on cup quality profiles (metabolic fingerprints) using the SPME GC-MS technology."

--Dr. Christophe Montagnon of CIRAD, personal correspondence

Joet et al, 2010 examined the influences of environmental factors and wet processing on the lipid, chlorogenic acid, sugar and caffeine content of green Arabica beans. Each of these biochemical markers representing key components of cup quality. He found that chlorogenic acids and fatty acids in the bean were controlled by the average air temperature during bean development. However, total lipid, total soluble sugar, total polysaccharide and total chlorogenic acid contents were not all influenced by the

climate in which beans were produced. Glucose content was positively affected by altitude and sorbitol content after wet processing was directly dependent on glucose content in fresh beans.

Molecular Markers

Molecular markers are widely used, through traditional chemical analysis, to investigate canephora and liberica gene introgression into Arabica lines as a resistance booster to pests and diseases. Coffee amplified fragment length, polymorphism and simple sequence repeats have been used to analyze the introgressions mentioned above. Villareal et al., 2009 found fatty acids in particular have proven effective for the discrimination of Arabica varieties and specific growing terriors. Crop to crop environmental factors where found to have a significant impact on fatty acid content and thus limit discrimination to moderate efficiency across a number of years. Posada et al., 2009 also found that correct classification and discrimination among different varieties of introgressed genetic material was possible through traditional chemical analysis to the tune of 79% accuracy. He also found in the same study that using spectral signatures in green beans provided 100% correct differentiation among varieties.

Farah et al., 2005 investigated Brazilian green and roasted coffee beans for correlations between cup quality and levels of sucrose, carreine, trigonelline and chlorogenic acids as determinded by HPLC analysis. They found that trigonelline and 3.4-dicaffeoylquinic acid levels in green and roasted coffee correlated strongly with high quality. To some extent caffeine levels were found to be associated with good quality. The amount of defective beans, the levels of caffeoylquinic acids, feruloylquinic acids and their oxidation products were associated with poor cup quality and the Rio-off-flavor. Similar correlations between cup quality and chemical attributes were observed in green and light roasted samples which indicates that chemical analysis of green beans may be used as an additional tool for coffee quality evaluation. Lindinger et al., 2009 draws a correlation between the fermented off-note and ethyl formate.

Harvesting and Post Harvest Handling

Photo of Washing Station Courtesy SPREAD, Rwanda

Ideal conditions for coffee production such as the agronomic factors of soil nutrition, shading, watering and superior genetics will not yield high cup quality without optimal harvesting, processing, storage and brewing. According to Van Der Vossen, 2009 only freshly harvested and fully ripe berries should be used in any of the three methods of primary processing. Those methods include washed, semi-dry and dry processing. Hand picking coffee beans is

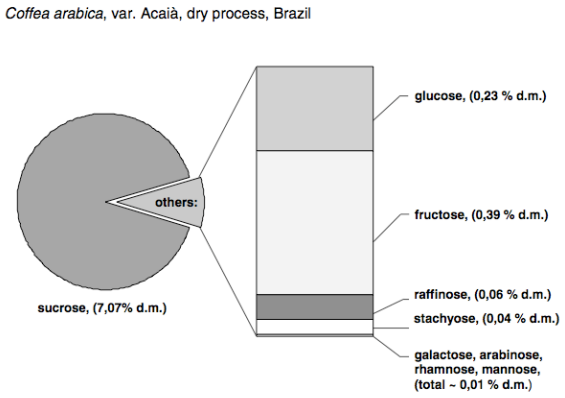
one method for accomplishing such distinction but there are methods of mechanized picking that separate the immature green from the ripe cherry before processing. Unripened coffee beans tend to produce astringent, bitter and "off" flavored beverages but unripened beans can be sorted before processing to mitigate negative effects on batch quality. Delays in depulping and prolonged fermentation often lead to onion flavor or unpleasant smells. Wet fermentation may improve flavor marginally as may soaking under water for 24 hours after mucilage removal and washing.

Below: A Survey on the low molecular sugars in a green coffee. The circle is representative of the low molecular sugars, totaling 7.79% DM.

According to Bytof et al., 2007 the specific ambient conditions of any type of post harvest processing can have significant impacts on the time course of the metabolic reactions that occur during that processing period. The extent and the time courses of germination in various coffee beans were found to be significantly different between dry and wet processing styles. The highest germination activity was found to occur 2 days after the onset of wet processing and approximately 1 week after the onset of dry processing. Bytof goes on to conclude that the substantial differences in flavor between wet and dry processed coffees are the result of the differential expression of germination processes, in other words, they are the result of differences in the metabolic activities that take place in each type of processing. (Bytof et al., 2007)

Knopp et al., 2005 states that flavor differences in part have to be attributed to differences in the thoroughness applied to either method of post harvest processing as well as the fact that only the fully ripe coffee cherries are typically used for wet processing as opposed to dry processing where fruits of varying stages of ripeness are commonly used. In his description of the *"Influence of processing on the content of sugars in green arabica coffee beans"* There is a close correlation between the type of post harvest processing and the content of fructose and glucose in the coffee bean. While in washed coffee beans only a small amount of either hexos were present, those in unwashed coffees were significantly higher. It has been revealed that low levels of both fructose and glucose are a result of decrease in the wet process. Fructose and glucose levels stayed near pre processing levels throughout dry processing according to Knopp.

Knopp concludes that the decrease in glucose and fructose in wet processed coffee is as a result of a fermentation enhanced glucose turnover from anaerobic fermentation in the coffee endosperm.
(Knopp et al., 2005)



Harvesting

When the coffee bean is ready for harvesting it turns a dark berry color. This will typically take place between September and March in the Northern Hemisphere and between April and May in the Southern

Hemisphere. In some countries where there is little clear distinction between dry and wet seasons a major and minor crop may be able to be harvested annually. Countries on the equator are able to harvest year round. Harvesting of superior coffees tends to be done by hand as mechanized picking can gather over ripe berries and an acrid taste may affect cup quality according to the FAO office for Asia and the Pacific. (Alastair Hicks) Of the various methods in practice, selective hand picking best ensures that only fully ripe beans are taken. However a cost benefit analysis will inevitably be undertaken by coffee growers as to whether the increased level of quality found in picking only the ripest cherries is worth the extra expense of undertaking multiple harvests in the same season.

Approximatley 20-25% of all Brazilian coffee production is affected by the Rio-off defect. This defect is characterized by a strong medicinal or iodine or musty and cedar-like character. Occasionally this defect has been observed in other countries. Spadone et al. contend that this defect is a result of wet and humid conditions during harvesting and is the consequence of a type of fermentation and bacterial growth and a high level of cell structure degradation that ensues. The principle compound associated with the Rio-off flavor was found to be 2-3-6 Trichloroanisole and is only perceptible at concentrations at or above 8ppm. (Spadone et al., 1990)

Dry Processing

Post harvest processes include both dry and wet methods used to process green cherry coffees. Dry processing is the simplest and least expensive method of coffee processing. It tends to produce "natural" tasting coffees and is used mostly in Western Africa and Brazil. Harvested berries are sorted and cleaned to remove dirt, twigs and leaves by hand . Berries are then spread out in the sun and raked regularly to keep fermentation at bay. In the dry method, coffee beans were dried as a whole with pulp and mucilage in the cherry state. Dry processing is slow and can lead to the translocation of chemical constituents from the pulp to the inner bean as well as chemical transformation that depends on ambient conditions.

It is noted by Clark, 1985 that naturally, dry, processed coffee has a better body due to the fact that the bean was in contact with its mucilage through a greater part of the processing phase.

Cantergiani et al., in 2001, found that earthy/moldy off-flavors that were produced in Mexican coffees were likely as a result of dry post harvest treatment. The compounds geosmin, 2-methylisoborneol (MIB), 2,4,6-trichloroanisole (TCA) were found to be the main contributors to the tainted flavor though at the time of Cantergiani's study the moldy /earthy defect had not yet been fully characterized. The concentrations found in samples exhibiting the moldy/earthy characteristic were between 100 and 1000ppm, 5-8 times more than in the reference sample. Cantergiani also identified alkyl methoxy pyrazines as having less significant contributions to the effect. 2-methoxy-3-isopropyl pyrazine, 2 methoxy-3-sec-butyl pyrazine and 2-methoxy-3-isobutyl pyrazine (MiPP, MsBP and MiBP respectively) were found in both reference and tainted samples with the concentration being only 1-2 times higher in tainted samples than in the reference sample. These chemicals evoke strong earthy, green and bell pepper notes and MsBP was detected in this study for the

first time in coffee. (Cantergiani et al., 2001)

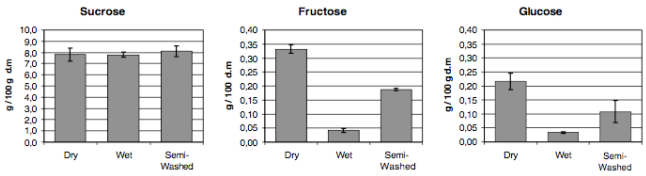
Spadone identified 2,4,6-trichloroanisole as primarily responsible for the Rio off-flavor in coffee. Vitzthum et al., propounds MIB as a key substance responsible for the earthy tone in Robusta coffee. Rougue et al., notes his view that the effect of MIB in Arabica coffees can be mitigated using steam-treatment and roasting.

Wet Processing

In the wet method coffee beans are pulped, fruit and skin are removed, or pulped and demucilated and mucilaginous mesocarp is removed under fermentation. In the wet method fermentation occurs in water at controlled temperatures which produce lower levels of undesirable flavors. For this reason the wet method is often associated with better cup quality. Gonzales-Rios et al., 2007 claim that the quality of green and roasted coffee, measured by aroma, was better after conventional fermentation than after mechanical mucilage removal.

Wet coffee readily takes up smells and aromas. Oil constitutes a major component of the coffee bean's composition and is able to take up and store smells and flavors before releasing them during roasting greatly affecting cup characteristics. According to the tea and coffee trade journal most cup defects are caused by wrong fermentation. In fermentation there are primarily two microorganisms at work to shape the eventual cup quality, bacteria and yeasts. During proper fermentation the bacteria feed on sugars in the mucilage. As soon as the sugars have been digested and the mucilage has been liquefied, the pH in the fermentation tank begins to decrease. It is at this point of lowering pH that the yeasts begin to become active. The yeasts go on to convert sugar to alcohol but are also metabolizing the solid parts of the mucilage resulting in aroma qualities that can have a negative impact on cup quality. This taste / smell characteristic is sometimes referred to as "fruity coffee." When coffee continues in this state even longer under reducing and acidic conditions, the yeast will convert sugars into acids as opposed to alcohol resulting in sour tasting coffee. (Tea & Coffee, November – December, 2005) Recommendations for avoidance of fruity and sour flavors include washing of beans as soon as fermentation has finished, when all mucilage has been liquefied. There is no across the board time frame for development of fruity and sour flavors as temperature and altitude play significant roles in those processes. It is noted that in general the best way to avoid these cup defects is to wash the parchment coffee as soon as fermentation has finished and parchment feels rough to the touch.

Below: The concentration of low molecular sugars in variously processed green coffees.



Clifford, 1985 proposes that Wet processed Arabica tends to be aromatic with a fine acidity but some astringency while dry processed Arabica tends to be less aromatic but produce greater body. This is largely due to the formation of acids in under water fermentation.

Gonzales-Rios et al., 2006 states that a comparison of green coffees from the different treatments (wet and dry processing) reveals the importance of mucilage removal in water to obtain coffees with better aroma quality. These wet processed coffees are in fact characterized by pleasant and fruity aroma characteristics whereas those obtained after a mechanical mucilage removal used in a more "ecolocial" process were characterized by less pleasant aromatic notes.

Kleinwachter and Selmar contend that when wet processed coffee beans are dried, there ensues a decrease in the water potential which causes a number of metabolic responses within the coffee bean. They found that the content of fructose and glucose decreased significantly within the first day of drying. This decrease in sugar content, they contend, proves that the lower contents of glucose and fructose that are generally found in wet processed coffees are, at least in part, due metabolic processes within the bean and are not the result of leaching of sugars into the water used for processing. (Kleinwachter and Selmar, 2010)

In 2001 Mendez et al. found that significant improvements could be made in customer receptivity to robusta coffees given high quality processing. The study revealed that when roasted at optimum ranges of 225 - 230* C for 22 to 28 minutes and wet processed, acceptance scores increased to "liked slightly" & "liked moderately" on the hedonic scale for both aroma and flavor. Mendez goes on to make the argument that with higher flavor and aroma scores a higher percentage of robusta may be used in blended coffees without adverse effects on customer satisfaction. (Mendez et al., 2001)

Storage

Significant defects can also arise as a result of insufficient drying and / or storage conditions as it is the drying process that prepares beans for processing later on as well as storage. When beans are insufficiently or unevenly dried a decrease in cup quality can occur much more rapidly than with beans that have undergone an ideal drying process. Stirling, 1974 shows a rapid decrease in cup quality level with increasing storage time from 6 to 18 months given various moisture contents. The decline in cup quality in wet coffee is due to mold and bacteria as molds and bacteria grow best in moisture rich environments and cup characteristics change as a result of bacteria and mould utilization of sugars in the coffee bean for metabolism. *Tea & Coffee* recommend a bean moisture content of 10 to 12% before packaging and storage.

One key aspect of coffee storage is bean respiration. Every 24 hours an average of 4.4 milligrams of CO_2 are produced by 100 grams of coffee beans and the 96 calories of heat produced by the 4.4 mg of CO_2 will raise the temperature of the beans .25° Celsius. A high respiration rate, in combination with heat generation, can cause a loss of weight and dry material in the bean as well as bean fat decomposition which plays a key role in the aroma of the cup. (Sivetz and Dosrosier, 1979).

"Stink coffee" can be produced as a result of excessive fermentation from the normal microbes that are at work in coffee processing. It is recommended that factory tanks and machinery be cleaned daily to ensure that old beans caught in crevices of machinery do not contaminate a later batch of coffee. Extreme over-fermentation

can germinate the coffee seed which dies quickly and leaves a hollow pit in the end of the bean. The dead bean then very quickly develops a cheese smelling texture which is highly distinctive when the bean is broken or cut. A single bean can contaminate and spoil an entire batch of perfectly good coffee. (Coffee & Tea, 2005)

Declining of cup quality is inevitable to some degree during storage. The reason for this decline, or aging, is surface oxidation from beans aided by microorganisms. The aging effect can be minimized by storing parchment and process beans in low temperature, low oxygen and low humidity conditions in order to dissuade bacterial, yeast and mold activity. Damaged beans tend to be much more subject to agind as the oils in the bean are extruding from the bean and provide a good growing ground for mold and bacteria. Molds have the potential to grow on dry surfaces and extract needed moisture from the air in storage rooms making humidity a key issue in storage facility design, maintenance and repair. One potential mitigation of the aging process on coffee beans is to utilize hermetically sealed containers or storage silos as opposed to bags. Such units could minimize oxygen levels as well as moisture contact metabolic rates of microorganisms and prolonging the amount of time in storage that would cause minimal affects on cup quality. Little information is available about the effect of CO_2 in such a system on the cup quality of the coffee stored.

Green beans can produce a "grassy" or harsh flavor cause by picking and processing immature cherries. Late in the picking season many cherries loose their green color but do not turn completely red. These unripe cherries will pulp easily but are full of chlorophyll. This is readily seen in fresh wet washed parchment which shows up the color of the silverskin underneath. One solution is to dun dry the coffee when weather conditions permit as ultraviolet light can bleach out the greenness in the silverskin. A slight degree of green color will often fade over time, making it undetectable at the final destination, but a strong degree of unripeness will facilitate chemical absorption back into the oil fraction of the final product.

Below: Aroma profiles of unstored raw coffee beans (gray line) and coffee bean with a water content of 13.5% stored for 9 months at 40*C under an atmosphere of 20% oxygen.

Onion flavor is another potential result of faulty post processing. Onion flavor occurs when the ration of soluble sugars to protopectins (contained in the mucilage) becomes too low. The primary rapid buildup of fermentation bacteria is fuelled by the relatively high level of sugar present within the ripened mucilage. If excessive fresh water is used in pre-washing of cherries and during the pulping process, most of these soluble sugars are leached out before normal fermentation takes place. Consequently, the beneficial soft rot bacteria can be overwhelmed later in the fermentation process not only by the yeasts but also by bacteria which convert acetic and lactic ac-

ids to propionic and butyric acids which cause the onion flavor. It has been found that this fault can be minimized by recycling of pulping water as maintaining a high level of sugars and enzymes in the water will facilitate normal bacterial action.

Scheidig et al., 2007 studied the atypical odors that develop during the storage of raw coffee beans and eventually influence the aroma of the coffee beverage. His results showed strong increases in damascenone (cooked apple-like odor), 2methoxy-4-vinyphenol (clove-like odor), and methyl 2-methyl and methyl-3methylbutanoate (fruity odor), with an increased water content and a storage time of 9 months at 40 *C. It was also found that earthy smelling 3-isopropyl-2-methoxypyrazine as well as 2-phenylethanol and 3-methozyphenol remained unchanged during the storage period. It was also found that a previously unknown odor in coffee, the intense smoky flavor caused by production of 2-methozy-5-vinylphenol, increased significantly due to storage. In conclusion, Scheidig recommends a reduction in water content of green beans in combination with lower storage temperatures to avoid aroma changes in raw coffee beans over long storage periods. (Scheidig et al, 2007)

Café Britt of Costa Rica, in conjunction with the Mesoamerican Development Institute, is experiencing positive results in the development of a hermetic storage unit. This unit facilitates long term storage of coffee in it's parchment state without the use of pesticides, the degradation of cup quality, aroma, or appearance for a period of five months or more. Coffee beans, even when properly dried can reabsorb fungus and bacteria encouraging moisture over time from the atmosphere. The storage of green beans can be even more problematic as they are more susceptible to quality deterioration. Hermetic enclosures manufactured by Grainpro Inc. in Concord, Massachusetts, are being used to store coffee. These enclosures use ultra violet light resistance PVC to provide an environment that maintains a very low moisture (humidity), low oxygen, high CO_2 environment. This type of environment is highly conducive to maintaining low levels of bacterial life, mold, insects and even prevents the formation of aflatoxins as a byproduct of mold development. Temperature and humidity ranges found in the hermetically sealed enclosures were also significantly narrower than for control groups of beans stored in silos or in bags in a warehouse. Cupping tests were done monthly on a five point scale and found that after two months there was a significant change in quality in beans stored in sacks and in silos, from 4.0 to 3.8 while cup quality stayed the same for beans stored in the hermetic enclosure. After a storage of five months cup quality for sacked coffee and coffee stored in a silo had decreased a full point to 3.0 and were described as "Slight old flavor perceptible in cup, slight harshness, tainted." The cup quality from beans stored hermetically was noted as "Very good flavor despite being from the previous harvest. Slight floral flavor." Cupping was done by Café Britt's cupper Carmen Lidia Chavarria as well as the cupper for the Costa Rican Consortium, COOCAFE, Jimmy Bonilla.

Roasting

Roasting has been called the most important step in the production of aroma and taste by Juerg Baggenstoss with the institute of Food Science and Nutrition in Zurich. As bean color turns to brown or even black in the roasting process brittleness is

greatly increased which facilitates the grinding and extraction processes. High temperatures, above 200* C, are necessary for the roasting process to occur. Green beans are especially hard due to unusually robust cell walls and a lack of intracellular space inherent in the coffee bean. As a result, coffee beans are regarded as an aggregate of micro reactor units that sustain a considerable pressure buildup due to the heat of roasting with theoretical values of up to 16 bars being produced within the cell walls with no evidence of the cell wall disruption being observed in scanning electron microscope investigation. This is thought to be due to the fact that at high temperature coffee cell walls change from a hard glassy state to a more elastic state which facilitates considerable volume increase without rupturing. It has been generally noted that convective heat transfer is the most effective for uniform roasting.

The state of roasted coffee is influenced by the roasting conditions in terms of degree of roast. A number of options exist for description of degree of roast; color development, roast loss, organic roast loss and water content. Of these, the color of the coffee bean or ground coffee is the most commonly used indicator of roast as bean color intensity has been correlated to roasting temperature. This however, is not a direct relationship as color does vary as a function of raw material and process conditions. (Baggenstoss et al., 2008)

Baggenstoss went on to explore the effect of roasting on aroma formation under different time-temperature conditions. When compared to low temperature-long time roasting, high temperature-short time roasting results in relevant differences in the physical properties of aroma formation. It was found that excessive roasting typically lead to decreasing or stable amounts of volatiles with the notable exceptions of haxanal, pyridine, and dimethyl trisulfide, whose concentrations increased continually during over roasting. When roasters were operated in the "temperature profile" mode, along the identical development of coffee bean temperature over roasting time, the kinetics of aroma generation were similar in both drum roaster and fluidizing bed roaster processes.

Franca et al., 2009 concludes that caffeine and pyridine were the main discriminating compounds for coffees roasted at high temperatures and more intense degrees of roast. Although discrimination of coffee samples roasted to different degrees was attained by analyzing the effect of hundreds of compounds together, the compounds that presented the most pronounced effect on the discrimination of roasting degrees and temperatures were those generated right after the onset of pyrolysis (decomposition brought about by high temperatures). The results presented in this study reveal that color and weight loss in and of themselves are not entirely reliable as roasting degree assessment criteria and the temperature at which beans are roasted must also be taken into consideration.

Brewed Coffee

Once coffee is brewed the decline of pH and the quality score were correlated at a number of storage temperatures by Rosa et al, 1989. Roas's sensory analysis allowed definition of a lower limit of pH at which coffee's shelf life ended. Sivetz and Desrosier, 1979 showed that the decline in pH comes as s result of the formation of caffein and quinic acids as breakdown products of chlorogenic acid. This process was found to accelerate with increasing storage temperature. Results show that coffee quality

remains high as long as pH remains high, in the 5.2 range, after brewing and that the ideal temperature regime for storage is near freezing at approximately 4°C.

The Impact of Climate Change

Global climate change in the coming years will have significant impact on the coffee producing regions of the world. Current correlations between altitude, temperature, rainfall and cup quality as well as yield will all be modified to some lesser or greater extent. It is generally recognized that higher mean temperatures and changes in precipitation regimes will typify the climate changes that we are likely to see across the globe in the next 50 years according to a number of global circulation models (GCM's).

Coffee systems are characterized by long lead times necessary for both farmers and their business partners to make accommodation for change in growing patterns, with an average of 8-15 years being required from decision to fruition. (Laderach et al., 2009) Laderach et al., 2008 predicts that climate change will shift the prime altitude range to higher elevations over time. He estimates that in Central America a shift will occur from 1200m for optimal plant health and cup quality to 1400m in 2020 and 1600m in 2050.

Overall climate will become more seasonal in terms of variability throught the year in terms of temperature and precipitation on the whole with temperature increasing in South America on the order of 2* C by 2050. Consequently, suitability for coffee will move upwards on the altitudinal gradient with climate change. Lower altitude areas will lose suitability due to their higher temperatures.

The areas that will be highly suitable for coffee production in 2050 are likely to be those areas that are highly suitable today, it is the large marginal areas that will probably lose their capacity for coffee production. Altitude and temperature have a fixed relation called the lapse rate which is equal to .6*C per 100m of altitude. Precipitation in the wettest month of the year and mean temperature of the coldest quarter of the year tend to be the most decisive factors in the suitability of an area for coffee production as stated by Laderach, 2009. Assuming that these findings are widely applicable, global climate change will require coffee producers to implement significant strategic planning to adjust their crops and production areas in order to mitigate the negative affects of changing climate patterns.

Conclusions

While the data support few universal equations for coffee quality, a few key tradeoffs are evident from literature. Firstly, that there is a tradeoff in perception, if not in fact, between disease resistance and cup quality. Further study has the potential to uncover thresholds in productivity and cup quality tradeoffs in this field. Soil nutrition will also be a key area of focus in the coming years as decreasing soil quality due to consistent high yield output could cause further constriction of the supply chain through decreasing yields. This is largely due to the inability of small land holder farmers to provide the inputs necessary for consistent and long term quality harvests. Larger scale inputs could be facilitated through larger scale farming techniques but significant tradeoffs exist due to the possibility of decreasing quality of coffees picked and processed mechanically at one time as opposed to hand picked beans picked at the height of their maturity. Post harvest separation of ripe from unripe beans remains a key quality control that has the potential to mitigate this issue if properly applied, as pointed out by Dr. Carlos Brando.

At this point major tradeoffs exist for storage as well. Increased storage times have traditionally meant supply chain stability at the expense of cup quality. However, technologies are being developed that could change even this paradigm in the near future.

The future of coffee is bright given the continued and expanded dissemination and implementation of cutting edge research at the farm level. Working in concert with one another as an industry to implement such research, there is no limit to our combined potential for producing coffee that is as excellent as it is unique in economically viable quantity.

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