SHADE COFFEE IN HAWAI'I – QUALITY, PHYSIOLOGY, AND BIOCHEMISTRY

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Dedication

I dedicate this dissertation to everyone who is trying to balance the benefits of modern, intensive agriculture with their environmental consciousness.

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ABSTRACT

To explore the effects of shade level and type on coffee in Hawai'i, *Coffea arabica* L. was shaded with varying degrees of black and aluminized shade cloth, macadamia trees, and a novel, spray-on shade composed mostly of kaolin. These treatments were compared to unshaded coffee. Two locations were used in this experiment: Kunia, O'ahu and Kona, Hawai'i. The shading was imposed after the first major flowering of the season and maintained for 2 complete harvests.

Measurements were made on yields, bean characteristics, specific leaf area, leaf temperature, leaf nutrient levels, nodal growth, organoleptic quality and photosynthetic response. Brewed coffee samples were analyzed using solid phase microextraction-gas chromatography to capture and analyze brewed coffee volatiles. These volatiles were used topredict organoleptic quality and group membership based on location, year of harvest and shade treatment. In addition, application of kaolin was explored using glass plates and slides to determine coverage and light transmittance.

Shading resulted in statistically different yields in the macadamia (16% of sun) and kaolin (199% of sun) treatments in the second year, although a negative, linear trend was observed with increased shading. The lack of significant differences in yields between the cloth shaded and sun treatments was likely a result of large yield variation. Bean sizes were generally larger in shaded treatments and only the percentage of defects and broken beans were lower for the kaolin treatment in the second year in Kunia. Kona bean sizes were larger in the sun treatment but no differences were observed in bean characteristics. Kaolin treated plants responded similarly to sun plants for most measurements, although the responses tended to be more extreme when compared to the shade cloth and macadamia

treatments. Kaolin treated leaves were 3.4 °C cooler than sun leaves and photosynthesized 71% more CO_2 than sun plants.

Shading did not appreciably affect organoleptic quality. Furthermore, brewed coffee volatiles were not good predictors of organoleptic quality. However, with few to no misclassifications, the volatiles could accurately predict group membership.

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Chapter 1
Introduction

Coffee has been cultivated as a crop for about 1500 years. For the vast majority of that time, it has been grown beneath taller forest trees – its natural habitat. With the invention of synthetic fertilizers and other agrochemicals, many growers have either taken it out of the forest or removed the forest in order to achieve greater yields and ease of production facilitated by accessible, soluble fertilizers (Perfecto et al, 1996).

Intensive scientific exploration of the differences between shade and sun grown coffee began in the late 1970's and 1980's, although some yield trials were reported earlier (Abruña et al, 1965; Boneta Garcia and Bosque Lugo, 1972). These studies examined areas such as pests, nutrient cycling, and microclimatic differences (Easwararamoorthy and Jayaraj, 1977, Aranguren et al, 1982; Barradas and Fanjul, 1986; Russo and Budowski, 1986). In general, these results indicate that growing coffee in the shade decreases yields. However, the shade trees can offer benefits that may include reduced pest pressure, amelioration of an imperfect climate, supplement of nutrients, and a decrease in the need for water inputs.

Shade trees have been shown to alter the microenvironment around coffee. These changes likely explain why some pests and diseases are less successful under shade (Nataraj and Subramanian, 1975; Muschler, 1998; Fawole, 1999; Samayoa-Juarez and Sanchez-Garita, 2000). Caramori et al. (1996), studying frost protection provided by *Mimosa scabrella* Benth, showed leaf and air temperatures remained 2-4 and 1-2 °C warmer at night, respectively, in shaded plots and reduced damage from cool temperatures. In Mexico, air temperature was 5.4 °C higher and the minimum 1.5 °C lower in sun compared to shade plantations (Barradas and Fanjul, 1986; Baggio et al., 1997). Piché evaporation, soil temperature, and

vapor pressure deficits also were lower under shade trees. Overstory trees also reduced wind speed below their canopies (Schroeder, 1951; Caramori et al., 1986).

Nitrogen supply, more than that of any other nutrient, limits coffee production (Carvajal, 1984). Coffee fields planted at densities below 5000 bushes·ha^{-1} require less than 100 kg·N·ha^{-1} annually (Bornemisza, 1982). Legume-shaded plantations acquire substantial N via the litterfall of overstory trees. Aranguren et al (1982) showed that N input from shade tree litterfall alone was approximately 95 kg·N·ha^{-1}·yr^{-1}. Fallen leaves from *Erythrina poeppigiana* and the debris provided by pollarding added 330.5, 269.3, and 173 kg·N·ha^{-1}·yr^{-1}, depending on whether trees were trimmed one, two or three times a year, respectively (Russo and Budowski, 1986). In addition, Babbar and Zak (1995) found that N lost by leaching in modern systems exceeded that in traditional systems by almost three-fold. However, results from laboratory experiments showed 60% greater denitrification rates in shaded systems.

Shading increases water availability, presumably by reducing soil evaporation (Velasco et al, 2001; Lin, 2007). Cassidy and Kumar (1984) and Cuenca et al (1983) found that most of the roots of shaded coffee plants occupy the upper 50 cm of soils, suggesting relatively little opportunity to interact with the typically deeper rooted overstory trees. Although not studied with coffee, it is possible that canopy trees may improve access to water by hydraulic lift (Horton and Hart, 1998).

Since the early research on shade coffee, yield has been an important component of experimental designs. Unfortunately, the results of all these studies do not show a consistent trend between light levels or agroforestry system and yields. As discussed by Beer et al (1998) and Perfecto et al (2005), shaded coffee systems can produce lower, higher or equal

yields relative to comparable sun systems. Muschler (1997) explains this variability in the context of the growing environment of the coffee. Under optimal climatic, hydrologic, and nutritional conditions, photosynthetically active radiation becomes the limiting factor in fruit production. However, in sub-optimal conditions, shade trees can compensate for the limiting factors or eliminate or reduce the stress that would be experienced under full sun conditions.

When researchers began examining biodiversity in coffee plantations in the mid-1990's, they discovered a paucity in the monoculture systems relative to the complex, shaded systems (Estrada et al, 1994; Perfecto et al, 1996). Concurrently, concern over the loss of biodiversity and habitat for migratory birds prompted The Rainforest Alliance and The Smithsonian Migratory Bird Center to establish criteria (unique for each organization) that defined a healthy shade coffee system. The criteria included a minimum amount of shade tree density, tree species diversity, and canopy strata. Absent from the criteria was any measure of coffee quality. Using these criteria, each organization began certifying coffee farms grown in shaded systems.

Operating under the assumption that shade grown coffee is more labor intensive and produces lower yields (and, consequently, profits), these organizations offered a price premium to the certified farms to offset the increased costs and lower yields. These premiums and the income from diversified farm products helped make the shaded farms profitable, though typically much less so than their sun grown counterparts (Oscar Hernandez et al, 1997; Gobbi, 2000; Gordon et al, 2007). They then encouraged consumers to purchase these higher-priced coffees, regardless of quality, with the understanding that they were protecting wildlife and rainforests.

The only other economic incentive of growing shaded coffee is the reduced risk associated with complex agroforestry systems that can provide other cash-earning crops (Herzog, 1994; Ramirez and Sosa, 2007). These, along with the aforementioned environmental benefits and a farmer's personal desire to grow shaded coffee, are the common factors that motivate farmers to grow coffee under shade. Regardless of the reasons a farmer may choose to use a coffee agroforestry system, the current model of support for these systems by the consumer is based upon the consumer's willingness to pay for coffee that they believe is grown in an environmentally and socially responsible way.

As information becomes easier to access and consumers' palates grow increasingly sophisticated, more coffee drinkers will seek coffees with an appealing taste, regardless of price and production method. One example of this growing trend is The Cup of Excellence (COE) program. The COE program attracts consumers worldwide and is constantly expanding to include additional producing countries. Producing countries host a series of internal competitions that are designed to discover coffees with excellent organoleptic properties. Internationally-respected coffee tasters are invited to judge the final competition. The winning coffees are then sold in an international auction. Coffees that are auctioned in the COE program sell for prices vastly higher than nearly any other available coffee. These winning coffees are grown by a myriad of production practices and are not necessarily certified as organic, shade-grown, or sustainable by any organization.

Agricultural products whose appreciation is based upon quality are tied closely to the consumer. Organoleptic quality, not social or environmental ethics, appears to be the major determiner of a consumer's choice to purchase coffee and, consequently, support a farm (de Ferran and Grunert, 2007; Wood, 2007). As a result, consumer preference can drive many

aspects of a coffee's production so long as the coffee has a valued organoleptic quality. Evidence of high quality, shade grown coffee will attract consumers. Conversely, low quality, shade grown coffee will discourage consumers and undermine its sustainability.

The persistence of certified shade grown coffees in the marketplace demonstrates a demand for these products, possibly from the individuals buying coffees based on an ethic rather than organoleptic quality. However, if organoleptic quality does not support the higher retail price for these coffees, shade grown production systems may not only fail to attract new purchasers but they may also lose current ones whose tastes become more sophisticated. Without a clear understanding of the effects of shade culture on coffee organoleptic quality, farmers cannot adjust growing practices accordingly to accommodate consumers.

In Hawai'i, shade coffee culture is rare. The traditional coffee growing region of Kona is typified by moderate climate, afternoon cloud cover, and rain during the period of intensive fruit growth. In addition, Hawai'i farmers have access to fertilizer and irrigation to sustain the higher yields associated with full sun production. With the expansion of coffee farming outside of Kona into less optimal growing environments and the increased eco-consciousness of farmers and consumers, interest in shade culture has blossomed. Furthermore, the increasing prices of agricultural inputs, such as fertilizer, are encouraging farmers to think differently about their standard agriculture practices. However, no research has been conducted on shade coffee agroecosystems in Hawai'i, leaving farmers with a dearth of information to make informed decisions. In addition to information on the effects of shade on organoleptic quality, basic research into coffee's response to shading in Hawai'i is needed.

Shade grown coffee has garnered the attention of many researchers in the last 3 decades (Beer et al, 1998; DaMatta, 2004). However, none have evaluated the actual impact of light reduction on organoleptic quality independent of an agroforestry system (Guyot et al, 1996; Muschler, 2001; Vaast et al, 2006). Thus far, most discussions have been based upon anecdotal information.

Not unexpectedly, lower light levels affect aspects of coffee physiology and quality aside from yield and organoleptic measures. Vegetative growth, as measured by nodal production, is lower in shaded versus sun grown coffee (Campanha et al, 2004; Morais et al, 2006, Ricci et al, 2006). Leaf shape is also heavily influenced by shading (references within Rena et al, 1994 and Barros et al, 1999; Bote, 2007). Bean sizes tend to be smaller in sun grown coffee (Abruña et al, 1965; Muschler, 2001). Bean characteristics, including the percentage of peaberries in a crop, tend not to differ due to shade, though this is not always true (Abruña et al, 1965; Muschler, 1998; Morais et al; 2006).

The biochemical responses of coffee seeds to growing conditions are not well documented. However, researchers measuring simple organic acids, sucrose, caffeine, trigonelline, and chlorogenic acids have discovered that light levels influence production of some chemicals (Guyot et al, 1996; Vaast et al, 2006). Unfortunately, the results are inconsistent for individual chemical groups.

The aim of this project was to explore the interaction of coffee organoleptic quality and shade culture. The project was designed to compare coffee that was shaded not only with different types of materials (trees, shade cloth, and a novel spray-on shade made from kaolin) but also to compare coffee subjected to different levels of shade that arise from the same material.

Over the course of two growing seasons, the coffees were harvested, processed in the same manner, and prepared for tasting. A panel of tasters was trained to evaluate the coffees according to scientific and industry standards. In addition, measures of quality that are also important to farmers were evaluated. Thus, yield, bean characteristics, and plant physiological responses were measured.

A primary goal of coffee science is to remove the subjectivity of human-measured taste-quality and define it using quantitative chemical indicators. Thus far, no research has convincingly shown any correlation between chemicals in green or roasted coffee and organoleptic properties. This project explored that relationship by using brewed coffee – a product closer to human experience than green or roasted coffee.

Human taste is mostly limited to four aspects (sweet, acid, salt and bitter) plus a more recent addition, umami (savoriness as exemplified by the response to monosodium glutamate; Lawless and Heymann, 1998). "Taste" thus becomes mostly an experience of volatile components reaching the scent receptors in the nose. To this end, aroma compounds of brewed coffee were used to correlate coffee chemistry to taste perception. The taste panel rated basic characteristics of the coffee organoleptic experience (dry aroma, wet aroma, acidity, body, flavor, sweetness, and aftertaste). Solid phase microextraction in conjunction with gas chromatography was used to capture and analyze the volatile components of those same brewed coffees.

The results of the analytical chemistry were put to further use. The coffee samples all came from known groups: location of farm, year of production and shade type. Using the multivariate analysis technique of discriminate analysis, the data set was used to discover if each group could be defined by and separated based upon its chemical profile.

Results of this research may be translated into recommendations for farmers. Farmers interested in shade coffee culture will be interested not only in yield responses but in field-level quality measurements such as bean size and characteristics as well. Undoubtedly, an understanding of the changes in the organoleptic quality will be desired by farmers striving to produce high quality coffee. Lastly, the ability to rapidly and accurately predict organoleptic properties from a biochemical profile will assist the entire Hawai'i coffee industry by removing some expense subjectivity of quality assessment.

This dissertation is divided into three primary chapters. Each chapter is written in a form that is appropriate for the scientific journal to which it will be submitted. Chapter 2 addresses all topics related to coffee quality and plant physiology except those pertaining specifically to the kaolin treatment. It was written for *Agroforestry Systems*. Chapter 3 discusses the novel, spray-on shade treatment (kaolin) and was written for and published in *HortScience*. Chapter 4 discusses the correlation of coffee aromas to organoleptic quality and group discrimination and was written for the *Journal of Agricultural and Food Chemistry*. The final chapter concludes the dissertation and makes a statement about growing coffee in the shade in Hawai'i.

Chapter 2
Shade coffee in Hawai'i: Quality, growth, yield and nutrition

Introduction

In the traditional coffee growing region of Kona, Hawai'i, shade culture has been uncommon. Kona is typified by moderate climate, afternoon cloud cover, and rain during the period of intensive fruit growth, obviating the need to shade the coffee. The presumed reduction in yield and increased management requirements associated with shade culture have also prevented widespread adoption of shade trees.

Some coffee growing has expanded out of the Kona region into areas that exhibit sunny, hot, and dry conditions that are not ideal for a shade tolerant plant. Consequently, there may be some benefits of shade culture for coffee growers in these areas. While sufficient fertilization and irrigation ameliorate harsh climatic conditions, shading can be a cost-effective cultural practice to address field and microclimate inadequacies (Beer et al, 1998). In addition, consumers and farmers often associate shade-grown coffee with environmental consciousness and sustainability, and it is the basis for some certification schemes (Perfecto et al, 2005). Furthermore, some evidence demonstrates that shade has an influence on coffee's organoleptic properties (Guyot et al, 1996; Muschler, 2001; Vaast et al, 2006). For Hawai'i, maintaining the reputation for high-quality coffee would be important as production expands into new areas.

No research has been conducted on shade coffee systems in Hawai'i and only some work has been conducted on physiological responses to light (Friend, 1984; Crisosto et al, 1990; Gutiérrez and Meinzer, 1994). Consequently, scientists can only rely upon results from studies in other coffee growing regions to make recommendations to farmers. In order to understand coffee's response to reduced light conditions and to be able to

generalize the results to a myriad of coffee agroforestry systems, abiotic shade sources were the main focus of this experiment. This research project explored the influence of abiotic and biotic shade sources on aspects of coffee physiology, morphology, yield, and organoleptic quality.

Materials and Methods

Experimental layout

Coffea arabica L. trees of the Typica landrace, cultivar Kona Typica, growing in Kunia, Oahu Island, Hawai'i (21°23'N 158°2'W, elevation = 83 m asl) and Kona, Hawai'i Island, Hawai'i (19°32'N 155°5'W, elevation 425 m asl) were chosen for this experiment. The Kunia trees were planted in 1987 and were in 1 x 5-6 m hedgerows (originally 1 x 3 m) during the experiment. The Kona trees were planted in 1992 in 1.2 x 3 m hedgerows. The trees were stumped in January 2004 to a height of 0.5 m. Four orthotropic shoots were allowed to regrow on the stump. In June 2005, all shoots were decapitated above the highest lateral branch supporting fruit and further vertical growth was suppressed by removing suckers as needed. All trees were drip irrigated and fertigated equally within a location.

Incident PAR was measured using a PAR Smart Sensor and logged every 2 minutes using a Hobo Weather Station (Onset Computer Corporation, Pocasset, MA, USA). Table 2.1 shows the average daily incident PAR between 800 and 1600 HR and the maximum value measured. The table presents data for the months with the highest and lowest averages.

Table 2.1. Average incident PAR[a]

	June 2005		December 2005	
Location	Average	Maximum[b]	Average	Maximum
Kona	1022	2500	889	2259
Kunia	1403	2500	956	2256

[a]$\mu mol \cdot m^{-2} \cdot s^{-1}$

[b]Sensor upper range limit = 2500

In Kunia, experimental units consisted of four consecutive trees. The two outer trees served as border trees and were not subject to data collection. Five rows in the field were selected as blocked replicates. In Kona, experimental units consisted of randomly selected individual trees with 6 replications.

Experimental units were randomly assigned to a shade treatment. In Kunia, the first year, the treatments were full sun, 40% aluminized shade cloth (Aluminet), 40% black shade cloth or a kaolin based spray-on shade as described by Steiman et al. (2007). Spraying commenced on 24 Feb 2005 and continued until 5 Dec 2006. In the second year, three blocked-replicates each of a 30% and 66% black shade cloth were added. In Kona, the treatments were full sun, Aluminet (40% shade), and macadamia trees (planted in 1988, spaced 7.5 m apart, 87-97% shade). The macadamia trees were planted in a specific section of the farm, so the experimental units within this treatment were randomly selected within this section. Aside from the macadamia trees, all shade treatments were first imposed after the first major flowering of the season.

Leaf temperature, growth, and nutrition

Leaf temperature measurements were taken between 1100 and 1200 HR the first week of May 2005 using a Mini IR Temp Meter (emissivity = 0.95 fixed; Spectrum

Technologies). Five (Kona) or six (Kunia) most recently matured leaves per experimental unit from both sides of the row were measured.

On 8 and 9 August 2006 (Kona and Kunia, respectively), 20 (Kunia) or 10 (Kona) lateral branches were randomly selected per experimental unit. To estimate lateral growth from the first season (2005), nodes supporting fruit or unopened flowers were counted on each branch.

Specific leaf area (SLA, $m^2 \cdot kg^{-1}$) was calculated from 8 pairs of recently matured leaves harvested on 13 September 2005 in Kunia. Prior to drying and weighing, their area was measured using a LI-COR 3100C leaf area meter (LI-COR Biosciences, Lincoln, NE, USA). On 6 February 2007, five leaves were harvested from each experimental unit in Kona and their area was measured with a CI - 202 Portable Leaf Area Meter (CID, Inc. WA, USA) before drying and weighing.

On 16 March 2005, 13 September 2005, 4 April 2006, and 3 July 2006, 10 pairs of the most recently matured leaves from each experimental unit in Kunia were collected and analyzed for nutrient concentrations according to Simonne et al. (1994) for N and Kalra (1998) for all other nutrients. On 23 April 2006, the same procedure was used to collect and analyze leaf tissue from Kona.

Coffee harvesting and processing

Each season, mature cherries were picked, as needed, until the trees were completely harvested. At the end of each harvest day, the coffee cherries were pulped and briefly soaked in enough water to remove the floaters. The seeds were then dried at 45 °C to 12% moisture content (wet weight basis). The floaters were dried separately from the heavier coffee. Once dry, the coffee was bulked with the samples that were previously harvested

and dried from that experimental unit. At the completion of the harvest season, the samples and corresponding floaters were hulled and winnowed. The green coffee was sorted by size using 64th inch screens (0.4 mm). In most cases, only beans from screen sizes 17 or 18 were used for the analysis. Occasionally, beans screened as 16 or 19 were used due to low amounts of sample. Defects, broken beans, and peaberries were manually removed. Defects were defined as beans with any amount of discoloration or malformation, regardless of their potential effect on organoleptic quality. All screen sizes, floaters, and separated bean characteristics were weighed and summed to calculate their percentages relative to total green bean yield.

The coffee was roasted in a Probat PRE-1 sample roaster. The dial on the roaster was kept at "60" and the air flow remained open. When the internal roaster temperature reached 220 °C, 120 g of coffee was added and allowed to roast for approximately 12 minutes, corresponding to a weight loss of 17-18%. All coffees within a block or replication were roasted on the same day. Roasted coffees were stored as whole beans in 475 ml glass jars at room temperature (23-25 °C). The following two days, the coffees were cupped and chemically analyzed, respectively. See Chapter 4 for the results of the chemical analysis.

Cupping

Each cupping day consisted of 2 sessions. Each session tested all the experimental units within a location and usually a single block or replicate. Samples were coded with a random, 3-digit number and randomized on the tray. All cupping took place in black, individual tasting booths. Each experimental unit was cupped once by a trained panel consisting of 9 or 10 people. Panelists were non-smoking employees or students of the University of Hawai'i.

Coffees were ground to a size of "Fin" using an I Santos grinder (Lyon, France) and 8.25 g was measured into 177 ml ceramic bouillon cups. Prior to adding 150 ml of 90 °C water, the dry aroma was assessed. Two minutes later, the crust was broken and wet aroma was assessed. Five minutes after the addition of water, acidity was evaluated, followed by flavor, sweetness, body, and aftertaste.

Scoring of the attributes was done with a mark intersecting an anchored, 2.0 cm line. The left anchor represented "not present" and the right anchor represented "intense." Ratings were converted to numbers 1-10 using a clear overlay sheet.

Statistical analysis

All statistical analysis was performed using JMP 7.0.1 statistical software (SAS Institute, Inc., Cary, NC, USA). Data from Kunia were analyzed as a randomized complete block design. Kona data was analyzed as a completely randomized design. The cupping data was analyzed as a split-plot with the cupper as the main plot and the treatment as the sub-plot. One-way analysis of variance was used to test treatment effects. Where significant treatment effects were indicated, the Tukey-Kramer HSD test was used for means separation.

Results

Organoleptic characteristics were not significantly different for most of the treatments at either location. Table 2.2 shows the cupping ratings and mean separation of the significantly different cupping characteristics. The complete data set can be found in Appendix A.1.

Table 2.2. Cupping characteristics that were significantly different in Kona[a]

	Aftertaste	Body
2006		
Aluminet (40%)	4.1a	4.8ab
Macadamia	3.2b	4.3b
Sun	3.8ab	5.2a
2007		
Aluminet (40%)	3.5b	
Macadamia	3.9ab	
Sun	4.5a	

[a]Different letters within a harvest year and column are significantly different at p = 0.05

Table 2.3 shows the leaf temperature and growth responses to the shade treatments. Leaf temperatures were cooler than full sun under all shading regimes. Nodal growth was only different in the macadamia treatment where it was about one third less than the other treatments. In Kunia, SLA of the two shade cloth treatments was significantly greater than the sun and kaolin treatments. In Kona, SLA of the macadamia treatment was higher than the sun and Aluminet treatments.

Table 2.3. Coffee leaf temperature and growth responses to shade[a]

	Leaf Temp (°C)		Nodal growth (nodes per lateral)		Specific leaf area ($m^2 \cdot kg^{-1}$)	
Treatment	Kunia	Kona	Kunia	Kona	Kunia	Kona
Macadamia		22.3c		3.8b		18.4a
Sun	37.1a	33.7a	12.2	10.5a	13.6b	14.3b
Aluminet (40%)	33.3b	27.6b	12.4	9.2a	15.2a	15.6b
Black (40%)	32.3b		12		15.6a	
Kaolin	33.7b		12.6		13.3b	

[a]Different letters within a column are significantly different at p = 0.05

In 2006, bean characteristics (floaters, defects, broken beans, and peaberries) were not significantly different between treatments in Kunia (Appendix A.2). Only a subsample

of coffee from Kona was processed in 2006; therefore, accurate bean characteristics and size data could not be compiled. In 2007, there were significant differences between treatments at Kunia for percent defects and broken beans (Table 2.4).

In Kunia, the sun and kaolin treatments had a greater percentage of smaller beans than all other treatments (Figure 2.1A). The proportion of size 16 and 17 beans from Kunia in 2007 were regressed against yield and shade level (with the kaolin treatment considered to have no shade). There was a significantly positive linear relationship with yield ($R^2 = 0.46$ and 0.61 for sizes 16 and 17, respectively) and a significantly negative linear relationship with shade level ($R^2 = 0.45$ and 0.44 for sizes 16 and 17, respectively; Appendix B.1 and B.2). No other bean sizes showed an appreciable relationship. The bean sizes from the 2007 Kona harvest were reversed from Kunia; greater light exposure translated to a greater percentage of larger beans (Figure 2.1B).

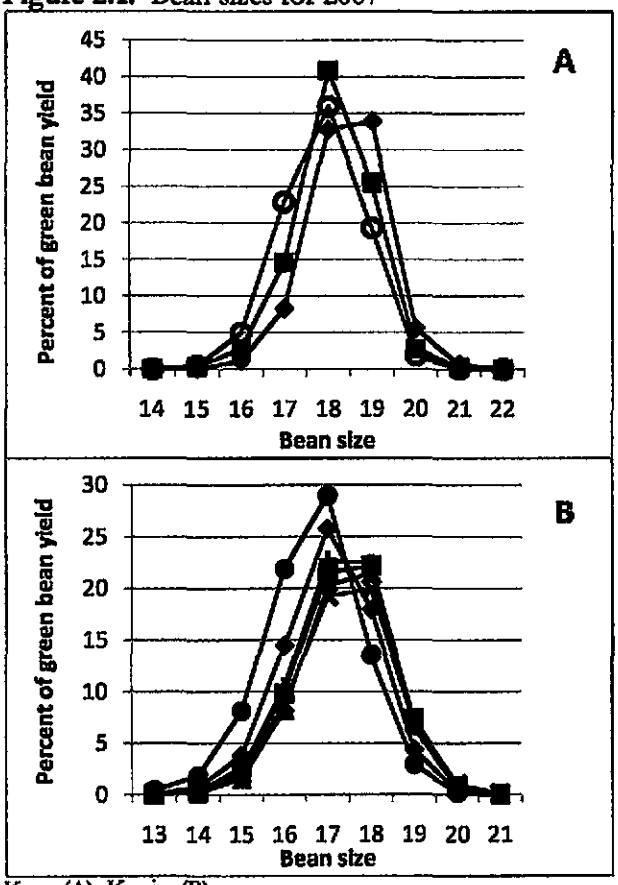
Table 2.4. Bean characteristics in 2007 as percent of green bean harvest[†]

	Floaters		Defects		Broken beans		Peaberries	
Treatment	Kunia	Kona	Kunia	Kona	Kunia	Kona	Kunia	Kona
Macadamia		2.2		4.6		2.8		4.6
Sun	4.7	1.3	9.9ab	3.5	12.0a	3.8	5.9	8.9[‡]
Aluminet (40%)	4.9	2	13.5ab	3.2	10.4ab	3.4	6.4	4.3
Black (30%)	4.1		18.5a		10.2ab		6.8	
Black (40%)	4.4		15.9a		7.9ab		6.5	
Black (66%)	4.5		15.7ab		13.9a		6.5	
Kaolin	4.2		6.5b		6.0b		5.4	

[†]Different letters within a column are significantly different at $p = 0.05$

[‡]The high value is a result of one tree producing 30% peaberries

Figure 2.1. Bean sizes for 2007



Kona (A), Kunia, (B)
♦ - sun, ■ – Aluminet, o – macadamia ● – kaolin, ▲- black (30%),
+ - black (40%), x – black (66%)

Table 2.5 shows the leaf nutrient concentrations for Kunia. In two of the four samplings, the shade cloth treatments had higher Fe concentrations than the other treatments and one sampling shows a separation of values. Significant differences between treatments for some nutrient concentrations existed for the 13 September and 4 April samplings; however, no pattern was discernible. In the 3 July 2006 analysis, the kaolin treatment showed significant differences from the other treatments in most nutrient categories. The sun treatment often had concentration levels similar to all other treatments and the shade cloth treatments always responded similarly to each other.

Leaf nutrient concentrations from Kona are shown in Table 2.6. Iron levels were higher in the macadamia treatment. Zinc levels were higher in the Aluminet treatment. Nitrogen, Ca and Mn also varied among treatments.

In 2006, green bean yields were not significantly different for any of the treatments at either location (Table 2.7). In 2007, yields for the kaolin treatment at Kunia were significantly greater than all other treatments. In Kona, yields for the macadamia treatment were significantly less than all other treatments.

Table 2.5. Leaf nutrient concentrations in Kunia[a]

Sampling date	N	P	K	Ca	Mg	Na	Fe	Mn	Zn	Cu	B
	%						ppm				
3/16/05											
Aluminet (40%)	2.83	0.14	1.31	0.74	0.55	0.01	84ab	139	5.6ab	11	40
Black (40%)	2.97	0.15	1.30	0.82	0.59	0.01	88a	150	6a	11	47
Kaolin	2.86	0.14	1.29	0.78	0.55	0.02	63c	142	5.2ab	11	45
Sun	2.85	0.14	1.36	0.73	0.52	0.02	75b	150	5b	11	43
9/13/05											
Aluminet (40%)		0.12	1.56ab	0.96	0.71b	0.018b	76	103b	5	8	63
Black (40%)		0.12	1.69a	1.15	0.78ab	0.028a	77	111ab	6	9	72
Kaolin		0.12	1.22b	1.14	0.86a	0.022ab	71	135a	7	9	67
Sun		0.12	1.43ab	1.05	0.79ab	0.024ab	79	133a	7	9	67
4/4/06											
Aluminet (40%)	2.70	0.15	1.58a	0.56b	0.43b	0.01	75	92	7a	11	32
Black (40%)	2.71	0.14	1.55a	0.63ab	0.46ab	0.01	77	118	7a	10	34
Kaolin	2.75	0.15	1.32b	0.76a	0.52a	0.02	50	141	5b	10	40
Sun	2.62	0.14	1.33b	0.68ab	0.49ab	0.01	61	133	5b	8	37
7/3/06											
Aluminet (40%)	2.78a	0.12	1.71a	0.67b	0.52b	0.13	136a	90b	9	12	42b
Black (40%)	2.92a	0.13	1.79a	0.72b	0.57b	0.11	135a	93b	8	17	47b
Kaolin	2.22a	0.12	0.94b	1.03a	0.77a	0.16	98b	139a	8	16	64a
Sun	2.66b	0.12	1.49a	0.75b	0.57b	0.11	118ab	119ab	7	10	52ab

[a]Different letters within a harvest year and column are significantly different at p = 0.05

Table 2.6. Leaf nutrient concentrations in Kona[a]

Sampling date	N	P	K	Ca	Mg	Na	Fe	Mn	Zn	Cu	B
	%						ppm				
4/23/2006											
Macadamia	2.57a	0.13	1.80	1.61a	0.44	0.02	153a	93a	7b	10	37
Sun	2.18b	0.15	1.61	1.22b	0.36	0.02	68b	53b	5b	12	37
Aluminet (40%)	2.47ab	0.14	1.56	1.49ab	0.44	0.02	84b	75ab	10a	10	38

[a]Different letters within a harvest year and column are significantly different at p = 0.05

Table 2.7. Total green bean harvest (kg/ha)[ab]

Kunia							Kona						
Treatment	Year						Treatment	Year					
	2006		2007		Total			2006		2007		Total	
Kaolin	1580	(305)	3030a	(445)	4610a	(541)	Macadamia	980	(1279)	460b	(209)	1440b	(1324)
Sun	1380	(841)	1520b	(794)	2900ab	(1605)	Sun	2340	(1172)	2920a	(1048)	5260a	(1340)
Aluminet (40%)	860	(462)	1300b	(713)	2160b	(1103)	Aluminet (40%)	1530	(660)	3140a	(1708)	4670a	(1444)
Black (30%)			1060b	(218)									
Black (40%)	800	(456)	1150b	(620)	1950b	(1042)							
Black (66%)			680b	(441)									

[a]Different letters within a column are significantly different at p = 0.05

[b]Numbers in parentheses are the standard deviation

Discussion

The results in this study agree with previous work; small organoleptic differences were found between some shade treatments. While the differences found here and in the literature have shown statistical significance, the practical implications of those differences must be realized; they are not large enough that the average coffee drinker would likely be able to discern them. The only exception to this may be the 2-point increase in "body" for the 'Catimor' found by Muschler (2001). However, as this study and Vaast et al (2006) showed a decrease in "body" with shading, no consistent influence of shade is likely to exist.

Even though Guyot et al (1996) were the first group to publish information on shade coffee culture and organoleptic quality, it was Muschler's (2001) seminal paper that first demonstrated any relationship. He found a statistical difference with shaded *C. arabica* 'Catimor 5175,' a *C. arabica* x *C. canephora* hybrid known for its resistance to pests and disease and not its organoleptic quality. The pure arabica, 'Caturra,' did not show a statistically significant response. Other studies using pure arabica cultivars have shown either no or very small statistical differences (Guyot et al, 1996; Vaast et al, 2006; reports within The Proceedings of the 2nd International Symposium of Multistrata Agroforesty Systems for Perennial Crops, 2007). Generally, shade does not impact coffee's organoleptic quality.

While shading does not impact organoleptic quality very much, it does alter coffee's biochemistry (see chapter 4; Guyot et al, 1996; Vaast et al, 2006). This suggests that shade either affects chemical attributes that do not play a role in organoleptic quality or that the chemicals and organoleptic characteristics chosen for analysis are not related.

The data on nodal growth produced under shaded conditions is contrary to other results (Campanha et al, 2004; Morais et al, 2006, Ricci et al, 2006) except for the heavily

shaded coffee under the macadamia trees; nodal growth decreases with shading. Coffee growing in the shade tends to grow taller than sun grown coffee due to longer internodes. As the trees in this study were decapitated during the time when vegetative growth was occurring, energy and resources may have been used for lateral, rather than vertical, growth. The differences in SLA and leaf temperatures between shaded and unshaded coffee leaves is consistent with other published results (references within Rena et al, 1994 and Barros et al, 1999; Muschler, 1998; Bote, 2007). Even though the kaolin leaves were shaded and had leaf surface temperatures similar to the shade cloth treatments, SLA was similar to sun leaves. This may be due to the bi-monthly spraying of the kaolin. Many of the leaves began their expansion before being sprayed and therefore may have been committed to developing as sun leaves prior to shading.

The smaller percentage of broken beans in the kaolin treatment may be a result of the smaller bean sizes. Beans can break during post-harvest processing when large beans pass through a pulper that is set for smaller beans. Consequently, while large beans from the other treatments were breaking, the smaller kaolin seeds escaped injury.

The differences in the proportions of defects cannot be explained with this data. Although Muschler (1998) showed that shading reduced the number of rejected fruits, the fruit types he rejected likely resulted from pest and disease pressures and not directly from the shading. However, in Hawai'i, those same pressures do not exist.

Year to year, bean characteristics and sizes in Hawai'i are known to differ (Virginia Easton-Smith, personal communication), an observation also made by Vaast et al (2006). Therefore, it is possible that the differences found in the second year of harvest are simply natural temporal variations.

Peaberry occurrence was not related to shading, which is in agreement with Abruña et al (1965) but contrary to Morais et al (2006), who found a larger percentage of peaberries in coffee when shaded by pigeon pea (12.25 vs 9.09%).

Many authors report on the relationship between increased shading and increased bean size, though no mathematical relationship has been proposed. The correlation of bean sizes 16 and 17 to shade level and yield suggest that both factors help determine bean size. Larger yields increased the percentage of these smaller seed sizes while shade decreased these sizes. Conversely, greater yields decreased the percentage of larger bean sizes (18-20) while shading increased these sizes.

In Kunia, the bean sizes were larger in the shaded treatments, with the exception of the kaolin treatment. Vaast et al. (2006) proposed an indirect relationship between yields and bean size linked to competition for carbohydrates. Under this mechanism, beans of shaded coffee plants are larger because lower yields under shade lead to reduced competition for available photosynthates. This would help explain why the bean sizes of the kaolin spray treatment were comparable to the sun treatment. Although the kaolin spray reduces light and leaf temperature at a comparable level to the shade cloth treatments (Steiman et al, 2007), yields were similar to or greater than under full sun. Thus, the larger bean sizes of shaded coffee may actually be a yield-bean size response instead of a shade-bean size response.

The larger bean sizes found in the sun treatment in Kona partially support this hypothesis. The Aluminet treatment, which had a slightly larger yield in 2007, had slightly smaller seeds than the sun treatment. However, the macadamia treatment, which had very low yields, had a larger percentage of small seeds relative to the sun treatment. In this case, an absolute lack of photosynthates may have inhibited bean-filling.

The coffee fields in both locations studied in this experiment were adequately watered and fertilized to support high fruit production. Thus, although leaf concentrations of a few nutrients were lower than recommended adequacy levels, nutrient deficiencies as presented by visual symptoms did not occur.

The higher leaf Fe concentrations in the shade cloth treatments seemed to persist for 3 of the 4 Kunia tissue analyses. This was also true for the macadamia treatment in Kona though not for the Aluminet treatment. Campanha et al (2004) also reported higher Fe concentrations in a coffee agroforestry system compared to its full sun counterpart. This is probably explained by the increase in number of PSII, Reiske Fe-S centers, and Cytochrome b6/f complexes in shaded relative to unshaded leaves (Buchanan et al, 2000). Coffee leaves respond quickly to shading as evidenced by the increase in Fe concentration seen in the first sampling, which occurred 5 weeks after the treatments were imposed. Leaf Fe concentration in kaolin leaves resembled sun leaves, which is further evidence that they developed as if they were exposed to full sun.

As discussed by Beer et al (1998) and Perfecto et al (2005), fruit production does not respond in a predictable way to shading. Many researchers agree with Muschler's model (1997) that shade can benefit coffee production when it ameliorates sub-optimal growing conditions but hinders it when conditions are ideal. As previously stated, Kona is considered to be an excellent location for growing coffee; whereas, Kunia presents a more stressful environment. Nonetheless, shading had almost no significant effect on coffee yields at these two sites, even though yields varied by more than 200% in some cases. The large standard deviations of the yield means may explain why the negative response to increased shading was not statistically significant at $p < 0.05$. Reducing this variation, by

using experimental units consisting of more than 1 to 2 trees or by using additional replications, may have shown significant differences between the higher sun and lower shade cloth treatment yields. Assuming our analysis suffered from low power (i.e., a Type II error), then shading coffee in these conditions tends to reduce yields

The high yield from the kaolin treatment in the second harvest is likely a result of an increase in fruits per node (Steiman et al, 2007). Additional research is necessary to understand the mechanism responsible for this response. The significantly lower yield in the macadamia treatment in Kona for the 2007 harvest was due to fewer nodes per branch and fruits per node (personal observation), likely a direct effect of the increasingly low light levels as the macadamia trees matured.

Cannell (1985) discusses coffee's well-known inability to shed fruit after the expansion stage. The lower yields in the shade treatments during 2006, which were imposed after flowering, suggest that the shaded coffee plants compensate for reduced light conditions by aborting fruits at an early growth stage. The following year, in Kunia, the seemingly diminished yields must have been determined by lower fruits per node because the trees were all of similar heights, likely had the same number of lateral branches and had the same number of nodes that season.

The high yields of the Aluminet treatment relative to the sun treatment in the second Kona harvest were surprising. Aluminet yields were 65% smaller than the sun yields in 2006 but 8% larger in 2007, a pattern not observed in Kunia. With both treatments having produced the same number of nodes, the response cannot be due to biennial bearing. The tissue sampling in Kona occurred shortly after flowering and represents the plant nutritional status as it moved into fruit growth and development. While all the treatments exhibited

lower Zn levels than recommended, the sun treatment had half the Zn content as the Aluminet treatment. Several authors report that application of Zn to Zn-deficient plants can increase coffee yields (Guimaraes et al, 1983; Lambot, 1990). It is possible that the sun treatment produced less than its potential due to Zn deficiency.

In Hawai'i, green coffee grades are based upon bean size and the number of defects in a 300 g sample, where larger beans command higher prices. At the time of this writing, prices for the top three grades of green Kona coffee ranged from \$5.90 to \$5.44·kg^{-1}. In Kunia, the prices for these grades ranged from \$3.81to \$3.40·kg^{-1}. Using these prices and only bean sizes, the treatments producing the largest yields would have the highest values; the higher prices gained from slightly larger bean sizes would not compensate for the lower yields. In addition, given the relatively low cost of the kaolin material and the ease of application, it is a promising addition to coffee agronomic practices, whether under shade or full sun.

Conclusion

By mostly using shade cloth to reduce light levels, this experiment was able to isolate the effects of shade from other interactions that may occur in agroforestry systems. Based on this data, shading has no appreciable impact on organoleptic quality and even lightly shaded coffee systems (30% shade) seem to depress coffee yields. Even though shading produces slightly larger beans, the higher prices offered for larger beans does not offset the revenue lost from the lower yields. As farmers are unlikely to cover their farms with shade cloth, further research with tree shade is necessary to explore possible advantages of shade coffee agroecosystems in Hawai'i. Unfortunately, the one tree species investigated in this

study, macadamia, does not appear to be a suitable shade tree for coffee. However, the significantly higher yields produced in the kaolin treatment offer a promising addition to coffee agronomic practices.

Chapter 3
Analysis of kaolin particle film usage and its application on coffee

The high yields in the kaolin treatment for the 2007 harvest were unexpected. In addition, the use of kaolin on coffee has not been previously reported. In order to explain the increase in yields, this chapter explores coffee's response to the kaolin treatment and analyzes the application of kaolin using glass plates and slides.

Introduction

Systematic research with kaolin as a particle film technology began in 1970 (Abou-khaled et al). This report stimulated research that contributed to the formulation of Surround WP, a commercially available kaolin-based powder. This product is currently used to reduce pest and disease pressures, improve fruit appearance and affect plant physiological responses (Glenn and Puterka, 2005).

Within a single plant species, physiological responses to kaolin particle film application, such as photosynthetic rate and leaf temperature, vary inconsistently (Gindaba and Wand, 2007). One possible explanation for this may be differences in application of the product. Most authors failed to calculate the amount of light transmitted through the kaolin, the amount of surface area covered or even the amount of kaolin on a typical leaf. In addition, different application rates and equipment are likely to contribute to differences in plant response.

This paper explores the application of Surround WP using glass plates and slides and field-grown *Coffea arabica* L. 'Typica'. Coffee is a shade-tolerant plant that produces high yields in unshaded conditions. However, high rates of fertilization and irrigation are

necessary to maintain such an output. The ecophysiological differences between sun and shaded coffee are well documented and the trade-offs understood (Cannell, 1985; Beer et al, 1998; DaMatta, 2004). Kaolin offers a novel method for shading coffee that appeals to producers.

Our objective was to determine the effect of different kaolin application rates on surface coverage, radiation transmission, and surface temperature of a glass substrate and how this translated into effects on the physiology of coffee leaves, a crop for which there are no previous reports of its use. Secondarily, we wanted to determine what information should be reported by researchers to maximize information transfer and facilitate new uses of this particle film technology.

Materials and Methods

Determination of PAR and UV transmittance, surface temperature, particle density, and percentage of surface area covered.

Glass plates (30 x 62 x .35 cm) were sprayed 0-4 times with Surround WP (Engelhard Corp, NJ, USA) at a concentration of 60 $g \cdot L^{-1}$ water under 345-415 kPa of pressure (approximately 500 $L \cdot ha^{-1}$) with 0.5% Umbrella (Monterey AgResources, CA, USA) as an adhesive. Plates were sprayed using a 20-L Field King backpack sprayer (The Fountainhead Group, NY, USA) fitted with a Uni-Jet flathead, brass nozzle (model 8002).

The spray tip was positioned approximately 1.0 m from the plates. Prior to spraying, four pre-weighed microscope slides were placed on each plate. Four light measurements were taken by placing a LI-COR LI-190SA quantum PAR sensor (LI-COR Biosciences, Lincoln, NE, USA) 3 cm beneath each glass plate. Light transmittance was measured by

dividing the PAR values for a sprayed plate by the average value of the unsprayed plate. The same method was used to measure UV transmittance (model UVM; range 250-400 nm; Spectrum Technologies, Inc., Plainfield, IL, USA) and surface temperature (emissivity = 0.95; model Raynger ST; Raytek, Santa Cruz, CA, USA).

After spraying, the microscope slides were dried and reweighed to determine the amount of kaolin dispersed per unit area. The percentage of area on each microscope slide covered by kaolin was determined using an Epson scanner with a black background. Scanned images were imported into Adobe Photoshop Elements 2.0. The image color was contrasted to force all spots on the image to be defined as pure white. A luminosity reading was calculated by the software and converted into a frequency histogram that showed clear separation between the black background and the white spots. This was used as the measure of the percent area covered by the kaolin.

Field experiment.

For a description of the coffee plot and its experimental design, see Chapter 2.

As a test of kaolin coverage on coffee leaves, 14 pre-weighed microscope slides were attached to coffee leaves with adhesive putty. The trees were then sprayed as previously described and the microscope slides removed to estimate the amount of kaolin applied and the percent leaf coverage.

Physiological response to kaolin coverage.

Leaf surface temperature, C isotope discrimination, CO_2 assimilation, branch growth extension, and yield were measured on plants in the field. The most recently matured leaves (4-6 weeks old) on each branch were used.

Temperature measurements were taken between 1100-1200 HR on 4 May 2005 using a Mini IR Temp Meter (emissivity = 0.95 fixed; Spectrum Technologies, Inc., Plainfield, IL, USA). Six leaves per experimental unit from both sides of the row were measured.

Eight pairs of leaves were collected from each experimental unit between 0730-0830 HR on 13 September 2005 and put in a chilled cooler. Leaf area was measured using a LI-Cor 3100C leaf area meter (LI-COR Biosciences, Lincoln, NE, USA). The leaves were dried at 70 °C for two days and then weighed. Dried leaves were then ground using a Wiley mill. Carbon isotope compositions were determined using an on-line carbon-nitrogen analyzer coupled with an isotope ratio mass spectrometer (Finnigan ConFlo II/Delta-Plus) at the University of Hawai'i Stable Isotope Biogeochemistry Laboratories. Isotope values were reported in standard d-notation relative to an international standard. The standard for carbon was V-PDB and was corrected for the contribution of ^{17}O using the method of Santrock et al (1985). A glycine standard was used to ensure accuracy of all isotope measurements.

Leaf CO_2 assimilation (A) measurements were taken with a CIRAS-1 portable photosynthesis system (PP Systems, Amesbury, MA, USA) between 0900-1200 HR on 2 August 2006 (CO_2 reference level = 375 ppm, settling time ~2 minutes). Measurements began with Block 1 and continued consecutively. Each block measurement lasted approximately 20 minutes. Ambient PAR values for this time period ranged from 425-2200 μmol quanta$\cdot m^{-2} \cdot s^{-1}$. Five leaves from each experimental unit each were measured once. Water use efficiency (WUE) was calculated by dividing A by stomatal conductance (G_s).

On 9 August 2006, 20 lateral branches were randomly selected per experimental unit. To estimate lateral growth, new fruitful nodes were counted on each branch. Fruitful nodes were defined as the number of fruiting nodes plus nodes with flower buds present.

Coffee was harvested for two consecutive seasons. Ripe cherries were harvested as necessary from 25 August 2005 to 7 February 2006 and 10 August 2006 to 5 December 2006. Cherries were processed to green bean and weighed.

In this chapter, the first and second harvests are denoted as "2005" and "2006," respectively. This is contrary to Chapters 2 and 4 where they are denoted as "2006" and "2007." This is an artifact of this chapter being published prior to the writing of the dissertation.

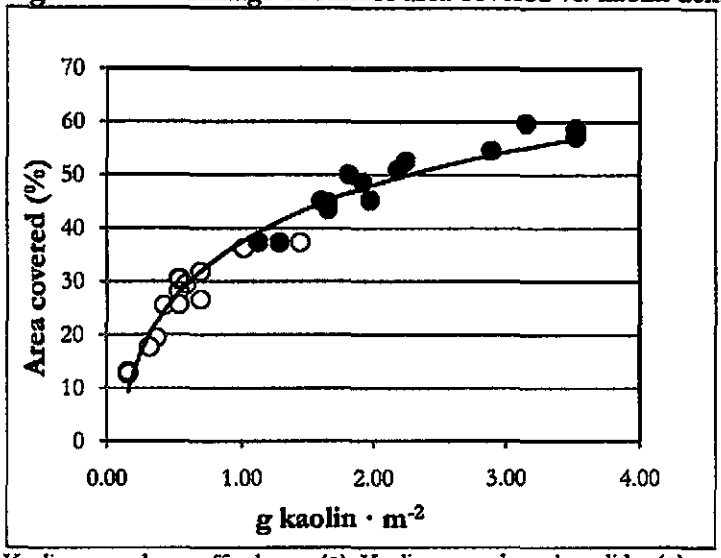
Statistical analysis

Physiological data were compared using Student's T test. All data were analyzed using JMP 5.0.1.2 statistical software (SAS Institute, Cary, NC, USA).

Results and Discussion

The amount of kaolin sprayed ranged from 0.16 – 3.52 $g \cdot m^{-2}$ (Figure 3.1). More kaolin was sprayed on slides during a single pass of the sprayer over the glass plates (first 4 closed circles) than on slides attached to coffee leaves (open circles). This likely occurred because leaves on trees are presented at different angles and distances from the sprayer.

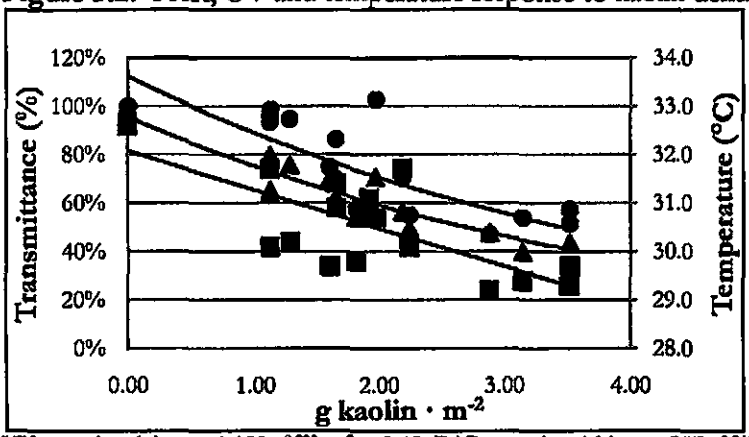
Figure 3.1. Percentage of surface area covered vs. kaolin density



Kaolin sprayed on coffee leaves (○); Kaolin sprayed on glass slides (●).
Coverage equation: $y = 15.37\ln(x) + 37.50$, $r^2 = 0.96$, $p < .0001$

PAR passing through the glass plates was reduced by as much as 56% after addition of kaolin (497 to 217 μmol quanta·m^{-2}·s^{-1}; Figure 3.2). UV radiation was reduced by 48% when the greatest kaolin density was on the glass plate (47.5 to 24.9 μmol quanta·m^{-2}·s^{-1}). The surface temperature of the glass plates decreased approximately 10% (32.6 to 29.4 °C).

Figure 3.2. PAR, UV and temperature response to kaolin density



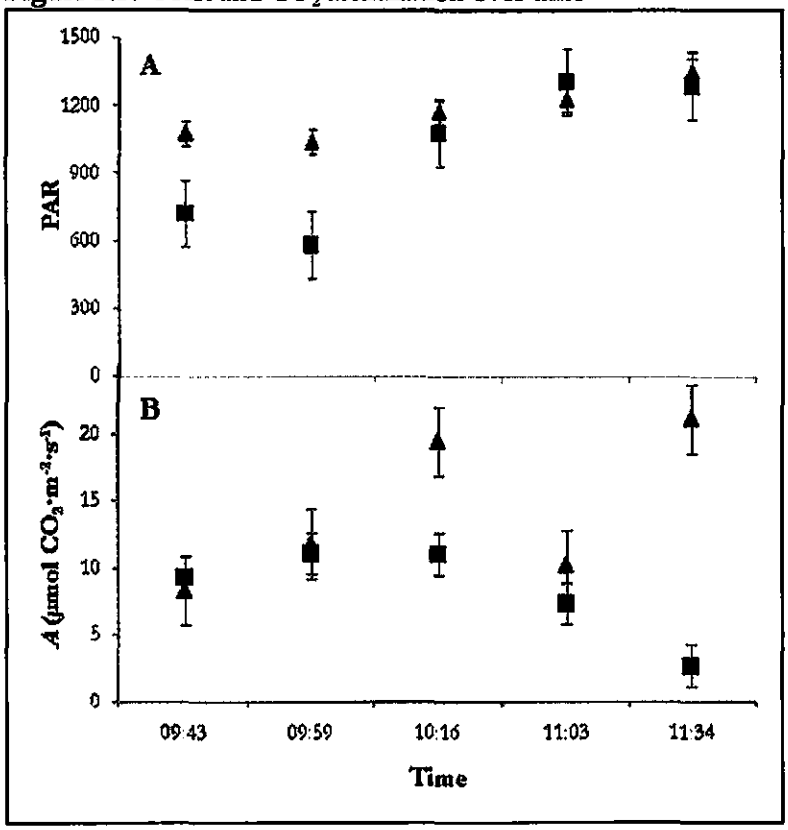
UV equation (●): $y = 1.123e^{-0.233x}$, $r^2 = 0.62$; PAR equation (▲): $y = 957e^{-0.241x}$, $r^2 = 0.85$;
Temperature equation (■): $y = 32.072e^{-0.028x}$, $r^2 = 0.53$. $P < 0.001$ for all equations.

Table 3.1 shows the physiological measurements of coffee in the field. Specific leaf area was similar between the sun and kaolin-sprayed leaves. Leaf surface temperatures in the kaolin treatment were significantly lower by 3.4 °C. Photosynthesis in kaolin leaves was significantly greater by 71% but water use efficiency was not different. Perhaps more importantly, net photosynthesis of sun leaves declined rapidly over time during the late morning whereas kaolin-sprayed leaves continued to exhibit high rates of net photosynthesis (Figure 3.3b). Yield of sprayed trees was 14% and 99% higher than sun trees for the first and second years, respectively. This difference was significant during the second year but not the first year.

Table 3.1. Physiological measurements on coffee plants

Trait	Kaolin	Sun	Significant at $P < 0.05$
Specific Leaf Area ($m^2 \cdot kg^{-1}$)	13.3	13.6	No
Leaf temp (°C)	33.7	37.1	Yes
Nodes per branch	13	12	No
A (μmol $CO2 \cdot m^{-2} \cdot s^{-1}$)	14.2	8.3	Yes
WUE ($A \cdot G_s^{-1}$)	0.44	0.12	No
^{13}C (o/oo)	-25.3	-25.9	No
Yield (kg green$\cdot ha^{-1}$)			
2005	1581	1381	No
2006	3031	1520	Yes

Figure 3.3. PAR and CO_2 assimilation over time[a]



[a]Times are an average of the time span each block was measured. Data points are an average of 5 leaves from each experimental unit for sun (■) and kaolin (▲) treatments. Error bars represent ± 1 standard error.

Published data of kaolin density on a leaf or glass surface ranges from 0.85 – 10.0 $g \cdot m^{-2}$ with most values averaging 5-6 $g \cdot m^{-2}$ for label recommended application rates (Glenn et al, 1999, 2001; Jifon and Syvertsen, 2003; Lombardini et al, 2005; Wünsche et al, 2004). The average density in the present study was 0.57 $g \cdot m^{-2}$, an order of magnitude lower than the published average. Even with 4 passes over the glass plates, the maximum kaolin density in the present study was less than 4 $g \cdot m^{-2}$.

The lower densities of kaolin in our study, however, reduced PAR transmission to the same extent as in previous work (Glenn et al, 1999; Jifon and Syvertsen, 2003). Previous studies attained 60% PAR transmittance at about 10 $g \cdot m^{-2}$, whereas the same reduction in

transmittance was attained with only 2 $g \cdot m^{-2}$ in the present study (Figure 3.2). While the data in the present study also show that UV transmission is reduced by kaolin, a direct comparison to work by Glenn et al (2002) is difficult to make; their study measured reflection at individual wavelengths, not an average of wavelengths. Both studies demonstrate that increased kaolin coverage reduces UV transmission.

Researchers using kaolin generally have used the label recommended concentration of 30-60 $g \cdot L^{-1}$. Thus, the large discrepancy between kaolin densities between previous studies and the present one may be related to application or measurement differences. The logarithmic relationship between kaolin density and surface area covered (Figure 3.1) suggests that repeated applications have a layering effect. Any factor affecting kaolin deposition and layering will also influence light transmittance. These factors include: spray solution adjuvant, the type of sprayer used (blast sprayer vs. hand pump), pump pressure, particle size and shape of the nozzle, distance from the object sprayed, the speed of movement over the object, and the number of passes made over the object. In addition, the type of light source and distance between the sprayed surface and the light sensor will also affect results. Because many of these factors are not reported in kaolin studies, it is unknown which may have accounted for the differences in kaolin densities between previous studies and the present one.

Kaolin reduces surface temperatures (Glenn et al, 2002; Jifon and Syvertsen, 2003; Wünsche et al, 2004), although, occasionally no difference is found (Russo and Díaz-Pérez, 2005). Photosynthetic responses to kaolin generally show a decrease in carbon assimilation (Gindaba and Wand, 2007; Lombardini et al, 2005; Russo and Díaz-Pérez, 2005, Wünsche et al, 2004); however, this is not always the case (Glenn et al, 2001; Jifon and Syvertsen, 2003).

The increased carbon assimilation of coffee leaves in the kaolin treatment is one of the largest observed with kaolin use. Carbon assimilation in coffee maximizes at 7-11 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ and saturates at 300-600 μmol quanta $\cdot m^{-2} \cdot s^{-1}$ (Rena et al, 1994). While the heavy fruit load on the kaolin-sprayed trees may have contributed to the increased photosynthesis, it can only account for a small percentage, possibly only 5% (Vaast et al, 2005).

Differences in A do not appear to be due to increased water stress in the full-sun plants as plants were irrigated as needed, including on the day photosynthesis measurements were taken. Furthermore, there were no differences in WUE or the leaf stable C isotope ratio. In coffee, little change, if any, occurs to stable C isotope ratios with moderate shading. While stable C isotope values could have been confounded with leaf age and shading, Gutiérrez and Meinzer (1994) concluded that older, self-shaded coffee leaves of 'Red Catuai' had greater WUE than younger, sun leaves. With shading of 50% using 'Yellow Catuai,' Carelli et al (1999) found no differences in stable C isotope values, although differences were detected with 80% shade. In addition, Lombardini et al (2005) found no affect of kaolin application on C isotope discrimination in pecan twigs.

Ambient PAR can reach over 2500 μmol quanta $\cdot m^{-2} \cdot s^{-1}$ in Kunia and photosynthesis in coffee leaves heavily declines above a leaf temperature of 35 °C (Rena et al, 1994). The increasing separation between the treatments later in the morning suggests that photosynthesis was shutting down in the full sun treatment but not in the kaolin treatment. Consequently, the smaller A in the sun treatment was likely due to prolonged exposure to higher than optimal temperatures or photoinhibition from high irradiance.

Well-tended coffee grown in full sun is expected to achieve the potential maximum yield for a tree. Since the kaolin application from the first season began after the first major

flowering event, the kaolin could only have affected yield by altering fruit abortion, fruit drop or bean size. Similar yields from both treatments suggest fruit abortion and fruit drop were not different. Average bean size was also similar (see chapter 2). In the second season, yields were doubled in the kaolin treatment. Since the trees were maintained at physiologically similar heights and had the same number of orthotropic shoots, fruitful nodes and green bean size (see chapter 2), the component of yield affected is most likely fruits per node. A possible explanation for this response is an increase in light reflected from the kaolin to the more shaded inner canopy nodes that resulted in increased floral initiation. It is also possible that a greater amount of starch was stored during the first growing season due to light and temperature amelioration. This might have permitted greater floral initiation and/or fruit production the following year (Cooil and Nakayama, 1953). Since lateral growth and specific leaf area were not different between treatments, any additional photosynthate was probably being partitioned to the developing fruits.

This data was collected as part of a larger shade coffee experiment and the positive yield response in the kaolin treatment was unexpected. Hence, the data presented are incomplete to fully describe the physiological explanation for the response to kaolin because the experiment was not designed to detect physiological changes due to kaolin application. While most of the data are single point-in-time measurements, the data consistently point to a clear difference between kaolin treated leaves and sun leaves. Further research is needed to elucidate this phenomenon.

While several studies, including this one, have demonstrated the benefits of kaolin on various crop species, the inconsistencies in the data are discouraging. Comparing studies using different species and application techniques does not allow us to understand these

responses to kaolin, especially if particle density and light transmittance through the kaolin are not equivalent. Consequently, comparing responses such as photosynthetic rate and water use efficiency between species, or even experiments, is meaningless unless all application factors can be accounted for.

Attempting to understand the underlying mechanism of any plant response is the motivation of this type of scientific inquiry and it is not discouraged. However, due to the current poor translation of kaolin effects between experiments, paramount to mechanistic data must be end-product criteria like plant growth, yield, or crop quality. Reports also should include kaolin coverage and effects on light transmittance, as these should have the largest effects on intercepted solar radiation and leaf temperature.

Chapter 4
Coffee (*Coffea arabica* L.) brew volatiles predict group membership but not organoleptic quality

Introduction

The biophysical (rather than psychosocial) aspect of an organoleptic experience is dependent upon the chemical composition of the item consumed. Understanding the relationship between the chemistry of a product and its organoleptic properties would permit an objective evaluation of quality that would obviate the need for human tasters. Partially due to its chemical complexity, this has not been accomplished for coffee. Another explanation may be that the form of coffee analyzed in the past, green bean, for example, may be too far removed from the tasting experience to accurately correlate the two (Steiman, 2003).

The major organ that perceives human taste is not the mouth. Rather, most of the taste perception is in the nose with the experience being derived from aroma compounds (Lawless and Heymann, 1998). Consequently, using volatiles emanating from brewed coffee as correlates to the organoleptic experience might prove successful. Liardon et al (1984) demonstrated some success with this method but seemingly neglected to pursue the research further. Bicchi et al. (1997) also explored this technique but reported no statistical comparison after claiming there was a relationship. Using PTR-MS, Lindinger et al (2008) established a predictive model between 16 volatile ions and 8 taste descriptors in espresso coffee.

Coffee volatiles captured using solid phase microextraction (SPME) have been used in conjunction with multivariate analysis to explore coffee geographic origin (within and between countries), species identification, and normal vs. defective beans (Bicchi et al., 1997;

Costas Frietas et al., 2001; Mancha Agresti et al., 2008). These studies used principal components analysis (PCA), an effective exploratory tool, to show separation of groups. Unfortunately, PCA is unable to mathematically differentiate or predict group membership. Consequently, the results have limited utility.

Samples from a shade coffee field experiment were rated by a trained panel of tasters. SPME and gas chromatography were used to capture and analyze the brewed coffee volatiles from these same samples. Canonical correspondence analysis and canonical discriminate analysis were used to explore the connection between the volatile compounds and organoleptic characteristics and to discriminate coffees by shade treatment, harvest year, and location.

Materials and Methods

Field experiment and cupping

For the coffee field layout and cupping procedures, refer to Chapter 2.

Chemical Analysis

After grinding the coffee for the cupping, a 3.3 g sub-sample was sealed in an air-tight, glass, 50 ml vial. On the day of the analysis, the coffee was transferred to a 150 ml headspace vial, brewed with 60 ml of 90 °C water, and sealed. After brewing for 5 minutes, a PDMS/CAR/DVB SMPE fiber (Supelco Inc., USA) was injected into the headspace and held for 5 minutes. The fiber was inserted into an HP 5890 GC injection port (250 °C). Chromatographic conditions were: Temperature program: 0-4 min: 40 °C, 4-45 min: 3°/min increase to 163 °C, 45-51.7 min: 20°/min increase to 230 °C, 51.7-61.7 min: 230 °C; Injection: splitless; Head pressure: 68.9 kPa; Detector: FID; Carrier gas: helium. The column

used was a Stabilwax DB, 30m length, .53mm ID. The FID detector signal was monitored using PeakSimple™ software (SRI Instruments, Torrance, CA, USA) to integrate individual peak areas.

Statistical analysis

To test for a direct gradient relationship between the coffee aroma and the cupping characteristics (dry aroma, wet aroma, acidity, body, flavor, sweetness, and aftertaste), the data were subjected to canonical correspondence analysis (CCA) using CANOCO for Windows version 4.55 (Biometris, Plant Research International, Wageningen). Canonical discriminate analysis (CDA) was performed using JMP 7.0.1 statistical software (SAS Institute, Inc., Cary, NC, USA) to test for group membership. The groups were shade treatment, harvest year, and location.

Results and Discussion

Gas chromatography of the coffee aroma detected 45 volatile compounds from both harvest years. Of those, 14 were poorly resolved and were removed from the data set for statistical analysis. Some macadamia and 40% black shade cloth experimental units did not produce enough coffee for analysis; thus, only 81 samples were used in the CCA and 82 in the CDA.

No direct gradient relationship was found between the aroma compounds and cupping characteristics. Forward selection of variables with Monte Carlo simulations (499 permutations) selected 30 aroma variables for the model. The total inertia (amount of variance in cupping data explained by the aroma compounds) was only 1%.

Discriminate analysis using coffee aroma compounds successfully predicted group membership of samples. The aroma compounds were subjected to forward stepwise regression for discrimination of samples by harvest year, location, treatment, and treatment but only with samples from the first year (harvesting ending in 2006). Backward stepwise regression was used for discrimination of samples from the second year (harvest ending in 2007). The direction and extent of the stepwise regression progressed until discrimination could be carried out with no misclassifications, less than 0.1 chance of misclassification to another group, and with the fewest number of compounds.

Table 4.1. Volatile aroma compounds used in group discrimination

Treatment both years	Treatment 2006	Treatment 2007	Harvest Year	Location
A1	A1		A1	
A2	A2	A2		
A3	A3			A3
B			B	B
C	C	C		
D	D	D		
E	E	E	E	
F	F	F	F	F
G	G			
I				
N		N	N	
O		O		
P	P			
Q	Q	Q		Q
S	S	S		
T	T	T		
V	V			V
X				X
AA	AA	AA		AA
AB	AB	AB		
AE			AE	
AF	AF	AF	AF	AF
AG		AG		
AJ				
AK		AK		AK
AL	AL	AL		AL
AM		AM		
AN	AN			AN
AO		AO		
AP		AP		AP
AQ	AQ	AQ		AQ

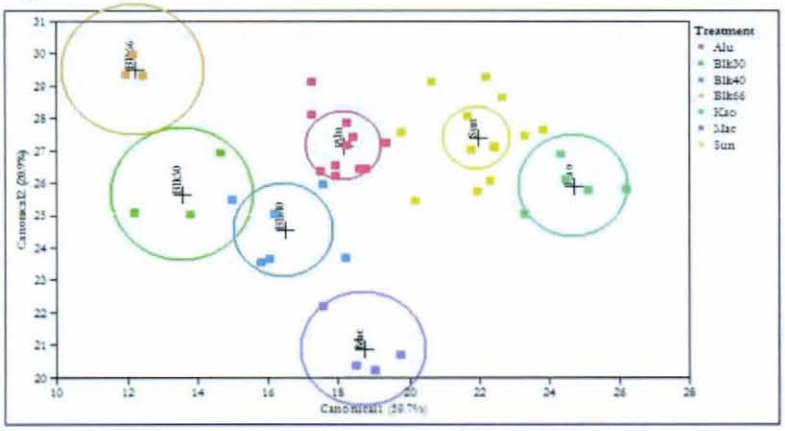
The peaks selected by the stepwise regression for the discriminations can be found in Table 4.1. These statistical analyses did not require that the identities of the volatile compounds be known. Due to insufficient access to a mass spectrophotometer, we chose to label GC peaks with arbitrary labels for use in the analyses. Alphabetical letters, beginning with "A1," correspond to the elution time of each peak.

Table 4.2 shows the number of compounds selected from the stepwise regression, the percent of samples misclassified and p-values for Roy's Max Root. Figures 4.1-4.3 show biplots of the first two eigenvectors for 3 of the discriminations. The other biplots can be found in Appendix B.

Table 4.2. Summary of statistical details for discrimination

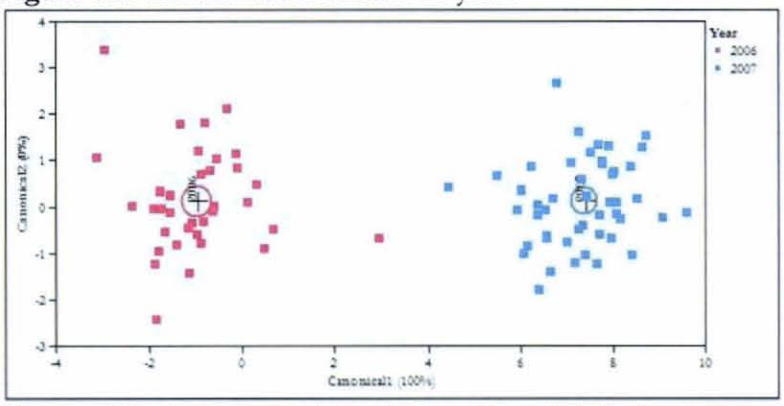
Discrimination	Number of compounds used	Percent misclassified	p for Roy's Max Root
Treatments both years	31	13.75	<0.0001
Treatments 2006	19	0	<0.0001
Treatments 2007	22	0	<0.0001
Harvest year	7	0	<0.0001
Location	13	0	<0.0001

Figure 4.1. Discrimination of treatments for the 2007 harvest[a].



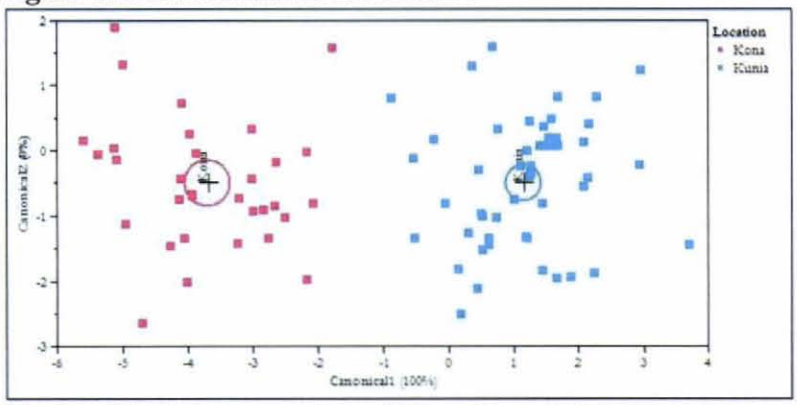
[a]The size of the circle corresponds to a 95% confidence limit for the mean.

Figure 4.2. Discrimination of harvest year[a].



[a]The size of the circle corresponds to a 95% confidence limit for the mean.

Figure 4.3. Discrimination of location[a].



[a]The size of the circle corresponds to a 95% confidence limit for the mean.

Until quite recently, no authors have reported a convincing relationship between coffee chemistry and organoleptic quality. With over 1000 volatile compounds (Ryan et al, 2004) and several hundred in the brew (Flament, 2002), it is unsurprising that no correlation to organoleptic quality has been established. Researchers' inability to correlate chemical profiles to coffee characteristics (attributes used herein like aroma, body, acidity, flavor, sweetness, and aftertaste) may be resultant of several factors. Simply, perhaps nobody has selected the proper chemicals that define the measured cupping characteristics. Alternatively, as both the absolute and relative amounts of chemicals in a food or beverage help determine its taste (Lawless and Heymann, 1998), the complex nature of coffee's biophysical organoleptic experience may be too overwhelming for the models currently being built. Lastly, it is possible that cupping characteristics are too complex to be defined by a limited set of chemical indicators.

Using principal component regression to build their model, Lindenger et al (2008) successfully mapped descriptive espresso descriptors using ionic aroma compounds. Their use of descriptors (such as flowery, cocoa, citrus, and butter), rather than basic characteristics, likely explains part of their success. Specific aromas and flavors can accurately be represented by individual compounds (Flament, 2002). Consequently, their selection of very specific descriptors and a large number of predicting chemicals supports a more fertile research approach.

The highly significant group discrimination must be interpreted with caution. As with all multivariate analysis, the ratio of samples to variables should be high, otherwise, overfitting the model to the data may occur. In addition, small, uneven group sizes can easily lead to a model of little use. In the present study, the discrimination model was not

robust as demonstrated by the discrimination being less precise when attempting to discriminate the treatments with harvest years combined.

Even with these shortcomings, interpretation of the data is still valid. The experimental procedure permitted the isolation of all variables from the ones tested. Consequently, other factors likely to affect coffee biochemistry, like interaction from shade trees, post-harvest processing, and roasting were all eliminated or standardized. Thus, even if the model is overfit, the biochemical differences seen are real and a direct result of the imposed conditions.

Different sets of volatiles, resulting from the stepwise regression, were used to discriminate the groups. However, the volatiles used to separate treatments within a harvest year were similar to each other and contained many of the compounds used to discriminate harvest year. This lack of variability confounded the discrimination of treatments with harvest years combined, resulting in imperfect classification. Interestingly, location did not impact the prediction of shade level; all sun and Aluminet covered trees, from both islands, were placed in their appropriate group.

The difference between the 40% shade treatments of the black and aluminized cloth was only the material from which they were made and the three black shade cloth treatments differed only in degree of light exposure. Each of these treatments intercepted light differently enough to cause the alteration of coffee's biochemical composition and permit discrimination with only a few volatile compounds. This demonstrates that small differences in a coffee's growing environment are translated into quantifiable biochemical responses. Larger differences that would likely arise from agroecosystem structure or fertilization

regime may also create identifiable biochemical fingerprints. Potentially, this methodology could assist organizations evaluating farms for organic or shade-grown certification.

The use of SPME and GC combined with discriminate analysis is a powerful tool for group discrimination of coffee in Hawai'i. Group discrimination on a global scale might be realized using this technique, particularly for origin authentication. However, given the low variation that prevented perfect discrimination of treatments (both harvests) in a small region like Hawai'i, the limited number of biochemical markers used herein may be insufficient. More elaborate analytical set-ups as described by Ryan et al (2004) or Lindinger et al (2008) that allow for large numbers of markers to be identified may accommodate the variation.

The utility of these results is not restricted to predicting group membership. Once the identities of discriminating compounds are determined, researchers will know, in small part, how coffee responds biochemically to specific agronomic practices. These changes can then be traced back, through roasting and other processing steps, to changes in fresh green bean. Ultimately, these chemicals can help illustrate the genetic response to agronomic conditions.

The power of the using volatiles and discriminate analysis lies in the condensation of many variables into smaller numbers of variables. Thus, this technique is likely useful for other crops with complex end products like chocolate, wine, and tea.

Chapter 5
Conclusion

With increased interest in shade coffee agroecosystems in Hawai'i and no previous research available, this study explored general topics of shade coffee culture. Coffee quality, measured both organoleptically and physically, was a primary focus of the research. Basic plant physiological responses to light, particularly yield, were measured in non-tree shade systems in order to generalize the results to all shaded systems. Brewed coffee aroma compounds were captured and analyzed to correlate them to the organoleptic properties of coffee. The aroma compounds were also used to discriminate the coffees into groups based on their harvest year, origin of production, or shade treatment.

In general, coffee quality was not significantly affected by shading. There were some small but significant differences in organoleptic quality, but they were inconsistent from year to year and are most likely too small to be noticeable to consumers. In addition, there were no important differences in percentage of defects or peaberries. Bean size increased in the shaded treatments at Kunia, although, this was not true in Kona.

The shade cloth fabrics at Kunia, in general, produced results consistent with expectations of coffee plants grown in the shade: specific leaf area was greater, leaf temperatures were lower, beans sizes were larger and yields were lower. Yields declined with increasing shade level (86-45%), although differences were not statistically significant. There were no real differences between the black and Aluminet shade cloth types. Under the high shade levels of the macadamia trees (approximately 90%), the coffee trees produced little vegetative and reproductive growth. Thus, it is not recommended that coffee plants be maintained under closed-canopy orchards of macadamia trees. The kaolin-treatment, which

was expected to produce shade cloth type responses, surprisingly led to extremely high levels of photosynthetic activity and also produced twice as much coffee as the comparable sun treatment the second year. The two most likely explanations for the greater yields are that light reflected from the white surfaces of kaolin-sprayed leaves stimulates floral initiation on inner-canopy nodes and that higher carbohydrate reserves from the first season permitted production of a greater number of flowers the second year.

The effects of shade on coffee can vary by location. At Kunia, coffee yields were lower under shade cloth, specific leaf area was greater, and beans were larger. In Kona, responses to shade varied by growing season. Coffee under shade cloth was no different than sun coffee in the second year. Unfortunately, this disparity cannot be confidently explained with the data from this study. The coffee plots in both locations were well tended with fertilizer and irrigation, were very similar genetically, and were subject to the same pruning regime. The only differences between the two plots were the soil and climatic conditions. It is reasonable to conclude that an interaction between the location and the shading treatment confounded any potential effects of shading alone. Observations across a range of tree-shaded farms in the Kona region suggest that moderate shading has no consistent effect on fruit loads of coffee plants (Travis Idol, personal communication).

Even though using brewed coffee aroma volatiles as chemical indicators for organoleptic quality is a promising strategy, there was no significant prediction of organoleptic quality using biochemical profiles in this study. The characteristics measured by the taste panel broadly define a coffee's organoleptic experience and too few aroma compounds likely were used to sufficiently describe those characteristics. Measuring more aroma compounds and selecting more specific descriptors may provide greater success

(Lindinger et al, 2008). The volatiles, however, did prove to be an immensely powerful tool for predicting group membership of the coffees, whether the group was the treatment, the year harvested or the growing location. In general, 19 or 22 chemicals (for harvest years 2006 and 2007, respectively) were needed to predict treatment across location, 7 were needed to predict year of production across all treatments and locations, and 13 were needed to predict growing location, regardless of year or treatment.

Using fabricated cloth to shade coffee is expensive and unlikely to be adopted by farmers. Nonetheless, the data generated from it and the other treatments can be used to begin making generalized statements about tree-shaded coffee in Hawai'i. Aside from the kaolin treatment, constant shading, even at 30%, tends to reduce yields of well-managed coffee, whether under the generally optimal conditions in the Kona region or under hotter and drier conditions such as central Oahu. For commercial farms, this may be unacceptable. However, the reduced yields and coincident reduction in necessary agricultural inputs may be appealing to organic farmers or those who don't rely entirely on income from coffee for their livelihoods. Yields and quality of moderately shaded coffee may be sufficient, given the benefits and amenities of incorporating trees on the farm. The reduced need for agricultural inputs of shaded coffee does not necessarily mean there is a reduction in the overall management needs. Even with a carefully selected shade tree species, trees are most likely going to require maintenance, as was exemplified by the dense canopy of macadamia trees. The extra work may be a deterrent to many would-be adopters of shade trees, especially with lower coffee yields.

One possibility for minimizing yield losses under tree shade is to prune or pollard the canopy prior to floral initiation. Regrowth of the canopy may then reduce stresses

associated with supraoptimal light levels and leaf temperature. Success of this practice, while not described in the literature, has been seen in Costa Rica (Philippe Vaast, personal communication).

Interestingly, the kaolin treatment may provide an alternative way to achieve the same result. If the kaolin treatment consistently increases yields due to increased floral initiation, then spraying shaded coffee plants prior to floral initiation may minimize the trade-off between yields and stress reduction under shade. Combining kaolin and shade management strategies may actually prove to increase yields by maximizing floral initiation and reducing stress, especially under sub-optimal growing conditions.

The successful prediction of group membership using brewed coffee volatiles has several important applications. As misrepresentation occasionally occurs, the local and global coffee industries need a tool to authenticate a coffee's origin. This technique, once tested against more realistic conditions and additional locations, may permit origin authentication, regardless of growing practices. As well, this method may be able to distinguish growing practices across different locations, such as the use of shade. The possibility exists to distinguish other growing practices, which may be useful for discriminating conventional from organically grown coffee, for example. This method has only been tested on single-origin coffees as opposed to coffee blends, which are common in the marketplace. Given the sensitivity of this technique and power of the statistical analyses utilized in this study, it is likely that blends could be easily distinguished from single-origin coffees. Furthermore, if single-origin coffees maintain distinctive chemical profiles, this method potentially could discern the proportional contribution of the various coffees to a blend.

This project was a first step towards examining shade coffee agroecosystems in Hawai'i. However, it leaves many questions about shaded systems still unanswered. Some additional important areas of research include:

- Do shade trees truly reduce stress of coffee plants and the need for agricultural inputs? By reducing the transpirational demand of the coffee, trees may reduce the need for irrigation and even assist non-irrigated farms in times of water stress (van Kanten and Vaast; 2006). Uptake of fertilizer nutrients by the trees can be returned in litterfall, increasing the overall efficiency of nutrient capture and reducing nutrient runoff and leaching (Aranguren et al, 1982; Russo and Budowski, 1986; Babbar and Zak, 1995). Non-competitive nutrient uptake by trees may also supplement the use of synthetic fertilizers (Huxley, 1999). Litter cover and the reduction in understory light may suppress some common weeds in Hawai'i (Goldberg and Kigel, 1986; Nestel and Altieri, 1992). Some farmers may decide that a reduction in yields is more than offset by these benefits.
- Can shaded coffee agroforestry systems be managed to maintain or increase yields relative to monoculture systems? Aside from the two shade scenarios- kaolin and managed shade - already proposed, judicious use of irrigation and fertilizers must be explored. Trials exploring different tree species must be conducted; not all trees are good shade trees.
- Can shaded coffee agroecosystems increase overall profits? Although net present value is a general analytical tool used to explore long-term profitability, the individual farmer determines the amount of profit that must be earned by a

production system to be sufficient for adoption. However, without adequate information, no farmer can make an informed decision. Many types of agroecosystems can be designed and some are likely to be more lucrative than others (Oscar Hernandez et al, 1997; Gobbi, 2000; Gordon et al, 2007). Agroecosystems can be designed for nutritional benefits from N-fixing trees, production of additional crops for sale or consumption on the farm, or long term profits by the harvesting and selling of the timber trees in a few decades (Beer, 1987; Herzog, 1994; Njoroge and Kimemia, 1995). For these reasons, multi-purpose trees are generally recommended for use in smallholder agroforestry systems to support growth of the main crop and reduce risk with crop diversification (Huxley, 1999). As many coffee farmers in Hawai'i do not rely solely on coffee for their income (Masuda, 2007), these benefits may be appealing once their economic impact is understood.

- What are the mechanisms behind the kaolin response? Future studies should elucidate why photosynthesis was greater, leaf nutrient content was different, and what caused the increase in flower production. Is the leaf structure different at the molecular level? Is the kaolin significantly ameliorating plant stress by reducing light intensity of both PAR and UV wavelengths? Does decreased stress permit extra carbohydrate storage for use in floral initiation? If light intensity is correlated with floral initiation, does light reflectance to the inner-canopy nodes explain the increased floral initiation? With detailed knowledge of these mechanisms, kaolin applications can be used to maximize efficiency.

- Does the kaolin offer benefits other than a yield increase or pose additional challenges? Agriculturally, kaolin was originally used as an anti-transpirant and pest suppressant (Abou-khaled et al, 1970; Glenn and Puterka, 2005). Coffee may respond with improved water use efficiency, even though water requirements will increase with increased yields. The difference in leaf nutrient composition suggests that nutrient use might be influenced by kaolin use, requiring additional nutrient inputs. Coffee pest pressures in Hawai'i are minimal (Bittenbender and Easton-Smith, 2004). However, green scale (*Coccus viridis)* can pose serious, localized threats. Kaolin may be a valuable tool to combat green scale and other insect pests.

Shade coffee culture in Hawai'i may never produce long term yields and, consequently, profits that are equivalent to full sun culture. With access to fertilizers, irrigation, equipment, and knowledge, coffee cultivation in Hawai'i does not need shade. However, until coffee agroforestry systems in Hawai'i are explored to uncover all their benefits and limitations, farmers and researchers will be unable to make informed decisions about the use of shade trees. The data herein suggest that there is little gain to be expected in coffee quality and yield but that optimal management of shade levels and the use of the novel kaolin spray-on treatment can minimize or perhaps even eliminate those yield losses under shade trees. Many other areas of research into shade coffee culture and agroforestry systems remain to be explored.

Appendix A
Additional Tables

Appendix A.1. Scores of cupping characteristics[a]

	Dry Aroma	Wet Aroma	Acidity	Flavor	Sweetness	Body	Aftertaste
Kona							
2006							
Aluminet (40%)	5.9	5.3	4.8	5.1	2.5	4.8ab	4.1a
Macadamia	5.9	4.8	4.8	4.7	2.5	4.3b	3.2b
Sun	6.3	5.3	4.6	5.2	2.4	5.2a	3.8ab
2007							
Aluminet (40%)	5.6	4.8	4.7	4.6	2.7	4.2	3.5b
Macadamia	6.2	5.0	5.1	5.0	2.6	4.5	3.9ab
Sun	6.2	5.1	4.5	4.9	2.7	4.6	4.5a
Kunia							
2006							
Aluminet (40%)	5.8	5.2	4.0	5.3	2.6	4.8	4.2
Black (40%)	5.8	4.9	4.1	4.9	2.4	4.7	4.1
Kaolin	5.7	5.1	4.3	5.0	2.3	4.6	3.6
Sun	5.5	5.0	3.7	5.4	2.4	5.2	3.9
2007							
Aluminet (40%)	6.3	5.3	4.3	4.9	3.0	4.2	3.8
Black (30%)	6.3	5.4	4.5	4.9	2.7	4.5	4.3
Black (40%)	6.2	5.4	4.6	5.2	2.5	4.3	3.9
Black (66%)	6.1	5.6	4.3	5.3	2.9	4.7	4.6
Kaolin	6.1	5.4	4.2	4.9	2.8	4.6	4.0
Sun	6.2	5.3	4.3	5.1	2.8	4.4	3.9

[a]Different letters within a harvest year, location, and column are significantly different at p = 0.05

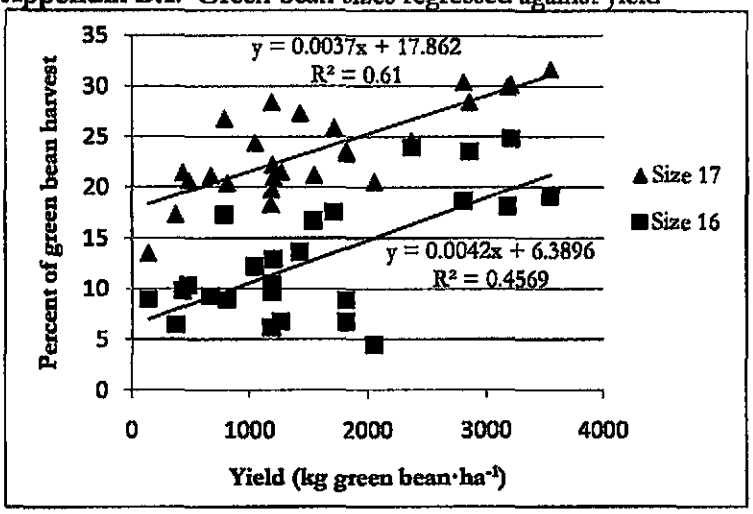
Appendix A.2. Bean characteristics in 2006, at Kunia, as percent of green bean harvest[a]

	Floaters	Defects	Broken beans	Peaberries
Treatment	Kunia	Kunia	Kunia	Kunia
Sun	2.7	9.2	6	5.4
Aluminet (40%)	2.7	7.9	4.8	5.2
Black (40%)	5.6	9.8	4.7	4.8
Kaolin	1.8	6.4	4	5.8

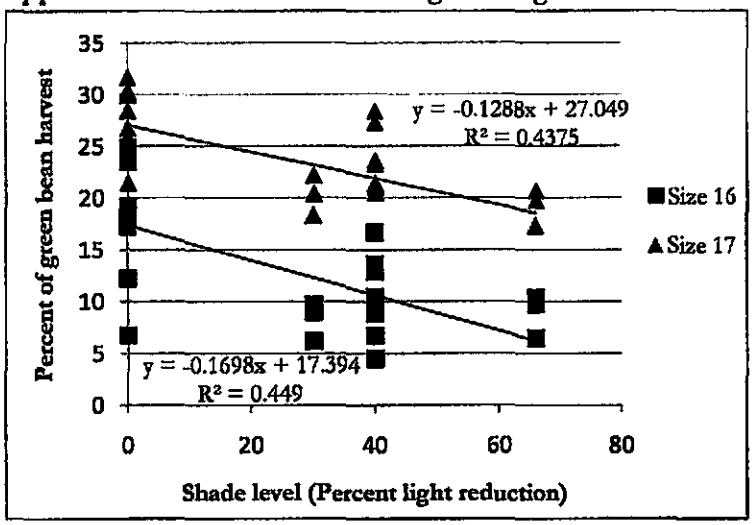
[a]Different letters within a column are significantly different at p = 0.05

Appendix B
Additional Figures

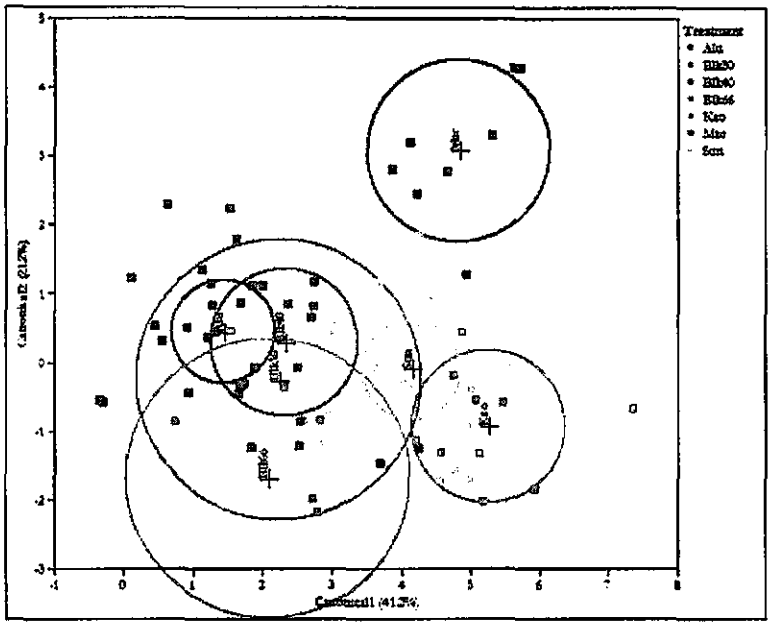
Appendix B.1. Green bean sizes regressed against yield



Appendix B.2. Green bean sizes regressed against shade level

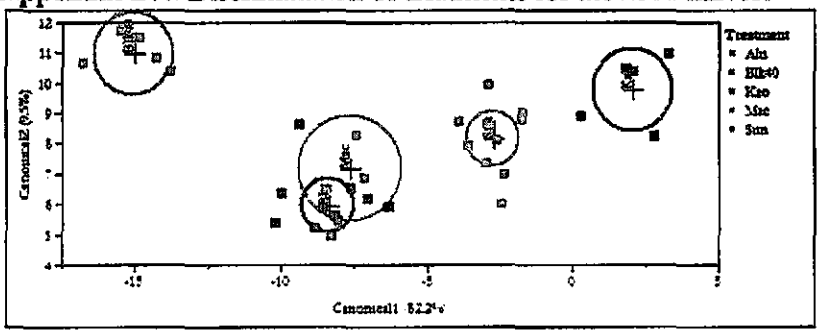


Appendix B.3. Discrimination of treatments for the combined harvests[a]



[a]The size of the circle corresponds to a 95% confidence limit for the mean.

Appendix B.4. Discrimination of treatments for the 2006 harvest[a]



[a]The size of the circle corresponds to a 95% confidence limit for the mean.

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