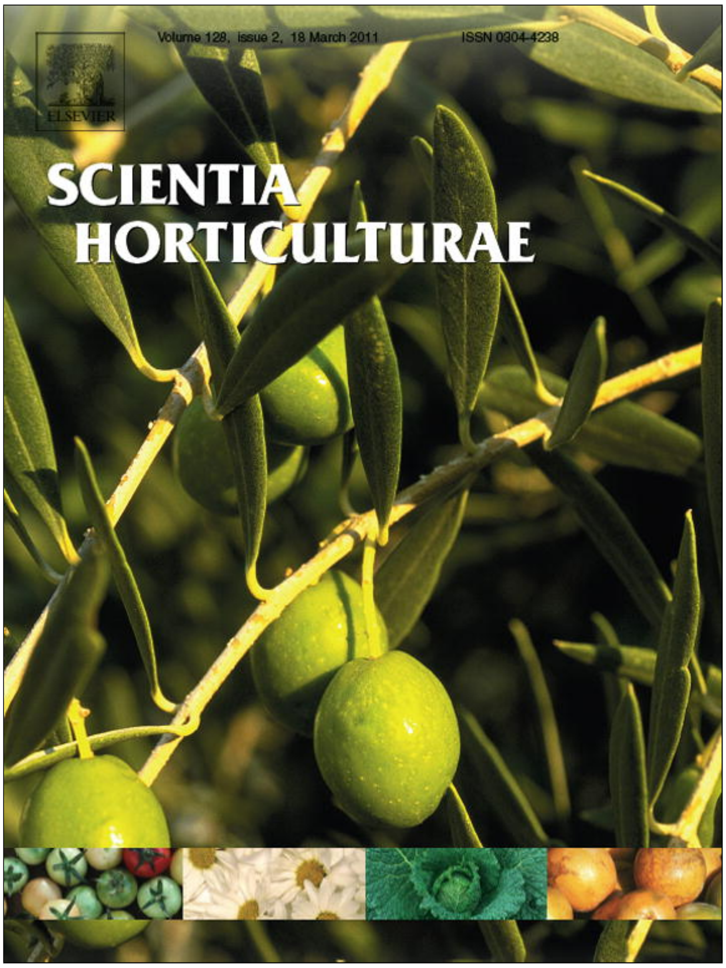
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Shade coffee in Hawai'i – Exploring some aspects of quality, growth, yield, and nutrition

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ABSTRACT

In a harsh (Kunia) and an ideal (Kona) growing region of Hawai'i, sun grown *Coffea arabica* L. was compared to coffee shaded with varying degrees of black and aluminized shade cloth, macadamia trees, and a novel, spray-on shade composed mostly of kaolin. Shading did not appreciably affect organoleptic quality. Shading resulted in statistically different yields in the macadamia (16% of sun) and kaolin (199% of sun) treatments in the second year compared to full sun treatments in their respective locations, although a negative, linear trend was observed with increased shading. The lack of significant differences in yields between the shade cloth and sun treatments was likely a result of large yield variation among replicates. Bean sizes differed little between shade treatments and the percentage of defects and broken beans were generally not significantly different among the treatments in Kunia. Kona bean sizes and characteristics were not different. Shading reduced surface leaf temperatures and increased specific leaf area but generally did not affect lateral nodal growth. Leaf nutrient concentration differed between treatments.

1. 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 benefits and increased sustainability, and it is the basis for some sustainability 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; Bosselmann et al., 2009). As organoleptic quality is vital to a consumer's decision to purchase coffee (de Ferran and Grunert, 2007; Wood, 2007) and Hawaiian coffees are generally more expensive than coffees from other origins, maintaining high-quality coffee is 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. This research project explored the influence of abiotic and biotic shade sources on some aspects of coffee physiology, morphology, yield, and organoleptic quality.

The goal was to understand coffee's response to reduced light conditions in Hawai'i in order to make recommendations to farmers. Two different growing regions in Hawai'i were used for this research – Kona, considered to be ideal for coffee growing and Kunia, a hot and dry region that is stressful for coffee.

2. Materials and methods

2.1. 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

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Table 1
Monthly average incident PAR[a] and ambient temperature at both locations for the months of highest and lowest PAR readings.

Location	June 2005		December 2005	
	Average	Maximum	Average	Maximum
PAR				
Kona	1022	2500[b]	889	2259
Kunia	1403	2500[b]	956	2256
Temperature (°C)				
Kona	23.4	37.0	20.5	27.9
Kunia	25.8	32.8	22.6	22.3

[a] $\mu mol\,m^{-2}\,s^{-1}$.
[b] Sensor upper range limit = 2500.

155°5′W, elevation 425 m asl) were chosen for this experiment. The Kona soil was a Honuaulu very stony silty clay loam with an average pH of 5.7. Annual rainfall for Kona is 1500–2000 mm. The Kunia soil was a Molokai silty clay loam with an average pH of 5.0. Annual rainfall for the Kunia site is 500–630 mm.

The Kunia trees were planted in 1987 as an experimental plot and were in 1 m × 5–6 m hedgerows (originally 1 m × 3 m) during this experiment. The row orientation was slightly Northwest–Southeast. The Kona trees were planted in 1992 in 1.2 m × 3 m hedgerows with a West–East row orientation on a commercial farm. 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 photosynthetically active radiation (PAR) and ambient temperature were measured using a PAR Smart Sensor and Temperature/RH sensor logged every 2 min using a Hobo weather station (Onset Computer Corporation, Pocasset, MA, USA) stationed in each location. Table 1 shows the average daily incident PAR between 800 and 1600 HR and the maximum value measured. Table 1 also shows the monthly average temperature and maximum value measured. The table presents data for the months with the highest and lowest PAR averages. In Hawai'i, daylength varies from about 11 to 13.5 h, depending on the time of year.

Due to the differences resulting in Kunia being an experimental field and Kona being an active commercial farm, different experimental designs were required for each location. As such, the two locations should be viewed as two similar yet separate experiments in different locations.

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 blocks, and one replicate of each treatment was randomly assigned to each block. In Kona, experimental units consisted of randomly selected individual trees with 6 replications of each treatment.

Experimental units were randomly assigned to a shade treatment. In Kunia, during the first year the treatments were full sun, 40% aluminized shade cloth (Aluminet), 40% black shade cloth, and a kaolin based spray-on shade as described by Steiman et al. (2007). Semimonthly spraying commenced on 24 February 2005 and continued until 5 December 2006. In the second year, three blocks each of a 30% and 66% black shade cloth were added. In Kona, in both years, the treatments were full sun, Aluminet (40% shade), and macadamia trees (planted in 1988, spaced 7.5 m × 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 imposed after the first major flowering of the season and remained in place until the completion of the experiment.

2.2. Coffee phenology in Hawai'i

Phenological development of coffee in these locations proceeds as follows. Flowering, typified by 2–4 major antheses, occurs between February and April, in the spring. Harvesting occurs August–December, in late summer through early winter. The large range of harvest times describes both locations, even with such different climates; the Kona region is geographically diverse and encompasses a range of micro-climates.

2.3. 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, Plainfield, IL, USA). 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, $m^2\,kg^{-1}$) 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.

2.4. 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 with the mucilage still present 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 previous samples from the same 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 in. (0.4 mm) sieves. In most cases, only beans from sieve sizes 17 or 18 were used for the analysis. Occasionally, beans screened as 16 or 19 were used due to low amounts of sample from the low yielding macadamia treatments. Under these circumstances, beans of only a single size, larger or smaller, were mixed to produce a large enough sample to roast. 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 (PROBAT-Werke, Emmerich, Germany). 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 min, corresponding to a weight loss of 17–18%. All treatments within a block (Kunia) or

Table 2
Cupping characteristics of all treatments from both locations and years.[a,b]

	Dry aroma	Wet aroma	Acidity	Flavor	Sweetness	Body	Aftertaste
Kona							
2006							
Aluminet (40%)	5.9	5.3	4.8	5.1	2.5	4.8 (1.5)ab	4.1 (2.2)a
Macadamia	5.9	4.8	4.8	4.7	2.5	4.3 (1.6)b	3.2 (1.9)b
Sun	6.3	5.3	4.6	5.2	2.4	5.2 (1.9)a	3.8 (2.1)ab
2007							
Aluminet (40%)	5.6	4.8	4.7	4.6	2.7	4.2	3.5 (1.8)b
Macadamia	6.2	5.0	5.1	5.0	2.6	4.5	3.9 (2.0)ab
Sun	6.2	5.1	4.5	4.9	2.7	4.6	4.5 (2.2)a
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 $p < 0.05$.
[b] Numbers in parentheses are the standard deviation.

replication (Kona) were roasted on the same day. Roasted coffees were stored as whole beans in 475 ml glass jars at room temperature (23–25 °C) and cupped the next day.

2.5. Cupping

Each cupping day consisted of two sessions. Each session tested coffee from a single location and usually all the experimental units within a single block or replication. 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 the 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.

2.6. 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. Kunia leaf nutrition data were analyzed as repeated measures. Where a time by treatment interaction occurred, a univariate analysis of variance was used to test for treatment differences at each sampling date. Where significant treatment effects were indicated, the Tukey–Kramer HSD test was used for means separation. Regression analysis was used to explore the relationships between bean size-yield and bean size-shade.

3. Results

Organoleptic characteristics were not significantly different for most of the treatments at either location. Table 2 shows all the cupping ratings and mean separation of the significantly different characteristics.

Table 3 shows the leaf temperature and growth responses to the shade treatments. Leaf temperatures under all shading regimes were cooler than full sun. Nodal growth was only different in the macadamia treatment where it was about one-third of 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.

In 2006, bean characteristics (floaters, defects, broken beans, and peaberries) were not significantly different between treatments in Kunia (data not shown). 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 but no differences were found in Kona (Table 4).

In Kunia, the kaolin treatment had a greater percentage of small beans than all other treatments in 2007, though, at screen size 17, it was no different than the Sun and 40% black shade cloth (Table 4). While no statistical difference in bean sizes greater than 17 existed, a trend towards larger bean sizes with shading may have begun. In Kunia in 2006 (data not shown), no bean sizes were statistically different but a similar trend towards larger bean sizes with shading was apparent. The bean sizes from the 2007 Kona harvest showed little significant difference. With so few treatments it is difficult to discern any trend (Table 4).

The proportion of size 16 and 17 beans from Kunia in 2007 were regressed against yield and shade level. Although the kaolin treatment produced shade conditions on leaves, rain, wind, lateral branch growth, and semimonthly sprayings prevented a reasonable estimate or quantification of the whole plant shading produced by kaolin. In addition, kaolin treated plants exhibited many sun-like responses. Consequently, for the regression analysis, it was 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

Table 3
Physiological characteristics of coffee plants at both locations.[a,b]

Treatment	Leaf temp (°C)		Nodal growth		Specific leaf area (m^2/kg)	
	Kunia	Kona	Kunia	Kona	Kunia	Kona
Macadamia		22.3 (1.0)c		3.8 (2.0)b		18.4 (3.4)a
Sun	37.1 (3.7)a	33.7 (2.6)a	12.2 (4.6)	10.5 (3.8)a	13.6 (.4)b	14.3 (3.0)b
Aluminet (40%)	33.3 (2.2)b	27.6 (2.3)b	12.4 (4.1)	9.2 (4.2)a	15.2 (.5)a	15.6 (2.8)b
Black (40%)	32.3 (1.7)b		12 (4.2)		15.6 (.7)a	
Kaolin	33.7 (3.0)b		12.6 (4.4)		13.3 (.5)b	

[a] Different letters within a harvest year and column are significantly different at $p < 0.05$.
[b] Numbers in parentheses are the standard deviation.

17, respectively) and a significantly negative linear relationship with shade level ($R^2 = 0.45$ and 0.44 for sizes 16 and 17, respectively; data not shown). No other bean sizes showed an appreciable relationship.

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 repeated measures analysis for the Kunia leaf nutrient content resulted in a time effect for all nutrients (data not shown). Significant time by treatment interactions were followed with one-way analysis of variance of the treatments. Table 5 shows the results of these analyses and the leaf nutrient concentrations. Iron did not have a time by treatment interaction. However, it did have a significant treatment effect. Consequently, the data for Fe were also analyzed as an ANOVA. A significant difference for Mn was not seen at $p < 0.05$. However, because a significant difference occurred at $p < 0.08$ and a discernible pattern appeared, the data were also subjected to means separation.

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 that explains all nutrients. 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 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 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.

4. 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 likely large enough that the average, untrained coffee drinker would 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* × *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; Bosselmann et al., 2009). Our results suggest shade does not affect the organoleptic quality of coffee from the 'Kona Typica' cultivar under either ideal or hot and dry growing conditions in Hawai'i.

No data exist in the literature for differences in taste between different seed sizes from sample composites of 2 or fewer trees. Informal, internal testing showed no differences in the taste of different bean sizes. The authors recognize different bean sizes may

Table 4
Bean sizes and characteristics in 2007 for Kunia and Kona as a percent of green bean harvest.[a,b]

	Screen size							Characteristics			
	14	15	16	17	18	19	20	Floaters	Defects	Broken beans	Peaberries
Kunia											
Kaolin	2a	8a	22a	29a	14	3	0	4.2	6.5b	6.0b	5.4
Sun	1	4	15	26a	18	4	0	4.7	9.9ab	12.0a	5.9
Aluminet (40%)	0	3	10	22b	22	7	1	4.9	13.5ab	10.4ab	6.4
Black (30%)	0	2	8	20b	21	7	1	4.1	18.5a	10.2ab	6.8
Black (40%)	0	2	11	23ab	22	7	1	4.4	15.9a	7.9ab	6.5
Black (66%)	0	2	9	19b	20	7	1	4.5	15.7ab	13.9a	6.5
Kona											
Sun	0	0	1	8	33	34	6a	1.3	3.5	3.8	8.9[c]
Aluminet (40%)	0	0	3	15	41	25	3ab	2.0	3.2	3.4	4.3
Macademia	0	0	5	23	36	19	2b	2.2	4.6	2.8	4.6

[a] Different letters within a location and column are significantly different at $p < 0.05$.
[b] Due to very small amounts, sizes 13, 20, and 21 have been left out of the table.
[c] The high value is a result of one tree producing 30% peaberries.

Table 5
Leaf nutrient concentrations in Kunia and the univariate ANOVA results.[a]

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

[a] Different letters within a harvest date and column are significantly different at $p < 0.05$ for all nutrients except Mn. Mn significance is at $p < 0.08$.

Table 6
Leaf nutrient concentrations in Kona.[a]

Sampling date	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	Fe (ppm)	Mn (ppm)	Zn (ppm)	Cu (ppm)	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 column are significantly different at $p < 0.05$.

not only taste different inherently, but the mixing of sizes may result in uneven roasting, even under the carefully controlled conditions of this experiment.

Samples were cupped in a fashion to best explore the agricultural variation of the experiment. Treatments were cupped by blocks as they existed in the field to maintain the field variation as it may be detected by the trained (not expert) panel. Each cupper was given one sample of each coffee due to the time and energy it would have taken on behalf of the experimenters and the volunteer cuppers. While a perfect sensory science experiment would have had each cupper cup each sample at least 3 times (to capture cupper variation), having at least 9 cuppers and a large number of field replications was an acceptable compromise.

While shading does not affect organoleptic quality very much, it does alter coffee biochemistry (Guyot et al., 1996; Vaast et al., 2006; Steiman, 2008). 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 did not change 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; 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 semimonthly 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

Table 7
Total green bean harvest from both locations and years (kg/ha).[a,b,c]

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.
[c] Plant densities per hectare were 2739 (Kona) and 1800 (Kunia).

post-harvest processing when large beans pass through a pulper that is set for smaller beans. Since there were a higher proportion of smaller beans in the kaolin treatment, more may have escaped injury during processing.

The lower proportion of defects for the kaolin treatment cannot be easily 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 shading. In Hawai'i, those same pressures do not exist. We found no differences between defects in the sun treatment and any of the conventional shading treatments.

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 the percentage of these sizes.

In Kunia, the bean sizes seemed to trend towards larger sizes in the shaded treatments, with the exception of the kaolin treatment. Vaast et al. (2005) 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 transmission 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.

Although the coffee plots were adequately fertilized, there was a need to begin exploring nutrient usage in both shaded and unshaded systems. If shaded coffee plants seem to have different nutritional requirements, agricultural practices will need to be adjusted accordingly.

The time effect from the repeated measures analysis of the Kona data was likely due to the phenology of the plant during the sampling dates. The March and April samplings occurred just after flowering and the July and September samplings occurred when a fruit load was maturing on the trees. During these different times, the leaves experience unique source–sink relationships, resulting in different nutrient concentrations.

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 (1998) 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 1–2 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 likely 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 due to fewer 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 in the second year, the response cannot be due to biennial bearing. Several authors report that application of Zn to Zn-deficient plants can increase coffee yields (Guimaraes et al., 1983; Lambot, 1990). 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 of the Aluminet treatment. 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} (USD). In Kunia, the prices for these grades ranged from \$3.81 to \$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.

5. 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, although, this was only true for only one location. Even if shading produces slightly larger beans, the higher prices offered for larger beans does not offset the revenue lost from the lower yields. Costs of applying kaolin and shade tree management along with the additional benefits that may be conferred by shade trees, e.g., increased biodiversity, nitrogen input via N-fixation, and potential food sources need to be considered along with the price earned directly from coffee when exploring coffee agroecosystems. 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, with the planting density and pruning regime used on the farm, does not appear to be a suitable shade tree for coffee. The significantly higher yields produced in the kaolin treatment offer a promising addition to coffee agronomic practices, though further study on its cost–benefit relationship is required.

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