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Growth, Yield and Value of Managed Coffee Agroecosystem in Hawaii.

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Abstract: Coffee can be cultivated under various management schemes from heavy shade to full sun. Higher yields are generally achieved in full sun but often at the expense of smaller beans and greater requirements for water and nutrients. We compared growth, yield, bean size, and total value in a coffee agroecosystem in Hawaii grown in full sun or at two shade levels (30 and 50%) under *Leucaena* variety KX2 trees. Coffee under full sun had more fruiting nodes per lateral and more beans per node, resulting in significantly greater yields. Bean size, however, increased with shade level. For both low and medium shade, the majority of the yield fraction was in the largest size class (≥ 19 mm). As a result, there was no significant difference between low shade and full sun in the total value of the beans. Within a mechanized production system, the low shade treatment with *Leucaena*-KX2 represents an optimum trade-off between yield and bean size.
Keywords: Shade coffee, Full-sun coffee, *Leucaena*-KX2, Coffee yield, Mulching, Agroecosystem, Bean size fractions, Shade management.

1. Introduction

Arabica coffee (*Coffea arabica* L.) is a cash crop of major economic importance in Hawaii and many other countries (Steiman, 2008; valos-Sartorio and Blackman, 2010). Hawaii has a reputation for producing coffee of high quality. This has radically modified agricultural practices, especially pruning and fertilization regimes, and often completely eliminated shade trees. However, these systems are not only more economically risky but also less ecologically sustainable (Cardoso et al., 2001; Campanha et al., 2004; Wintgens, 2004).

Various attempts have been made to determine the importance of numerous factors that affect growth and bean quality in coffee agroecosystems, including climatic conditions, shade management, fertilization regimes, and adequate pruning. (Wintgens, 2004; Steiman, 2008; Bosselmann et al., 2009; valos-Sartorio and Blackman, 2010).

Shade management ranges from coffee systems under natural unmodified forest cover over scattered multipurpose trees to highly controlled shade in commercial agroforestry systems (Perfecto et al., 2005; Siles et al., 2010). Some work has been done to document the relationship between shade and coffee yield, e.g. Beer (1987) and DaMatta (2004) found positive effects in suboptimal locations, whereas Soto-Pinto et al. (2000) and Elevitch et al. (2009) found negative effects when shade level was above 50%. Lin (2009) found that high shade (60-80%) coffee flowers equally well to the medium-shade (30-50%) in low-input coffee farms of Chiapas, Mexico. Results differ because the environmental factors and the coffee varieties examined vary among the studies, and issues of exact environmental needs are difficult to quantify because of the variation (Carr, 2001).

Optimal shade levels are likely to be below 50%, especially for coffee that receives fertilization or supplemental irrigation. What is unknown is whether the tradeoff of yield with bean size, flavor profile, or other aspects of quality, that can occur with shade results in a net benefit to the producer.

The objectives of this study were to examine the effect of three shade levels (full-sun, low and medium) in a coffee-*leucaena* agroecosytem in Hawaii on: 1) growth and yield, 2) bean size fractions as an indicator of quality, and 3) total value of bean yield based on the market prices for the various size fractions. We hypothesized that shade levels would decrease growth and yield but increase bean size, resulting in similar total value among the three shade levels.

2. Material and Methods

2.1. Study site

The study was carried out at the University of Hawaii, College of Tropical Agriculture and Human Resources, Waimanalo Research Station on the windward side of the island of Oahu. The site is 20 m above sea level and is classified as a humid tropical environment (Giambelluca et al., 1986). Mean annual rainfall is 1080 mm (National Climatic Data Center, 2002) with distinct wet and dry seasons, annual rainfall from 2007-2009 were 1268, 968 and 1115 mm, respectively (Fig.1). The soils are generally unconsolidated colluvium from the volcanic Koolau Mountains, mixed with coral from the nearby oceanic shoreline. They are classified mainly as Vertic Haplustolls, dominated by the Waimanalo series, Dark clay soils formerly in sugar cane. These soils are typically base rich, high in organic matter, and relatively fertile (Ikawa et al., 1985).

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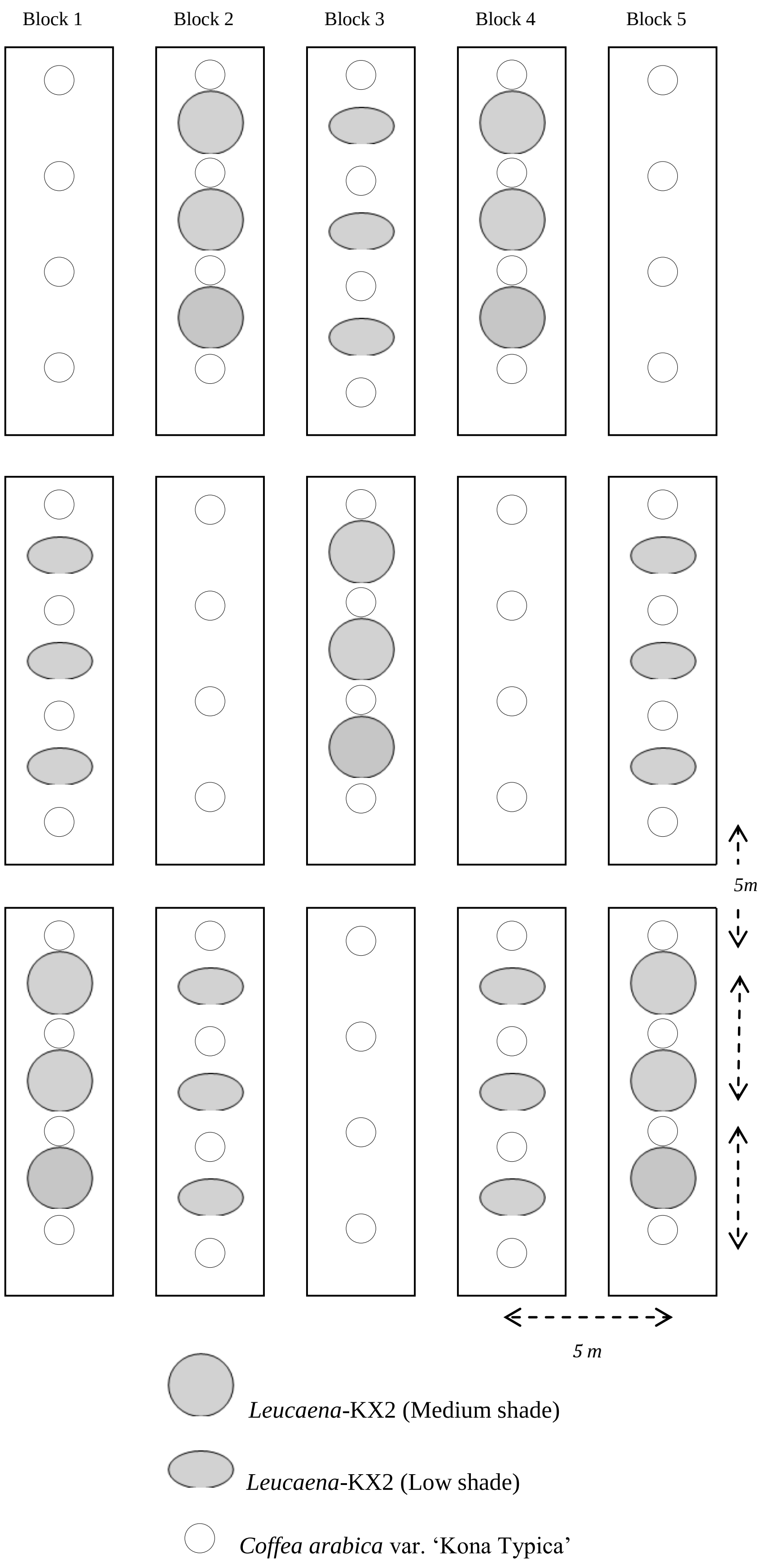

Fig.2: Layout of *Coffea-Leucaena* agroecosystem field in Waimanalo.

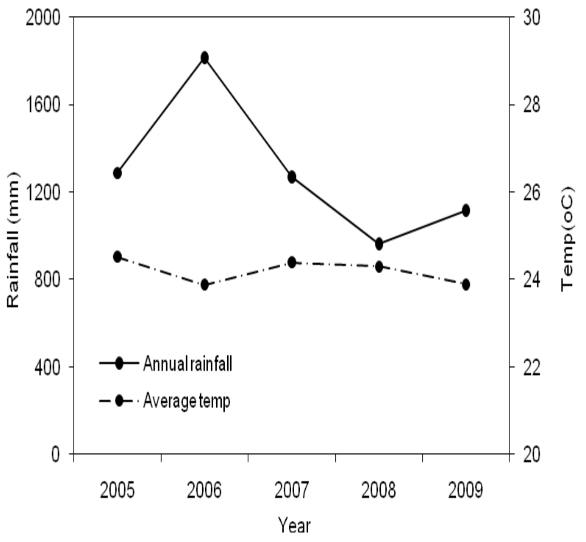

Fig. 1: Annual rainfall and average temperature in Waimanalo from 2005 to 2009

2.2. Experimental layout

Fifteen plots were established within 5 rows, 3 plots per row. Each plot was 8 m long within a row. Within- and between-row distances were both 5 m (Fig. 2). Each row was considered a block. Twenty-year-old *Coffea arabica* L. plants of the Typica landrace, cultivar 'Kona Typica', growing in Kunia, Oahu Island, Hawaii (21°23'N 158°2'W, elevation = 83 m asl) were selected for this experiment. The Kunia plants were planted in 1987 in 1 m x 5-6 m hedgerows (originally planting in Kunia at 1 m x 3 m) (Steiman, 2008). Sixty selected trees were marked and stumped at 50-cm height. On 23 March 2007, the marked trees were dug out with a backhoe and transplanted to Waimanalo. Stump diameter (D) at 25 cm height above soil level was measured by diameter tape and recorded as initial diameter. Before planting, roots were pruned at approx. 60-cm distance from the stump. Trenches were prepared in each plot to a width and depth of 1 m. Four stumps were planted in each plot, each 2 m apart. Drip irrigation was applied (2 drip per stump) to all plots during dry periods to maintain plant survival and growth. All new lower vertical sprouts on each stump were removed periodically. Four to six orthotropic shoots (verticals) were allowed to regrow on each stump, and each of these verticals was marked with a number.

On 07 May 2007, three *Leucaena* variety KX2 seedlings (2 months old) were planted between the coffee stumps in two randomly assigned plots in each block to establish the shade treatments. The other plots were left with coffee trees alone as full-sun. On 7 August 2007, all *Leucaena* trees in the plots were pollarded at 1 m above ground level. The harvested biomass was chipped in a mechanical tree chipper and distributed uniformly back to the leucaena plots as mulch (average 5.46 kg dry weight per plot). On 4 January 2008, all leucaena trees in the plots were pollarded at 2.5 m above ground level. The harvested biomass was chipped and distributed as before. Two shoots per leucaena stump were left to grow and others were removed. On 4 April 2008, plots with leucaena trees were randomly assigned to either the low and medium shade treatment and were pruned to achieve target shade levels of either 30 or 50%, respectively. Trees were pruned every 3 months thereafter until 4 October 2009 to maintain the target shade level.

Shade levels were measured every 6 months by comparing photosynthetically active radiation (PAR) between full-sun and shaded treatments, using LI-COR LI-191SA line quantum sensors (LI-COR Biosciences, Lincoln, NB). A single sensor was placed parallel to the ground but perpendicular to the solar track just above the height of the two inner coffee plants within each plot in a single block (~2.5 m aboveground). The sensors were attached to LI-1400 data loggers and allowed to collect data on PAR from 8 AM to 6 PM for a single day. Light levels in the open-grown coffee were assumed to be equivalent to the incident PAR. In order to monitor incident PAR over the year, a single point quantum PAR sensor was located in the open and attached to a HOBO microstation datalogger (Onset Computer, Bourne, MA) (Fig. 3).

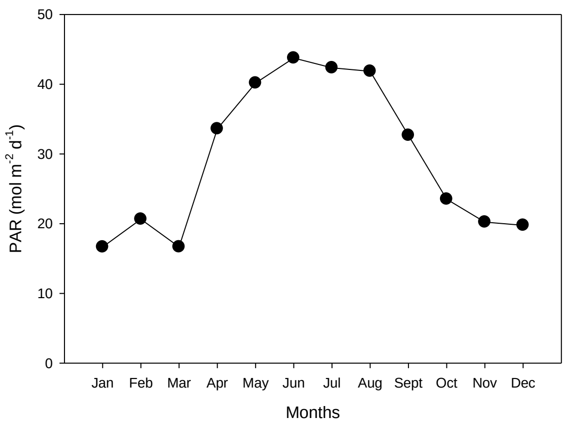

Fig. 2: Monthly average PAR (mol m^{-2} d^{-1}) in 2008 at the Waimanalo Research Station

Shade level was estimated in the month before and after each pruning event using a hemispherical-mirror densiometer in order to check the adequacy of pruning to achieve desired shade levels. The densitometer measures overstory cover across a 135-degree arc and can be used as a proxy for shade level. We compared densiometer to PAR measurements on two occasions to derive a relationship between overstory cover and light reduction (%PAR) (Fig. 4).

Nitrogen fertilizer (46-0-0) was applied to full-sun plots only, according to Bittenbender and Smith (1999) after each pollarding. The amount of N added was based on N content of the mulch added to shaded plots (Table 2).

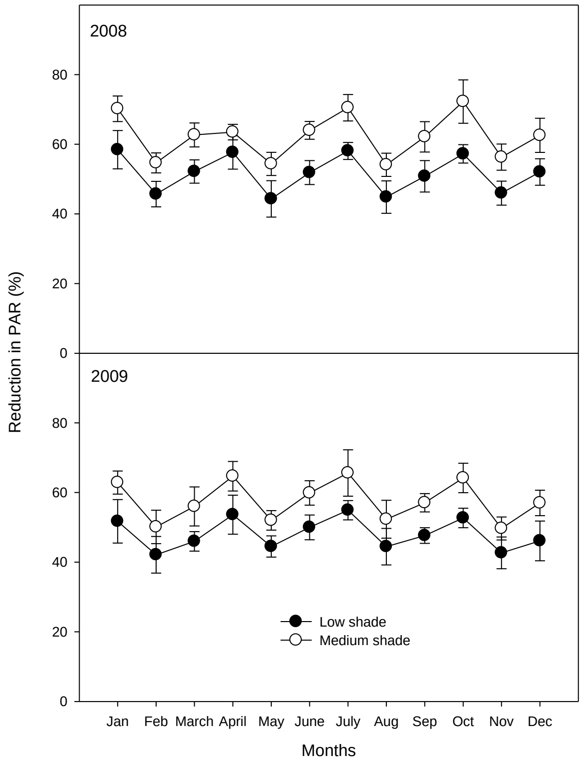

Fig.4: Monthly predicted reduction in PAR(%) of 2008 and 2009.(*)present pollarding month.

2.3. Growth and yield measurements

One year after transplanting coffee stumps, 95% of the 60 plants had survived. For all measurements the two outer coffee trees on the border were not subjected to data collection. Height of all verticals per plant were measured and recorded on 15 December of 2007, 2008 and 2009. Diameter at 5 cm from the base of all verticals per plant was measured using a small caliper at the same time of height measurement. The number of fruits per node, and fruiting nodes per lateral and laterals per vertical were counted on 5 September 2007, 2008, and 2009.

During 2008 and 2009, mature cherries were harvested twice monthly from 15 September until 15 December. At the end of each harvest day, the coffee cherries were dried at 50 °C (72 hours). The total weight of cherries (g) per tree for 2008 and 2009 were determined by summing the oven-dry weight of all harvests. Because the experimental rows were spaced widely to prevent shading from adjacent rows, yields are reported on a per plant rather than a per area basis.

Green bean weight at each harvest was estimated by drying a 1-L sample of cherries (approx. 500 g) at 50°C (48 hr). Each sample was then processed through a huller machine (Limprimita-John Gorden & CO LTD Epping, Essex, England) to crush the skin. A winnower machine (John Gordon) was used to separate the skin, parchment and other light impurities from the bean. Both the huller and winnower processes were repeated until the whole green bean samples were determined to be clean. Random samples of 100 green beans from each sample were taken, oven dried for 24 hr at 50°C and weighed.

2.4. Coffee yield grading and evaluation

The grading process of green beans (from 1-L of each sample of cherries) was done based on Hawaiian Administrative Rules-Standards for Coffee (Department of Agriculture-State of Hawaii, 2001) using the screening size method. Green beans are passed through a series of sieves (19, 18, and 16-mm mesh openings and a blank), to separate the beans into four fraction grades. Beans remaining on these sieves (large to small mesh size) were graded as Hawaii extra fancy, Hawaii fancy, Hawaii #1 and Hawaii prime, respectively. All screen sizes of green beans were weighed and summed to calculate their proportion of total green bean yield. The value of each fraction was estimated by multiplying the weight of each fraction by its price. Prices were based on personal communication with coffee farmers in Kona and Oahu.

2.5. Soil and tissue samples

Initial soil samples were taken from the field in 20-cm increments to a depth of 1 m and analyzed for physical and chemical properties by the University of Hawaii Agricultural Diagnostic Service Center (ADSC). Soil pH was measured in a 2:1 soil:water mixture; soil total C and N content were analyzed using an elemental analyzer; the soil total content of other nutrients was analyzed by ADSC using an inductively coupled plasma emission spectrometer. Bulk density was determined from core samples (Anderson and Ingram, 1990). Initial characteristics from the 0-20 cm depth increment are presented in Table (1). The mulch added to each plot after each pollarding was weighed in the field. Nitrogen concentrations of mulch samples were estimated using a combustion furnace elemental analyzer by ADSC. Dry mass and N content of mulch additions are listed in Table (2).

Table 1: Initial soil characteristics (2007) in coffee stump agroecosystem farm.

	Soil depth (cm)			
	0-20	20-40	40-60	60-100
pH	7.1	7.2	6.90	6.80
EC (mmhos/cm)*	0.34	0.33	0.31	0.32
B.D.(Mg m^{-3})**	1.02	1.12	1.15	1.20
C (g kg^{-1})	23.50	14.80	10.20	11.20
N (g kg^{-1})	1.90	1.40	1.00	1.00
C:N	12:1	11:1	10:1	11:1
P (mg kg^{-1})	207	204	103	114
K (mg kg^{-1})	1544	1426	737	752
Ca (mg kg^{-1})	5564	5394	4472	4670
Mg (mg kg^{-1})	1121	1180	1473	1453
Sand (%) †	6.4	6.4	ND	ND
Silt (%) †	29.3	29.3	ND	ND
Clay (%) †	53.3	53.3	ND	ND

* EC: Electrical Conductivities; ** B.D.: Bulk Density; † Soil texture (Source: El-Swaify 2001).

In order to determine coffee nutritional status, 10 pairs of the most recently matured leaves (3rd or 4th pair from the terminal) from lateral branches from each plot were collected on 15 March 2008 and 14 March 2009. Leaves were analyzed for N concentration using a combustion furnace elemental analyzer by ADSC (Table 3).

Table 2: *Leucaena*-KX2 mulch and N additions (kg plot^{-1}) from tree pollarding during the experiment.

Addition date	Mulch (kg plot^{-1})	N (kg plot^{-1})
Aug 2007	5.46	0.12
Jan 2008	9.02	0.19
April 2008	13.70	0.29
July 2008	18.22	0.39
Oct 2008	22.45	0.48
Jan 2009	24.30	0.52
April 2009	25.15	0.53
July 2009	27.26	0.58
Oct 2009	28.55	0.61

Table 3: Average N concentration (%) in leaf tissue of full-sun and shaded coffee of 2008 and 2009 samples.

Shade Level	2008		2009	
	Leaf N (%)	SE	Leaf N (%)	SE
Full-sun	2.21	0.46	2.31	0.40
Low	2.12	0.31	2.14	0.48
Medium	2.19	0.19	2.22	0.53

2.6. Statistics

One-way ANOVA using a randomized complete block design (RCBD) was used to compare growth, yield, and value of the various fractions. Where significant differences were indicated, means were compared using Tukey's honest significant difference test. All analyses were carried out using SAS 9.1.3 (SAS Institute Inc. 1990).

3. Results

3.1. Coffee growth

There were no significant differences by shade treatment in coffee vertical D or H; however, the number of fruits per node, fruiting nodes per lateral and laterals per vertical decreased with increased shade level in both 2008 and 2009 (Table 4). The weight of 100 green beans, conversely, was significantly lower in full-sun treatment.

Table 4: Growth characteristics of coffee plants based on shade treatments in 2008 and 2009*.

Variables	2008			2009		
	Shade Level			Shade Level		
	Full-sun	Low	High	Full-sun	Low	High
Vertical H (cm) / plant	82.70 a	76.07 a	74.31 a	137.23 a	125.64 a	112.80 a
Vertical D (cm) / plant	1.36 a	1.24 a	1.21 a	2.53 a	2.28 a	2.08 a
Fruits / node	12.80 a	9.60 b	6.60 c	14.00 a	10.80 b	7.40 c
Nodes / lateral	14.85 a	11.08 b	8.17 c	19.31 a	16.00 b	13.17 c
Laterals / vertical	13.20 a	11.42 ab	10.50 b	25.23 a	20.15 ab	17.93 b
100 green beans (g)	14.69 b	17.51 a	17.76 a	17.77 b	19.13 a	19.77 a

* Means in the same row with the same letters in each year are not significantly different based on Tukey's Studentized Range (HSD) Test.

Table 5: Mean green bean yield by size fraction per tree based on shade level treatments in 2008 and 2009*.

Grade Mesh size (mm)	Hawaii Extra fancy ≥ 19	Hawaii Fancy 18-19	Hawaii #1 16-18	Hawaii Prime < 16	Total
Shade level	Yield (g tree^{-1})				
	2008				
Full-sun	75.52 b	172.15 a	206.34 a	73.21 a	527.22 a
Low	108.29 a	117.20 a	121.97 ab	40.94 ab	388.40 b
Medium	111.79 a	58.86 b	52.59 b	20.65 b	243.89 c
	2009				
Full-sun	218.44 a	350.23 a	287.15 a	186.43 a	1042.25 a
Low	305.51 a	245.80 b	169.11 b	97.58 ab	818.00 b
Medium	326.19 a	146.47 c	81.76 c	57.32 b	611.74 c

* Means with the same letter in the same column of each year are not significantly different based on Tukey's Studentized Range (HSD) Test.

3.2. Yield and fractions

Shade affected both yield and the distribution of bean sizes (Table 5). Total green bean yield declined significantly with shade level in both 2008 and 2009; however, the yield fraction in the Hawaii extra fancy grade (≥ 19 mm mesh) was higher in the shaded treatments. In 2009, this fraction constituted approx. 40% of the total yield for the low and medium shade treatments but not quite 30% for the full-sun treatment (Fig. 5). By contrast, the yield of beans in the Hawaii #1 and Hawaii prime grades were higher in the full-sun treatment, constituting approx. 40% of the total, compared to only 30% of the total yield for the low and medium shade treatments.

Table 6: Green bean value per tree (US $) based on shade level treatments

Shade level	Hawaii Extra fancy	Hawaii Fancy	Hawaii #1	Hawaii Prime	Total
			2008		
Full-sun	2.24 b	4.73 a	5.22 a	1.69 a	13.89 a
Low	3.22 a	3.22 a	3.09 ab	0.95 a	10.47 a
Medium	3.32 a	1.62 b	1.33 b	0.48 b	6.75 b
			2009		
Full-sun	6.49 b	9.63 a	7.26 a	4.31 a	27.69 a
Low	9.07 a	6.76 a	4.28 ab	2.25 ab	22.37 ab
Medium	9.69 a	4.03 b	2.07 b	1.32 a	17.11 b

Means with the same letter are not significantly different based on Tukey's Studentized Range (HSD) Test. Each value represents the fraction percent multiplied by the estimated value of that fraction. Based on personal communication from Kona and Oahu, current market prices were $(USD) 30, 28, 25, 23 kg^{-1} for Hawaii extra fancy, Hawaii fancy, Hawaii #1, and Hawaii prime, respectively.

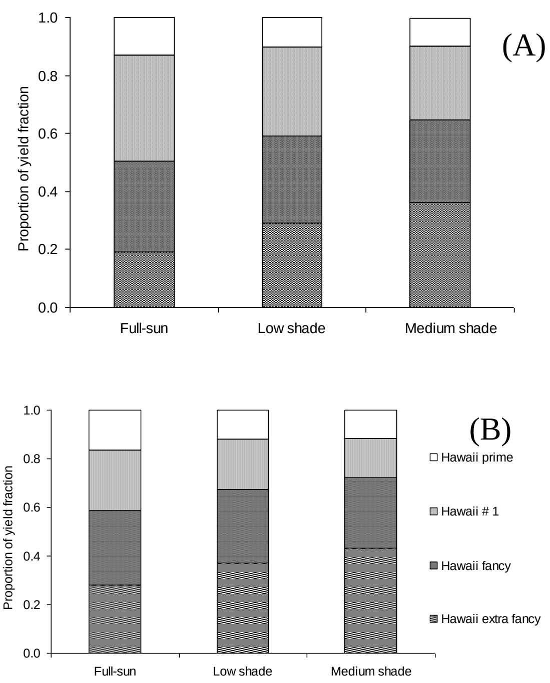

Fig. 5: Proportion of coffee yield in size-grades based on shade level from harvests in (A) 2008 and (B) 2009.

3.3. Evaluation of yield fractions

Because of the higher proportion of Hawaii extra fancy beans in the low and medium shade treatments, the estimated total value of green beans in the Hawaii market was more similar among shade treatment than was total yield (Table 6). There was no significant difference in total value between full-sun and low shade treatments in either year. The total value from the full-sun treatment was still significantly greater than in the medium shade treatment. The percent of the total value derived from Hawaii fancy and Hawaii extra fancy grades in 2009 was approx. 60, 70, and 80% for the full-sun, low, and medium shade levels, respectively.

4. Discussion

The greater number of fruits per node and nodes per lateral produced under full-sun was responsible for the greater coffee yield in this study; and this was contrary to other results (Campanha et al., 2004; Wintgens, 2004; Morais et al., 2006). However, some other reports have suggested that coffee plants that receive more sunlight will produce a greater number of flowers (Beer et al. 1998; Lin, 2008 and 2009) because of more nodes formed per lateral or more flower buds existing at each node (Montoya et al. 1961; Wintgens, 2004). Montoya et al. (1961) also reported a significant positive correlation between the increase in the number of nodes per branch and yield per plant the following year. Cannell (1975) stated that the most important component of yield is the number of nodes formed. Therefore, it seems logical to conclude that, because the number of nodes formed and the number of fruit set at each node can both be affected by light levels, shading can directly reduce coffee yields even when all other growth factors are favorable.

Results of field studies have not shown a consistent trend between light levels in agroforestry systems and green bean yield. In this study, moderate levels of shade (40-60%) reduced yield; in the medium shade treatment (actual shade level of 50-60%), the yield was half that in full-sun. Lagemann and Heuveldop (1983) found that higher shade reduced coffee yield. Conversely, in some trials in Costa Rica, production of the varieties Bourbon and Caturra under biannually pollarded *Erythrina poeppigiana* shade was equal to or greater than production from unshaded coffee under the same management (Ramirez, 1993). As discussed by Beer et al. (1998) and Perefecto et al. (2005), shaded coffee can produce lower, higher or equal yields relative to comparable sun systems. In Mexico, Soto-Pinto (2000) found that shade had a positive effect between 23 and 38%, and yield was maintained up to 48%. Production may decrease under shade cover >50% (Elevitch et al. 2009).

Previous studies have shown an increase in bean size with shade level. Vaast et al. (2006) hypothesized that competition for carbohydrates was the main reason and there was an indirect relationship between yield and bean size linked to that. 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 green bean weight and size produced under low and medium shade in this study were larger than the full-sun treatment.

The full-sun plots in this experiment were adequately fertilized to support high fruit production and maintain the same nutrient regime as shaded plots that received tree mulch (Table 3). Leaf N status showed adequate N concentration (Table 3) and no nutrient deficiencies based on recommendations by Bittenbender and Smith (1999). This suggests that the N provided by pruning the *Leucaena*-KX2 shade trees was sufficient for the coffee plants at this location. *Leucaena* has been used as an N source for coffee in other parts of the world (e.g. Snoeck, 1961). The yields in our study were not among the highest reported for Hawaii-grown coffee (Elevitch et al. 2009), but they are comparable to yields reported for the same plants grown at their original location in Kunia, Oahu at similar shade levels but with much higher fertilization (375-800 g plant^{-1}, Steiman, 2008).

In Hawaii, green coffee grades are based upon bean size, with larger beans commanding higher prices. The prices range from approx. \$30 kg^{-1} for Hawaii extra fancy to \$23 kg^{-1} for Hawaii #1. This price differential combined with the greater proportion of larger beans in the shade treatments greatly reduced the difference in value among the treatments, but the much higher yields in the full sun still resulted in a greater total value of the beans. The value of the low shade treatment (30-50%) was not significantly less than in full-sun, so this provides some potential to incorporate shade trees, which can provide other benefits, such as carbon sequestration (e.g. Youkhana and Idol, 2009), reduction in stress to the coffee plants, improved soil cover as mulch, and support for low-input or organic management.

Active management of shade is essential to maintain optimal levels and provide mulch and green manure. We pruned our trees four times yr^{-1}, but shade levels directly overhead still exceeded our target levels. Although the wide spacing minimized side shading from trees or coffee plants in adjacent rows, a more typical operational spacing of approx. 3 m between rows (Steiman 2008) would result in significant shading from trees in adjacent rows that are taller than approx. 5 m.

Finally, although we manually harvested the coffee and pruned *Leucaena*-KX2 trees, this system was designed for mechanical management of the coffee and shade trees. Wide spacing between rows and trees allows for tractor or other machine access, such as a brush chipper. Maintaining a single KX2 stem to a height of 2.5 m (above the coffee plants) allows for mechanical harvesting of the coffee trees and for mechanical pruning of the KX2 canopy. The cost of the labor required to manually prune the KX2 trees is much greater than any improved value of the coffee through larger bean size or reduction in cost for N fertilizer.

5. Conclusion

In a low-elevation coffee agroecosystem in Hawaii, the green bean yield declined as shade level from *Leucaena*-KX2 trees increased. This was due to fewer fruits per node and nodes per lateral. However, shade increased the proportion of larger bean sizes. This increased the value of the beans from shaded plants, although the full-sun treatment still resulted in the highest total value. Active management of *Leucaena*-KX2 shade to achieve optimal levels (30-50%) can provide relatively similar overall value of coffee, with a greater proportion of high-grade beans, in addition to benefits of shade for carbon sequestration, stress reduction, and support for low-input management.

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