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Effects of Agroforestry on White Coffee Stem Borer Incidence and Arabica Coffee Quality along the Slopes of Mount Elgon, Eastern Uganda

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Abstract
Agroforestry is promoted in coffee systems for climate regulation and soil improvement, but its effects on white coffee stem borer incidence and bean quality remain uncertain. This study identified shade-tree species, compared white coffee stem borer (Monochamus leuconotus Pascoe) incidence, and evaluated Arabica coffee quality in shaded and open farms in Kamogo and Kabeywa sub-counties, Kapchorwa District, eastern Uganda. Fifty farms were surveyed. On each farm, 20 shaded and 20 open coffee trees were monitored, giving 2,000 trees. Infestation was diagnosed from ring-barking, exit holes, wood shavings, pupation galleries, leaf chlorosis and related symptoms. Beans from shaded and open, infested and uninfested plants were wet processed and assessed for caffeine, titratable acidity, total solids, dry weight and sensory quality. Cordia africana was the most frequent shade tree, followed by Persea americana, while Polyscias fulva was least frequent. Infestation occurred on 575 of 1,000 shaded trees (57.5%) and 550 of 1,000 open trees (55.0%); every sampled farm contained infested trees, with farm-level incidence ranging from 20.0% to 92.5%. Pairwise tests based on laboratory triplicates found no significant shaded-open differences in caffeine, acidity or total solids within infestation categories ($P > 0.05$). Parchment and green-bean dry weights also did not differ significantly among categories ($P = 0.49$), and sensory scores were tightly clustered in the low-to-mid 70s. The modest descriptive difference in infestation and variable quality responses support managed, species-appropriate shade rather than complete shade removal. Species-specific trials that account for farm clustering, shade intensity and altitude are recommended.

Keywords: Agroforestry, Arabica Coffee, Coffee Quality, Mount Elgon, Shade Trees, White Coffee Stem Borer

Introduction

Coffee is an economically important tropical crop and a major source of income for smallholder households. Coffea arabica is especially valued for its aroma, beverage quality and comparatively low caffeine content, while roasted coffee contains a complex mixture of volatile compounds that determine flavour (Yeretzian et al., 2003).

Coffea arabica originated in the highlands of eastern Africa and is now cultivated widely in tropical highland environments (Gole et al., 2001; Mishra and Slater, 2012). In Uganda, Arabica coffee is concentrated in highland areas, including the slopes of Mount Elgon, where production supports farm income, trade and rural livelihoods (Jassogne et al., 2013).

Coffee production and quality are sensitive to temperature, rainfall, soil moisture, pests and diseases. High temperatures and unreliable precipitation may reduce yield and quality and may alter the development and distribution of insect pests. These risks have increased interest in coffee agroforestry as a climate-adaptation strategy.

Shade trees can moderate solar radiation and daily temperature fluctuations, retain soil moisture, contribute litter and diversify farm products. Their effects are nevertheless context dependent. Dense or poorly managed canopies may increase competition for water and nutrients or create humid microsites that favour some pests and pathogens (Beer et al., 1998).

White coffee stem borer (Monochamus leuconotus Pascoe) is an important pest of Arabica coffee in the Mount Elgon region (Kyamanywa et al., 2011). Because farmers have associated borer damage with shaded fields and have responded by removing trees, locally grounded evidence is needed. This study therefore examined shade-tree composition, compared borer incidence in shaded and open coffee, and assessed physical, chemical and sensory quality of beans from infested and uninfested plants.

Problem Statement

Arabica coffee is central to household income on the slopes of Mount Elgon, yet production is constrained by white coffee stem borer damage. Farmers in Kapchorwa District have linked the drying of coffee trees to shade-tree intercropping and, in some cases, have removed shade trees. Although the pest is endemic in African coffee systems (CAB International, 2006), the local relationship among shade, infestation and coffee quality had not been adequately quantified. Decisions based on perception alone could either retain conditions favourable to the pest or remove agroforestry benefits unnecessarily.

Justification

The study responded to concerns raised by coffee farmers and extension personnel in Kapchorwa and neighbouring districts. Evidence on shade-tree use, borer incidence and coffee quality was required to guide canopy management, pest monitoring and future species-specific research in the Mount Elgon Arabica production zone.

Objectives of the Study

Identify commonly used shade-tree species in Kapchorwa District and document farmers' reasons for retaining them.

Compare white coffee stem borer incidence in open and shaded Arabica coffee plantations.

Compare the quality of beans from infested and uninfested coffee plants under open and shaded conditions.

Hypotheses

White coffee stem borer incidence does not differ between shaded and open Arabica coffee.

Coffee quality does not differ between open and shaded environments within infestation categories.

The number of plants affected by white coffee stem borer is not greater in open coffee than in shaded coffee.

Literature Review

Shade Trees in Coffee Systems

Recommended coffee shade trees in East Africa include Ficus species, Albizia species, Gliricidia sepium, Grevillea robusta, Cordia africana and Polyscias fulva (Greenberg et al., 1997; Meunier et al., 2010). Species differ in crown architecture, rooting pattern, litter quality, growth rate and products supplied to households; these traits influence their suitability within coffee fields.

Albizia species can contribute biologically fixed nitrogen, while Polyscias fulva provides relatively light and even shade. Cordia africana supplies shade, fodder and mulch but requires pruning to prevent excessive canopy development. Species choice and canopy management therefore need to reflect local climate, soil conditions, coffee spacing and farmer objectives.

Regular pruning is important because shade benefits decline when canopies become too dense. Managed litter inputs can improve soil organic matter and nutrient cycling, whereas unmanaged tree-crop competition can reduce coffee productivity (Mulumba and Lal, 2007).

Role of Tree Shade in Sustainable Coffee Production

Shade can lower canopy temperature, reduce evaporative water loss and buffer climatic extremes. Tree litter and pruning residues can add organic matter and nutrients, while structurally diverse farms may provide habitat for beneficial organisms. Several studies have reported larger beans or improved physical quality under suitable shade conditions (Geromel et al., 2008; Muschler, 2001; Vaast et al., 2006).

These benefits are not universal. Shade trees may compete for water and nutrients, and dense canopies may favour particular pests or diseases. Effects vary with altitude, shade intensity, species composition and management. Findings from Ethiopia and Latin America therefore cannot be assumed to apply directly to Mount Elgon (Bote and Struik, 2011; Bosselmann et al., 2009; Muleta et al., 2011).

Prevalence and Importance of White Coffee Stem Borer

White coffee stem borer is a major pest of Arabica coffee in Africa and Asia. It has been recorded across elevations in the Mount Elgon region, with substantial implications for plant survival, yield and household income (CAB International, 2006; Kyamanywa et al., 2011). Larval feeding beneath the bark and tunnelling within stems disrupt vascular tissues and may ultimately kill affected trees.

Factors Affecting Pest Incidence

Pest incidence in coffee reflects interactions among crop vigour, shade structure, temperature, humidity, farm sanitation, pesticide use and natural enemies. Climate influences insect development and survival, while indiscriminate pesticide use may suppress beneficial organisms and contribute to secondary pest outbreaks (Bale et al., 2002; Khaliq et al., 2014).

Rising temperatures and altered rainfall may change the distribution and number of insect generations. However, insects respond to a range of interacting abiotic and biotic conditions; temperature alone is not sufficient to explain field incidence. Local comparisons should therefore consider shade together with altitude, crop condition and management.

Field Symptoms of White Coffee Stem Borer

Common field symptoms include ring-barking, stem holes, expelled wood shavings, internal galleries, leaf chlorosis, wilting and dieback. Because some canopy symptoms can have other causes, diagnosis is strengthened when external symptoms are considered together with characteristic stem damage (CAB International, 2006).

Light and Caffeine Content

Caffeine is produced mainly in young leaves and developing fruits and accumulates during maturation

(Zheng and Ashihara, 2004). Light can affect photosynthesis and the availability of carbon and nitrogen substrates used in alkaloid metabolism.

Published responses are inconsistent. Some studies have reported increased caffeine under high light, while others found reduced or unchanged concentrations under shade treatments (Ashihara and Crozier, 2001; Marcelo et al., 2013; Tolessa et al., 2016). Genotype, altitude, nutrient status and developmental stage may account for part of this variation.

Caffeine also contributes to chemical defence in young coffee tissues; consequently, its concentration reflects both plant development and environmental conditions.

Shade and Sensory Quality

Shade may slow berry development and promote more uniform ripening in warm environments, but excessive shade at cool, high-altitude sites can reduce solar exposure and may adversely affect sensory attributes. Bosselmann et al. (2009) showed that the direction and magnitude of shade effects varied between production areas, while Muschler (2001) and Vaast et al. (2006) reported quality benefits under specific conditions. These differences reinforce the need for site-specific assessment.

Knowledge Gap

Earlier studies established that shade can alter coffee pests, bean development and beverage quality, but they did not resolve how white coffee stem borer incidence and quality respond under Mount Elgon conditions. The present study addressed this gap by comparing shaded and open coffee within the same farms and by evaluating field infestation together with laboratory and sensory measures.

Materials and Methods

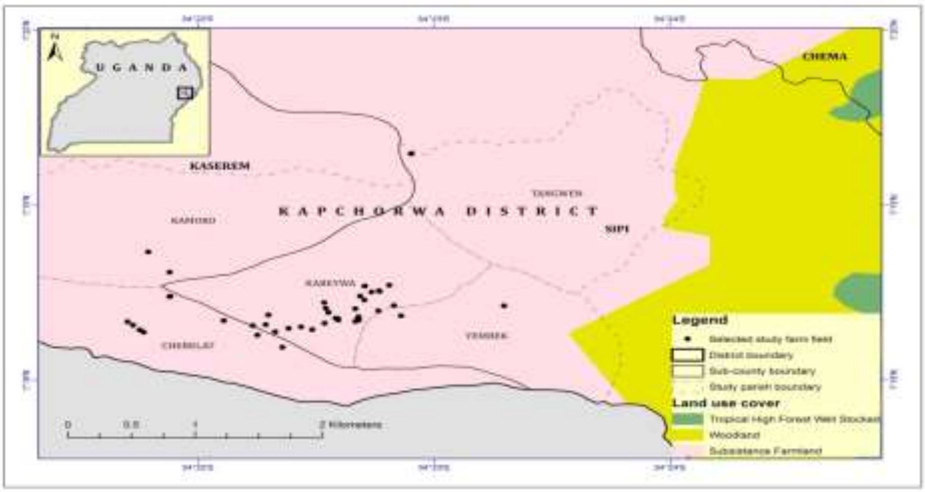
Study Area

The study was conducted in Kamogo and Kabeywa sub-counties of Kapchorwa District, eastern Uganda. The sampled farms occurred between approximately 1,109 and 2,015 m above sea level on the northern slopes of Mount Elgon.

Location

Kapchorwa District lies in eastern Uganda near the border with Bulambuli District. Kamogo and Kabeywa were selected because Arabica coffee is a principal cash crop and because farmers and extension personnel had reported persistent white coffee stem borer damage. Altitude at each farm was recorded using a Global Positioning System receiver.

Figure 1: Location of the Study Area in Kapchorwa District



Climate

The district has a cool highland climate with a drier, windy period from December to February and principal rainfall periods from April to July and September to December. Rainfall and temperature vary strongly with elevation (Ministry of Trade, Industry and Cooperatives, 2016).

The study sites fall within productive Mount Elgon highland and farm-forest agroecological settings, where annual rainfall commonly exceeds 1,200 mm and average elevation is about 1,450 m above sea level (NEMA, 1997).

Vegetation and Land Use

Vegetation ranges from savannah at lower elevations to mixed montane vegetation and forest at higher elevations. The farm-forest landscape is intensively cultivated, with Arabica coffee, banana, beans and maize among the principal crops.

Soils

Soils are derived mainly from volcanic parent material and are generally well-drained, highly leached clay loams with relatively good nutrient supply (Wortmann and Eledu, 1999).

Research Design and Sampling

A within-farm comparative design was used on 50 farms: 20 in Kamogo and 30 in Kabeywa. Each farm contributed 20 coffee trees under shade and 20 trees in an open, unshaded area. The 40 trees were randomly selected and tagged, giving 2,000 monitored trees, equally divided between shaded and open conditions. From the tagged trees, 12 trees per farm were randomly selected for cherry sampling: three infested and three uninfested trees in each shade condition. One 0.5 L mug of fully ripe red cherries was harvested from each selected tree, giving samples from 600 trees.

Shade-Tree Identification

Shade trees were identified using observable traits including habitat, crown form, bark, branching pattern, leaf arrangement, leaf complexity, venation and leaf margins. Species frequency was determined by physical counts on each sampled farm.

Representative leaves were labelled in the field and compared with specimens at the Masaka Agroforestry Demonstration Centre arboretum. Confirmed common species included Cordia africana, Persea americana, Grevillea robusta, Ficus species, Markhamia lutea and Polyscias fulva.

Assessment of White Coffee Stem Borer Incidence

All tagged trees were inspected for white coffee stem borer damage. Infestation status was assigned from characteristic stem and canopy signs, including ring-barking, exit holes, wood shavings, pupation galleries and associated leaf chlorosis.

The diagnostic signs are illustrated in Figure 2(a)-2(g). Where necessary, damaged stems were opened to confirm internal galleries or immature stages.

Infested trees were counted separately for shaded and open environments on every farm. Monitoring ran from January 2016 to March 2018, a period of 25 months.

Figure 2(a): Ring-Barking on a Coffee Stem

Figure 2(b): Adult Stem Borer Exit Hole

Figure 2(c): Wood Shavings Exuded from an Infested Stem

Figure 2(d): Stem Borer Pupation Galleries

Figure 2(e): Leaf Chlorosis Associated with Stem Damage

Figure 2(f): Pre-pupal Stem Borer Larva

Figure 2(g): Adult White Coffee Stem Borer, Monochamus leuconotus Pascoe

Source: Kateregga A.K. (2018).

These symptoms formed the field diagnostic criteria used to compare incidence in shaded and open coffee.

Assessment of Coffee Bean Quality

Sampling and Post-harvest Processing

Beans were sampled from shaded and open areas and from infested and uninfested plants. Within each category, cherries from three selected trees were combined into a composite sample, labelled and transported to Kyagalanyi Coffee Factory in Mbale for processing.

Harvest and post-harvest procedures were standardized. Only fully ripe, bright-red cherries were picked during the October-January peak harvest. Samples were wet processed by pulping, fermentation, washing, drying and hulling.

Cherries were pulped on the day of harvest with a Penagos DH-4 hand pulper. Parchment was fermented in separate containers for 24 hours, washed to remove mucilage and sun-dried on clean tarpaulins to a moisture content of 9%-12%. Approximately 200 g of parchment per composite sample was stored in perforated bags under common conditions before analysis.

Drying

Samples were dried separately on clean tarpaulins to limit soil contact and fungal contamination.

Moisture Content

Bean moisture was measured with a SINAR AP 6060 moisture analyser and maintained below 13% for all samples to reduce weight differences caused by unequal moisture.

Preparation for Chemical and Sensory Analysis

Dry Weight

Parchment and hulled green-bean mass were measured with a high-precision Smart Weigh SB-3000 balance and reported in grams per unit sample volume.

Caffeine Analysis

Roasting and Grinding

Beans were medium roasted at 200-230 °C for 4-7 minutes in a Joper roaster. A consistent roast was used to avoid scorching and masking of sensory attributes.

Roasted samples were air-cooled and held for 24 hours before grinding.

Samples were coarsely ground using a Joper MH 80 grinder.

Iodometric Determination of Caffeine

Caffeine was determined by iodometric back-titration based on Ho et al. (2014). Coffee powder (4.58 g) was boiled in 100 cm^3 of distilled water and cooled. A 15 cm^3 aliquot was acidified with 10 cm^3 of sulfuric acid, reacted with 25 cm^3 of 0.028 M iodine and filtered. Residual iodine was titrated with 0.0595 M sodium thiosulfate using starch near the endpoint. Each sample was analysed in triplicate.

$C_8H_{10}N_4O_2 + 2I_2 + KI + H_2SO_4 \rightarrow C_8H_{10}N_4O_2{\cdot}HI{\cdot}I_4 + KHSO_4$ (1)

$I_2 + 2Na_2S_2O_3 \rightarrow 2NaI + Na_2S_4O_6$ (2)

Equations (1) and (2) describe the caffeine-iodine reaction and titration of residual iodine, respectively.

Samples, Equipment and Reagents

Four composite roasted-coffee samples were analysed: A1, shaded uninfested; A2, shaded infested; B1, open uninfested; and B2, open infested. Equipment included conical flasks, burettes, beakers, filter paper and a retort stand. Reagents were 0.028 M iodine, 0.0595 M sodium thiosulfate, starch solution and 0.2 M sulfuric acid.

Titratable Acidity

Titratable acidity was determined using the method described by Butt et al. (2011). Coffee powder (10 g) was extracted with 75 mL of 80% ethanol for 16 hours with intermittent shaking. A 10 mL aliquot of filtrate was titrated against 0.1 N sodium hydroxide using phenolphthalein. Citric acid was used as the predominant-acid equivalent, and each sample was analysed in triplicate.

Titratable acidity (%) = $V \times 0.064$ (3)

Sensory Evaluation

Three trained baristas evaluated ten randomly selected farm samples by cup tasting. The attributes were fragrance, acidity, flavour, body and aftertaste. Infested and uninfested samples from shaded and open environments were represented.

For each sample, 8.25 g of roasted, coarsely ground coffee was infused in 150 mL of water at 92-96 °C. Five cups were prepared per sample to support uniform assessment.

Each attribute was scored from 1 to 10 using the Specialty Coffee Association of America cupping form. Attribute scores were summed and interpreted using the classification in Appendix 1.

Green-Bean Defects

Defective green beans were hand-sorted and weighed. Defect percentage was calculated as defect mass divided by parchment mass, multiplied by 100.

Total Solids

Total solids were determined using the AOAC oven-drying method (AOAC, 1990). Approximately 10 g of each sample was weighed into an aluminium dish, dried at 105 °C for 16 hours to constant mass, cooled in a desiccator for 30 minutes and reweighed. Each category was analysed in triplicate.

Total solids (%) = $(M_D \div M_I) \times 100$ (4)

where M_D is the dry sample mass and M_I is the initial sample mass.

Quality Assurance

Glassware was cleaned thoroughly, analytical-grade reagents were used and balances were calibrated according to manufacturer instructions. Roasting temperature, cooling time, grind setting, water temperature and moisture range were standardized across samples.

Data Analysis

Field data were coded and analysed in SPSS version 20. Frequencies, means and standard deviations were used for description. One-way analysis of variance was used for dry-weight comparisons. For publication, shaded-open contrasts in caffeine, acidity and total solids were checked from the reported triplicates using two-sided Welch independent-samples t tests because variances could differ. Statistical significance was assessed at $P < 0.05$. These laboratory comparisons are exploratory because each category contained only three analytical replicates.

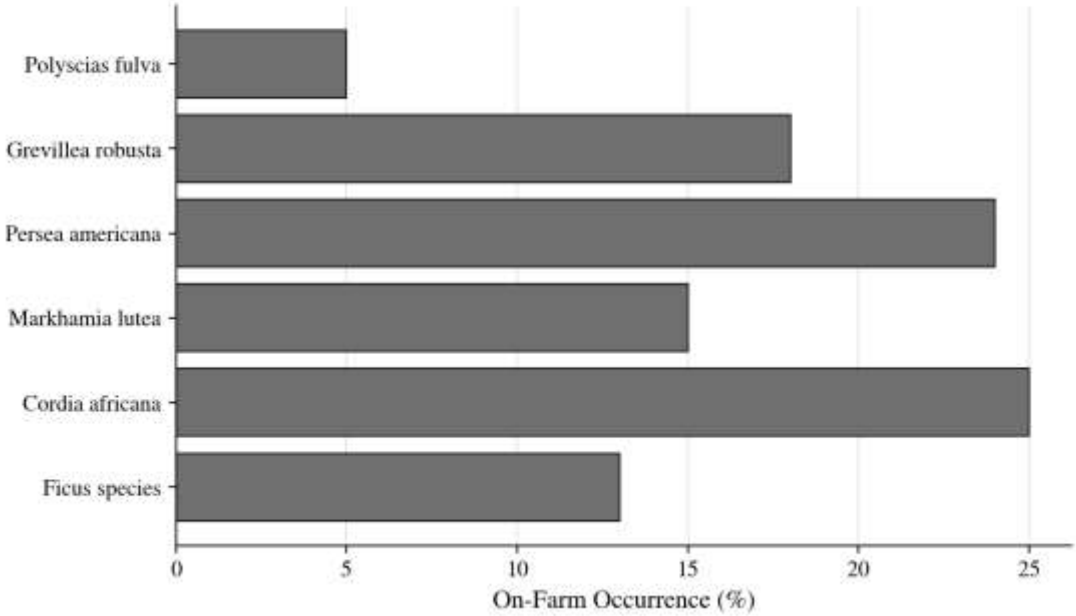
Results and Discussion

Shade-Tree Occurrence and Farmer Preferences

Cordia africana had the highest on-farm occurrence, followed by Persea americana, while Polyscias fulva was least frequent (Figure 3). Farmers valued Cordia africana for its broad, readily decomposed leaves, adaptable growth, timber, fuelwood and bee forage. Persea americana supplied fruit, income and timber.

Grevillea robusta was retained for rapid growth, light shade, timber, poles and wind protection, although farmers regarded it as a strong competitor and noted that its litter decomposed slowly. Markhamia lutea was used for timber, poles, tool handles, medicine and boundary planting. Ficus species were valued for rapidly decomposing litter, moisture retention, fodder, fuelwood and timber. Polyscias fulva provided a high, light canopy and wood products, but farmers reported limited seed availability and germination.

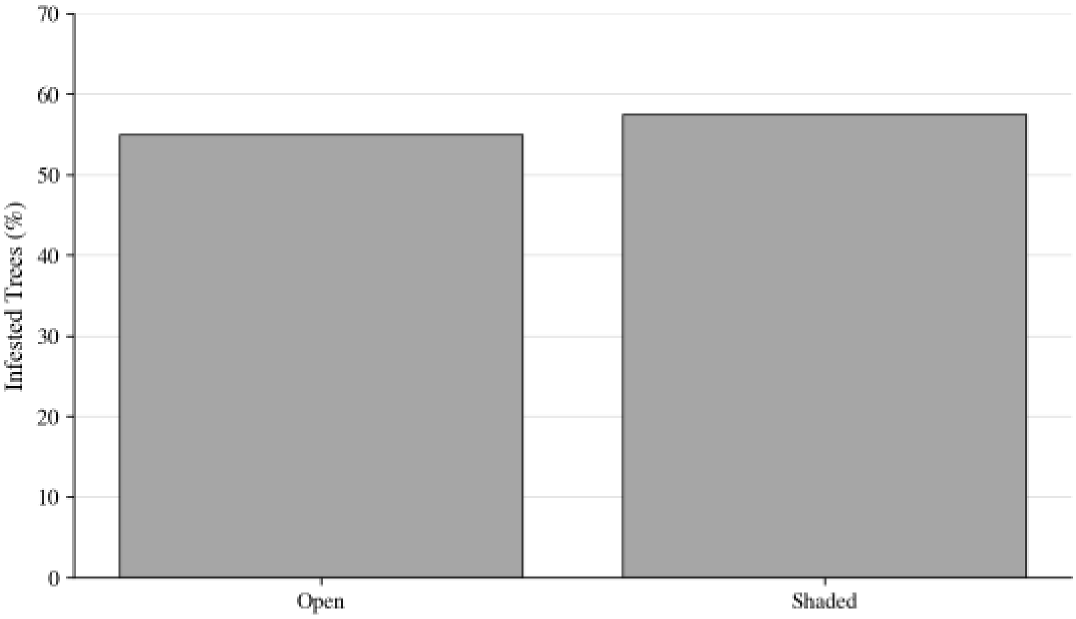
Figure 3: On-Farm Occurrence of Common Coffee Shade Trees



The pattern demonstrates that shade-tree selection was driven by multiple farm functions rather than shade alone. Species that combine compatible crowns with food, timber, fodder or soil benefits were more likely to be retained. Management recommendations should therefore recognise livelihood value as well as ecological performance.

White Coffee Stem Borer Incidence

Figure 4: White Coffee Stem Borer Infestation in Shaded and Open Coffee



Infestation was recorded on 575 of 1,000 shaded trees (57.5%) and 550 of 1,000 open trees (55.0%), a descriptive difference of 2.5 percentage points. Every sampled farm contained infested trees, although farm-level incidence ranged from 20.0% to 92.5%. The small overall difference does not by itself establish a causal shade effect because trees were clustered within farms and shade intensity, altitude and management were not included in an adjusted model. The widespread infestation in both environments indicates that monitoring and sanitation are required irrespective of shade status. Shade may influence pest microclimate and concealment, but crop vigour, natural enemies and farm practices are also plausible drivers.

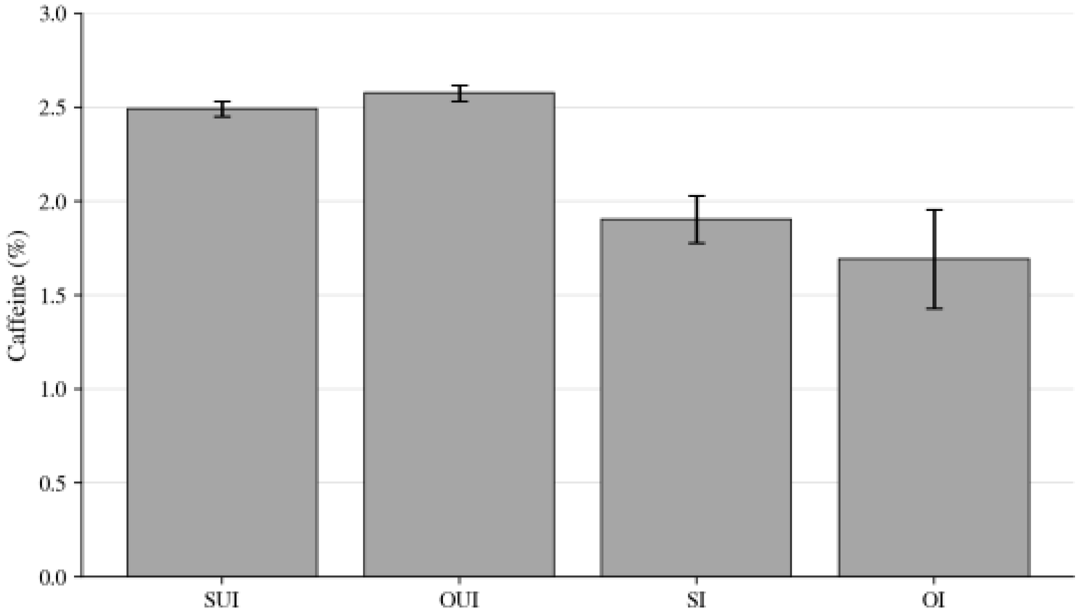
Coffee Bean Chemical Quality

Table 1: Chemical Properties of Coffee by Shade and Infestation Status

Property	Shaded Uninfested	Open Uninfested	P Value	Shaded Infested	Open Infested	P Value
Caffeine (%)	2.491 ± 0.042	2.575 ± 0.042	0.070	1.903 ± 0.126	1.693 ± 0.262	0.303
Titratable Acidity (%)	1.587 ± 0.032	1.611 ± 0.007	0.331	1.583 ± 0.043	1.510 ± 0.017	0.083
Total Solids (%)	98.099 ± 1.205	97.601 ± 1.436	0.670	94.766 ± 6.354	97.545 ± 1.437	0.531

Note: Values are mean ± standard deviation (n = 3). P values are from two-sided Welch independent-samples t tests comparing shaded and open samples within infestation status.

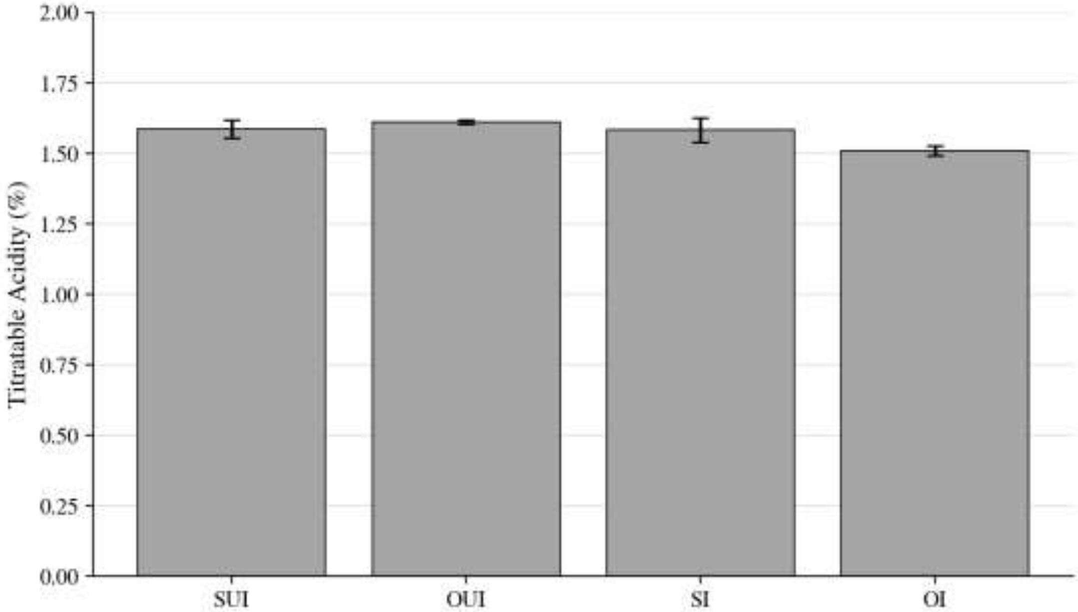
Figure 5: Caffeine Content of Infested and Uninfested Coffee from Shaded and Open Environments



Mean caffeine was higher in open uninfested coffee than in shaded uninfested coffee, whereas shaded infested coffee had a higher mean than open infested coffee (Table 1 and Figure 5). Neither shaded-open comparison was statistically significant at the 5% level. The direction changed with infestation status, suggesting that the observed pattern cannot be attributed to shade alone.

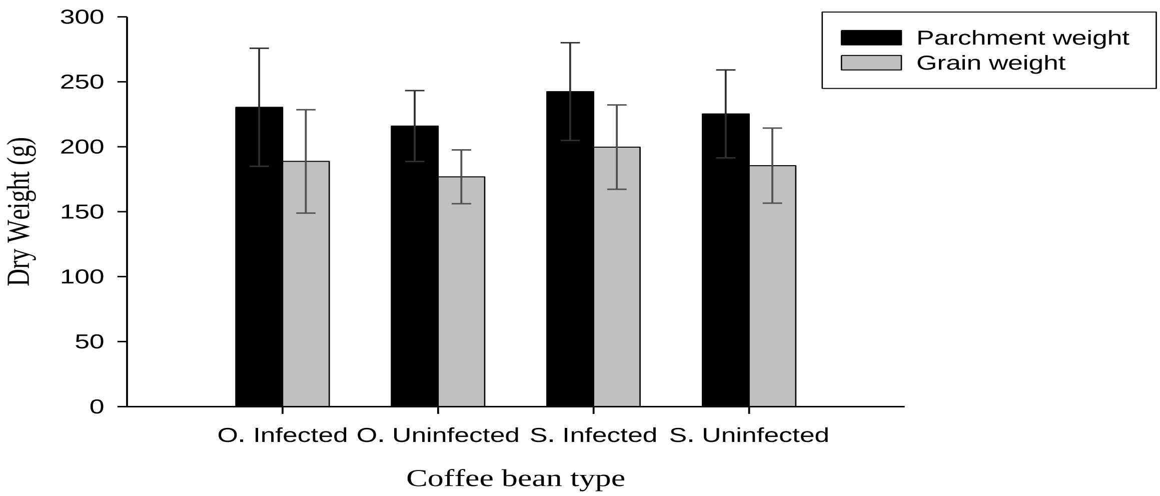
Titratable acidity showed the same interaction-like pattern: open uninfested samples had a slightly higher mean than shaded uninfested samples, while shaded infested samples exceeded open infested samples. Neither pairwise contrast was statistically significant. Variation in altitude, ripening, plant condition and post-harvest handling may have contributed to the differences.

Figure 6: Titratable Acidity of Infested and Uninfested Coffee from Shaded and Open Environments



Dry Weight

Figure 7: Dry Weight of Infested and Uninfested Coffee from Shaded and Open Environments



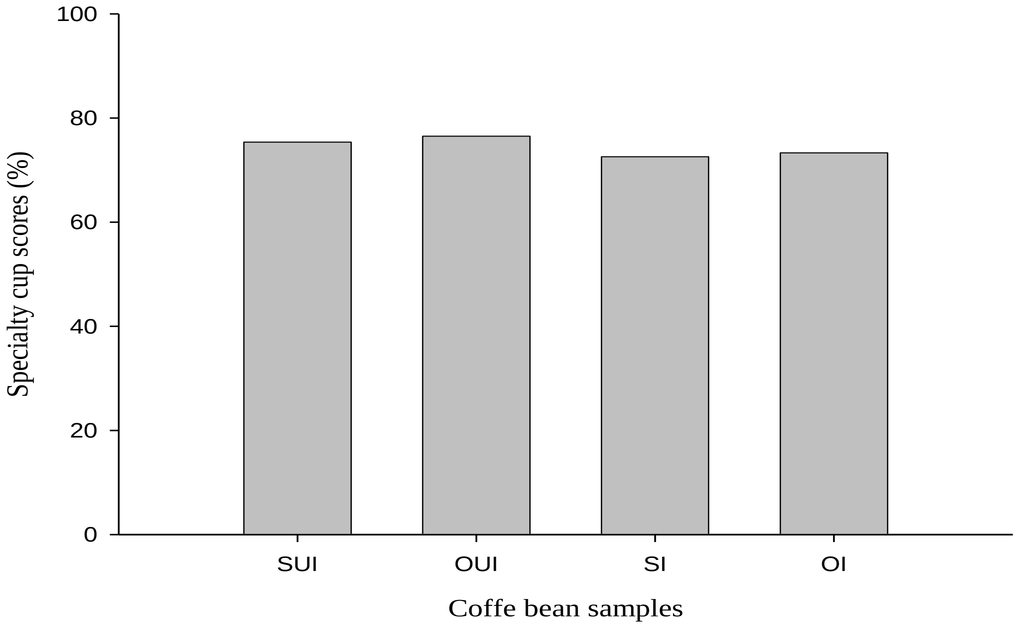
Parchment dry weight did not differ significantly among the four coffee categories (one-way analysis of variance, $F = 0.81$, $P = 0.49$). Green-bean dry weight also did not differ significantly ($F = 0.82$, $P = 0.49$).

Although earlier studies have reported larger beans under suitable shade (Geromel et al., 2008; Muschler, 2001; Vaast et al., 2006), the present sample did not provide evidence of a dry-weight difference.

Sensory Quality

Ten farm samples were evaluated for fragrance, acidity, flavour, body and aftertaste. Figure 8 presents the resulting cup scores.

Figure 8: Specialty Cup Scores for Infested and Uninfested Coffee from Shaded and Open Environments

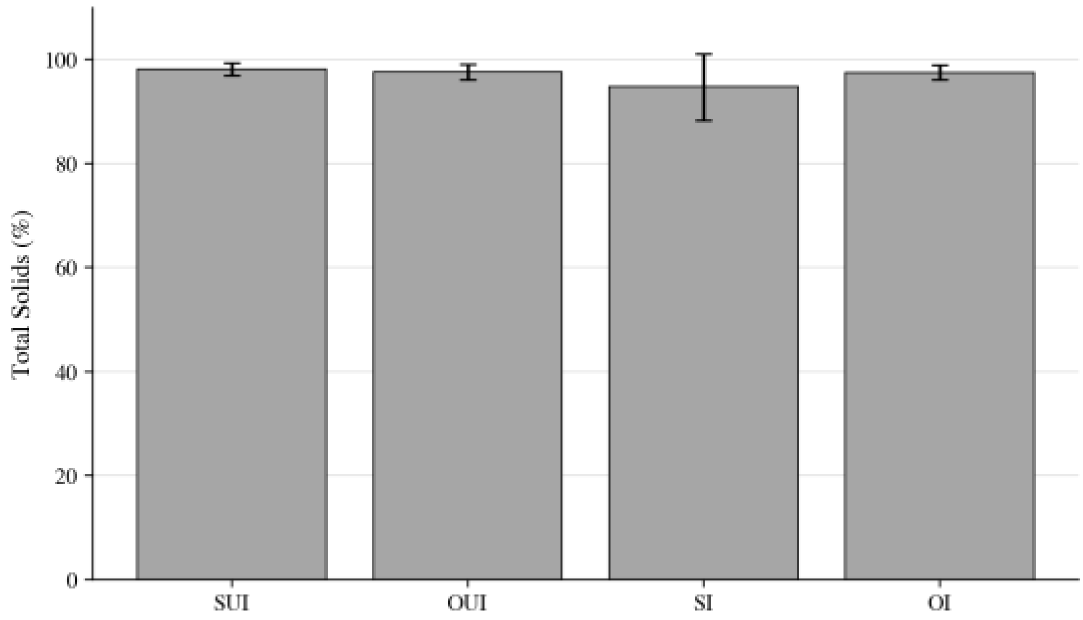


Scores were tightly clustered at approximately 73-77. Under the classification in Appendix 1, the uninfested samples fell in the usual-good-quality band, while the infested samples were near the average/usual-good threshold. None reached the premium threshold of 80. The narrow range suggests limited sensory separation among categories and supports cautious interpretation of shade and infestation effects.

Total Solids

Total solids were marginally higher in shaded than open uninfested coffee, but the pattern reversed among infested samples. Pairwise shaded-open differences were not statistically significant (Table 1 and Figure 9). The large standard deviation in shaded infested coffee was driven by one low replicate and reduced precision.

Figure 9: Total Solids in Infested and Uninfested Coffee from Shaded and Open Environments



Conclusions

Six commonly retained shade-tree groups were documented in Kapchorwa District: Cordia africana, Persea americana, Grevillea robusta, Ficus species, Markhamia lutea and Polyscias fulva. Farmers selected trees for shade together with food, timber, fuel, fodder, soil and boundary functions.

White coffee stem borer infestation was widespread in both shaded and open coffee. The shaded environment had a slightly higher descriptive incidence, but the study design and available analysis do not establish that shade caused the difference. Chemical quality measures varied by both shade and infestation status, and no shaded-open pairwise comparison for caffeine, acidity or total solids was significant. Dry weight also did not differ among categories, while sensory scores remained within a narrow low-to-mid-70s range.

The findings do not support indiscriminate removal of shade trees. They instead support integrated management that combines species selection, canopy pruning, field sanitation, pest surveillance and sound harvest and post-harvest practices. Interpretation should account for the limited number of laboratory replicates and the absence of a farm-clustered multivariable analysis.

Recommendations

Farmers should retain useful shade trees but manage crown density through regular pruning so that canopies do not create persistently dense, humid conditions. The locally proposed target of approximately 40% canopy cover should be tested by altitude and species before being adopted as a uniform prescription.

Indigenous and locally adapted species such as Ficus species, Cordia africana, Polyscias fulva and suitable Albizia species should be prioritised where their rooting patterns, canopy form and household benefits are compatible with coffee.

Cordia africana can provide shade, fodder and readily decomposed litter, but its crown should be pruned seasonally to prevent excessive shade and competition.

Grevillea robusta may be retained for light shade, timber and fuelwood, preferably along boundaries or at appropriate spacing, with regular crown management and monitoring for competition during dry periods.

Because coffee price depends strongly on quality, farmers should harvest only ripe cherries, keep samples off bare soil, standardise fermentation and drying, and store parchment at safe moisture levels.
Further research should use replicated, species-specific shade treatments; measure canopy cover, temperature, humidity and altitude; analyse farms as clusters; and follow borer incidence, yield and cup quality across seasons.

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