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Monitoring Coffee Leaf Rust (*Hemileia vastatrix*) on Commercial Coffee Farms in Hawaii: Early Insights from the First Year of Disease Incursion

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Abstract: Coffee leaf rust (CLR, *Hemileia vastatrix*) is considered the most damaging coffee disease worldwide, causing reduced yields and even plant death. CLR was detected in Hawaii for the first time in 2020, and quickly spread across the state. We initiated a CLR monitoring program in Kona, West Hawaii Island, to track the spread of this new invasive disease across a broad elevational gradient. The goals of the program were to assist growers in the early detection of CLR, to characterize patterns of disease incidence across the region, and to collect information on farm agronomics, management practices, and costs to apply fungicides, all of which can be used to develop Integrated Pest Management (IPM) strategies for this pathogen. We monitored 30 coffee lots in Kona, located between 204 and 875 m elevation. Average CLR incidence remained below 4% early in the season and increased to 36% during harvest. We observed no significant difference in CLR incidence between low-, mid- and high-elevation farms. A significant reduction in the number of leaves per branch was observed at the end of the harvest season, and a significant negative correlation was found between the number of leaves per branch and maximum CLR severity. Mean disease incidence and mean severity were observed to have a significant positive correlation. Incidence increased above threshold levels (5%), despite most growers applying preventative fungicides 3–10 times throughout the season, suggesting that improved coverage and timing of applications is needed along with the addition of systemic fungicides. Our study provides the first insights into CLR disease patterns under the unique and variable conditions under which Hawaiian coffee is grown, and will aid in the development of IPM programs that can be used to sustain Hawaii's coffee industry under this new threat.

Keywords: agroecosystem; *Coffea arabica*; cultural control; defoliation; disease incidence; fungicides; integrated pest management; plant pathogen; resistant varieties; severity



Citation: Aristizábal, L.F.; Johnson, M.A. Monitoring Coffee Leaf Rust (*Hemileia vastatrix*) on Commercial Coffee Farms in Hawaii: Early Insights from the First Year of Disease Incursion. *Agronomy* **2022**, *12*, 1134. <https://doi.org/10.3390/agronomy12051134>

Academic Editors: Mario Contarini, Angelo Mazzaglia, Roberto Mannu and Luca Rossini

Received: 14 April 2022

Accepted: 5 May 2022

Published: 8 May 2022

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1. Introduction

Hemileia vastatrix Berk & Broome is the most devastating plant pathogen affecting coffee crops worldwide [1,2]. This fungus is an obligate parasite that attacks the leaves of coffee, causing reduced photosynthesis, defoliation, and yield losses. Symptoms of the disease, referred to as coffee leaf rust (CLR), first appear as yellow spots on the upper leaf surface, which then enlarge over time and form lesions on the lower leaf surface capable of producing 300,000 spores over a period of 3–5 months [3]. Spores are dispersed across the landscape by wind, vehicles, people, and animals [4,5]. The high dispersibility and virility of spores, and the subsequent need to manage the disease year-round with good agronomic practices and fungicides, make CLR particularly difficult to control. Under favorable environmental conditions, CLR can cause high levels of defoliation, resulting in yield reductions of more than 70%, and even plant death [6].

CLR was first reported in the Hawaiian Islands in October 2020 on the island of Maui, and in November 2020 on Hawaii Island [7,8]. The disease quickly spread and

was detected on the neighboring islands of Lanai in December 2020, Oahu in January 2021, Molokai in June 2021, and Kauai in July 2021. Most of the 3000 ha of planted coffee in Hawaii are CLR-susceptible cultivars including Typica, Bourbon, Caturra, Catui and Geisha. A recent network analysis using simple sequence repeats (SSRs) from CLR isolates collected in Hawaii and 17 other countries suggests that the CLR found in Hawaii most likely originated in Central America or the Caribbean [9]. The same study also examined global wind patterns in the months preceding the introduction of CLR to Hawaii and found that the predominant winds to the archipelago were from North America or from storms that developed in the Pacific Ocean, making long-distance wind dispersal to the islands unlikely; a more plausible scenario involves the introduction of CLR to Hawaii on the clothing or other materials brought with migrant workers or travelers from Central America [9].

The Hawaii coffee industry is small relative to other producing regions but has an excellent reputation on the world specialty market due to the high quality of beans grown in the islands. Coffee is one of the most economically important crops in the state, with a value of \$113 M estimated for green (unroasted) coffee alone [10]. CLR threatens the viability of Hawaii's coffee industry and the many families, communities and small businesses that rely on the crop for their livelihood. In response to this new incursion, we initiated a CLR monitoring program in the Kona coffee-growing district on the island of Hawaii. Kona was one of the first areas to plant coffee commercially in the state, with a long history of coffee agriculture dating back to 1828. This region is comprised of ~800 small, mostly family-owned farms that rely on manual labor to manage and harvest coffee planted on the rocky volcanic terrain.

Monitoring is widely recognized as a key practice for successfully managing crops and is essential for timing spray applications to control major pests, such as coffee berry borer (CBB) in Hawaii [11,12]. Monitoring of CLR in other countries has allowed for disease characterization under local weather and socioeconomic conditions so that resources may be targeted to maximize control and minimize chemical inputs [1,13–15]. The goals of our monitoring program in Hawaii were to assist growers in the early detection of CLR, to characterize patterns of disease incidence across the region, and to collect information on farm agronomics, management practices, and the costs associated with CLR control, all of which can be used to develop IPM strategies for this pathogen.

2. Materials and Methods

2.1. CLR Incidence, Severity and Defoliation

Thirty commercial coffee lots (1–3 acres) in the Kona district of Hawaii Island (Figure 1) were surveyed for CLR from late December 2020–December 2021. Six survey rounds were conducted at roughly 60-day intervals for each coffee lot throughout the year. A standardized methodology was established for conducting CLR surveys of incidence and severity in Hawaii [16]. Coffee trees were randomly selected in a zig-zag pattern across each lot. For small lots (<1.5 acres), 15–19 trees were surveyed, and for large lots (>1.5 acres), 20–25 trees were surveyed. In each coffee tree, two branches were randomly selected: one from the lower-canopy and one from the mid-canopy. For each branch, the total number of fully developed leaves and the number of leaves showing CLR symptoms (yellow lesions with sporulation) were counted (Figures 2 and 3). The incidence of infection (%) was calculated as the total number of infected leaves divided by the total number of leaves examined and multiplied by 100. From a subset of seven farms, CLR severity was estimated by collecting one random infected leaf per surveyed tree and taking a photograph of the underside of the leaf with a ruler for scale. Leaves were then scored for severity in the program ImageJ [17] by using the threshold function to calculate the total area of the leaf and the area of the leaf covered by CLR lesions. The severity (%) of infection was calculated as the infected area divided by the total leaf area and multiplied by 100.

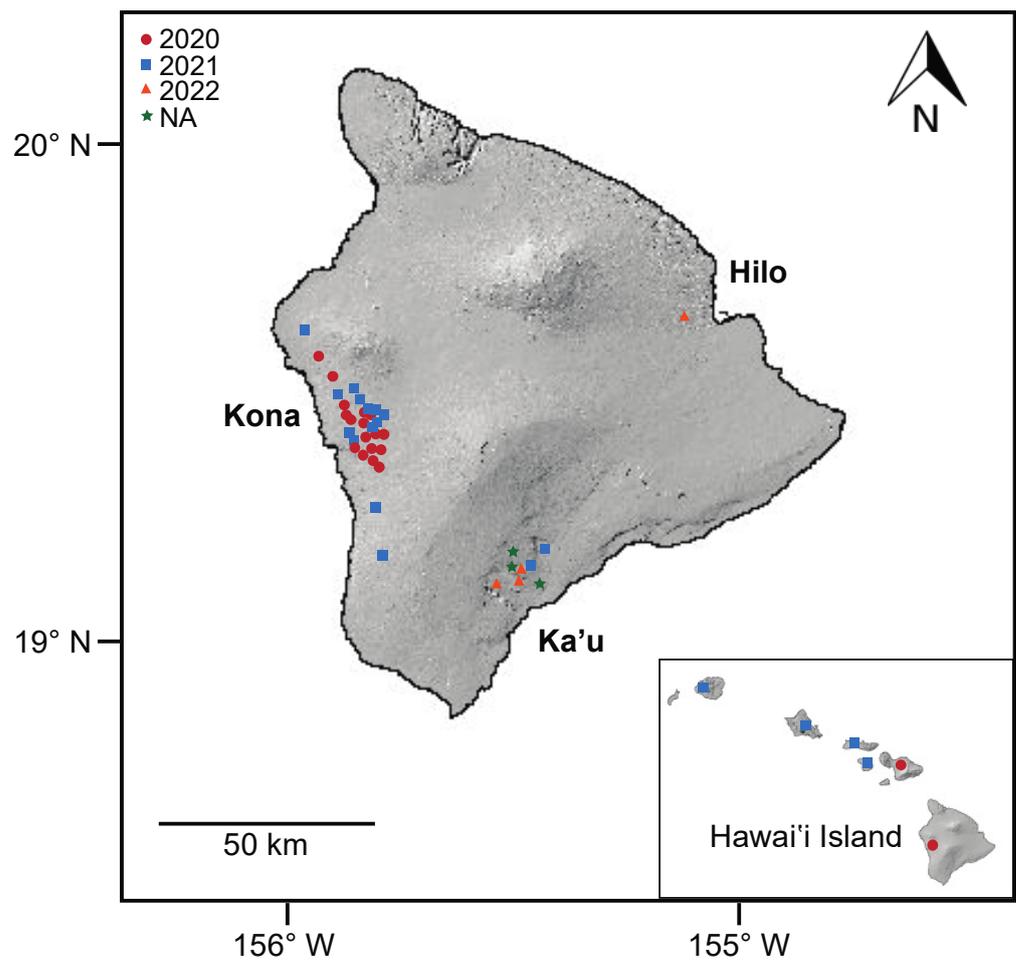


Figure 1. Map of Hawaii Island showing positive coffee leaf rust (CLR) detections on surveyed commercial coffee farms across the growing regions of Kona, Ka'u and Hilo. Colored symbols refer to the year that CLR was detected (see top left legend); “NA” means that CLR has not yet been detected on these farms. Inset map shows location of Hawaii Island within the Hawaiian archipelago and the spread of CLR up the island chain.



Figure 2. Symptoms of CLR infection on the upper leaf surface: initial infection with a single yellow lesion (A); as the disease progresses multiple lesions appear (B); advanced infection with many yellow lesions and tissue necrosis (C). Photos by Luis F. Aristizábal.



Figure 3. Symptoms of CLR infection on the lower leaf surface: active sporulation seen as powdery orange lesions (A); as the disease progresses severity increases, and tissue necrosis occurs (B). Photos by Luis F. Aristizábal.

2.2. Identification and Management Recommendations

During surveys, growers were shown how to identify CLR in their fields and best practices to prevent and control the disease were discussed. Given that this is a new disease in Hawaii, there are no specific recommendations for controlling CLR under Hawaii's unique conditions. Recommendations were therefore based on research and extension publications from other coffee-producing regions around the world that have experience dealing with CLR [1,18–20]. Standard cultural and chemical control practices including weed management, application of fertilizers, pruning, regulation of shade trees, and sprays of preventive fungicides were recommended. Preventive fungicides containing copper (copper hydroxide and copper oxychloride), or strains of *Bacillus* (*B. subtilis* and *B. amyloliquefaciens*) were available to coffee growers in Hawaii from the start of the outbreak [21]. A systemic fungicide (Priaxor® Xemium®, BASF, Florham Park, NJ, USA; fluxapyroxad + pyraclostrobin) was later approved for Hawaii coffee (May 2021), but with several restrictions including a pre-harvest interval of 45 days, a 25-foot buffer between fields, and notification of Hawaii Department of Agriculture (HDOA) 10 days before application of the product [21]. Protocols for sanitation and disinfection of clothing, shoes, vehicles, and tools [22] were followed during all surveys and recommended to growers to prevent the spread of CLR within and among farms. The execution of these practices and the application of fungicides was at the discretion of each coffee grower.

2.3. Cost of Fungicide Applications

To calculate the cost of applying fungicides to control CLR on commercial coffee farms in Hawaii, management and harvest information was collected from a subset of seven coffee farmers. Estimates were based on the cost of fungicide products (product type and rate of application), labor (hourly wage, trees/acre, and method of application) and coffee production (lbs of cherry per acre), with a market value of USD 2.40 per lb of cherry (prices for 2021 coffee season in Kona, Hawaii).

2.4. Data Analysis

Descriptive analyses were conducted to estimate mean CLR incidence, mean and maximum CLR severity, and the mean number of coffee leaves per branch for each lot across the sampling period. Proportions were arc-sin transformed prior to analysis. Data was assessed for normality using a Shapiro–Wilk test, and equal variances were assessed using an *F*-test. A comparison of mean CLR incidence for coffee lots located at low (200–400 m), mid- (401–600 m) and high (601–900 m) elevations was conducted using a Kruskal–Wallis for non-normal data. Mean CLR incidence on low vs. mid branches was examined using a paired Wilcoxon test. Defoliation was assessed by conducting a paired *t*-test on the mean number of leaves per branch at the end of the harvest season for 2020

(pre-CLR) and 2021 (post-CLR). Finally, a Kendall's rank correlation test was conducted to describe the relationship between 1) mean CLR incidence and mean CLR severity, and 2) maximum CLR severity and the mean number of leaves per branch. All statistical analyses were done using the stats package in R v. 3.5.2 [23].

3. Results

3.1. Farm Characteristics

Coffee farms were highly variable in terms of agro-ecological conditions and management (Table 1). Farms spanned across a ~30 mile stretch of the Kona coffee-growing region and ranged from 204–875 m a.s.l. (Figure 1, Table 1). The coffee varieties planted in surveyed lots were *Coffea arabica* var. Typica and Caturra, both of which are susceptible to CLR. Planting density ranged from 450–1500 trees/acre, and the age of trees ranged from 3–100+ years old. Most coffee lots were planted in full sun, while only 30% of lots had various tropical fruit, macadamia nut, or native/non-native trees inter-planted with the coffee. The majority of lots used conventional management, while only 23% of lots followed organic practices.

Table 1. Agronomic and management characteristics for 30 coffee lots located in the Kona district of Hawaii Island.

Farm Location	Elevation (m)	Variety ¹	Density (Trees/ac)	Age (yrs)	Shade Trees	Management ²	Fungicide ³
Honaunau	204	T	1200	40	Yes	C	P
Honaunau	285	T	450	70	Yes	C	P, S
Kealakekua	305	T	900	20	No	C	P
Napo'opo'o	316	T	600	19	Yes	C	P, S
Holualoa	366	T, C	900	20	No	C	P, S
Holualoa	375	T, C	900	20	No	C	P, S
Holualoa	426	T	500	50	No	C	P
Honaunau	434	T	900	50	No	C	P, S
Kealakekua	442	T	900	25	No	C	P
Holualoa	454	T	450	20	Yes	C	P
Capt. Cook	457	T	700	50	Yes	O	P
South Kona	457	T	850	50	Yes	C	P, S
Capt. Cook	457	T	700	50	Yes	O	P
Honaunau	454	T	500	25	No	C	P
Capt. Cook	488	T	650	50	No	O	P
Capt. Cook	549	T	800	3	No	O	P
Kealakekua	564	T	900	20	No	C	P
Kealakekua	564	T	800	3	No	C	P
Kealakekua	570	T	800	3	No	C	P
Kealakekua	594	T	800	3	No	C	P
Capt. Cook	607	T	650	100	Yes	C, O	P
Kealakekua	610	T	800	4	No	C	P
Kealakekua	623	T	800	4	No	C	P
Capt. Cook	640	T	900	6	No	O	P
Capt. Cook	640	T	700	50	Yes	O	P
Kealakekua	715	T	800	4	No	C	P
Kealakekua	725	T	800	4	No	C	P
Kealakekua	867	C	1500	3	No	C	P
Kealakekua	869	T	900	5	No	C	P
Kealakekua	875	C	1500	3	No	C	P

¹ T: Typica, C: Caturra; ² C: Conventional, O: Organic; ³ P: Preventative, S: Systemic.

3.2. CLR Incidence, Severity and Defoliation

Across all 30 lots, mean CLR incidence remained $\leq 4\%$ (range = 0–34%) early in the season (January–June) and increased to 36% (range = 0–77%) during the peak harvest (September–December). A four-fold increase in average incidence was observed from

July–August at the start of the coffee harvest. We observed no significant difference in CLR incidence between low-, mid- and high-elevation farms from January–June ($X^2 = 3.00$, $df = 2$, $p = 0.22$) (Figure 4). During the peak harvest, mid- ($n = 14$) and high- ($n = 10$) elevation farms had higher mean incidence relative to low-elevation farms ($n = 6$), although this result was not significant due to the lower sample size for low-elevation lots ($X^2 = 4.75$, $df = 2$, $p = 0.09$) (Figure 4). The mean incidence across the entire season was 7.16% at low-elevation lots, compared to 17.79% and 17.80% at mid- and high elevations, respectively. Within trees, branches in the lower canopy were found to have significantly higher mean CLR incidence relative to mid-canopy branches ($t = 2.95$, $df = 205$, $p = 0.002$). We also observed a significant reduction in the number of leaves per branch at the end of the 2021 harvest season compared to that of the 2020 season ($t = 3.84$, $df = 29$, $p < 0.001$). A significant positive correlation was found between mean disease incidence and mean severity ($z = 7.26$, $p < 0.001$, $\tau = 0.60$). In contrast, a significant negative correlation was found between maximum CLR severity and the number of leaves per branch ($z = -3.87$, $p < 0.001$, $\tau = -0.32$) (Figure 5).

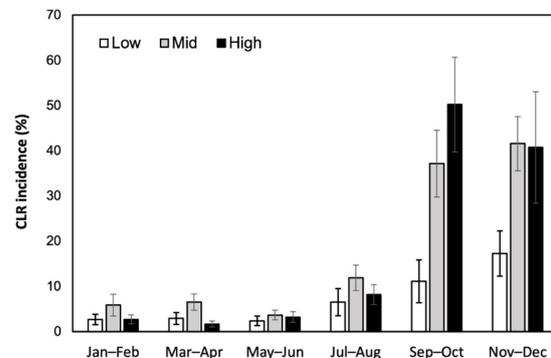


Figure 4. Mean CLR incidence across low- (200–400 m), mid- (401–600 m), and high-elevation (601–900 m) coffee lots in Kona from January–December 2021. Although a trend of lower incidence at low elevations was observed at the end of the season, this difference was not significant due to uneven sample size.

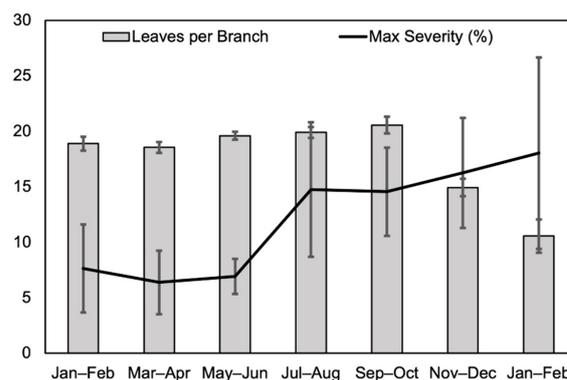


Figure 5. Mean number of leaves per branch as a measure of defoliation, and maximum CLR severity for commercial farms in Kona from 2021–2022. Maximum severity peaked at the end of the harvest, while the mean number of leaves per branch fell by ~50%.

3.3. Management of CLR

Of the 30 coffee lots monitored, 29 applied preventive fungicides 3–10 times during the 2021 season to protect coffee leaves and prevent the germination of CLR spores. Commercially available fungicides based on copper (Kocide[®] 3000, Certis Biologicals, Columbia, MD, USA; Badge[®] X2, Gowan Company, Yuma, AZ, USA) and *Bacillus* strains (Serenade ASO, Bayer CropScience, Clayton, NC, USA; Double Nickel 55, Certis Biologicals, Columbia, MD, USA) were commonly used by farmers, with the systemic fungicide

(Priaxor[®] Xemium[®], BASF, Florham Park, NJ, USA) applied 1–2 times on 20% of the lots. Hydrogen Dioxide + Peroxyacetic Acid (OxiDate[®] 2.0, BioSafe Systems, East Hartford, CT, USA) was applied on 43% of lots for initial knockdown and suppression of CLR hotspots of infection. Foliar fertilizers containing minor elements that support the health of coffee trees were added to many of the tank mixtures along with fungicides. The entomopathogenic fungus *Beauveria bassiana* (commercially available as BotaniGard[®] ES, Bioworks Inc., New York, NY, USA; used to control the coffee berry borer *Hypothenemus hampei*) was also occasionally added to compatible fungicides to reduce labor costs.

Sanitation pruning to remove branches and trees that were severely infected by CLR was done on 27% of lots during the season. Regulation of shade from other tropical trees (mango, avocado, macadamia nut, banana, monkeypod, etc.) interplanted with coffee was done in 50% of shaded lots to improve air-flow and increase solar radiation, which can help to suppress CLR germination. Weed control was done using a combination of manual labor and/or herbicide applications on all lots. Harvesting started in late July at low-elevation coffee lots and late August–early September in mid- and high-elevation coffee lots, with most lots harvested four times throughout the season. In response to high CLR incidence and severity, 30% of lots were subjected to heavy pruning and/or stumping following the last harvest. This cultural practice is conducted to remove all infected foliage and allows the growth of new leaves.

3.4. Cost of Fungicides to Control CLR

Across the subset of seven lots used to estimate control costs, fungicide was applied 3–10 times during the 2021 season to prevent and suppress CLR (Table 2). In the beginning of the year, five lots added BotaniGard[®] ES (Bioworks Inc., New York, NY, USA; used for CBB control) to tank mixtures along with compatible fungicides (Serenade ASO, Bayer CropScience, Clayton, NC, USA; or Kocide[®] 3000, Certis Biologicals, Columbia, MD, USA). However, we limited our cost analysis to include only products used to control CLR. Four lots used a backpack sprayer, while three lots used an air blast sprayer mounted on a tractor (Figure 6). The cost of fungicide products ranged from USD 90–472/acre, while the cost of labor (USD 15–20/h using a backpack sprayer, USD 40/h using a tractor sprayer) to spray fungicides ranged from USD 210–520/acre. The cost to monitor CLR across the entire season was USD 150–175 based on 6–7 CLR surveys at a cost of USD 25/h. For the full coffee season, the total cost to manage CLR ranged between USD 450–1167 per acre (0.4 ha). Production per acre ranged from 3888–11,312 lbs of coffee cherry, which was sold for an average of USD 2.40/lb, resulting in profits of USD 9331–27,149 per acre. The total estimated cost for CLR management using fungicides on these coffee lots ranged from 2.07–10.58% of the total profits per acre.



Figure 6. Spray application of fungicide using an air blast sprayer mounted on a tractor (A) and a backpack sprayer (B). Spraying with a tractor provides effective coverage of the foliage but requires wider row spacing and flat terrain. Backpack sprayers are more difficult to use effectively and can be more costly in terms of labor and time but are necessary on many farms in Kona where the terrain is steep and rocky, and trees are planted close together. Photos by Luis F. Aristizábal.

Table 2. Information used to calculate costs to manage CLR during the 2021 season for seven commercial coffee lots on Hawaii Island. Total cost to manage CLR per acre was based on the number of fungicide sprays and the combined cost of products (excludes cost of *B. bassiana* used for CBB management), labor (backpack sprayer: USD 15–20/h, tractor sprayer: USD 40/h) and monitoring (USD 25/survey). Estimates for profit/acre (USD) were based on yield/acre (lbs) and a market value of USD 2.40/lb for coffee cherry. The final cost was estimated as the percentage of total profits per acre spent to manage CLR.

Coffee Lot	Spray Method	Fungicide Sprays	Fungicide Cost/Acre (USD)	Labor Cost/Acre (USD)	Monitoring Cost/Acre (USD)	Total Cost/Acre (USD)	Yield/Acre (lbs)	Profit/Acre (USD)	CLR Cost/Acre (%)
1	Backpack	10	417	495	150	1062	4183	10,039	10.58
2	Backpack	10	472	520	175	1167	5033	12,079	9.66
3	Tractor	7	255	315	150	720	10,000	24,000	3.00
4	Backpack	6	220	480	150	850	3888	9331	9.11
5	Backpack	3	90	210	150	450	4500	10,800	4.17
6	Tractor	6	142	270	150	562	11,312	27,149	2.07
7	Tractor	6	155	240	150	545	8257	19,817	2.75

4. Discussion

4.1. CLR Dispersal on Hawaii Island

In the present study, our surveys of commercial coffee lots revealed insights into the direction and timing of CLR dispersal across Hawaii Island. When surveys were first initiated in December 2020/January 2021 (just one month after the initial detection in Kona), 64% of commercial lots surveyed from across the Kona coffee-growing region were already CLR-positive; this number increased to 80% by March, 87% by June, and 100% by November 2021. CLR was detected in Hawaii Island's other major coffee-growing district of Ka'u (Southeast Hawaii Island; Figure 1) just 11 months (September 2021) after it was detected in Kona (M. Johnson, pers. obs.). We estimate that 70% of the farms in the Ka'u district are now infected. On the East side of Hawaii Island, the first detection in a commercial coffee farm was in February 2022 (M. Johnson, pers. obs.). The rapid spread of CLR across the entire coffee-growing landscape of Hawaii Island within a single year demonstrates the high dispersibility and adaptability of this disease, despite the efforts of coffee farmers to apply protective, and in some cases systemic, fungicides. Our findings provide important insights into the first CLR epidemic in Hawaii.

4.2. Patterns of CLR Incidence and the Incidence-Severity Relationship

During the first half of the season, mean CLR incidence was low (<4%) in 93% of surveyed coffee lots in Kona. However, the situation changed dramatically coming into the harvest season. From July–August, mean incidence increased to 9%, and from September–December the mean CLR incidence across Kona was 36%. The association between harvest and increases in CLR incidence have been described in other regions, as infected trees show a weakened physiological response due to resources being directed into fruit production instead of disease resistance [24–26]. Some of the worst CLR epidemics in Brazil have been reported during years of high yield, with incidence reaching 90% in susceptible varieties when environmental conditions are favorable to spore development [1]. After the harvest, disease intensity decreases due to cooler temperatures and leaf loss; CLR incidence the year following an epidemic is typically <25% because of low production [1]. Our observations in Kona seem to fit the scenario for a high-yielding year, with a 17% increase in coffee cherry production for the 2021–2022 season compared to the previous season (26.7 M lbs vs. 22.7 M lbs) [10]. In line with observations elsewhere for high yielding years, we also saw CLR incidence peaking at harvest and then declining at the start of the new season, likely due to a combination of leaf loss and cooler, drier conditions. Studies are currently underway to elucidate the relationship between variables such as temperature,

humidity, rainfall, leaf wetness and solar radiation and the development of CLR symptoms in Hawaii.

We also found a positive correlation between mean CLR incidence and mean severity across all farms. As CLR incidence increased throughout the year, so did severity, although it remained considerably lower than incidence. For the subset of seven farms that we investigated, mean CLR incidence across the entire year averaged 20% while mean CLR severity averaged only 3%. Similar trends have been reported in several other studies on CLR [27–30], wherein incidence may be quite high, but severity remains low.

Given that the estimation of severity is time consuming and prone to error (particularly if using scales to visually estimate), several studies have sought to investigate incidence–severity relationships for CLR [27,31,32]. A strong positive relationship between these variables would indicate that incidence, which can be quickly estimated with greater precision, could be used to infer severity, particularly for chemical control programs and host resistance programs that often rely on severity thresholds. Silva-Acuña et al. [27] found a strong positive relationship between incidence and two measures of severity (leaf area with rust and average sporulating pustules per leaf, $R^2 = 0.87–0.97$) at two locations in Brazil over a period of three years, suggesting that incidence can be used to estimate both measures of severity. Although the correlation between incidence and severity was not as strong in the present study ($R^2 = 0.60$), our data implies that a similar relationship exists in Hawaii; additional data are needed to determine if this relationship holds over multiple years.

4.3. CLR Incidence across an Elevational Gradient

We found no significant difference in CLR incidence among coffee lots located at low (200–400 m), mid- (401–600 m) and high (601–900 m) elevations, suggesting that environmental factors are generally not limiting to CLR survival and germination on commercial farms in Hawaii. Although we observed increased CLR incidence during the end of the year (harvest season) at mid- (37–42%) and high- (41–50%) elevation lots relative to low-elevation lots (11–17%), this trend was not statistically significant due to uneven sample sizes. Future studies should include a larger number of low elevation farms and data for multiple years to determine if these farms have consistently lower CLR pressure relative to mid and high elevation farms.

Our finding of increased CLR incidence at higher elevations contrasts with that reported in other studies. Bigirimana et al. [29] found a significant negative correlation between CLR severity and elevation in Rwanda. In Southwest Ethiopia, Daba et al. [25] reported higher CLR incidence at low elevations compared to high elevations. Leibig et al. [33] observed reduced CLR infection at high elevations in comparison with mid- and low elevations in Uganda. Similar observations were made by Belachew et al. [34] in a large-scale survey across Ethiopia; however, additional factors aside from altitude appeared to contribute to higher CLR infection at low elevations, including less diversification (plantation systems), more unmanaged farms, and the planting of more CLR-susceptible varieties in comparison to farms at higher elevations. Differences in our findings relative to these studies may be explained by variation in microclimate due to altitudinal differences (e.g., our highest elevations were <900 m, while the lowest elevations sampled in previous studies elsewhere were >1000 m), more pronounced seasonal changes in other countries relative to Hawaii, as well as differences among coffee agroecosystems and management practices, all of which affect the development of CLR [35].

4.4. Defoliation and the Correlation with CLR Severity

We observed significantly fewer leaves per branch at the end of 2021 (post-CLR) compared to that observed in late 2020 (pre-CLR). For the 19 lots that showed a decrease in the number of leaves per branch, an average of 6.84 leaves were lost (35% decrease). On a subset of seven lots, a correlation analysis on maximum severity and the number of leaves per branch revealed that these variables have a significant negative correlation, such that as

maximum severity increased on a given lot, the number of leaves per branch decreased. During the first half of the season, the average maximum severity ranged from 7–10%, and then steadily increased over the second half of the season, peaking at 18% in December. Defoliation did not become apparent until the end of harvest (November–December) on most lots; on the subset of seven lots, we observed that defoliation continued into January–February (Figure 7). Similar results have been reported in India, with defoliation closely linked to severity, and both severity and defoliation increasing into the harvest [36]. We also observed significantly higher CLR incidence on low vs. mid-canopy branches, and this was reflected in the order of defoliation, with lower branches losing leaves first, followed by mid-canopy branches as the infection increased (Figure 7A). Initial defoliation of the lower branches is likely the result of self-shading within trees, which can produce conditions that are ideal for CLR survival and germination by limiting solar radiation and increasing the duration of leaf wetness [24,37]. Defoliation reduces the photosynthetic area of the plant, which directly impacts production, resulting in crop loss and reduced quality of the fruit the year following high levels of infection [35,38]. The reduction of growth potential caused by defoliation also limits the production of new branches and leaves. To mitigate the effects of defoliation and encourage the development of new healthy leaves, growers should sample their soils and leaf tissue to identify any nutrient deficiencies that can be corrected at the start of the season [35].



Figure 7. High levels of defoliation were observed at a farm in Kona with poor agronomic management and inefficient application of preventative fungicides (A), compared to a farm in Kona with good management and efficient applications of preventative and systemic fungicides that ended the season with no defoliation (B). Both photographs were taken in March 2022. Photos by Luis F. Aristizábal.

4.5. Agronomic Characteristics and Cultural Controls

Characteristics of the coffee crop will inevitably affect the management of CLR, with yields, row spacing, type of cultivation system, topography, available labor, weather conditions and costs/benefits all being important considerations. Most of the coffee lots surveyed were comprised of the tall low-yielding variety *Typica*, with only two lots having the dwarf higher-yielding *Caturra* variety, and two lots being a mixture of these varieties. Both are considered to have very high susceptibility to CLR; we did not observe any obvious differences in terms of incidence or severity between these two varieties, although studies are needed to determine if different varieties have varying levels of susceptibility under Hawaii's unique growing conditions. Of the 30 lots surveyed, 43% had trees that were between 21–100 years old. Ehrenbergerová et al. [39] found that coffee plant age was the second most important factor (after variety) in explaining patterns of CLR incidence in Costa Rica; the critical age at which infection increased appeared to be 15–20 years old for the *Catimor* variety.

Plantations with high planting density have also been shown to have higher CLR incidence [39–41]. High plant densities can promote the survival and germination of spores by increasing self-shading and humidity, as well as promote the spread of CLR within a

plot by increasing contact between leaves [42–44]. A wide range in planting density was observed in the present study with 450–1500 trees/acre; 20 out of the 30 lots examined had a higher planting density compared to what is commonly considered optimal for var. Typica (725 trees/acre) [45]. Although we did not attempt to estimate shade levels, only 30% of lots had shade trees interplanted with the coffee. Shade has been found to have varying effects on CLR. Heavy shade can increase sporulation due to increased duration of leaf wetness [24] or the reduction of spore wash-off by rain [46]. Conversely, shade can reduce fruit load, thereby decreasing the risk of infection [24], as well as promote the growth of beneficial mycoparasites [47] (Figure 8A).

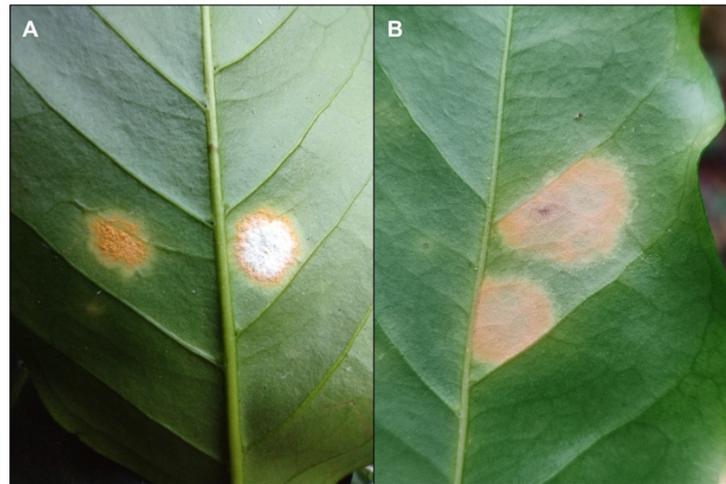


Figure 8. Active sporulation (A, left) and attack of CLR by a mycoparasite (A, right); dried appearance of CLR lesions sprayed with a systemic fungicide (B). Photos by Luis F. Aristizábal.

All growers implemented a combination of cultural control practices including pruning, weed management, and fertilization. The proper implementation of these cultural controls together can reduce CLR incidence and severity while facilitating chemical controls. Pruning was done at the start of the new coffee season (January–March) on all lots, with some farms implementing the Kona-style of pruning (verticals of multiple ages) and others conducting Beaumont-Fukunaga pruning (multiple same-age verticals renewed every 3–5 years). All lots also controlled weeds using either herbicide or manual removal, but the frequency varied greatly depending on the weather and availability of labor (some monthly, some only several times per year). All growers applied fertilizer, although the methods (broadcast by hand, foliar feed by tank, fertilize by irrigation), amount, products and frequency varied widely. Further studies are needed to collect more detailed information on cultural control practices and agronomic characteristics to determine optimal management strategies for CLR in Hawaii.

4.6. Chemical Controls and Associated Costs

Preventative fungicides were applied on all but one lot, while systemic fungicides were applied on six lots (Figure 8B). Given that systemics were applied on so few farms, and that there were notable differences in methods and timing of application, we were not able to compare the efficacy of various fungicide regimes among farms. There are many considerations for applying fungicides that growers must consider for chemical controls to be effective in disrupting the host–pathogen cycle. Much work remains to be done to determine the optimal products, timing, dosage, frequency, and rotation schedule for fungicide use in Hawaii. In addition, growers will have to carefully consider the application technology used to apply contact and preventative products to ensure that good coverage is obtained on both sides of the leaves (Figure 6). This will be particularly challenging for Hawaii farms that are located on rocky steep terrain and are thereby limited to the use of backpack sprayers. Weather conditions must also be carefully considered, as high

temperatures and rain can compromise spraying efficiency; in Brazil, it is recommended that sprays be conducted in the late afternoon or early evening to avoid the hottest hours of the day and an adjuvant added to ensure longer protection [20]. The number of applications and interval times between sprays are also dependent on weather, plant nutrition, planting density, fruit load, and pruning. It is likely that the interaction of these factors, along with issues such as improper dosage, frequency, timing, and coverage, contributed to the high CLR incidence observed across Kona in 2021. Additionally, infection rates on some farms were at or above the 5% threshold (often used as a baseline for spraying fungicides) prior to the initiation of monitoring. Research in Brazil has shown that the efficacy of fungicides is diminished after the onset of symptoms [20], highlighting the importance of monitoring to aid in early detection, as well as to determine the efficacy of fungicide sprays (Figure 8B).

In addition to the logistical considerations for spraying fungicides, the costs of chemical control must be properly estimated such that they include products, labor, and monitoring. In the present study, the three farms that used tractor sprayers had an average cost of USD 91–103 per spray, compared to the four farms that used backpack sprayers at an average cost of USD 106–150 per spray. Additionally, farms that used tractor sprayers had higher yields relative to the farms that used backpack sprayers, such that the final cost to apply fungicides was considerably smaller for farms that used tractor sprayers (2–3% of profits vs. 4–11% of profits). It is important to point out that the slope and terrain on most farms in Kona prohibit the use of tractors and will require the use of manual sprayers, while most farms in Ka'u have terrain and row spacing that will allow mechanized spraying. Growers in Kona may therefore be limited in their ability to use chemical controls, and this will increase the need for resistant cultivars.

5. Conclusions

In the present study, we observed the rapid spread of CLR across multiple growing regions on Hawaii Island. Our surveys on commercial coffee farms in Kona revealed an average CLR incidence of 36% during the 2021 harvest season, followed by severe defoliation on farms spanning a range of elevations. Consequently, many coffee lots were pruned or stumped across Kona at the end of the 2021 season, and it is likely that high levels of defoliation will result in reduced coffee production during the 2022 season. Although it is difficult to estimate how much yields will decrease in Kona, similarly high incidence (>30%) [48] during the 2008–2013 CLR epidemic in Latin America resulted in a yield decrease of 16% in Central America [6], 31% in Colombia [6], and up to 50% in Brazil [1]. It is possible that similar decreases in yield could be observed in Kona. A combination of many factors, including suitable environmental conditions, the presence of susceptible coffee varieties, old trees planted on thin, nutrient-poor soils at high densities, wide variation in implementation and frequency of cultural and chemical controls, and a lack of knowledge and expertise, all contributed to the first CLR epidemic in Hawaii. Many other factors were associated with the 2008–2013 CLR epidemic in Latin America including climate change (meteorological anomalies, particularly a reduction in diurnal thermal range), socioeconomic conditions, low coffee prices, and inappropriate fungicide applications [6].

Our observation of high incidence and defoliation after just one season of CLR in Hawaii points to the need for CLR-resistant cultivars, since the reliance on fungicides to manage this disease is not a sustainable long-term solution. Cultural control practices (fertilization, pruning, sanitation, control of weeds, regulation of shade trees, etc.) that improve coffee tree health are also essential for reducing CLR pressure. In addition, monitoring CLR incidence is a key practice for establishing a rotational fungicide application program to protect coffee leaves when they are most susceptible to CLR attack (45–180 days after flowering). Despite the use of cultural and chemical controls, disease incidence increased above threshold levels (5%) on most Kona coffee lots. This suggests that improved plant nutrition, proper pruning, wider spacing, consistent weed management and a better under-

standing of optimal timing, frequency, product rotation and coverage of fungicide sprays (preventative and systemic) are needed to keep incidence at manageable levels.

Author Contributions: Conceptualization, L.F.A. and M.A.J.; methodology, L.F.A. and M.A.J.; validation, L.F.A. and M.A.J.; formal analysis, L.F.A. and M.A.J.; investigation, L.F.A. and M.A.J.; resources, L.F.A. and M.A.J.; data curation, L.F.A. and M.A.J.; writing—original draft preparation, L.F.A. and M.A.J.; writing—review and editing, L.F.A. and M.A.J.; visualization, L.F.A. and M.A.J.; supervision, L.F.A. and M.A.J.; project administration, L.F.A. and M.A.J.; funding acquisition, L.F.A. and M.A.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the United States Department of Agriculture—Agricultural Research Service (USDA-ARS), and the Synergistic Hawaii Agricultural Council (SHAC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data supporting this study is deposited in the Dryad Digital Repository.

Acknowledgments: We thank Austin Bloch, Colby Maeda, Jared Nishimoto and Karma Kissinger for their technical assistance with data collection in the field and laboratory. We are grateful to all the growers that allowed access to their fields and provided management records. Thank you to Lisa Keith for developing sanitation protocols for field visits and Arturo Correa for field collaboration. The USDA is an equal opportunity employer.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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