British Society for Plant Pathology

Coffee Leaf Rust

Back with a Vengeance

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Editor Eric Boa

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PLANT PANDEMIC STUDY 5

Short Study Awards

This is one of a series of case studies, sponsored by the British Society for Plant Pathology, on damaging plant diseases which have had – and continue to have – major economic, social and environmental impacts around the world. The case studies provide an historical overview of how scientists have responded to plant pandemics and the evolution and effectiveness of management strategies. The purpose of the reports is to raise awareness of plant pandemics and to stimulate wider interest in their consequences for all, including current and future researchers.

Copies of the report are available from the BSPP | www.bspp.org.uk.

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The report has been edited and formatted by Eric Boa.

Cover photo

Orange powdery spots indicate the distinctive presence of masses of spores of *Hemileia vastatrix*, the fungus that causes coffee leaf rust.

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Foreword

This report has been fuelled by many cups of strong coffee. The chocolatey aromas of freshly ground beans act as a heavenly bouquet awaking our senses. The first taste of liquid gold sparks inspiration before the caffeine kicks in and propels us forward on the tasks ahead. It is difficult to fathom the idea of a coffee-less world, let alone reduce our consumption of it. Yet the ubiquity of coffee in our everyday lives is under constant threat from a plethora of plant pests and diseases.

Coffee leaf rust (CLR) is the oldest documented plant disease on one of the world's most valuable commodity crops. This report describes where the disease came from, how it spread around the world and the damage it has caused. We also look at the success of attempts to control the disease and future prospects for reducing the impact of CLR. Information has been gleaned from the scientific literature and from interviews with colleagues who've worked with coffee leaf rust for many years. The report is aimed at a broad audience. It is a blend of technical information about the disease and *Hemileia vastatrix*, the scientific name of the fungus pathogen that causes CLR, as well as the wider consequences to the many people who rely on coffee to provide an income, often in the poorest countries.

Figure 1.Traditional coffee making in Ethiopia, the centre of diversity of Arabica coffee.

CLR is more than a leaf disease. It has seriously affected cultivation and production of coffee for over a century and a half, defoliating trees and sapping the vigour of coffee plants from Africa to Asia, and more recently in the Americas. Many farmers who rely on coffee as a cash crop have few other viable alternatives. Threats to livelihoods have many other consequences, such as forced migration to search of jobs. It is important that the continuing threat and impact of CLR is recognized and that action is taken by governments, scientists and extension and advisory services to limit those threats and risks.

Figure 2. Danish coffee lovers pay a high price for their daily brew or "liquid gold". Sipping a double espresso shot in one of the Coffee Collective cafés in central Copenhagen cost £3.20 (28 DKK). If you like your coffee on the milky side, then prepare to pay up to £4.90 (43 DKK) for a large café latte. All prices as of 2022.

We start with an historical overview of coffee cultivation and trade in colonial times. We consider the relevance of CLR to coffee production today, with a focus on the Americas, and summarise hypotheses on the cause of recent epidemics. We review old and new options for management of the disease. We also consider the likelihood of a yet undetected alternate host of *Hemileia vastatrix* as an additional piece of the epidemiological puzzle. Finally, we reflect on the interactions between *H. vastatrix* and a changing climate. We hope this report aids the greater coffee community's preparation for the challenges which CLR poses under future production environments.

The Beginning and the End

Coffee was introduced to Ceylon (today's Sri Lanka) in the early 19th century. The hilly slopes of the great western highlands **(Fig. 3)** provided cool and ideal temperatures for cultivation, allowing coffee plants to thrive and the establishment of extensive plantations. From around 1830 to the mid-19th century, coffee production reached its peak and contributed hugely to Ceylon's economy, then under the control of the British, and provided employment to many.

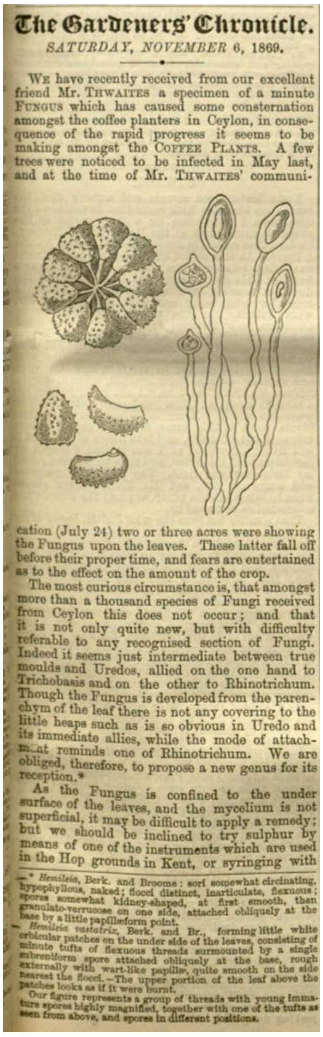
The coffee boom was abruptly cut short by the discovery of a leaf disease in 1869, characterized by orange, powdery patches. Nicknamed by colonial officers as 'Devastating Emily', a moniker derived from its scientific name, and by one British scientist as the 'malaria of coffee' (McCook, 2006), the arrival of Coffee Leaf Rust (CLR) signalled the beginning of the end for coffee production in Ceylon.

Figure 3. *left* Spring Valley coffee estate in Bij Badulla, Ceylon1889. Overhead lines enabled coffee pickers to cope with the steep slopes. *right* Estate workers pounding Ceylon Coffee in the late 1870's.

CLR was first discovered on wild coffee in 1861 by a British colonist, near the shores of Lake Victoria in Kenya. The two main species of coffee, *Coffea arabica* and *C. canephora,* commonly known as Arabica and Robusta, originate from Africa. The south-western highlands of Ethiopia are the centre of diversity of Arabica coffee, while Robusta has a more widespread origin in the lowland forests from Guinea in west Africa to Uganda in the east. CLR is caused by a fungus which is thought to have co-evolved with wild coffee in equatorial Africa. Its first discovery is unlikely to have caused much alarm. Coffee had yet to be grown on a large scale in plantations.

The Ceylon arrival and ruinous spread of the rust dramatically changed this and stimulated studies to understand the cause of the disease and how to manage it. The fungus was given its scientific name, *Hemileia vastatrix*, by the Reverend Berkeley and his colleague Mr Broome in 1869. '*Hemileia*' refers to the semi-smooth surface of the spores (urediniospores) and '*vastatrix*' for the damaging and devastating nature of the disease. Berkeley never saw the disease in the field (as he was a mycologist rather than a plant pathologist). Berkeley's reputation as an expert in identifying fungi resulted in many people sending him samples (**Fig. 4**).

It was not until much later, when the young plant pathologist Harry Marshall Ward was posted to Ceylon in 1880, that the causal link between the fungus and disease was established (Ward, 1882). For many years coffee planters and field staff attributed the onset of CLR to poor plant growth and humid environments and thus promoted practices to bolster plant vigour and growth. Ward showed that "Devastating Emily" was instead caused by a fungus and made other important discoveries about the disease (Ayres, 2005).



The Gardeners' Chronicle.

SATURDAY, NOVEMBER 6, 1869.

WE have recently received from our excellent friend Mr. THWAITES a specimen of a minute FUNGUS which has caused some consternation amongst the coffee planters in Ceylon, in consequence of the rapid progress it seems to be making amongst the COFFEE PLANTS. A few trees were noticed to be infected in May last, and at the time of Mr. THWAITES' communication (July 24) two or three acres were showing the Fungus upon the leaves. These latter fall off before their proper time, and fears are entertained as to the effect on the amount of the crop.

The most curious circumstance is, that amongst more than a thousand species of Fungi received from Ceylon this does not occur; and that it is not only quite new, but with difficulty referable to any recognised section of Fungi. Indeed it seems just intermediate between true moulds and Uredos, allied on the one hand to Trichobasis and on the other to Rhinotrichum. Though the Fungus is developed from the parenchym of the leaf there is not any covering to the little heaps such as is so obvious in Uredo and its immediate allies, while the mode of attachment reminds one of Rhinotrichum. We are obliged, therefore, to propose a new genus for its reception.*

As the Fungus is confined to the under surface of the leaves, and the mycelium is not superficial, it may be difficult to apply a remedy; but we should be inclined to try sulphur by means of one of the instruments which are used in the Hop grounds in Kent, or syringing with

* *Hemileia*, Berk. and Broome: sori somewhat circinating, hypophyllous, naked; flocci distinct, inarticulate, flexuous; spores somewhat kidney-shaped, at first smooth, then granulato-verrucose on one side, attached obliquely at the base by a little papillæform point.

Hemileia vastatrix, Berk. and Br., forming little white orbicular patches on the under side of the leaves, consisting of minute tufts of flexuous threads surmounted by a single subreniform spore attached obliquely at the base, rough externally with wart-like papillæ, quite smooth on the side nearest the flocci.—The upper portion of the leaf above the patches looks as if it were burnt.

Our figure represents a group of threads with young immature spores highly magnified, together with one of the tufts as seen from above, and spores in different positions.

Figure 4. The first scientific account of coffee leaf rust and naming of the fungus.

We are still uncertain how "Devastating Emily" arrived in Ceylon and why the outbreak was so severe. Long distance wind transfer of spores is a likely explanation (as has been seen more recently for the spread of wheat stem rust), although it is difficult to understand why the Americas avoided CLR for so long when the disease had already spread to other parts of Asia. Prevailing wind patterns and the fact that CLR was not recorded in Angola until 1966 might explain this late arrival. Four years later CLR was discovered in Brazil by a pathologist who, perhaps coincidentally, had just been to Angola on a coffee study tour (Money, 2006). Physical transfer of spores by people, on clothing and other goods are all plausible entry mechanisms for the rust, as are undetected infections.

The increasing movement of coffee plants as coffee-growing spread worldwide in the late 19th and 20th century, together with a huge expansion of trade and movement of people all hastened the eventual spread of CLR to many new places (McCook, 2006). The wider impacts of the disease will be discussed later, but a notable consequence of the destruction of the end of major coffee production in Ceylon was the rise of another valuable commodity and new wealth.

Sir Thomas Lipton (**Fig. 5**), a Scotsman born to Irish parents, was one of a generation of successful merchants in the British colonial era, and creator of the Lipton tea empire. He started with a small provision shop that later led to a proliferation of grocery retailers throughout the United Kingdom by the late 19th century. Lipton purchased several tea, coffee, and cocoa plantations in Ceylon to supply his shops with exotic and highly sought-after goods.

Figure 5. Sir Thomas Lipton on his yacht in 1903. When coffee failed, tea made him wealthy.

Another Scotsman vital to the establishment of tea growing in Ceylon was James Taylor. His early experiments in growing tea began shortly before the CLR outbreak, while his continuing efforts to innovate and develop tea helped lay the ground for the mass roll out of tea plantations (**Fig. 6**) in previous coffee growing zones (MacKenzie, 2018).

By the early 1900s, coffee growing in Ceylon had declined from its peak in the 1860s of 68,787 ha to 14,170 ha (Waller et al. 2007). *H. vastatrix* was the sole reason for this decline. It is often said that this is why the British drink more tea than coffee, even today. Although this is a compelling story, there is no evidence to support the popular belief that the collapse of Ceylon's coffee industry reduced the consumption of coffee and led to the dominance of tea as a beverage in the UK. Any shortfalls in coffee yields from Ceylon could have easily been offset by imports from other coffee-producing countries.

Figure 6. *left:* the devastating losses caused by coffee leaf rust paved the way for tea plantations.
right: an early Lipton tea packet from the1900's.

Although Lipton made his fortune from tea, rather than coffee, his early investments in the latter means he was a prominent figure in the first commercial outbreak of coffee leaf rust.

Coffee Leaf Rust Today

People are drinking more coffee than ever before. Upwards of three billion cups are consumed per day worldwide. Over the last two decades, demand for coffee products has increased by 65%. Global coffee production has kept up with growing demand largely due to expansion of cultivation into southeast Asia (Thang et al. 2009).Vietnam is now the second biggest producer of coffee through its wide use of intensive agronomic practices (Guhl, 2008). Today the coffee industry boasts an economy of more than $200 billion per year with a forecasted 2.2 % annual market growth (Sach et al. 2019). Large international coffee traders, such as Neumann Kaffee Gruppe and ECOM, are responsible for most of the freight and handling costs which contribute to the high consumer price tag of a daily *cuppa* (**Fig. 2**). The cost of coffee in rich countries is misleading; of the 12.5 million coffee farmers, around 5.5 million live below the poverty line, with a household income of only USD 3.20 per day[1].

Ceylon was the start of a rapid spread of CLR throughout Asia and further, arriving in Oceania by 1878 (**Table1**). The most significant geographic jump was to Brazil in South America in 1970, later spreading to Mexico and eventually Hawaii. CLR has been recorded from around 70 countries, though not all are major producers.

Table 1. Coffee leaf rust spreads around the world (Schieber, Zentmeyer, 1984; McCook, Vandermeer, 2015 and other sources).

First Report	Country
1861	EAST AFRICA: Kenya (Lake Victoria region)
1869	SOUTH ASIA: Ceylon (Sri Lanka)
1870	Pakistan
1870	India
1878	Mauritius
1878	South Africa
1878	OCEANIA: Fiji and Australia
1878	SOUTHEAST ASIA: Indonesia (Java)
1886	Madagascar
1890	Philippines
1890	EAST ASIA: Vietnam
1892	Papa New Guinea
1894	Uganda
1894	Samoa
1910	New Caledonia

First Report	Country
1912	Kenya
1930	Angola
1940	Mozambique
1942	China
1946	Zanzibar
1951	WEST AFRICA Ivory Coast
1970	SOUTH AMERICA: Brazil
1976	Ecuador
1976	CENTRAL AMERICA: Nicaragua
1978	Peru and Bolivia
1979	El Salvador
1980	Honduras and Guatemala
1981	NORTH AMERICA: Mexico
1983	Colombia and Costa Rica
2020	Hawaii

Coffee is attacked by several damaging diseases and pests (Koutouleas et al. 2022a), yet despite many years of scientific research CLR still poses a critical challenge to low-resource farmers across most coffee growing regions (Avelino, et al. 2012a). New challenges await, with forecasts of increased disease severity and incidence under changing climates (Castillo et al. 2020). The most recent reminder of this was

[1] https://www.thecoffeeguide.org

renewed outbreaks of CLR in Central and South America from 2008 to around 2013. CLR epidemics occurred with greater intensity than previously recorded (Avelino et al. 2015), dubbed the "Big Rust" by Peter Baker (Baker, 2014). Coffee production during this period was reduced by up to 70% (Dupre et al. 2022), with unrelenting impacts on the livelihoods of thousands of smallholder farmers and coffee workers. Huge financial losses were incurred.

Other diseases such as coffee wilt disease and coffee berry disease are restricted to Africa and, though also damaging, their financial and social impacts are less global than CLR. This is considered the most significant coffee disease with estimated costs to the coffee industry of between $1 – 2 billion USD annually (Wellman, 2021). The recent Latin American CLR epidemics alone have been estimated to cost up to $1 billion of losses and the disappearance of 250,000 jobs, mainly on farms (Mallén, 2014).

The impact of CLR epidemics often goes beyond individual countries, with huge disruptions to rural populations. "I didn't leave my country because I wanted to. I left because I had to", according to Antonio Lara, a coffee harvester who migrated from Honduras to the U.S. in 2014 because of the economic impact of CLR (Milman et al. 2018). "Coffee is the only source of income for our family, the only crop that maintains our livelihood... the rust destroyed all our plants" reports a Mexican coffee farmer in Santiago Atitlán (Rojo, 2022).

H. vastatrix has been described as the unseen driver behind the mass migration of undocumented workers from Mexico and Central America into the U.S. (**Fig. 7**) following the outbreaks (Mallén, 2014; Milman et al. 2018). A recent analysis reported that household emigration from Guatemala almost doubled from 2007 – 2016, with particularly strong links to households relying on coffee growing and therefore most badly affected by CLR (Dupre et al. 2022).

Figure 7. The exodus of Hondurans to the US through Chiapas, Mexico in 2018 has been strongly linked to the economic impact of CLR epidemics. Photograph: Johan Ordonez/AFP/Getty Images.

States of emergency were declared by the governments of Costa Rica, Honduras and Guatemala between 2012-13; national initiatives were launchd to combat the disease. MAG (Ministerio de Agricultura y Ganadería), ICAFE (Instituto del Café de Costa Rica), IHCAFE (Instituto Hondureño del Café) and ANACAFE (Asociación Nacional del Café de Guatemala) mobilised political and economic resources to provide fungicides, subsidies, and technical assistance to coffee farmers in the fight against the resurgence of CLR (Avelino et al. 2015).

Hawaii is not a major coffee producer, although it has been grown for over 170 years. For many years it remained as an outlier, one of the few – if not only country growing coffee – that has avoided CLR. The first report was in 2020, from the island of Maui, spreading to the neighbouring islands of Lanai, Oahu, Molokai and Kauia over the next nine months. Coffee growing has waxed and waned, with a revival starting in 1990s. The island has historically grown a range of susceptible cultivars, such as Typica, Bourbon, Caturra, Catuai and Geisha.

Figure 8. Coffee growing is embedded in highland agriculture, as shown in this mural from Antigua, Guatemala. CLR is disrupting a major crop that sustains many rural livelihoods.

The establishment of new plantations and renewal of old ones have provided opportunities for the introduction of CLR, together with changes in climate. The old plantations received little attention while new ones have brought in new varieties. It has also been suggested that the withdrawal of fungicides and general lack of knowledge and expertise on managing CLR have played a part in the establishment of the disease (Aristizábal & Johnson, 2022).

Several coffee species were originally grown, but now *Coffea arabica* and *Coffea canephora* (Robusta) dominate. Arabica coffee produces a superior quality bean but is also most susceptible to the rust. The movement of Arabica planting material (**Fig. 9**) reflects its popularity. Despite its much higher susceptibility, Arabica still dominates global coffee production, though the proportion of Robusta coffee continues to increase annually.

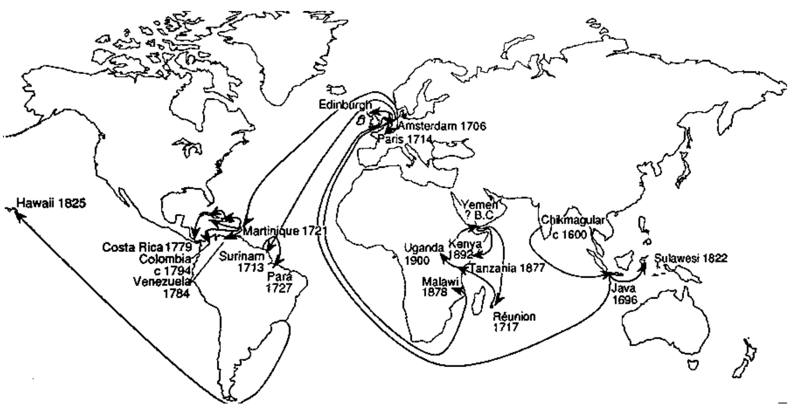


Figure 9. Arabica has been largely replaced by Robusta in Java, another consequence of CLR. From Smith et al. (1992) *Tropical Forests and their Crops.*

Why are Outbreaks of CLR so Bad in the Americas?

Dr. Peter Baker, a climate and coffee senior scientist with more than 20 years' research experience, was working for CABI in Honduras and Guatemala when new outbreaks of CLR took place in the Americas in the early 2010s. He recalls the chaos following the discovery of the intensity of the disease attack by farmers and governments: "Eleven countries declared a state of emergency between 2010 - 2013". A series of outbreaks were considered some of the worst seen since Ceylon in the 19th Century.

Coffee farmers were of course already familiar with CLR, a disease some had known for up to forty years. They were able to manage small outbreaks with regular fungicide applications or "just-in-time" sprays (Baker, 2015). Yet this experience proved to be of little use. Dr Baker stated that "it is still not fully understood what happened in that time and why the disease hit the coffee farming community so ruthlessly". So why did CLR cause such damage and losses on a scale never seen before in the region?

A number of plausible causes and reasons have been put forward (Baker, 2014, 2015; Vandermeer & Rohani, 2014; Avelino et al. 2015). We describe the main four hypotheses offered by researchers and analysts. The first concerns the rust fungus and the discovery of new races and heightened virulence. The second focuses on coffee farmers and the available resources (time, fertilizer, renewing stock and general care) they allocated to management of gardens in the years before the *Big Rust* hit. The third hypothesis considers changes in climate and agricultural practices and their effect on disease progression. The fourth hypothesis suggests that habitat degradation and changes in land use, especially the removal of shade trees, were the main underlining causes for the increased severity of disease attack.

The fungus evolves: the virulence hypothesis

H. vastatrix has considerable genetic variation, with more than 50 races identified (Quispe-Apaza et al. 2017). Races are distinguished by unique sets of virulence genes (Zambolim, 2016; Talhinhas et al. 2017). Races from the same geographical range have similar genetic composition (Gouveia et al. 2005). When CLR started to explode in the 2010s, the emergence of new and highly virulent strain of *H. vastatrix* was mooted (Baker, 2015). Researchers compared spore samples taken from before and after the 2008 Colombian CLR epidemic (Rozo et al. 2012). Genetic marker assays and inoculation challenge studies (*in vivo*) failed to support the "virulent race" hypothesis. They concluded that excessive rainfall was the more likely cause of the Colombia outbreak.

Recent studies have unveiled three divergent genetic lineages within *H. vastatrix*, known as C1, C2 and C3 (Silva et al. 2018). The ability of these fungal subtypes to infect coffee plants is defined according to their evolution with different coffee species. The C1 and C2 lineages of the fungus are thought to be ancestral lineages, which tend to infect diploid coffee species (*C. canephora, C. racemosa, C. liberica* and *C. excelsa*). The latter three species are of negligible importance today in global coffee production.

The C3 group represents the so-called "domesticated" lineage, which exclusively infects commercial cultivars, such as tetraploid *C. arabica* and interspecific hybrids of the same species. The three genetic lineages of the rust also have the ability to hybridise and thus generate new races which can infect a wider range of cultivars of Arabica and Robusta. New races of *H. vastatrix* were found in Honduras, Guatemala and Costa Rica after the outbreaks had started. It is thought unlikely that they were linked to the increased impact and intensity of CLR epidemics in these countries. The new races were a consequence rather than cause of the severe outbreaks.

Money, money, money: the people hypothesis

Coffee prices are in constant flux and inevitably this has economic knock-on effects at the farm level. Farmers were making little money from coffee leading up to the Latin American epidemics because of record low prices they were receiving. The majority of coffee farmers had little incentive or money to invest in their coffee, whether through buying fertilisers or hiring labour to prune and tend their plants. Poor management of coffee farms and low growth vigour (Zambolim, 2016) increased the vulnerability of coffee pests and diseases (Avelino et al. 2015; Baker, 2015) such as CLR.

Figure 10. Coffee farming family near Zipaquira, close to Bogotá in Colombia. The low profitability of coffee and other crops limits farmer responses to disease outbreaks.

But there were also reasons unrelated to coffee which limited farmers ability to look after their crops. In the period before the first severe Colombian CLR outbreak, a flurry of Ponzi schemes, led to many people, including farmers, losing money on scam investments[2]. By the time these get-rich-quick schemes were exposed, just over 1% of Colombia's annual GDP had been frittered away, never to be seen again. For coffee farmers already facing low coffee prices and high fertiliser costs, the consequences of these failed investments were devastating. It created a 'perfect storm' which enabled coffee leaf rust to easily spread across Colombian coffee growing regions. Although these conditions were unique to Colombia (**Fig. 10**), they highlight the economic fragility experienced by coffee farmers in many other countries and the effect this has on keeping CLR at bay.

A recent study directly links the socio-economic status of Nicaraguan coffee farmers to the damage caused by CLR disease. The researchers found that farmers with low income, little education, training and minimal access to technical services experienced the greatest losses due to CLR (Villarreyna et al. 2020). There is other evidence which supports the strong link between coffee profitability, technical knowledge and access to advisory services and the impact of CLR outbreaks (**Fig. 11**).

Figure 11. Chemical control against CLR at the beginning of the rainy season in Nicaragua.

Weather patterns: the climate hypothesis

Like most fungal pathogens, the disease cycle of *H. vastatrix* is primarily mediated by temperature and humidity (Sera et al. 2022). Although farmers are at the mercy of the weather, temperature and humidity within coffee plantations and gardens can be modified by the use of shade trees and density of planting (**Fig. 12**). Germination of *H. vastatrix* spores requires 6 – 24 hours of leaf wetness, with an optimal

[2] https://intelligence.coffee/ponzi-schemes-coffee-leaf-rust-epidemic/

temperature range of 21 – 25 ◦C (Sera et al. 2022). If these conditions persist then the time between infection cycles by *H. vastatrix* (commonly 25 to 35 days) is shortened. More infection means more disease and greater losses.

The 2008 CLR outbreak in Colombia is thought to have been largely triggered by unusually high rainfall (Rozo et al. 2012; Avelino et al. 2015). The later outbreaks in Central America may have been due to abnormally low rainfall in the wet season and higher rainfall during the dry season (Avelino et al. 2015; McCook & Vandermeer, 2015). There was also a reduced diurnal variation of temperatures during the same periods (*i.e.*, higher minimum and lower maximum mean daily temperatures) at the same time in Central American countries most affected by the CLR epidemics (Avelino et al. 2015); perfect conditions for CLR to multiply and reduce yields.

Figure 12. Banana protects young coffee plants and provides additional income as they start to bear fruit, as seen here in Quindío, part of the Zona Cafetera in Colombia.

It is also important to consider the impact of microclimates within coffee plantings on CLR development. Greater disease severity has been reported in the humid microclimates created when plants are close together and crowded canopies of individual plants that are irregularly pruned. Coffee agroforestry, where the crop is mixed with taller timber and fruit trees also increases humidity lower down (Koutouleas et al., 2022b; Sera et al. 2022). Work by Avelino et al (2006, 2012b) suggests that shade trees, soil pH, fertilisation and altitude all have a more prominent effect on CLR development and severity compared to general rainfall. The interactions between light intensity, temperature variation and fertilisation rates (N supply) and *H. vastatrix* sporulation have been examined under controlled conditions (Toniutti et al. 2017). A higher temperature range of 22 - 27 °C resulted in 2000 times higher sporulation of spores compared to a range of 18-23°C. High light intensity combined with low nitrogen fertilization also resulted in high sporulation. It is clear that climate change, as described above, has contributed to higher incidences of CLR. How this happens is still not fully understood.

Land use: the environmental collapse hypothesis

There has been a strong shift away from traditional shaded-coffee systems (**Fig. 13**) towards more intensive, full-sun cultivation. Some have suggested that the resulting loss of diversity in flora and fauna has reduced the availability of natural enemies of coffee pests and diseases and increased the vulnerability of coffee plants (Vandermeer et al. 2009; 2014). Increasing habitat complexity is also reported to be good for the health of coffee plants (Bukomeko et al., 2018). The ecological collapse or degradation hypothesis has many adherents yet there is disagreement about the link between the biological diversity of coffee plantations and outbreaks of CLR. Other evidence suggests that coffee agroforestry systems lead to higher rates of infection by CLR because of favourable microclimatic conditions. Avelino and colleagues (2012b) found there was greater dispersal of rust spore clusters in plantations grown next to pastureland and exposed to prevailing winds. This led to more infections.

Forest corridors and "islands" in coffee shaded systems (**Fig. 14**) can act as physical barriers, reducing spore dispersal and spread of disease.

Figure 13. *Coffea arabica* grows naturally in the understory of dense Afromontane forests in Ethiopia. Other species are also associated with in these forests. Traditional coffee cultivation in many countries mimics this by using Agroforestry systems (AFS) *i.e.* intercropping coffee plants with shade or "neighbour" trees, some native, others introduced. The benefits of this farming system include a buffering of temperatures, exposing coffee plants to fewer extremes, habitats for birds, reptiles, and pollinating insects, higher nutrients in soils and greater water retention. But these conditions also favour coffee leaf diseases, including CLR, because of higher relative humidity and reduced run-off of spores when it rains.

Dr. Avelino has worked for more than three decades on CLR epidemiology, most recently looking at the effects of shaded-coffee systems on rain patterns in the understory and CLR infections. It is clear that shade trees reduce spore wash-off (Gagliardi et al. 2017; Avelino et al. 2020). Having worked on different tree species, including *Chloroleucon eurycyclum*, a tree with a dense canopy, Dr Avelino cautions that "not all shade trees are equal". The diversity of coffee agroforestry plots means that the influence of shade trees on CLR development will vary.

There are other indirect effects that coffee agroforestry may have on CLR. High fruit loads have been reported to coincide with a high CLR incidence (Avelino et al. 2006). The exact reasons are unclear, though there could be a link with the migration of protective phenolic compounds from leaves to fruits, exposing leaves to infection. Shaded coffee could help alleviate disease pressure by reducing variations in fruit production and limiting migration of phenolic compounds (Vaast et al. 2006). Overall coffee yields tend to be lower under shade but are more stable year-to-year (López-Bravo et al. 2012; Koutouleas et al., 2022b).

Figure 14. Replanting of coffee in Risaralda, Colombia in full sun. Small islands of other vegetation may harbour natural enemies of coffee pests and diseases, but lack the diversity seen in shaded and 'rustic' coffee plantations.

There is no single explanation why CLR outbreaks in the Americas were so severe in recent years. Changes to the pathogen, farming systems and the climate have all contributed. Studies to identify their relative importance continue, for example through advanced statistical approaches utilising geographically relevant data sources (Liebig et al. 2019; Merle et al. 2020), are paving the way to a better understanding of complex plant disease epidemics such as CLR.

Nicaragua: a case study

Nestled in the lush, mountainous valleys of Matagalpa lies one of the biggest coffee growing regions of Nicaragua (**Fig. 15**). Visitors enjoy coffee farm tours and tastings throughout the land of "eternal spring". Characterised by its mineral-rich volcanic soil and moist climate, coffee plants sprawl across the hillsides in abundance. All seems well, but the countless tourists that flock here know little about the ongoing battle that coffee farming communities have with CLR.

"Learning to live with the CLR is our reality" says Dr. Melanie Bordeaux, director of NICAFRANCE Foundation's research centre, based at the coffee farm "La Cumplida" in Matagalpa. Dr. Bordeaux has been based here since 2015, when she took on the new and challenging role of directing research and development of coffee, cacao, and agroforestry systems. Her job brings her into close contact with an array of coffee workers, farmers, traders, national agencies and researchers.

Figure 15. Coffee growing country around Jalapa, Nicaragua.

CLR is no stranger to Nicaraguan coffee growers. "*La Roya* (local name for CLR) is not a new disease for the coffee communities here – the first official report was as early as 1976 in the Carazo district" says Dr. Bordeaux. It is still a mystery why CLR arrived in Nicaragua before other coffee-growing countries in Central America. CLR arrived late in the Americas, with the first report from Brazil in 1970. The disease has spread far and wide around the world, covering vast distances (Bowden et al. 1971; Schumann, 1991) aerially as spores and in the movement of people and plants as coffee growing spread (see the earlier chapter on 'Coffee Rust Today').

By the early 80's other Central American countries were also affected by CLR (Schumann, 1991). In Nicaragua, the disease led to the widespread transformation of coffee farming. National strategies encouraged farmers to adopt intensive, large scale cultivation reliant on the increased use of agrochemicals in open-field conditions (Schuppener et al. 1977; Rice, 1990). Low-input traditional coffee farming methods were seen as less efficient. The new strategies had unfortunate consequences, notably in forest cover. "Before 2010, there was a nationwide tendency for de-forestation (linked to agriculture), including coffee farming" says Dr Bordeaux. "Fortunately, since those times re-forestation has become a priority."

Resistance to CLR has broken down in many of the commercial coffee cultivars grown in Nicaragua over the past half-decade. Low coffee prices in the years leading up to the recent Central American epidemics made it more difficult for Nicaraguan coffee producers to invest in their coffee fields. Management of plants was neglected and low vigour contributed to the intensity of rust outbreaks. CLR has done much to undermine the faith of farmers in coffee as a reliable and profitable crop.

Since 2015, the NICAFRANCE Foundation has overseen coffee renovation programs using agroforestry practices as well as the introduction of high-yielding coffee cultivars and hybrids which are less susceptible to rust. CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement – an international French organisation) and ECOM Agroindustrial Corp.[3] have both supported breeding programs.

"La Cumplida" and the surrounding farms working with NICAFRANCE account for over 1,500 ha of coffee cultivation (**Fig. 16**), the majority of which is shade-grown[4]. An EU funded project BreedCAFS (Breeding Coffee for AgroForestry Systems[5]), working with the foundation, has established rigorous in-field trials of new F1 hybrids of coffee, measuring performance under shaded (agroforestry) conditions (**Fig. 6**). They have also used interspecific grafting in the hunt for resistance against pests such as soil-borne nematodes. The close contact with farmers and field trials makes it easier and quicker to introduce new management practices.

Figure 16. La Cumplida coffee estate is experimenting with a large-scale conversion of conventional coffee farming to organic, where a range of rust-resistant *C. arabica* cultivars are grown with the help of bio-based products and the use of novel management practices to promote growth vigour.

Promotion and technical assistance provided by ECOM has led more farmers to renovate their farms using new coffee hybrids. "We have witnessed an increase in the adoption of hybrids on various coffee farms in Nicaragua" says Dr. Bordeaux. She hopes that there work with farmers will reverse the ill-effects of agrochemical use over main years, which has led disturbed soils and ecosystems. She also

[3] www.moringapartnership.com/cafetalera-nica-france

[4] www.lacumplida.com/historia/index.html

[5] www.breedcafs.eu/

commented on the low prices paid to farmers and their low resilience to the arrival of CLR, and that many relied on popular coffee cultivars which were susceptible in the most recent outbreaks.

"La Cumplida" continues its widespread efforts to shift coffee plantations that relied on high chemical inputs, including pesticides and herbicides, towards more organic practices. "If we can achieve organic pest and disease control with our farmers, the same approach could be applied to other farms in Nicaragua" says Dr. Bordeaux. The default (today) is organic" says Dr. Bordeaux. This is more for pragmatic reasons – farmers cannot afford to pay for expansive chemical inputs – than a primary motivation to make their coffee attractive to niche hipster coffee drinkers.

Figure 17. *left* Franklin of PRODECOOP checks coffee seedlings in San Juan del Rio; *right* Guillermo, a local coffee farmer, brings his coffee to sell to the local coop in Jalapa on two horses.

The use of chemical control of coffee rust in Nicaragua is greatly influenced by economic factors (Waller, 1982; Villarreyna et al. 2020). "Nicaraguan farmers who can afford it use copper fungicides and others to manage CLR. These are applied preventatively (normally at the beginning of the rainy season) and/or curatively (once CLR is present) (Villarreyna et al. 2020). How (dosing, volume) and when (timing and frequency) sprays are applied is critical in halting the progress of CLR (Waller, 1982). The association of cooperatives of small coffee producers of Nicaragua (CAFENICA) have introduced an early-warning systems for CLR[6] to help farmers plan in advance. Collaborative efforts with CIAT (International Center for Tropical Agriculture) are disseminating climate data that can help coffee farmers make appropriate and timely decisions on CLR, and reduce the risk of damaging losses. ExpeRoya, a model built by CIRAD via the Procagica project[7] is being used in Central America and the Dominican Republic in conjunction with IICA to forecast outbreaks of CLR (Motisi et al. 2022).

When asked what the challenges Nicaragua face in their future of coffee production, Dr Bordeaux answered concisely: "we need to learn how to sustainably keep up the quality and yield under the (constant) disease and pest pressure". No easy feat. Despite the difficulties in protecting yields coffee farming contributes almost 20% of Nicaraguan GDP (Läderach et al. 2017). Its status as a key commodity product will, hopefully ensure that local and international research agencies, farmer associations and the farmers themselves (**Fig. 17**) will continue to develop new ways to managed CLR.

[6] (https://cafenica.net/2018/04/17/alerta-temprana-para-la-mejora-de-la-calidad-del-cafe-y-la-calidad-de-vida-de-pequenos-productores-y-productoras/)

[7] www.iica.int/en/press/news/eu-iica-program-procagica-presented-its-achievements-ministers-agriculture-central

Old and New Control Methods

Following the arrival of CLR in the 1970s, coffee farmers in the Americas learnt how to manage sporadic outbreaks of the disease with fungicides. They were ill-prepared for the intensity of the severe outbreaks four decades on. Governments were in a state of alarm at the losses that were being seen. National agencies worked feverishly to provide advice and financial assistance to farmers but were always on the "back foot", struggling to keep up with the rate of spread and impact of CLR. The delayed responses meant that many coffee farmers suffered such catastrophic losses that they found it easier to give up on farming. Most have not returned since.

Organic coffee farms were particularly vulnerable to CLR attack because of the lack of effective alternative control methods and poor support from National Agencies[8]. At a summit in 2016[9], PROMECAFE (Cooperative Program for the Protection and Modernization of Coffee Crop in Mexico, Central America and Panama) advised organic farmers to temporarily use conventional methods to limit the spread of CLR.

When the international agricultural research (CG) centres were set up in the second half of the 20th century, coffee was not part of their mandate. The general belief was that coffee (and other) commodity crops would receive support from the commercial sector and governments keen to protect a valuable source of income. CATIE (Tropical Agricultural Research and Higher Education Center), based in Costa Rica and with links to agricultural agencies throughout the Americas, played an important part in studying coffee production systems, including agronomic practices. In 2019, CATIE produced a comprehensive handbook for technical staff and extension services and facilitators on how to prevent and control CLR (Virginio Filho & Astorga Domian, 2019). This handbook continues to be used by many and is highly regarded. It has been an invaluable source of wide ranging information relevant to this chapter

In this section we consider chemical and non-chemical methods for the control of CLR. These range from the use of fungicides to biological control agents and management of coffee plants. We also explore continuing efforts to identify unknown alternate host(s) of *H. vastatrix* and the implications for managing CLR.

Chemical control

Contact and systemic fungicides have been widely used for the control of CLR. There are three main groups of fungicide used today; those that are copper-based (contact); those based on triazoles (systemic); and those combining triazoles with strobilurins (mixed or mesosystemic). Contact fungicides form a protective barrier on leaves and prevent entry and penetration by *H. vastatrix* spores. Systemic fungicides work from within the plant, disrupting the early infection stages. Mesostemic fungicides have a dual function, acting on both the leaf surface and within the plant tissue.

Bordeaux mixture, a combination of copper sulphate, lime and water, is one of the oldest fungicides in use. It is regularly used for the control of CLR and is a contact fungicide. It is much less effective than

[8] https://www.coffeehabitat.com/2013/06/coffee-rust-and-organic-coffee/

[9] http://promecafe.net/wp-content/uploads/2016/09/II-Coffee-Rust-.pdf

other copper-based and triazole fungicides and is of dubious value (Merle et al. 2020). It remains an attractive option in Central America, however, because it is approved for use in organic coffee production.

The timing of fungicide sprays is crucial. Critical times for applications are determined by the growing season, the load of coffee berries (from the previous harvest) or triggered by disease monitoring schemes. Application usually begins at the start of the rainy season. Up to five applications can occur in large coffee growing countries such as Brazil for high loads of coffee berries. Field assessments of disease using a score matrix and trained eye is also useful for determining what type of fungicide is used. In Brazil, contact fungicides are recommended for farms exhibiting less than 5% incidence (Zambolim, 2016). Systemic fungicides are typically advised for higher incidences, but this recommendation differs from country to country.

Non-chemical control

The availability and affordability of chemical control methods also determines control strategies used by farmers (Sera et al. 2022). An increasing awareness of fungicide resistance highlights the danger of relying on chemical control. Other negative consequences of using pesticides have resulted in greater interest in non-chemical means (Duong et al. 2020; Hu & Chen 2021), together with wider adoption of organic methods of producing coffee. Organically certified coffee is increasingly attractive to coffee consumers and attracts a premium price (Gatti et al. 2022).

Regular pruning of coffee was one of the main practices promoted after recent CLR outbreaks in the Americas epidemic of 2012, to aid recovery of coffee plants and reduce future infections. Recommendations varied depending on the size of the farm and available labour, from pruning by row, by plot or selectively – targeting plants with dead and unproductive branches. Pruning during the dry season aims to open out canopies and reduce the humid conditions which favour the sporulation of *H. vastatrix.* Pruning later in the season aims to stimulate new leaf growth and improve the flow of air within plants and between rows. These actions lower the humidity within plots. Timely pruning of shade trees prior to the onset of rainy seasons also aims to improve air flow in plots and reduce humidity, again restricting sporulation of *H. vastatrix* (Avelino et al. 2020).

Older coffee plants require more frequent fertilisation to maintain good growth vigour and strengthen mechanisms of defence against CLR. Complete renovation of old coffee farms is also recommended, particularly where highly susceptible cultivars have been planted. Promoting good agronomic practices is a sound way ahead in managing CLR, but their success will always depend on the ability and willingness of farmers to carry them out.

Resistant cultivars

The use of resistant cultivars has been a long-term mainstay in efforts to control CLR. But resistance is only one of several key characteristics for assessing planting material. Wild Ethiopian landraces such as Geisha have exceptional quality potential and exhibit partial resistance. Yet they are less popular for use in modern coffee farming systems because of their height and brittle branches[10]. Other discoveries of resistance in coffee have been more successful. The discovery of a spontaneous hybrid called 'Híbrido

[10] https://varieties.worldcoffeeresearch.org/varieties/geisha

de Timor' has been used in breeding programmes focusing on CLR (Zambolim, 2016; Talhinhas et al., 2017). The commercial varieties collectively known as the Catimores and Sachimores carry CLR resistant genes S_H derived from 'Híbrido de Timor' (Sera et al. 2022). Resistant genotypes were bred with susceptible cultivars such as Catuaí and Mundo Novo to produce an additional suite of resistant cultivars with other preferred traits, including good bean quality and dwarf stature (Zambolim, 2016).

These resistant cultivars were used in national campaigns to renovate coffee plantations after the major CLR epidemics in the Americas. Any respite against future epidemics may only be temporary; the frequent emergence of new *H. vastatrix* races (49 have been described thus far – Barka et al 2020) has led to a breakdown in resistance over the past decade (Jibat, 2020). The promise of new resistant coffee cultivars bred has not been fully met, though there is a definite disease reduction compared to cultivars susceptible to CLR (Cristancho et al. 2014).

Efforts continue, with novel molecular research and plant breeding efforts being used to characterise S_H related candidate genes for resistance (Barka et al. 2020) and developing new cultivars which can better tolerate high CLR infections and still maintain high yields (Jibat, 2020; Badillo, 2021).

Biological control agents

For insights into the potential of BCA against CLR, we interviewed Melida Rojas Chango, an industrial Ph.D. fellow working in collaboration with VTT Technical Research Center of Finland and the University of Helsinki. She highlighted the potential of both existing and new organisms antagonistic to *H. vastatrix*. She is hopeful for the wider use of BCAs in coffee field but warned that their introduction into a new environment is always a matter of concern and needs to be handled with caution. "We don't want any surprises such as negative knock-on effects caused by the organism interacting in a non-native environment" says Ms. Rojas.

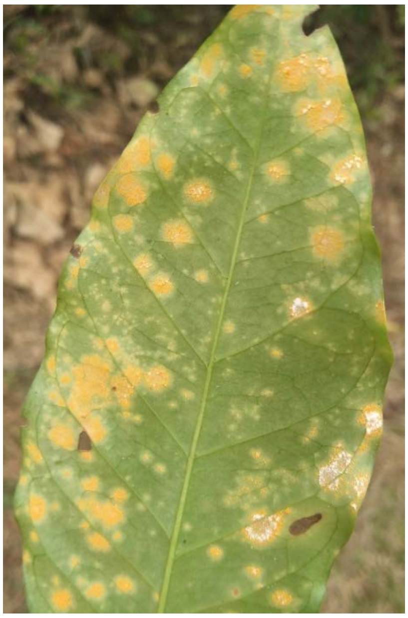


Figure 18. Natural colonization by *Lecanicillium lecanii* (white spores) on *Hemileia vastatrix* urediniospores (orange spores) on a coffee leaf (left side) in Matagalpa, Nicaragua.

The use of specific fungi, bacteria, and insects against CLR in controlled trials has been recently reviewed (Zambolim, 2016; Koutouleas et al. 2022a). But there are still major gaps in how these BCAS would work in the field. The most documented BCA is the fungus, *Lecanicillium lecanii* (previously *Verticillium lecanii*). It has frequently been reported to occur on coffee plants naturally infected by *H. vastatrix* (**Fig. 18**). It has been studied through *in vitro* challenges over the past three decades (Shaw, 1987; Vélez & Rosillo, 1995) and further research continues on its antagonistic mechanisms against CLR (reviewed by Koutouleas et al. 2022a). The timing of *L. lecanii* applications appears to be critical in its effectiveness against CLR (Vélez & Rosillo, 1995); it needs to be established in the field prior to the introduction of *H. vastatrix*. Shifts in the onset of CLR will determine whether *L. lecanii* works against CLR.

Other fungal BCAs known to be effective against CLR include *Calonectria hemileiae, Mycodiplosis hemileiae* and *Trichoderma harzianum* (Nicoletti & Becchimanzi, 2020; Ramírez-Rodríguez et al. 2020; López-Velázquez et al. 2021; Salcedo-Sarmiento et al. 2021). Bacterial BCAs which have been trialled include *Bacillus cereus, Bacillus lentimorbus, Bacillus subtilis* and *Pseudomonas sp.* Other fungi have been investigated: *Acremonium* sp, *Aspergillus* sp, *Cladosporium* sp., *Fusarium* spp. and *Penicillium* sp. (Koutouleas et al. 2022a).

Promising results and potential as BCAs have been shown by the mite *Ricoseius loxocheles* and gastropod *Bradybaena similaris* (Oliveira et al. 2014; Ajila et al. 2018; Hajian-Forooshani et al. 2020). Both were found to feed on the spores of *H. vastatrix* in controlled settings and under natural conditions for *B. similaris* only **(Fig. 19)**. Other research efforts have looked at the coffee microbiome and the role of endophytic microorganisms in CLR development (Silva et al. 2012; as reviewed in Duong et al. 2020). Some endomycorrhizal fungi present coffee root systems have been linked to reduction in CLR infections *H. vastatrix* (Monroy et al., 2019). These are some of the first results to suggest that such fungi may help the coffee plant mitigate biotic stress such as CLR and raise the potential of soil inoculation with indigenous fungi.

Figure 19. *Bradybaena similaris* feeding on *rust* urediniospores (orange spores).

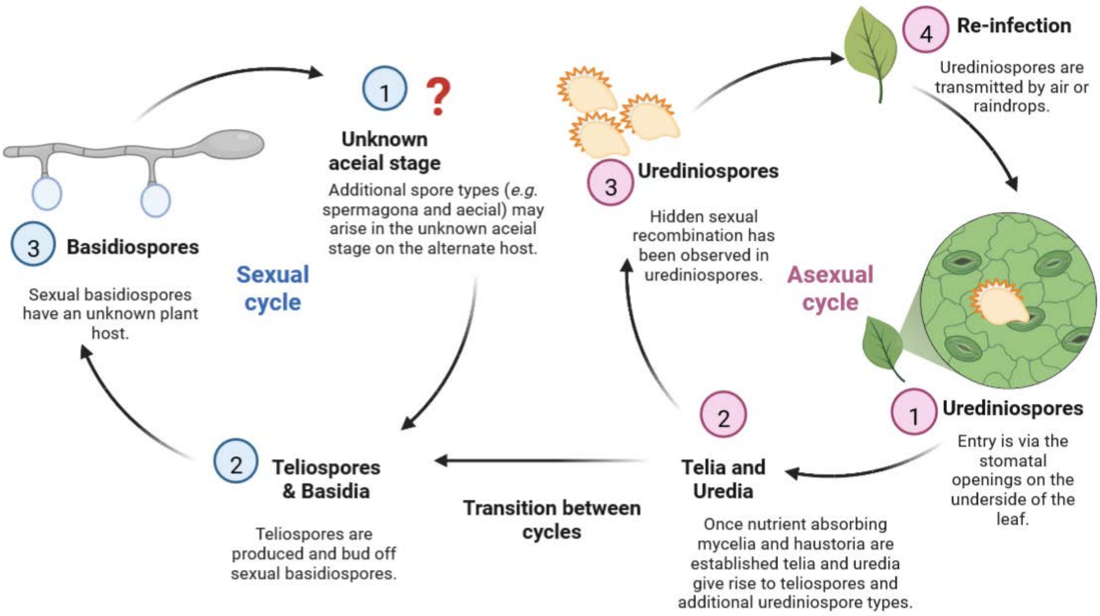


Figure 20. Disease cycle of *Hemileia vastatrix* including missing or unknown sexual stages.

The field application of BCAs requires careful thought. For successful control of CLR, the timing of BCA application must coincide with vulnerable stages in the disease cycle of *H. vastatrix*. BCAs need alternative food resources to survive during *H. vastatrix* latency periods, when the fungus is not sporulating. Even after 40 years of research on *L. lecanii,* this BCA has not lived up to its promise. Funding for large-scale field trials is needed to fine-tune the practical and handling aspects of using *L.*

lecanii against CLR. The production facilities required to ensure supply and quality control of *L. lecanii* need major investment and the prospect of steady financial returns.

There is concern that the use of BCAs against CLR is unlikely to work in the field because they are not specific to rust and most are dependent on specific soil types to continue their life cycles. It has proved difficult so far to find BCAs which can thrive in all coffee-growing environments.

Alternate hosts for *H. vastatrix*

Rust fungi tend to have complex life cycles and may produce up to five specialised spore types. Many rust fungi have alternative hosts, where they can survive when the main host is absent. No alternate host has been found for coffee rust. *H. vastatrix* produces three out of the five different spore types associated with rusts: urediniospores, teliospores and basidiospores. More than 150 years ago after the discovery of the fungus, two major mysteries concerning its disease cycle still exist (**Fig. 20**). Is there another host where the fungus completes its sexual cycle? Are pycniospores and/or aeciospores produced on a yet-to-be discovered alternate host (Koutouleas et al. 2019)? Limited efforts have been made to inoculate potential alternate hosts or search for natural infections in and around coffee plantations or in natural habitats. Some have suggested that the alternate plant host is in the *Orchidaceae* family (Rodrigues, 1990), but no conclusive evidence has been provided for this claim.

All the findings so far point towards the clonal reproduction of *H. vastatrix* throughout most of its geographical ranges including Central Africa, Southeast Asia, the Caribbean, and the Americas (Ramírez-Camejo et al. 2022). The discovery of a hidden sexual reproduction cycle during asexual spore formation has given rise to the "cryptosexuality" theory, explaining the emergence of new race types without the need for sexual spores (basidiospores) (Carvalho et al. 2011). An intriguing part of the disease cycle of *H. vastatrix* is that the fungus produces basidiospores (Fernandes et al. 2009), despite the absence of an alternate host. The "cryptosexuality" theory does not explain why the fungus continues to produce basidiospores.

New techniques have been used to identify potential alternate hosts (Koutouleas et al. 2019). This study suggested that the highest-ranking probable alternate host(s) of *H. vastatrix* are *Psychotria mahonii, Rubus apetalus* and *Rhamnus prinoides.* Other plant species of *Croton*, *Euphorbia*, and *Rubus* also have the potential to act as alternate hosts Given these new findings, agricultural extension advisors could include brief on-farm surveys of flora in these genera, when conducting interview sessions with coffee farmers. This information could further map the potential plant species which may harbour other spores critical to the *H. vastatrix* disease cycle.

Climate Change and the Resurgence of Leaf Diseases

The links between CLR and global climate variation are difficult to disentangle. Studies by Avelino and colleagues have shown a close link between disease progression and anomalous temperatures and rainfall, in particular the earlier onset of rainy seasons. Ecological modelling of disease outbreaks in Colombia (Bebber et al. 2016) and Brazil (Alves & Sanches, 2022) gave contradictory results. Using historical data, Bebber et al. (2016) was unable to explain the 2008 CLR outbreak based on a "climate change hypothesis". Modelling efforts in Brazil have also failed to conclusively show clear links between outbreaks of CLR and climate variations.

We discussed the future of CLR with Dr. Jacque Avelino of CIRAD. He has devoted more than 30 years to studying coffee pests and diseases and has worked in the field for extended periods in Costa Rica, Guatemala, Honduras, Mexico and throughout the Caribbean. These missions have provided Dr. Avelino with first-hand experience of the major CLR Latin American outbreaks, and generated-field data to predict future trends in the progression of CLR.

Figure 21. *left* American leaf spot aka. "ojo de gallo" (Nicaragua), caused by *Mycena citricolor. right* Mixed infection with coffee leaf rust., Dominican Republic.

"In Central America we have always had two main coffee diseases – CLR and American leaf spot (ALS) caused by *Mycena citricolor*" according to Dr. Avelino. ALS is more commonly known as *ojo de gallo* in Spanish-speaking coffee regions (**Fig. 21**). Prior to 2012, ALS was the major disease that plagued coffee producers and was linked to long rainy periods with cool temperatures (Avelino et al. 2007). Since then ALS has almost completely disappeared, which he suggests is likely due to a loss in overall humidity and rainy seasons now interspersed with dry days. These are the conditions which favour CLR. "*H. vastatrix* need higher temperatures. Water is required only for spore for germination and can be supplied by morning dew on leaf surfaces". Dr Avelino and colleagues discovered that disease pressure decreased when rain washed off *H. vastatrix* spores from coffee leaves. Less rainfall is therefore likely to promote CLR disease progression. "With less days of rain predicted and higher temperatures across the tropics, CLR will be the main problem of our future" states Dr. Avelino.

As growers seek to avoid CLR, old problems return. Coffee farms, which have been renewed with resistant CLR cultivars, have been found to be more susceptible to infection by *M. citricolor*. In years with cool temperatures and high rainfall, CLR intensity is likely to decline, only to see a resurgence of ALS. Climate change poses continuing challenges for keeping coffee plants free from disease.

Coffee Leaf Rust is Here to Stay

CLR is a devastating disease, which has plagued coffee cultivation for more than 150 years. This fungal leaf disease has played a role in history by mediating colonial shifts in trade, mass migration of central Americans and a great demise in the livelihoods of coffee farmers. The severe Latin American epidemics occurring from 2008 – 2012 may have been attributed to a combination of factors relating to new physiological races, poor plant health status, climate or ecological degradation. No matter the cause, there is still a need for more applied research exploring different modes of control of the disease.

Both chemical and non-chemical approaches are essential for implementation of an integrated pest-disease management system against CLR. Renovation of old coffee farms with less susceptible or more tolerant coffee cultivars could be a proactive approach to controlling the disease in the future. This is a costly practice in terms of time and resources. Although with complete renovation of old coffee farms, the overall plant health status would improve (due to the younger age of the plants and more vigorous vegetative growth) and a lower genetic susceptibility to CLR could be achieved. BCAs against CLR are still an under-utilised control method likely due to its variation in efficacy and lack of field data to support its mainstream use.

Previous estimates of global improvement strategies for the coffee sector are upwards of $5 billion USD (Sach et al. 2019). These estimations include costs relating to improved access to basic services and/or technical support for farmers across major coffee-growing regions worldwide. A concerted effort must be implemented by national coffee authorities together with the private sector in order diverge these necessary funds. A portion of such investments could be earmarked for the control of future outbreaks of CLR under challenging meteorological and geopolitical geographies.

Photo credits

Cover photo: Coffee rust and beans, North Kivu DRC. Photo Eric Boa.

Figure 1. Traditional coffee making in Ethiopia. Photo Eric Boa.

Figure 2. Coffee Collective Menu Board. Photo credit: https://www.brian-coffee-spot.com/2016/10/27/coffee-collective-torvehallerne/

Figure 3 (left). Coffee plantation. Travel memories Ceylon/ Aden and the Suez Canal. Oct 28, 1889 - Dec 30, 1891. Unknown author, CC BY 4.0 <https://creativecommons.org/licenses/by/4.0>, via Wikimedia Commons https://commons.wikimedia.org/wiki/File:KITLV_A512_-_Spring_Valley_coffee_ estate_bij_Badulla,_KITLV_98797.tiff . **(right)**. Coffee pounding in Ceylon in 1870's. Charles T. Scowen (Scowen & Co. Ceylon). https://lankapura.com/2008/06/pounding-ceylon-coffee-late-1800s/ CC BY 4.0.

Figure 4. The first scientific account of coffee leaf rust and naming of the fungus. Extract from The Gardeners' Chronicle and Agricultural Gazette (1869).

Figure 5. Sir Thomas Lipton ... on his yacht. Miscellaneous Items in High Demand, PPOC, Library of Congress, Public domain, via Wikimedia Commons. www.commons.wikimedia.org/wiki/File:Sir_Thomas_Lipton,_full-length_portrait,_standing_at_rail_of_his_yacht,_the_%22Erin%22_LCCN2005687140.jpg CC BY 4.0

Figure 6. (left) the devastating losses caused by coffee leaf rust paved the way for tea plantations. Photo Eric Boa.**(right)** Lipton Tea Canadian grocer July-December (1908). Publisher: Toronto: Maclean-Hunter Pub. Co. [1887]. Contributing Library: Fisher - University of Toronto CC BY 4.0.

Figure 7. Honduran migrants traveling to the US through the Chiapas state, Mexico in 2018. Photograph: Johan Ordonez/AFP/Getty Images. Accessed via [https://www.theguardian.com/world/2018/oct/30/migrant-caravan-causes-climate-change-central-america] on 8th June 2022.

Figure 8. Coffee growing is embedded in highland agriculture. Photo Eric Boa.

Figure 9. Arabica has been largely replaced by Robusta in Java, another consequence of CLR. Extract from Smith, N. J., Williams, J. T., Plucknett, D. L., & Talbot, J. P. (2018). Tropical forests and their crops. In Tropical Forests and Their Crops. Cornell University Press.

Figure 10. Coffee farming family near Zipaquira, close to Bogotá in Colombia. The low profitability of coffee and other crops limits responses to disease outbreaks. Photo Eric Boa.

Figure 11. Manual application of chemical control against CLR in coffee fields at the beginning of the rainy season (Nicaragua). Photo Yader Barrera (provided by Melanie Bordeaux).

Figure 12. Banana protects young coffee plants and provides additional income as they start to bear fruit, as seen here in Quindío, part of the Zona Cafatera in Colombia. Photo Eric Boa.

Figure 13. Shaded-coffee. Photo Benoit Bertrand.

Figure 14. Replanting of coffee in Risaralda, Colombia in full sun. Photo Eric Boa.

Figure 15. Coffee growing country around Jalapa, Nicaragua. Photo Eric Boa.

Figure 16. La Cumplida coffee estate. Photo Melanie Bordeaux.

Figure 17. (left) Franklin of PRODECOOP checks coffee seedlings in San Juan del Rio; **(right)** Guillermo, a local coffee farmer, brings his coffee to sell to the local coop in Jalapa on two horses. Photo Eric Boa.

Figure 18. Natural colonization of entomogenous fungus *Lecanicillium lecanii* on *Hemileia vastatrix* in Matagalpa, Nicaragua. Photo Melanie Bordeaux.

Figure 19. *Bradybaena similaris* feeding on *Hemileia vastatrix* urediniospores. Photograph by Gif by Zachary Hajian-Forooshani accessed via [https://www.nationalgeographic.co.uk/animals/2020/03/how-this-invasive-snail-could-save-your-coffee-from-destruction]

Figure 20. Disease cycles of *Hemileia vastatrix* made by Athina Koutouleas in BioRender.

Figure 21. (left) American leaf spot aka.or "ojo de gallo" (Nicaragua), caused by Mycena citricolor. **(right)** Mixed infection with coffee leaf rust., Domincan Republic. Photos Eric Boa.

Sources of Information and References

This report was based on an extensive scientific literature review. We have listed all the papers consulted below. Most of the key papers are referenced in the text at least once but others are not.

We have also consulted general sources of information, including Britannia online for details of Sir Thomas Lipton and FAO. FAOSTAT regularly updates area and production data for all coffee producing countries. The International Coffee Organisation provides an industry overview and perspective but with limited information on CLR. *The Coffee Guide* is an invaluable summary of all aspects of coffee production, including pests and diseases. The most recent edition (2021) is available online and has several useful nuggets on CLR. There are of course many other sources of information on coffee – too many to consider, and often quoting second-hand and ever more distant from an original account or paper – which also mention CLR.

We have interviewed several people to obtain a first-hand perspective and personal experiences of CLR. Individuals are named in the acknowledgements and in the main text.

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