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REVIEW ARTICLE

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Coffee wilt disease: The forgotten threat to coffee

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Abstract

Coffee is attacked by several highly damaging pests and diseases, which include coffee wilt disease (CWD). Despite a devastating impact in recent years, CWD receives little attention and its importance is downplayed or simply ignored. Memories are short and knowledge of past outbreaks fragmentary. Nearly two decades after the last major outbreaks, CWD has quietly faded into the background. This review describes a series of outbreaks of CWD across Africa, from Uganda to Guinea, from the first discovery in the 1920s to a hugely damaging recurrence that began in the 1970s and lasted through to the 2000s. This second wave had devastating impacts on growers and communities in the Democratic Republic of Congo and in Uganda. This review examines the origins of the disease, how and why it spread, and attempts to manage the outbreaks. Recent work on new pathogen variants is also considered. This review aims to recount these events and to evaluate the strategic successes and failures at national, regional and international levels in tackling the second wave of CWD.

KEYWORDS
Fusarium xylarioides, robusta and arabica coffee

1 | A CENTURY OF COFFEE WILT DISEASE

Coffee is attacked by several highly damaging pests and diseases. Coffee rust is perhaps the best-known disease and is caused by the fungus *Hemileia vastatrix*. It has a global distribution, is easily identified and has a significant effect on yields. Coffee berry disease, another high-profile fungal disease, is feared by growers in Africa, especially by those countries yet to record the disease. Both diseases can cause yield losses of up to 75% in severe outbreaks (Rutherford & Phiri, 2006).

These two diseases regularly feature in the news and scientific literature and are widely recognized as major threats to production. Coffee wilt disease (CWD) receives much less attention, despite its devastating impact in recent years, and its importance is downplayed or simply ignored. Memories are short and knowledge of past outbreaks fragmentary. Nearly two decades after the last major outbreaks, CWD has quietly faded into the background.

This review describes a series of outbreaks of CWD across Africa, from Uganda to Guinea, from the first discovery in the 1920s to a hugely damaging recurrence of CWD which began in the 1970s and lasted through to the 2000s. This second wave had devastating impacts on growers and communities in the Democratic Republic of Congo and in Uganda. This review examines the origins of the disease, how and why it spread, and the attempts to manage the outbreaks. Recent work on new pathogen variants is also considered. One of the purposes of this report is to recount these events and to review the strategic successes and failures at national, regional and international levels in tackling the second wave of CWD.

After the first wave of outbreaks, CWD seemed to disappear. A successful campaign to manage CWD in the 1950s appeared to have vanquished the disease. Yet the disease has always persisted, the pathogen hidden from view, ready to exploit weaknesses and break out again. The second wave began in the 1970s in the Democratic

Republic of Congo. Growers may not have recognized the disease while management of plantations continued to decline. Those that suspected the return of CWD had few ways of telling others about their concerns, nor was it clear who might respond to them. Over a period of about 15 years, the disease quietly proliferated in the north of the Democratic Republic of Congo before reaching Uganda.

The most important lesson from CWD is that the risk of disease re-emergence is greatly exacerbated when production systems collapse and trade is disrupted by conflict. It is difficult to prioritize action on a plant disease at a time when humanitarian help is most pressing. This is not, however, a binary choice. Focusing on a key crop and money earner, like coffee, could have resulted in a more secure future for hundreds of thousands of farmers emerging from unrest and disorder.

2 | THE RISE AND FALL OF CWD IN AFRICA

During the last century, CWD devastated coffee production in key producing regions of Africa, with catastrophic impacts for farmers and trade. In the last 30 years, at least $1 billion were lost and widespread farm closures occurred (Phiri & Baker, 2009). Uganda's coffee exports did not surpass pre-outbreak levels until 2020 (ICO, 2022). The disease was first observed in 1927 on *Coffea excelsa* in today's Central African Republic (Figueres, 1940). There were serious outbreaks of CWD in the 1940s and 1950s, referred to in this report as the first wave, before the disease faded from view. Improved sanitation measures and plant breeding programmes appeared to have banished CWD, at least until the second wave began in the 1970s in the Democratic Republic of Congo.

The first wave of CWD, in the 1940s and 1950s, was responsible for the commercial failure of *C. excelsa*, and changed the coffee production landscape of Africa. *C. excelsa* (now referred to as *C. liberica*) remains a minor species today in global coffee production; *C. arabica* and *C. canephora* (robusta) now dominate.

The onset of the second and more deadly wave of CWD, which began in the Democratic Republic of Congo, attracted little attention for many years. Coffee plantations that were affected by the disease were in areas of the country where civil society was weak and government authority was fraying. An increasingly uncertain business environment led to an exodus of owners and abandonment of unprofitable farms. CWD spread insidiously amidst growing social disruption and weakening technical advice and support. Coordinated responses to a dangerous and highly damaging disease did not take place.

Weak reporting and sharing of information compounded the failure to stem the advance of CWD beyond eastern Democratic Republic of Congo. Even when the threat posed by the disease to coffee growers in Uganda and further afield became apparent, there was a tardy response by institutions, governments and the international donor community. The result was that key research and coordinated responses to CWD did not begin until the early 2000s, more than 20 years after the disease had re-emerged.

BOX 1 Names change: A short guide

Scientists are used to seeing new names for fungi and other plant pathogens. Advances in genetic analyses have revealed new links and led to changes in genus and species names. The move to 'one fungus = one name' has also meant name changes. The coffee wilt pathogen *Fusarium xylarioides* is also referred to as *Gibberella xylarioides* in the earlier literature.

The scientific names of plants also change. *Coffea robusta* is now named *Coffea canephora*, but still referred to as robusta coffee; *Coffea excelsa* is now named *Coffea liberica*.

The post-colonial era often meant new names for countries, cities and provinces across Africa. The Belgian Congo became Zaire then the Democratic Republic of the Congo.

All changes to names are noted. Current names are usually used for consistency, even if a different name was in use at the time.

2.1 | The forgotten *Fusarium*

CWD is caused by *Fusarium xylarioides*, a soilborne fungus that induces a vascular wilt and kills coffee plants (see Box 1 for clarification of names and name changes). Although the disease was first identified in 1927, the precise cause was not confirmed until the late 1940s (Heim & Saccas, 1950; Steyaert, 1948). There are many important plant diseases caused by *Fusarium* species and they have been the target of extensive research. Much less research has been carried out on *F. xylarioides*; knowledge of CWD has, until relatively recently, been weak. We now know that CWD spread widely in the second wave because of the emergence of host-specific pathogen populations, one affecting robusta coffee (*C. canephora*) and the other affecting arabica coffee (*C. arabica*). The discovery of the robusta strain—the one that has caused most damage—was only identified many years after the second wave began and CWD was already widely established.

2.2 | The first wave of outbreaks and the loss of *C. excelsa*

Global coffee production is worth $22 billion in export value for green coffee beans (FAO, 2022) and is dependent upon two main species: *C. arabica* and *C. canephora*. At the time of the first major CWD outbreaks in the 1940s, coffee production in west and central Africa relied on a wider diversity of species. As the disease became widespread across this region, so coffee varieties succumbed to CWD; first *C. excelsa* and later other coffee species, notably *C. neo-arnoldiana*. It spread from the Central African Republic to *C. excelsa* plantations in the north-east of the Democratic Republic of the Congo and close to the border with South Sudan (Figure 1a) (Fraselle, 1950; Steyaert, 1948). *C. excelsa* in Cameroon became infected, as well as *C. canephora* plantations in the Ivory Coast (Flood, 2009). These outbreaks had devastating consequences, wiping out *C. excelsa* production in the Central African Republic and Cameroon, and spreading far and wide on robusta coffee in the Democratic Republic of the Congo and Ivory Coast, halving their coffee production and destroying key cultivars. By the late 1950s, CWD had reduced coffee production by 50% in Guinea (Chiarappa, 1969). Commercial production of *C. excelsa* (now *C. liberica*) in Africa never recovered (Rutherford, 2006).

In a relatively short space of time, CWD had spread extensively in east and central Africa. The spread to Ivory Coast in western Africa appears to have happened without CWD being found in intervening coffee-producing countries such as Nigeria. It is unlikely, however, that minor producers such as Nigeria had escaped CWD (Figure 1c), as Figure 1a might suggest, and more probable that the disease was missed or that reports were not widely shared. A later report of *F. xylarioides* on rotting tomato fruits in a market in western Nigeria (Onesirosan & Fatunla, 1976) was published, and author's unpublished data (L. D. Peck) have established that *F. xylarioides* is able to infect and damage tomato fruits.

The disease had travelled far from its origins and was causing increasing alarm internationally. A broad consensus was reached on how to manage this escalating disease: the systemic uprooting and burning of all infected trees; the search for host resistance in both wild and cultivated varieties; and breeding programmes to incorporate host-plant resistance in commercial varieties. These actions were successful across west and central Africa, with the recovery of robusta coffee production. Major reductions in the incidence and severity of CWD were seen. But this was not the end of CWD.

2.3 | The second wave of outbreaks and the decimation of coffee in the Democratic Republic of Congo and beyond

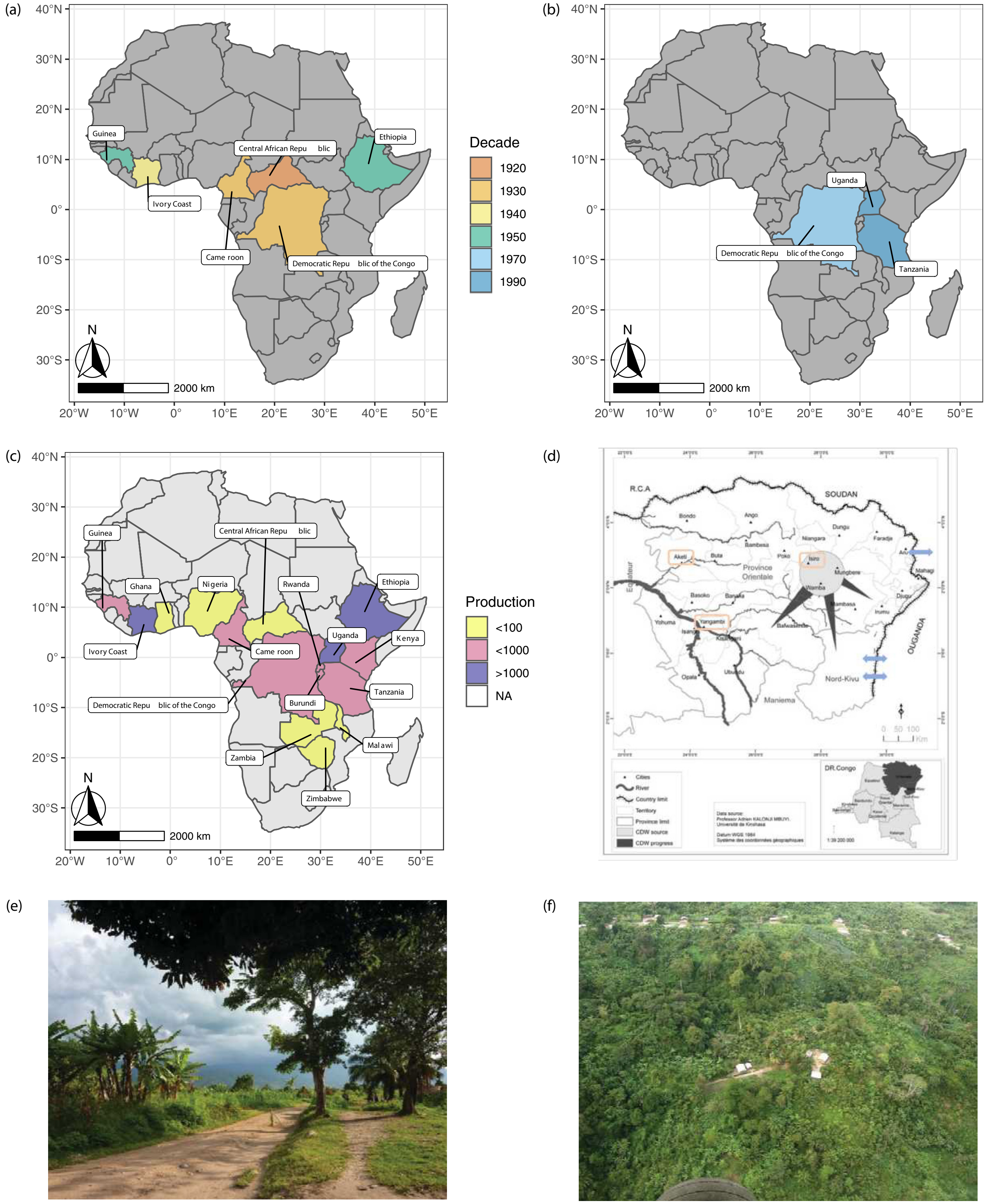
It was widely believed that the systematic uprooting and burning of infected trees and breeding programmes in response to the first outbreaks had removed the threat of CWD to *C. canephora* coffee production in Africa (Flood, 2009). There have been no subsequent records of CWD in Guinea, Cameroon or the Central African Republic, although recent reports suggest a re-emergence in Ivory Coast. Yet the disease had not gone away. It was still present in remote areas of the Democratic Republic of Congo, quietly spreading throughout the 1970s and 1980s in abandoned coffee plantations (Figure 1b). There were reports of a wilt-like disease from Aketi and Isiro, as well as from Yangambi, the site of an important research station close to Kisangani, a major city on the River Congo (Kalonji-Mbuyi et al., 2009). The reports describe a disease present over a huge area (Figure 1d)—Aketi to Isiro is almost 700 km by road—albeit in an area that remained neglected by the scientific and development communities. The re-emergence of CWD was confirmed in Haut-Uélé district in 1982 (Katenga, 1987).

By the mid-1970s, CWD had re-emerged on *C. excelsa* and robusta coffee on abandoned farms in the Democratic Republic of Congo and reached epidemic levels on robusta coffee by the 1980s (Phiri & Baker, 2009). By the early 1990s, it had spread into eastern regions of neighbouring Uganda and was endemic by the latter half of the decade (Birikunzira & Hakiza, 1997). The disease marched on and was reported in northern Tanzania for the first time in 1995 (Kilambo et al., 2009).

Subsequent research in the 2000s confirmed that the triangle formed by the territories of Isiro, Wamba and Mungbere was the primary source of epidemics in the north-east of the Democratic Republic of Congo. The spread of CWD steadily followed corridors of robusta coffee production for almost two decades, moving unchecked and eventually arrived in Uganda by 1993 and Tanzania in 1996 (Figure 1d) (Phiri & Baker, 2009). The disease was notably absent from Rwanda, even though CWD was widespread in neighbouring Democratic Republic of Congo, Uganda and Tanzania. Coffee production in Rwanda is based on arabica cultivars while surrounding countries predominantly grow robusta coffee.

The Democratic Republic of Congo experienced political turmoil and civil unrest from the moment it became independent in 1960. The eastern part of the country is physically and politically remote from central government and heavily affected by events in neighbouring countries, particularly Rwanda. The violent chaos that

FIGURE 1 Outbreaks of coffee wilt disease (CWD) detected in Africa over the past century. (a) The first wave of CWD (1920s–1950s) and CWD in Ethiopia. CWD originated in the Central African Republic in 1927 spread to surrounding countries and eventually reached the Ivory Coast and Guinea. CWD was reported in Ethiopia in 1957 and is considered to be a separate outbreak and not part of the first wave. Shading represents the decade in which CWD was first identified. (b) Second wave of CWD from the 1970s to present. Shading represents the decade in which CWD was first identified. (c) Coffee-producing countries and production. Shading represents coffee production in thousand 60-kg bags of coffee. (a–c) drawn in Rstudio using ggplot2 (R Core Team, 2021; Wickham, 2016). (d) CWD returns: the start of the second wave. The second wave of CWD began in the north-east Democratic Republic of Congo in Orientale province and progressed over about 20 years into North Kivu province. The initial source of the second wave was the triangle made up of Isiro, Wamba and Mungbere (shaded grey). Symptoms of CWD occurred over a wide area, as far west as Aketi and Yangambi (Flood, 2009; Kalonji-Mbuyi et al., 2009). CWD then moved across the border between North Kivu and Orientale provinces and Uganda. Main border crossings into Uganda are shown by double blue arrows, from Aru to Bundibugyo and Kasindi, furthest to the south. Infected material will also have been moved over porous intervening areas. RCA, Central African Republic; Soudan, Sudan; Ouganda, Uganda (from Kalonji-Mbuyi et al., 2009). (e) Kasunga border crossing from Bundibugyo, on the north edge of the Ruwenzori in Uganda to Kamango in Democratic Republic of Congo in 2009, showing the post that was unmanned from late afternoon to early morning. (f) Mixed farming, including coffee, on a typical smallholding near Bundibugyo in Uganda (close to Democratic Republic of Congo border). [Colour figure can be viewed at wileyonlinelibrary.com]



resulted from incursions, social disruptions and wrestling for control of key natural resources had huge impacts on the spread of CWD.

Illegal trafficking of coffee to Uganda accelerated with the first civil war in Democratic Republic of Congo, from 1996 to 1997 (Preface by Caleb Dengu, page IX, in Flood, 2009). There is little doubt that unregulated movement of coffee helped to spread the disease to Uganda and beyond (Flood, 2009). Internal conflict in the Democratic Republic of Congo flared up again in 1998 and unchecked movement of coffee over border crossings continued across a broad front (Figure 1d,e). Ugandan military personnel were taking coffee cherries, some still attached to bushes, for processing and sale back home (Preface by Caleb Dengu, page IX, in Flood, 2009).

The border between the Democratic Republic of Congo and Uganda has many coffee farms (Figure 1e). Coffee farmers who lived along the border crossing routes between the Democratic Republic of Congo and Uganda became aware of CWD symptoms in the 1990s. Coffee bushes were dying, though there was little understanding of the cause. There were reports of farms losing over half of their production and profits. In 1995, Philip Betts, the Managing Director of Esco Kivu, a commodity exporter, sent samples of diseased coffee plants to CABI in the United Kingdom and *F. xylarioides* was confirmed as the cause of the wilting epidemic (Flood, 1996). Finally, the international community took action and Dr Julie Flood, a CABI scientist, was asked by the International Coffee Organization to investigate further.

Flood travelled to North Kivu in the Democratic Republic of Congo in July 1996 and found many of the coffee growers in complete despair. It was for many the last in a series of disasters. 'They said they had previously felt lucky because they had beef, coffee and tourism as income sources. But guerrillas had stopped tourism [it was no longer safe to visit the gorillas in Virunga National Park], Rwandan refugees were stealing their cattle, and now they had this "coffee AIDS that is killing our coffee bushes"'. This local name of "coffee AIDS" for CWD encapsulated the fear that farmers had for its effect on coffee production.

In 1997, Flood carried out fact-finding surveys with the Uganda Coffee Development Authority and local scientists and extension officers to document the distribution and impact of CWD. Uganda knew that *F. xylarioides* had been identified from (robusta) coffee-growing areas in districts of the Democratic Republic of Congo close to the border. The surveys covered 10 major coffee-growing districts: Mukono, Mubende, Mpigi, Ntungamo, Kasese, Kabarole, Rukungiri, Bundibugyo, Kiboga and Masaka; all were infected with CWD. The disease had spread far and fast; Mukono, close to Kampala, is over 450 km from the nearest border crossing with the Democratic Republic of Congo.

The confirmation that CWD had spread over such a large area hastened the development of a major research proposal. In 2000, 3 years after the surveys, a wide-ranging regional coffee wilt programme began, with funding from the Common Fund for Commodities, the European Union and the UK Department for International Development. Finally, 25 years after CWD's re-emergence, and more than 5 years after detection in Uganda, a coordinated response was being taken (Phiri et al., 2009). The failure of research institutes, governments and extension services to work together was a key reason why CWD had re-emerged and spread in the Democratic Republic of Congo and had paved a path of destruction all the way to Uganda.

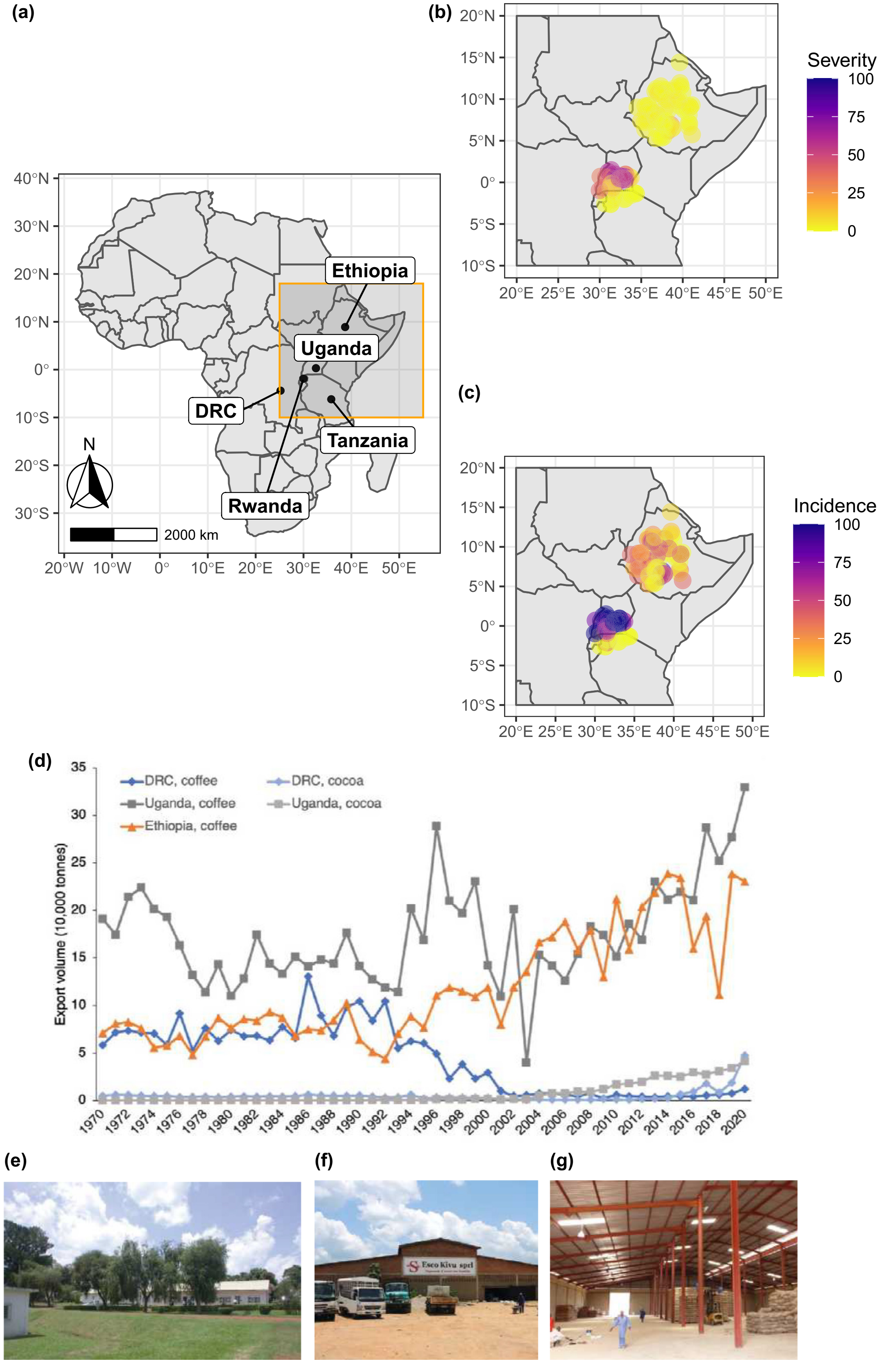
2.4 | Coffee wilt disease in Ethiopia

Ethiopia is the centre of origin and genetic diversity of arabica coffee and has the longest tradition of coffee consumption (Girma et al., 2009). The arabica strain of the CWD fungus was detected comparatively late, in 1957 (Lejeune, 1958), but it is likely that the disease had been present for some time, having co-evolved with its *C. arabica* host (Adugna, 1997; Girma et al., 2009). However, the CWD outbreak in Ethiopia was separate from the two waves of outbreaks recorded in other countries.

CWD was widespread on arabica coffee in Ethiopia by the 1970s, but by 2002, the incidence (30%) and severity (3%) of CWD were still relatively low (Figure 2b,c). This lower disease pressure in Ethiopia is thought to be linked to limited seed dispersal of arabica coffee trees compared to robusta and other coffee species, plus high levels of variation in CWD resistance in local coffee varieties (Adugna et al., 2009; Girma et al., 2009; Girma & Hindorf, 2001). Greater host heterogeneity is thought to reduce susceptibility to CWD and restricts the rapid spread of the disease (Getachew et al., 2012, 2013; Zeru et al., 2009). CWD is considered to be a minor problem in Ethiopia, and its coffee exports have yet to suffer large drops (Figure 1d). Arabica coffee is an important export crop, though volumes from Ethiopia are lower compared to other producers. Despite the economic value of arabica coffee to Ethiopia, the crop remains relatively under-exploited with the genetic potential of arabica coffee yet to be fully explored. Coffee production is largely on smallholder subsistence farms with traditional, low-input low-output systems, while plantation coffee is comparatively recent and still limited in extent.

However, over the last two decades, the impact of CWD has increased from an average of 30% incidence in 2002–2003 to an average of 42% in 2016–2017 (with 3/4 regions surveyed reporting

FIGURE 2 The impact of coffee wilt disease (CWD) on coffee trees and production across east and central Africa. (a) The countries surveyed for CWD incidence and severity in 2003. (b) Disease severity in the farms surveyed. Shading represents the percentage of trees affected by CWD on farms visited. (c) Disease incidence in the farms surveyed. Shading represents the percentage of farms with CWD presence. Only arabica coffee was affected in Ethiopia and only robusta coffee in Uganda and Tanzania. No data for the Democratic Republic of Congo; no CWD recorded in Rwanda. (a–c) drawn in Rstudio using data from Oduor et al. (2003) in ggplot2 (R Core Team, 2021; Wickham, 2016). (d) The impact of CWD upon exports from Uganda and Democratic Republic of Congo. The steep decline in coffee exports from 1995 to 2003 is closely linked to the impact of CWD and coffee exports are particularly reduced in volume in the Democratic Republic of Congo; note the rise of cacao exports, a replacement crop, as coffee exports fade and the rise of Ugandan coffee exports from 2004, possibly due to better yielding clones. Data from FAO, 2022, accessed 20 May 2022. (e) Mukono Agricultural Research Centre 2004: Uganda has a well-established network of institutes to investigate crop diseases. (f,g) The Esco Kivu factory in Beni, North Kivu was originally used for processing coffee. The factory has been renovated and new storage space added for cacao, which has largely replaced coffee in the province. [Colour figure can be viewed at wileyonlinelibrary.com]


(a)
Ethiopia
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(b)
Severity
100
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(c)
Incidence
100
75
50
25
0
(d)
DRC, coffee
DRC, cocoa
Uganda, coffee
Uganda, cocoa
Ethiopia, coffee
Export volume (10,000 tonnes)
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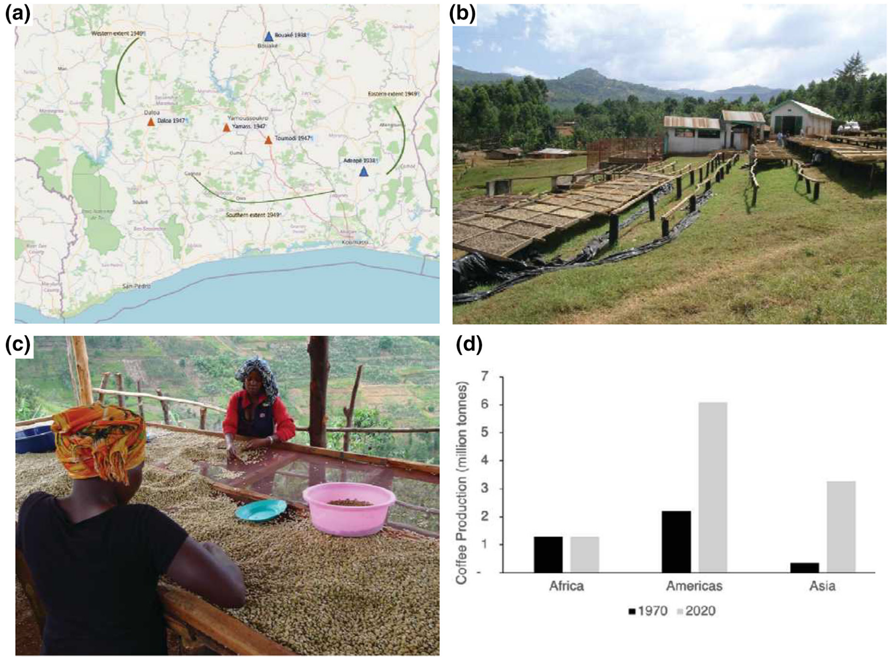

FIGURE 3 (a) A recent re-emergence of coffee wilt disease (CWD) in Ivory Coast. Early records describe CWD in Bouaké and Adzopé in the late 1930s (blue triangles, Meiffren, 1961). The disease reached Toumodi, Yamoussoukro and Daloa by 1947 (red triangles), suggesting an earlier development in eastern regions. Recently, CNRA, the national agricultural research organization, found that 14% of orchards were affected by CWD in Gagnoa, near the historic southern extent of CWD, in 2022 (Doua, 2023). (b) Coffee beans dry in the sun in western Uganda. (c) Selecting the best beans at a coffee co-op in Rwanda. In the distance, coffee is grown on many nearby small farms. (d) Global production of coffee in Africa, the Americas and Asia in 1970 and 2020. Data from FAO, 2022, accessed 20 May 2022. [Colour figure can be viewed at wileyonlinelibrary.com]

>42% incidence) (Mulatu & Shanko, 2019; Oduor et al., 2003). Higher incidences of CWD are found on coffee grown in gardens and plantation-grown coffee, linked to regular slashing, hoeing and pruning, practices that can inadvertently spread the pathogen; in contrast, forest and partially forested coffee systems, where wild and semiwild coffee trees are harvested, have lower CWD incidence (Getachew et al., 2012, 2013; Mulatu & Shanko, 2019; Zeru et al., 2009).

3 | DISEASE IMPACT

The re-emergence of CWD in the second wave had a profound effect on coffee production in Africa (Phiri et al., 2009). From 1970 to 2020, African coffee declined from nearly 35% of global production to 12% (Figure 3d), even though its coffee-growing area remained steady, at around 30% of the global total. Other diseases, such as coffee leaf rust and coffee berry disease, are an acknowledged reason for this decline, yet the impact of CWD is often underestimated. It is 15 years since the Regional Coffee Wilt Programme ended and the awareness of the disease has faded. It is therefore important to recall the changes that CWD brought about.

As already mentioned, prior to CWD, farmers grew a greater variety of coffee species. *C. excelsa* (now *C. liberica*) did not recover as a commercial crop in Africa, although *C. liberica* is still highly valued in countries such as Vietnam.

The Regional Coffee Wilt Programme was active across east and central Africa and worked in Ethiopia, Uganda, the Democratic Republic of Congo, Rwanda and Tanzania (Figure 2a). Wide-ranging activities (Phiri & Baker, 2009) included surveys of over 5000 farms to estimate incidence (proportion of coffee farms with infection) and severity (proportion of coffee trees infected per farm) on arabica and robusta coffee (Oduor et al., 2003). The surveys showed that, on average, farms had very old trees (50% over 15 years), low inputs and weeding by machete or hoeing and that the average incidence of CWD was surprisingly high (>30%) for a systemic disease that ultimately kills plants. As a soilborne fungal pathogen, it is typically not spread by pests or animals but has been found to expand locally over short distances (3–5 m) from infected trees, as well as over longer distances >15 m from infected trees and over 100 m in some cases (Pinard et al., 2016). Short-distance dispersal mechanisms include water run-off or root contact (Ploetz, 2006), while long-distance mechanisms are undetermined; aerial spore dispersal has been hypothesized (Saccas, 1951, 1956) but not reported for CWD, and human-assisted transport of infected plant material remains the most likely mechanism (Pinard et al., 2016). Disease incidence was always highest on older trees over 15 years and on farms with minimal maintenance and low inputs (Oduor et al., 2003; Pinard et al., 2016). The most associated human-drivers of disease incidence were the removal of weeds by slashing with a machete, which damages stems and provides an entry point, and the transport and use of infected wood elsewhere, with all types of infected wood debris able to trigger infection (Muengula-Manyi et al., 2016). The coffee cherries or their harvest were typically not associated with disease incidence. Thus, the specific features of coffee production in CWD-affected countries contributed to an ever-rising disease incidence.

The impact of CWD on farmers was made worse by repeated cycles of infection. In an interview with a Ugandan coffee farmer close to the Democratic Republic of Congo border at the end of 1999, Caleb Dengu noted "This farmer had 1000 coffee trees on his one hectare farm. He was originally earning US$ 1000 per annum from approximately 1000 kg of green coffee he produced from his field. He had a family of seven, with five children between 5 and 15 years. He did not hire any outside labour to assist with crop harvesting and processing. He supplemented his income by intercropping his coffee with bananas, a staple food crop in the area. By 1999, the yield from the coffee farm had reduced from 1000 kg to 400 kg, a 60% decline in income." (in Flood, 2009). CWD had a devastating impact on the farmer's family, his children's ability to attend school, the affordability of healthcare and basic foods for survival.

Based on average coffee yields, losses due to CWD in Uganda were estimated to be 350 kg per hectare per annum and 276 kg per hectare in Ethiopia. This represented annual losses per hectare of $232 and $275, respectively, vast sums for smallholders with small plots. Surveys in Uganda, Ethiopia and Tanzania in the early 2000s revealed that nearly 30% of coffee farmers interviewed had sold land, livestock and even bicycles to make up for shortfalls in income. This loss of income meant that growing coffee was no longer a reliable way to sustain livelihoods for many farmers. Lower incomes made it difficult to afford the inputs needed to manage plots and attempt to restore productivity (Charveriat, 2001). Matters were made worse by the falling price of coffee on global markets. But it was CWD that, for many, had the clearest direct impact. The surveys found an increasing despondency among farmers; a majority abandoned attempts to control CWD because it was time-consuming and having little effect in their plots. But this also allowed infections to continue and for CWD to spread to new areas.

4 | THE AFTERMATH OF COFFEE WILT DISEASE

4.1 | Recovery of coffee production in Uganda

By 2009, it was estimated that a third of coffee farms in the Democratic Republic of Congo had been abandoned (Kalonji-Mbuyi et al., 2009). Annual exports had collapsed from an average of 85,000 tonnes between 1985 and 1995 to less than 20,000 tonnes in the following decade (Figure 2d). At the same time as this decline, Ugandan coffee exports peaked, largely because of the removal of tightly controlled quotas and opening of its coffee markets. This trade liberalization drew in coffee from the Democratic Republic of Congo, and, most probably, plant material infected by CWD. From 1996 onwards, CWD caused the collapse of Ugandan coffee production; nearly half of Uganda's robusta crop was destroyed, with losses of over $100 million; around half of Uganda's smallholder farms were badly affected (Phiri & Baker, 2009; Uganda Coffee Development Authority, 2015). Ugandan coffee exports continued to decline for nearly a decade before they began to recover in 2005. The original volume of coffee exports in 1995 was not regained until 2020. The coffee industry of Democratic Republic of Congo never recovered.

Uganda was able to weather the impact of CWD because it had better governance, stronger institutes and responsive markets. Yet the Ugandan government was also slow to respond to CWD despite the persistent concern expressed by scientists. It did not help that others considered CWD to be a minor disease until overwhelming evidence of the threat was impossible to ignore. The international response to CWD was, for many years, underwhelming. The International Coffee Organization only took decisive action in 1996, nearly 25 years after reports of the disease's re-emergence in the Democratic Republic of Congo.

Funding for research and farmer initiatives in eastern Africa started in the early 2000s under a regional coffee wilt programme. Although late to get under way, these collaborations helped Uganda to respond decisively. The Ugandan Coffee Development Authority, National Coffee Research Institute and Agricultural Research Centre Organization were key partners in initiatives to help farmers (Phiri et al., 2009) (Figure 2e). Uganda had experienced plant pathologists and coffee breeders plus strong political support. The Ugandan government distributed newly developed clonal coffee trees to farmers who were being asked to destroy their crops in order to reduce the threat of CWD. Some farmers replanted with cacao and bananas. Farm advisors (extension agents) were trained to disseminate information and coffee-growing was moved to new areas in the north. Positive steps were taken to help farmers recover and rural economies to stabilize. However, despite these positive responses, the impact of CWD in Uganda, as discussed in a later section, remains deep.

4.2 | Coffee's collapse in Democratic Republic of Congo and the rise of cacao

CWD was one of many problems facing coffee farmers in the Democratic Republic of Congo. Persistent fighting between different groups, fuelled by rivalries between and within neighbouring Uganda and Rwanda, had huge disruptive effects on coffee production. Farmers also had problems getting their crop to market. A collapse in the global coffee price in the early 2000s inflicted further pain. The ability of farmers to withstand these shocks was undermined by the inability to prove legal ownership of their land. Without this, they were unable to declare bankruptcy and start anew. Following CWD's decimation of production, the Democratic Republic of Congo coffee industry did not recover. Many factories in eastern regions, which once processed up to 3000 tonnes of coffee per year, now stand empty (Figure 2f,g).

Weak governance and a lack of social support services in Democratic Republic of Congo meant that farming families were exposed to financial ruin when coffee failed. The advisory services that had existed to support commercial plantations had gone by the time CWD started to wipe out coffee production. Universities were in disarray and poor security meant that it was difficult for development projects to function. This relentless sequence of problems and challenges facing farmers and the people of the Democratic Republic of Congo will be familiar to anyone reading news reports from the mid-1990s to the early 2000s. Eastern Democratic Republic of Congo is an unstable region and there are many dangers and challenges to overcome, especially in agriculture, which was the dominant enterprise for the millions of people living there. Yet despite the catastrophic impact of CWD, there is good news to report.

Even before CWD became a major problem, there were uncertainties in relying on coffee for a steady and reliable return. When coffee no longer became a viable crop, businesses and farmers sought alternatives. Despite the many ructions and decline in commercial businesses, many private enterprises continued to function in eastern Democratic Republic of Congo. The region exports papain (from papaya) and is a major producer of quinine bark. The land is fertile and the farmers are resourceful, willing to work hard and prepared to try new crops. Over the last 20 years there has been a dramatic emergence of cacao as a key commodity in North Kivu, a crop championed by Philip Betts of Esco Kivu and implemented by a dedicated team of local staff, including agronomists.

The growing conditions for cacao in North Kivu are excellent, as indicated by a well-established cacao industry centred on Bundibugyo in neighbouring Uganda. Cacao has many advantages compared to coffee, with higher international prices and a harvest period spread over 8 months, in contrast to coffee, which is harvested once a year over a short period of weeks. The success of cacao as a replacement crop for many farmers in North Kivu is demonstrated by the 50,000 tonnes exported in 2020, making the Democratic Republic of Congo one of the top producers globally. While cacao production in the Democratic Republic of Congo is not in the same league as in Ivory Coast or Ghana, the top two global producers, the rapid increase in output over the last 20 years has been a stunning achievement and one that deserves to be more widely acknowledged and celebrated.

4.3 | Revisiting Ivory Coast

In February 2023, it became apparent that there has been a resurgence of CWD in Ivory Coast, within the same area as the earlier outbreak (Figure 3a). A news report (Doua, 2023) stated that

> According to the National Center for Agronomic Research (CNRA), tracheomycosis (coffee wilt disease) appeared in Côte d'Ivoire in the 1930s and 1950s, destroying many agricultural plantations. At that time, the colonizer found a solution to introduce new, more resistant varieties of coffee. This is how robusta coffee made its appearance in the Ivorian agricultural world. More than half a century later, tracheomycosis is back. It is found in all coffee-producing areas of the national territory.
>
> A survey carried out last year (2022) by the Centre Nationale pour La Recherche Agricole (CNRA) reveals that in Gagnoa, 14.2% of the orchard is affected by tracheomycosis, out of 169 plots visited. In the sub-prefecture of Guépaho, in the department of Oumé, around the 2000s, we had 16,000 hectares of coffee, compared to 5000 hectares today. In the Upper Sassandra region, for example, the orchard contamination rate is estimated at 50%.

Extension agents from the national agency for rural development support were trained in methods for combating CWD. The training also included water-saving techniques based on mulching (Dogoui, 2023). The exact details of what are happening in Ivory Coast, and indeed in other countries in West Africa that have previously reported CWD, are still unclear. But there is little doubt that, despite past efforts to eradicate the disease, the pathogen is still present.

5 | COFFEE IN AFRICA

Coffee is one of the most popular drinks around the world. It has a complex production chain and is a multibillion-dollar business. Together, arabica and robusta coffee account for most of the global coffee trade. Arabica coffee occurs naturally in mountainous areas of around 1500 m a.s.l. and above in Ethiopia and South Sudan, where the risk of coffee leaf rust is lower. Coffee leaf rust is a major yield-limiting disease, harder to control than CWD because it is readily dispersed by airborne spores, whereas CWD is primarily spread by humans. Robusta coffee has a wider geographic origin, from Liberia in western Africa to the Congo basin. It is a hardier crop, cultivated at warmer, lower tropical altitudes, between about 800 to 1500 m a.s.l.

Arabica coffee has been cultivated in Ethiopia for many years. Wild relatives are thought to have been consumed for millennia (Davis et al., 2019). Robusta coffee is a relatively new species, only officially recognized at the turn of the twentieth century. In less than 150 years robusta has grown from a minor African crop to a major global commodity. It rapidly increased in popularity due to its resistance to coffee leaf rust, higher productivity and more flexible growing requirements. However, its overall taste profile is considered inferior to arabica coffee; robusta is widely and primarily used in instant coffee.

Coffee is the most traded tropical product around the world (FAO, 2022). Coffee beans are usually exported, with little added value for producing countries from processing and marketing. Some countries have invested in facilities for domestic sales and export, but quality control is challenging.

Despite the lack of added value in sub-Saharan Africa, coffee is a mainstay of national economies in over 20 countries. It contributes significantly to foreign exchange earnings and plays a key role in employment and as a source of income. Ethiopia and Uganda rely on coffee exports for over half of their foreign exchange earnings, contributing nearly $750 million and $515 million, respectively in 2020 (FAO, 2022).

Most coffee farms are small and family run (Figure 3b), with an average size in central Africa of 1.3 hectares (approximately two football pitches) (Figure 3c). Although well-managed commercial plantations still exist, the majority of production is from plots that have low inputs, old trees (over 15 years), poor soil and low yields (Phiri & Baker, 2009). Coffee production in Africa has struggled to keep pace with producers in South America and Asia, hampered by low investments, limited used of improved cultivars and poor management.

CWD has reduced yields significantly and encouraged farmers to look at alternative crops (such as cacao in the Democratic Republic of Congo). However, there remains a lingering attraction for coffee, given that it has been grown for many years, even if yields are suboptimal and prices vary. Farmers in North Kivu still grow coffee and, apart from cacao, alternative crops may have a lower value and limited markets.

6 | THE PATHOGEN AND HOST SPECIFICITY

There has been considerable debate over the naming and identity of *F. xylarioides* since its initial description by Steyaert (1948). The fungus was formally but incorrectly described in 1971 as a heterothallic species, with perithecia (the fruiting bodies) formed when two mating types grew together (Booth, 1971). The existence of 'male' and 'female' strains was later questioned by Gerlach and Nirenberg (1982) and Nelson et al. (1983). They agreed with Steyaert's original description, in which he described only a 'female' strain. Booth's 'male' strains of *F. xylarioides* were later assigned to a different species, *F. stilboides* (Gerlach, 1978). It took many more years before Geiser et al. (2005) confirmed that the 'female' strains are *F. xylarioides* and the so-called 'male' strains correspond to *F. lateritium*.

The mistake in characterizing *F. xylarioides* took over 50 years to correct, muddying attempts to confirm the cause of CWD and potentially delaying decisive actions to control it. However, it is also important to note that Booth had limited material to examine. Collecting samples from CWD-affected areas and sending fresh material to expert mycologists was always a fraught exercise.

6.1 | The discovery of host-specific strains

Two distinct host-specific strains exist, one restricted to arabica in Ethiopia and the other infecting robusta in Uganda, the Democratic Republic of Congo and northern Tanzania (Figure 4a,b). This explains the absence of CWD from Rwanda, where arabica coffee predominates. Neighbouring Democratic Republic of Congo, Uganda and Tanzania all have the robusta-specific pathogen. Recent work has shown that the two strains diverged before the start of the second wave (1970s onwards) and are thought to have co-evolved with their hosts (Buddie et al., 2015; Phiri & Baker, 2009). This host divergence has resulted in distinct phylogenetic lineages, suggesting that *F. xylarioides* is a species complex containing several cryptic lines, and not a single species (Lepoint et al., 2005). Of concern, each host-specific strain is able to infect *C. arabica* or *C. canephora* from different countries, making CWD a potential global threat to coffee production (Girma et al., 2007).

6.2 | Arabica-specific fungal populations

It is important to emphasize that the *F. xylarioides* arabica strain is only found in Ethiopia. Its discovery on wild forest coffee in Ethiopia highlights a wider risk to cultivated coffee and a threat to natural populations of coffee (Adugna et al., 2005; Girma et al., 2009). The arabica strain is clearly a threat to other countries growing this coffee variety and needs careful monitoring (Girma et al., 2007).

6.3 | Robusta-specific fungal populations

The *F. xylarioides* robusta strain is found across east and central Africa, is well established throughout Uganda and the Democratic Republic of Congo, and is restricted to the north-east region of Tanzania that borders Uganda and Rwanda. The robusta strain causes a more serious disease than the arabica strain (Oduor et al., 2003), although differences in severity have been observed between strains (Tshilenge-Djim et al., 2011). Surveys in Uganda in 2002 revealed that CWD was found on 90% of farms and 45% of coffee bushes, with a national yield loss of 80% (Figure 2a–c) (Oduor et al., 2003).

In 1997, Lukwago and Birikunzira (1997) estimated that up to 50% of coffee trees in the western region of Uganda had been killed by CWD. The rapid disease spread of CWD to eastern Uganda was linked to the collection and transplanting of contaminated forest seedlings and forest soil, a cheaper source of new plants compared to the more expensive but cleaner nursery-raised seedlings.

6.4 | Genetic diversity of *F. xylarioides*

Work continues on the different phylogenetic species of the pathogen, using live material stored in different culture collections, notably that maintained by CABI in the United Kingdom. Its collection contains nearly 70 living isolates of *F. xylarioides* dating back to the 1950s. The first suggestion of cryptic species, that is in addition to the two host-specific strains, was made in 2005 by Geiser and colleagues. They showed that the arabica and robusta groups had different alleles for a single gene used in comparing *Fusarium* species. These alleles were not found in pre-1970s strains—those associated

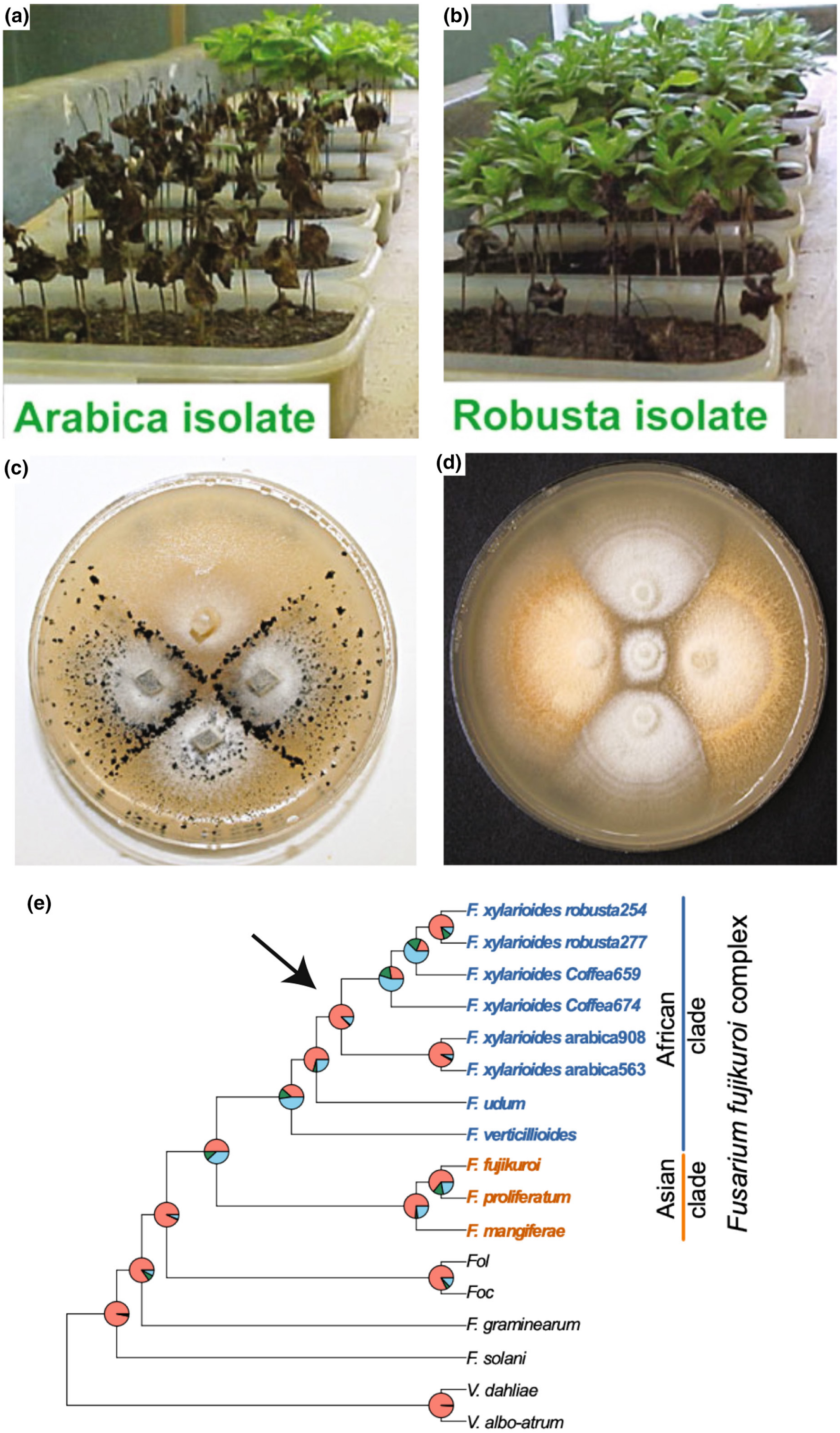

FIGURE 4 Arabica and robusta host-specific strains of coffee wilt disease. (a) Arabica and (b) robusta strains of *Fusarium xylarioides* were used to artificially inoculate seedlings of both *Coffea* types. Only the *Coffea* host types associated with each *F. xylarioides* strain type became infected and developed symptoms, as represented by the dead and dying seedlings in the foreground. Unaffected seedlings at the rear are the unassociated cultivars in each instance. Photographs: CABI. (c) Isolates of the same strain produce perithecia (fruiting bodies, black dots) along the crossing boundaries between *F. xylarioides* arabica strains (white). Photograph: Mike Rutherford. (d) Incompatibility of the host-specific strains. The arabica (white) and robusta (orange) strains do not produce perithecia at the boundaries of growth. The absence of perithecia suggests they are separate biological species. Photographs: Mike Rutherford. (e) Phylogenetic tree of relationships between *Fusarium* species. *F. xylarioides* strains have a single common ancestor (shown by the single branch denoted with an arrow) and are part of the *Fusarium fujikuroi* species complex. The pie charts show the resolution of the species clade phylogeny, with the pink shading representing the number of genes that support this phylogenetic tree. Blue and green shading represent alternate tree topologies. From Peck et al. (2021). [Colour figure can be viewed at wileyonlinelibrary.com]

with the first wave of outbreaks. Lepoint et al. (2005) subsequently showed that the pre-1970s strains (first wave) were sexually incompatible with isolates associated with the second wave in the Democratic Republic of Congo, Uganda and Tanzania (Figure 4c,d). Molecular differences between the arabica and robusta populations were further described (Adugna et al., 2005; Buddie et al., 2015; Olal et al., 2018).

The first analyses of historic genetic material were on highly degraded isolates; molecular markers and target probes targeted a small number of genes (Brewer et al., 2019). Recent advances in genome sequencing and bioinformatic analysis, combined with living isolates held in culture collections, offer new opportunities to explore the full genetic diversity of *F. xylarioides*. Unlike dried plant specimens, isolates stored using cryopreservation, for example, can be cultured and analysed using advanced techniques in the same way as freshly collected isolates. Peck et al. (2021) used six historic isolates from the CABI culture collection to describe high-quality genome assemblies of two strains from the earliest outbreaks (pre-1970s). The isolates included those from the first wave as well as two isolates each from robusta and arabica outbreaks from the mid-1990s, when the second wave was under way.

This genomic data support the independent emergence of the arabica and robusta host-specific strains. The arabica strains are a distinct evolutionary group from the robusta strains and those isolated from the first outbreak, called 'coffea' for their ability to infect multiple *Coffea* species (shown by their independent branch in Figure 4e); in contrast, it appears the robusta strains from the second wave evolved from the coffea strains from the initial 1920s to 1950s outbreak (Figure 4e). The arabica strain in Ethiopia did not originate from the second wave in the Democratic Republic of Congo and beyond. This strain has been present in Ethiopia for some time, as originally suggested by Flood and Rutherford at CABI. Recent data have revealed the presence of four genetically distant populations: arabica, robusta and two populations within the historic coffea strain group (L. D. Peck, unpublished data).

The ability to characterize and trace the origins of strains demonstrates the importance and value of culture collections. The results help to understand the historical spread and impact of CWD. Peck and colleagues work shows the importance of high-throughput genome sequencing in revealing the emergence and divergence of *F. xylarioides* by analysing the genetic footprints of earlier disease outbreaks preserved in collections. Further analyses may help to reveal how the different disease populations emerged and how host specificity arose.

7 | DISEASE DIAGNOSIS AND DETECTION

F. xylarioides is a soilborne fungal pathogen, is the primary cause of CWD, and coffee is its only known major host. In Uganda, a large study which tested 270 non-coffee plants taken from areas surrounding infected coffee trees failed to isolate *F. xylarioides* (Kangire et al., 2002). However, there are a handful of instances where the fungus has been isolated from other plants. It was found on banana roots together with *Fusarium oxysporum* (the cause of Panama wilt) in Uganda (Serani et al., 2007) and on cotton seeds (Pizzinatto & Menten, 1991). There is also a report of *F. xylarioides* on tomato fruit in a market in Nigeria (Onesirosan & Fatunla, 1976). Replication of the methods of Onesirosan and Fatunla (1976) confirmed tomato fruits as additional hosts in which they were damaged by infection (L. D. Peck, unpublished data). Other hosts are therefore likely to exist, albeit they are as yet undetermined.

The wilt associated with *F. xylarioides* infections results from a proliferation of the fungus within the host and subsequent blocking of xylem vessels, which transport water within the plant. Leaves dry up, plants are defoliated and branches die back (Figure 5a,b,g,h). CWD produces a characteristic blue-black staining underneath the bark. Cracks develop and trunks swell and, under the right conditions, fungal fruiting bodies (perithecia) are produced on dead tissue (Figure 5c–f; Flood, 2009).

The fungal pathogen can infect coffee plants of all ages, from seedlings to mature trees. Plants are killed and die between 3 and 15 months after the first appearance of symptoms (Flood, 1996). Spores are spread 3–5 m to adjacent coffee plants by soil, rain and wind, as well as to greater distances of more than 15 m by long-distance dispersal mechanisms that are probably human assisted (Pinard et al., 2016). The physical movement of infected plants by people hastens the spread and distribution of the disease and removing weeds with a machete can inadvertently wound stems, providing an entry point for the fungus (Oduor et al., 2003).

7.1 | In the field

Confusion in identifying *F. xylarioides* was only part of the problem in reacting swiftly to the second wave of CWD in the 1970s. Identification of *F. xylarioides* was historically based on morphological characteristics, and it requires mycological expertise to distinguish the CWD pathogen from other *Fusarium* species associated with damage to coffee (though of lesser significance). Of arguably greater importance in diagnosing CWD, however, was the unfamiliarity of the disease to farmers and extension staff, and confusion in identifying the symptoms in the field. There is no doubt that a shortage of experienced extension staff and lack of information on CWD hampered early detection. Yellowing of leaves, leaf drop and decline of coffee plants can occur for many reasons. Few understood the importance of looking under the bark for the darkened tissues, a distinctive feature of CWD (Figure 5d–f).

A recent article in New Vision, a leading newspaper in Uganda, described an attempt to identify the cause of wilting and death of plants during the outbreaks in the 1990s.

> When the bark was scraped off from stems of affected plants, there was no blue-black streak characteristic of *F. xylarioides*; instead, only brown to dark brown disintegrating or rotting tissues were observed. From the samples collected, the fungi recovered in the laboratory were *F. stilboides*, *F. lateritium*, *F. solani* and *F. oxysporum*, which can also cause wilting, and (suggested) death of plants under stress. In addition, there was a high incidence of stem borer attacks leading to wilting and death of trees in the same fields. Subsequently, CWD was recovered when the other fungi had become less frequent.

Extract from *Kibirige's Innovation Saved Coffee Sector* published 9 May 2022 (Kato, 2022).

FIGURE 5 Symptoms and treatment of coffee wilt disease (CWD). (a) Loss of leaves, wilting and death of coffee cherries. (b) One-sided dieback (denoted with a white circle). The plant will die. (c) Leaves dry up as stems dieback. (d) Well-defined border between stained (dead and dying) and healthy tissue. (e) Bark cut away to confirm typical blue-black staining. (f) Perithecia (fruiting bodies) of the fungus in bark cracks. (g) Initial wilting of infected plant and mild yellowing. (h) Poor management and care of plants can lead to death of branches and yellowing. (i) Uprooting and burning is the most effective eradication strategy for CWD. (j) Farmers practise a new pruning technique to reduce wounds to the coffee trees. (k) A coffee farm mulched with dry grass to suppress weeds. (l) Underplanting with *Desmodium intotum* to suppress weeds. [Colour figure can be viewed at wileyonlinelibrary.com]

There was low awareness of CWD in the 1990s and few farmers in the Democratic Republic of Congo and Uganda knew of the disease. This did not stop farmers recognizing the importance of this unknown wilt and giving it local names, all variations on "the one that wilts".

7.2 | Advances in laboratory diagnosis

New molecular tools are available to analyse and compare fungal DNA. All require specialized equipment, chemicals and materials that are only found in advanced laboratories. There are few plant diagnostic laboratories in North Kivu and none with the facilities to undertake molecular identification. Morphology is still a useful way to identify *F. xylarioides* (Kato, 2022), but cannot distinguish between the arabica and robusta strains. It is possible to distinguish the strains when grown on a nutrient-rich potato dextrose agar medium with exposure to UV light: only the robusta strains develop an orange pigmentation.

Previously, biological species recognition was used to differentiate strains, in which different species were recognized if their sexual stages could not undergo mating (Lepoint et al., 2005). However, molecular methods offer the greatest accuracy in identifying *F. xylarioides* and have replaced the now outdated biological species concept. These methods were still at the early stages of development in the 1990s. Since then, researchers have used individual gene studies and random amplified polymorphic DNA (RAPD) analysis to differentiate arabica and robusta strains (Adugna et al., 2005; Buddie et al., 2015; Olal et al., 2018). With the recent development of next-generation sequencing, the evolutionary history of the host-specific strain groups has begun to be elucidated.

8 | STOPPING THE SPREAD

Much more could have been done to raise awareness of CWD and limit movement of planting material following the onset of the second wave. Simple steps would have slowed and even stopped disease spread, such as training farmers to recognize the disease and working with extension and advisory services to promote recommended integrated pest management measures. Better reporting and coordination of information on outbreaks and disease advances would have encouraged stronger interventions.

There is no quick fix for CWD, no magical chemical treatments. Control is all about prevention, stopping the spread, early detection and eradication. Planting healthy coffee seedlings free from soil reduces the risk—most commercial arabica and robusta coffee is grown from seed, along with significant volumes of clonal propagation, particularly from disease-resistant varieties identified in trials. Some farmers may propagate their own seed, either to save money or because they cannot get hold of superior clones. Recommendations to avoid movement of infected coffee plants within farms—let alone between neighbours or further afield—limits spread. Encouraging farmers to stop using machetes to clear weeds by encouraging the use of mulches to suppress weeds and the use of cover crops (Figure 5j–l) requires more concerted effort but is still feasible. A rigorous and systematic programme in which affected trees plus their surrounding neighbours or whole farms are burnt (Figure 5i), with farmers compensated and helped to diversify into alternate food crops would help to break the pathogen lifecycle (Tshilenge et al., 2010). It was common practice to use infected wood as firewood or as fencing material for other crops. When giving advice it is important to consider practical alternative methods or sources of material that farmers can use.

Host-resistance is a promising avenue to prevent future spread. While there are currently no commercial varieties that are resistant to CWD, recent work in this area found genetic variation in host resistance in clonal trials, and that genetic improvements in resistance are possible by focusing upon tolerant parent lines in breeding programmes (Musoli et al., 2013).

9 | FINAL THOUGHTS

Over the past century, two major waves of CWD outbreaks had a huge impact on coffee growing in Africa. The first discovery of the disease in the 1920s in the Central African Republic presaged a spread throughout eastern and western Africa, eventually reaching as far as Guinea in the late 1950s. This changed the coffee production landscape, devastated livelihoods and had wide social and economic consequences. A key commercial species *C. excelsa* (*C. liberica*) was wiped out during the first outbreaks, while the second wave of CWD, beginning in the 1970s, destroyed coffee production in eastern Democratic Republic of Congo where many coffee farmers now grow cacao, and in Uganda export volumes did not recover until 2020.

Today, CWD appears to be managed well in robusta-growing areas in eastern and central Africa. There are reports of a worsening impact on coffee in Ethiopia, but CWD is still a relatively minor problem there. There are some suggestions that CWD is active in Ivory Coast after 70 years of absence, though information is sparse, and thus, there is no excuse for complacency. The second wave of CWD showed that the disease can easily re-emerge and spread. It is important that governments across Africa and beyond are prepared for new outbreaks of CWD and that the coffee community, extension systems and researchers are ready to respond quickly. The same applies to other coffee diseases (as well as other major crop diseases).

CWD is considered to be an African disease but, given that coffee germplasm from other coffee-producing and -exporting countries around the world is also susceptible to *F. xylarioides*, awareness of the global threat from CWD needs to be raised. There are worries that CWD could spread into new Afrotropical coffee-producing and -exporting countries, or beyond into Asia and South America. For many years the Americas remained free of coffee leaf rust, which also originated in Africa, until the 1970s. It then spread rapidly beyond Brazil to Central America and Mexico. Although the risk of CWD spreading outside Africa is low—spread is mainly through movement of infected planting material—Brazil and Vietnam should be alert to possible incursions. Both have extensive plantings of robusta, the mainstay of a valuable coffee-based trade. It is unclear what actions are being taken to strengthen links to research institutes in Africa or to select coffee lines that exhibit resistance to CWD. If we are to avoid future plant pandemics, we must heed the lessons of the past.

Early reporting is vital, as is confirming an outbreak. Much more could have been done to raise awareness of CWD and limit the movement of planting material following the onset of the second wave. One of the pitfalls of CWD was the delay both to recognize the second wave itself, and to establish the on-the-ground Regional Coffee Wilt Programme. The process of obtaining international funding is slow and often convoluted, and such delays are a symptom of this process. If the key coffee stakeholders, from coffee roasters to research institutions, could agree to prioritize funding for disease prevention and preparedness, we may never reach the point of a third wave. Ensuring an easy supply to farmers of commercial coffee varieties that are resistant to CWD is important, as is connecting research and technical advances. Rapid diagnostic tests and an emergency plant health fund to tackle initial responses to disease outbreaks, combined with strengthened networks of trained extension agents would mitigate the impact on crops beyond just coffee. These would facilitate a monitoring and early-warning system, and costs could be shared across diverse crops. The international community should act to support such a move, not just to protect their morning espresso, but to protect a food-secure future and the livelihoods of our international smallholder growing communities.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed.

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