

Article

Epidemiology of Cocoa Swollen Shoot Disease (CSSD) on Rehabilitated Cocoa Farms in South-Western Côte d'Ivoire

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Simple Summary

Cacao is an important commodity in the production of chocolate, and Côte d'Ivoire currently leads the global cocoa bean supply, with 40% of production. The sustainability of cacao production, mostly grown by smallholder farmers, is, however, threatened by the cocoa swollen shoot disease. This study was thus designed to understand the occurrence, distribution, and progression of this disease on rehabilitated farms. The goal is to use epidemiological knowledge to support the disease control strategy based on the removal of all infected cacao plants, to be replanted with tolerant cacao varieties. The results of this study indicate that the disease can reappear more rapidly than expected under specific conditions linked to cultural practices, the resistance level of the cacao planting material, and farmer awareness. The lessons learnt from this study are important for the integrated management of the disease and for the efficient protection of young and replanted farms. This study highlights the need for a collaborative effort to control cocoa swollen shoot disease in West Africa, thereby enhancing the livelihoods of cocoa farmers and improving the resilience of the cocoa supply chain.

Abstract

This study was conducted to understand the reinfection pattern of cocoa swollen shoot disease (CSSD) in rehabilitated plots in the cocoa landscape of the Nawa region (Soubré) in Côte d'Ivoire. CSSD was monitored over time on a sample of 200 farms randomly selected from 1200 rehabilitated cocoa farms. Disease epidemiological parameters were assessed through field observations and molecular diagnostic analysis at farm and landscape levels. The results of this study showed that reinfection occurred earlier than expected, with a high disease incidence estimated at 6.95% from 2020 to 2022. Grafting with clones on mature cocoa trees was more susceptible to reinfection than grafting on seedlings and hybrids. The use of PCR as a molecular diagnostic tool indicated missed infections in the current removal strategy when considering the buffer zone recommended in the cutting out process currently in place. Recommendations for the efficient protection of rehabilitated farms after cutting out campaigns are highlighted.



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Keywords: cocoa replantation; grafting technology; virus epidemic; CSSD reinfection; PCR

1. Introduction

Cocoa swollen shoot disease (CSSD) is a vector-transmitted disease that causes drastic yield decreases and the rapid decline of infected cocoa trees. The main symptoms of the disease are red vein banding symptoms on young cocoa leaves, a fern pattern mosaic on old leaves, and shoot swelling [1]. The disease was first reported in Ghana in 1936 [2]. Since its reappearance in Côte d'Ivoire in 2003 [3], a cumulative area of 130,986.90 ha of infected trees has been cut off from 2018 to 2022. Meanwhile, at least 60,000 ha of cocoa trees are still affected [4]. These figures do not include the cocoa trees in fields that have already died from this disease [5]. The disease is caused by a complex of Badnavirus species, namely, the cocoa swollen shoot virus (CSSV). A complex strain of the species has been reported in Togo, Nigeria, Ghana, and Côte d'Ivoire, where virulent strains have been identified [6–12]. The CSSV genome is a circular, double-strained DNA of 7.2 kpb [13], with five open reading frames (ORF) [14]. At least 14 species of mealybugs, belonging to the Pseudococcidae family, are vectors in the natural transmission of the virus [15]. Several tree species have been identified as CSSV hosts from which cocoa can become infected [16]. CSSD is controlled by cutting out infected areas, including a buffer zone, then replanting trees with tolerant planting material and applying good agricultural practices (GAP), including agroforestry systems [17–21]. However, after 100 years of combatting CSSD in West Africa, limited knowledge of the disease epidemiology has led to mixed results [22]. Cocoa farmers in the endemic areas are still reluctant to adopt the removal method to combat CSSD. Instead, they continue to apply unsustainable practices such as deforestation. This leads to landscape degradation and unresilient cocoa systems that suffer under climate variation. In Côte d'Ivoire, the re-emergence of the disease and its quick spread across the cocoa belt [7] led to the intensive cut and replant campaign of 2018 to combat the disease [4]. The limited success of the replanted areas is partly why there was a ban on improved planting material propagation in order to better understand how the disease spreads in the field. Applying epidemiological principles to CSSD field management will help optimize the protection of replanted areas as part of an integrated management plan. This study evaluates the status of rehabilitation technologies, and their disease propagation patterns in replanted areas, with the aim of informing policy decisions on replantation campaigns. In this paper, we report the monitoring of CSSD in experimental trials over time by assessing the epidemiological pattern of the disease through field observations combined with molecular data at both the farm and the landscape level.

2. Materials and Methods

An on-farm cocoa rehabilitation pilot trial of 1200 plots without plant barriers was set up in 2016, including three technologies: grafting on asymptomatic mature trees (GVV), replantation with grafted seedlings (RPG), and replantation with hybrid seedlings (RPH). Four cocoa clones (C1, C9, C15, and C16), selected through the second recurrent cocoa (*Theobroma cacao* L.) selection cycle in Côte d'Ivoire, were used for grafting into old trunks and seedlings, whilst the hybrid material consisted of an improved cocoa planting material with the commercial name “Mercedes,” already distributed to farmers [23–25]. Selection criteria for the clones included productivity (more than 2 tonnes ha^{−1}), cocoa butter quality, resistance to black pod disease, and compatibility with the above planting materials. The approach of this study was based on three interventions: (i) a survey at the landscape level for the presence/absence of the disease in the replanted plots; (ii) on-farm observations

of the CSSD characteristics in infected plots; and (iii) molecular analysis in the laboratory through asymptomatic cocoa leaf samples collected around the CSSD outbreaks in the field.

2.1. Assessing CSSD Epidemiology at Landscape Level in the Rehabilitated Farm

- Determining prevalence and incidence of the swollen shoot disease at the landscape level

The prevalence rate was calculated using the number of infected farms/trees out of the total number observed. Disease incidence was calculated as the proportion of farms (or trees) that became newly infected between two consecutive surveys among those that were disease-free at the time of the previous survey. CSSD prevalence and incidence were monitored through on-site field assessments from 2020 to 2022, which was 4–6 years after the pilot implementation. Two surveys for the presence or absence of the disease in the rehabilitated plots were conducted. The first survey, in 2020, was carried out on a randomly selected representative sample size of 234 plots from the 1200 plots of the pilot. The second survey was conducted from 2021 to 2022 on 200 different plots of the same pilot.

The farms were investigated individually for symptoms appearance during the most appropriate period of the year (February to April). Only characteristic symptoms, namely, red vein band, fern pattern mosaic, and swollen shoots, were considered as indicators of CSSD presence. Incidence data and geospatial information were collected on each farm.

- Evaluation of CSSD impact on cocoa yield

The effect of CSSD on yield was estimated by collecting production data on 68 selected plots from only the GVV areas of the pilot, based on the early pod-bearing characteristic of this technology. Production data was collected every two weeks in 2021 from quarter 1 to quarter 3 (Q1–Q3) by counting the number of healthy pods harvested.

2.2. On-Farm Characterization of CSSD Typical Infection

CSSD characterization on farms was performed on selected sites where the disease was present through the field survey described above. For statistically significant data analysis, three sites of observation per technology were considered. An equal number of infected plots per technology was required, and technologies with insufficient infected plots were excluded. The sites were selected from the list of infected farms within each technology-defined area based on the degree of degradation and accessibility.

Data on the typical CSSD infection pattern were collected at the farm level, encompassing the number and size of disease outbreaks, prevalence, incidence, severity across cocoa varieties and clones, and mealybug vector abundance. The selected plots were revisited three months after the initial recording. Thus, the number of outbreaks per farm was determined by identifying and localizing the disease outbreaks by analyzing CSSD-specific symptoms, die-back, and cocoa tree mortality in groups. The prevalence and the incidence was also assessed by counting symptomatic cocoa trees over time. Only characteristic symptoms, i.e., red vein bands, fern pattern mosaic, and swollen shoots, were considered to indicate CSSD presence on the farm. The GPS coordinates of infected cocoa trees were recorded per farm, and neighboring infections were identified and mapped. Disease severity was estimated per clone and per rehabilitation trial using the following scale [19,21]: 1—red vein banding on flush leaves; 2—chlorotic vein flecking; 3—chlorotic vein clearing/green vein banding; 4—diffused flecking; 5—swelling and die-back; 6—death of plants. For the vector, mealybug abundance was determined on cocoa stems between ground level and at 1.5 m in height by examining the pods and young leaves using a magnifying glass. The mealybugs mostly colonized the cocoa pods on the trunk and the young leaves on the shoots. The 1.5 m area at the bottom of trunk is where the field staff can easily

count and identify the different insects present [1]. Mealybugs were counted separately on symptomatic and asymptomatic cocoa trees.

2.3. Molecular Characterization of CSSD Epidemiology

Polymerase chain reaction (PCR) was used for the diagnosis of asymptomatic trees in the latency phase, in which infected cocoa trees did not show any symptoms. Latency phase infections were assessed across three buffer zones, namely, 6 m, 12 m, and 18 m, measured from symptomatic trees at each outbreak, in accordance with the currently enforced cutting-out procedure. A randomized sample of 10 asymptomatic cocoa trees per buffer zone was taken for laboratory PCR analysis. A total of 3–5 leaves were collected per sampled tree. The DNA extraction of each leaf sample was performed the day after sampling at the West and Central African Virus Epidemiology laboratory. DNA was extracted using the Plant DNeasy kit (Qiagen, Hilden, Germany) according to the manufacturer's instructions, with 50 mg of leaf tissue removed from the abaxial surface of the leaf blade. The DNA solution obtained was stored at $-20\text{ }^{\circ}\text{C}$ for PCR analysis. Taq DNA polymerase (Promega, Madison, WI, USA) was used to amplify the viral DNA and the specific primers, i.e., CSSD1 R/F (5'-CTTCYTCYCCAATTATCCAGACTGC-3' and 5'-AAYTGGCARAAYGGAGARGC-3'), of 400 bp designed in the ORF3 of the CSSV genome [11].

The PCR mix of 25 μL contained forward and reverse primer (0.4 μM each), Taq DNA polymerase (0.625 U), 1X PCR buffer, dNTPs (0.2 mM), MgCl_2 (1 mM), and DNA (1 μg). The amplification program, run in a Mastercycler Eppendorf type flexlid (Eppendorf, Hamburg, Germany), consisted of 35 cycles with an initial denaturation at $94\text{ }^{\circ}\text{C}$ for 2 min, further denaturation for 20 s, primer annealing at $55\text{ }^{\circ}\text{C}$ for 15 s, and extension at $72\text{ }^{\circ}\text{C}$ for 30 s, followed by a final extension of 5 min at $72\text{ }^{\circ}\text{C}$. At the end of the amplification process, 10 μL of amplified product was used for electrophoresis in 0.8% agarose gel and photographed under UV illumination with an imaging system (UV Transilluminator, VWR, Radnor, PA, USA). A cloned CSSV DNA for CSSD1 F/R primers, provided by the University of Arizona (USA), was used as a positive control. Only visible bands on agarose gel were considered positive following electrophoresis.

2.4. Data Analysis

The yields were estimated using the following formula: $Y\text{ (kg. ha}^{-1}\text{)} = N * D * 0.04$ (N = Number of healthy pods per tree. D = number of trees per hectare; 0.04 = bean weight (kg) per pod [26]. The resulting production count was compared between asymptomatic and symptomatic plots at the landscape level.

The severity data at the farm level was analyzed by cumulating the score for each infected cocoa clone. CSSD vectors were characterized by mealybug observations on each of the selected farms. Statistical comparative analyses were conducted using IBM SPSS Statistics version 20. SPSS. Diagrams and box plots were generated using the same software with additional graphical elements prepared using Microsoft Office 365 (Excel and PowerPoint). Maps were generated using QGIS software version 3.16.8 (Hannover, Germany).

3. Results

3.1. CSSD Epidemiology at Landscape Level

3.1.1. Prevalence and CSSD Mapping in the Pilot Network

Characteristics of the CSSD infection rate on the pilot plots network during the three surveys revealed that the disease appeared in the rehabilitated farms with a prevalence of 3.42% in 2020, i.e., four years after field implementation. Also, the number of infected plots in the observed sample more than doubled from year 5 (2021) to year 6 (2022) (from

10 to 23 infected plots). The location of asymptomatic and CSSD diseased pilot farms is shown in Figure 1. Infected farms are unequally distributed in the areas covered by the rehabilitation in the Nawa region. Infected farms are mostly observed in the areas of Méagui, Gnammangui, and Buyo. No infection was observed in the areas of Dabouyo and Okrouyo near Gueyo.

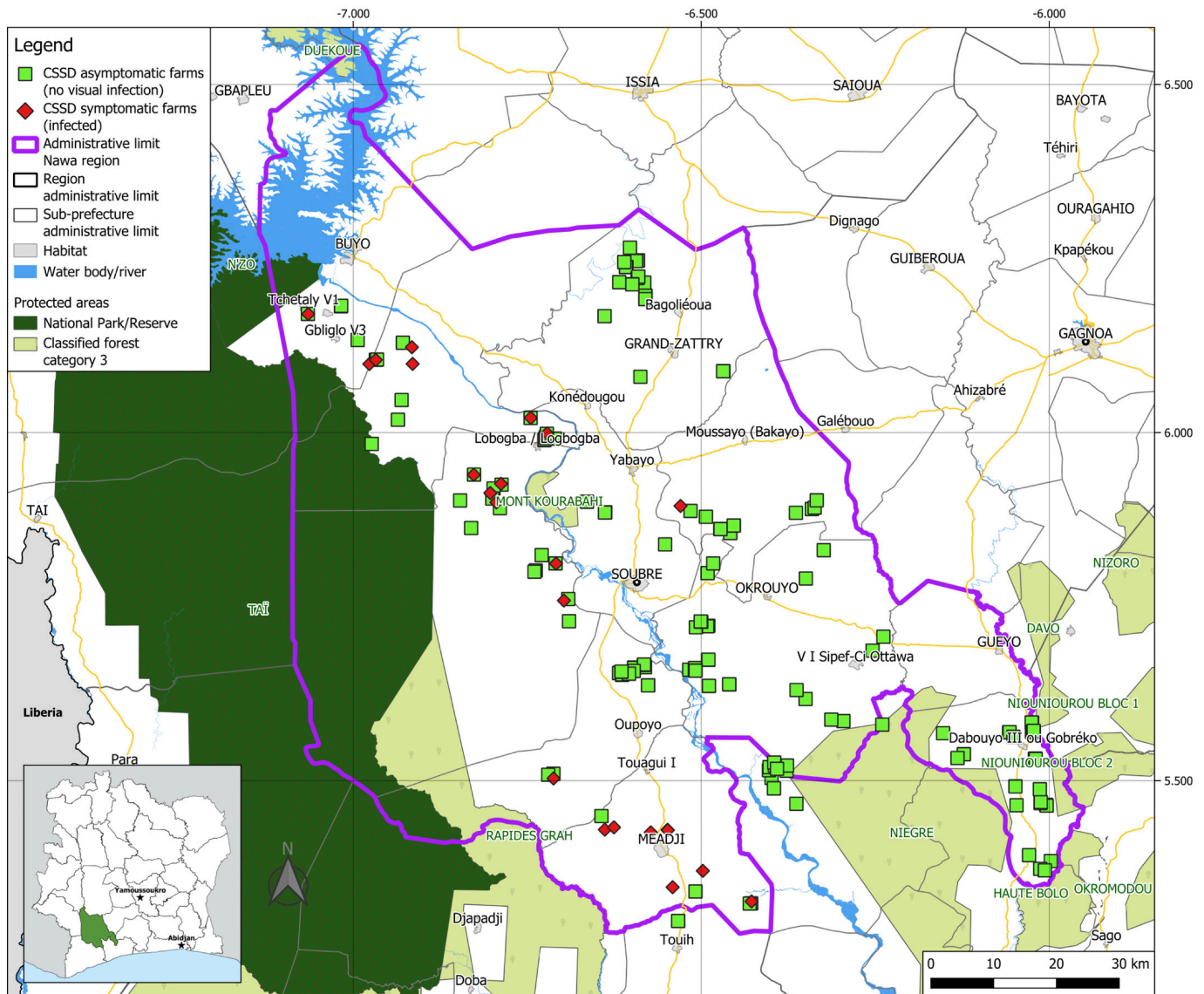


Figure 1. Distribution of the CSSD infection in the rehabilitated pilot farms in the Nawa region of Côte d'Ivoire.

3.1.2. Spread Dynamics of CSSD Infection Within the Rehabilitation Pilot

Infection data of the selected samples throughout the three surveys for 2020, 2021, and 2022 show a CSSD incidence rate of 1.05% between year 4 (2020) and year 5 (2021) after planting. This rate increased exponentially between year 5 (2021) and year 6 (2022), where an incidence rate of 6.95% was observed (Figure 2). These results indicate that CSSD spreads rapidly over time in the rehabilitation plots despite the use of improved planting material. Furthermore, the distribution of infected plots by technology showed a high infection rate in GVV plots (70%), whilst RPG presented the lowest rate (10%) (Table 1).

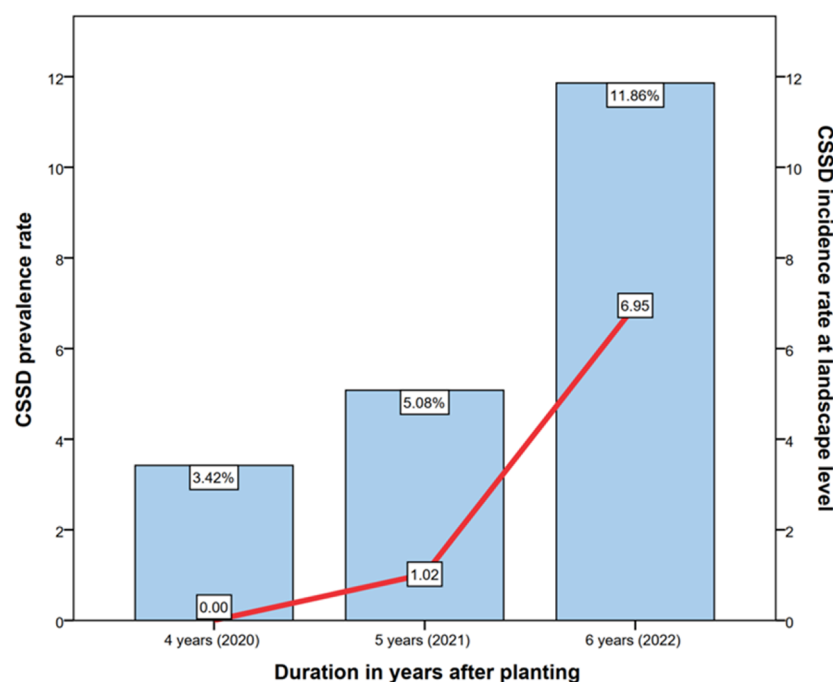


Figure 2. Characteristics of CSSD propagation over time in the pilot plots from 2020 to 2022. Note: The red line with numbers represents the evolution of CSSD incidence rate at the landscape level of the pilot farms.

Table 1. Distribution of CSSD prevalence by technology in 2021.

Variable	No Infection Plots	CSSD Infection Plots	Overall	<i>p</i> -Value
				0.076
Total plots (%)	171 (94.48%)	10 (5.52%)	181	
grafting on asymptomatic mature trees (GVV)	57 (33.33%)	7 (70.00%)	64 (35.36%)	
replantation with grafted seedlings (RPG)	58 (33.92%)	1 (10.00%)	59 (32.60%)	
replantation with hybrid seedlings (RPH)	56 (32.75%)	2 (20.00%)	58 (32.04%)	

3.1.3. Impact of CSSD Infection on Cocoa Yield in the Pilot

Of the total of 68 GVV plots monitored for cocoa production in quarters 1 and 3 in 2021, 52 were asymptomatic and 16 were symptomatic. The overall recorded yield was between 1000 and 1900 kg/ha. No significant difference was found for cocoa yield between symptomatic and asymptomatic plots when considering the entire cocoa plot irrespective of the cocoa variety and technology applied (Table 2). This result indicated that at the initial phase of CSSD infection, the decreasing yield was not perceptible and the infected trees continued producing normally until the virus load reach a threshold.

Table 2. Trends of estimated cocoa yield (kg/ha) on symptomatic and asymptomatic plots via GVV technology in the rehabilitation pilot in the Nawa region.

Pod Production Parameters	Cocoa Yield and CSSD Status on GVV Plots (0.25 ha) in Q1 and Q3 in 2021			<i>p</i> -Value
	Asymptomatic Plots (N = 52)	Symptomatic Plots (N = 16)	Total Plots (N = 68)	
Mean (SD)	1533.73 (857.97)	1315.68 (491.2)	1482.42 (789.18)	0.474
Median (Q1; Q3)	1479.5 (1111.25; 1884.5)	1388 (1069.75; 1616)	1,460,000 (1111.25; 1834.5)	

3.2. CSSD Epidemiology At-Farm Level

3.2.1. CSSD Mapping on Rehabilitated Farm

The required number of tree-infected plots for this study was obtained with GVV and RPH rehabilitation technologies. The mapping of CSSD-infected cocoa trees inside the six selected farms for GVV and RPH technologies indicated unequal distribution of the infection on each plot. In the GVV trials, CSSD presented massive infection rates on cocoa trees in the center of the plots and at sporadic points along the borders. When using improved planting material (RPH), CSSD infections were identified mostly at the plot borders of the rehabilitation plots. This shows that the reinfection of replanted young farms after the cutting out process depends on the disease pressure in the neighboring plots. There were fewer CSSD reinfections in RPH trials when the surrounding CSSD outbreaks were limited in size (see the cases of Koda and Logboya 1). However, the disease spread rapidly, and the number of infected trees grew in line with the size of neighboring outbreaks (see the case of Logboya 2).

In both cases (GVV and RPH), rehabilitation was at risk of infection in the presence of bordering CSSD outbreaks. This had previously occurred in Petit-Tiémé and Krohon B for GVV, and at Logboya 2 for RPH (Figure 3).

3.2.2. CSSD Prevalence and Incidence on Farm

Prevalence and incidence were high on GVV farms compared to RPH farms, confirming the mass infection on the farms with grafting technology (GVV) (Table 3). The results indicate that CSSD propagates more rapidly on GVV farms where the initial number of infected trees was high. CSSD infection spread slowly on farms that were replanted entirely.

Table 3. Prevalence and incidence rates of CSSD-infected farms in the pilot five years after field establishment.

Technologies	Villages	Prevalence (%)	Incidence (%) 3 Months After Initial Recording
GVV	Krohon A	34.96	15.38
	Krohon B	28.7	49.1
	Petit Tiémé	16.89	9.13
RPH	Lobogba 1	2.3	6
	Lobogba 2	2.92	4.5
	Koda	0.5	0

CSSD infected cacao tree distribution on the pilot plots 5 years after replanting

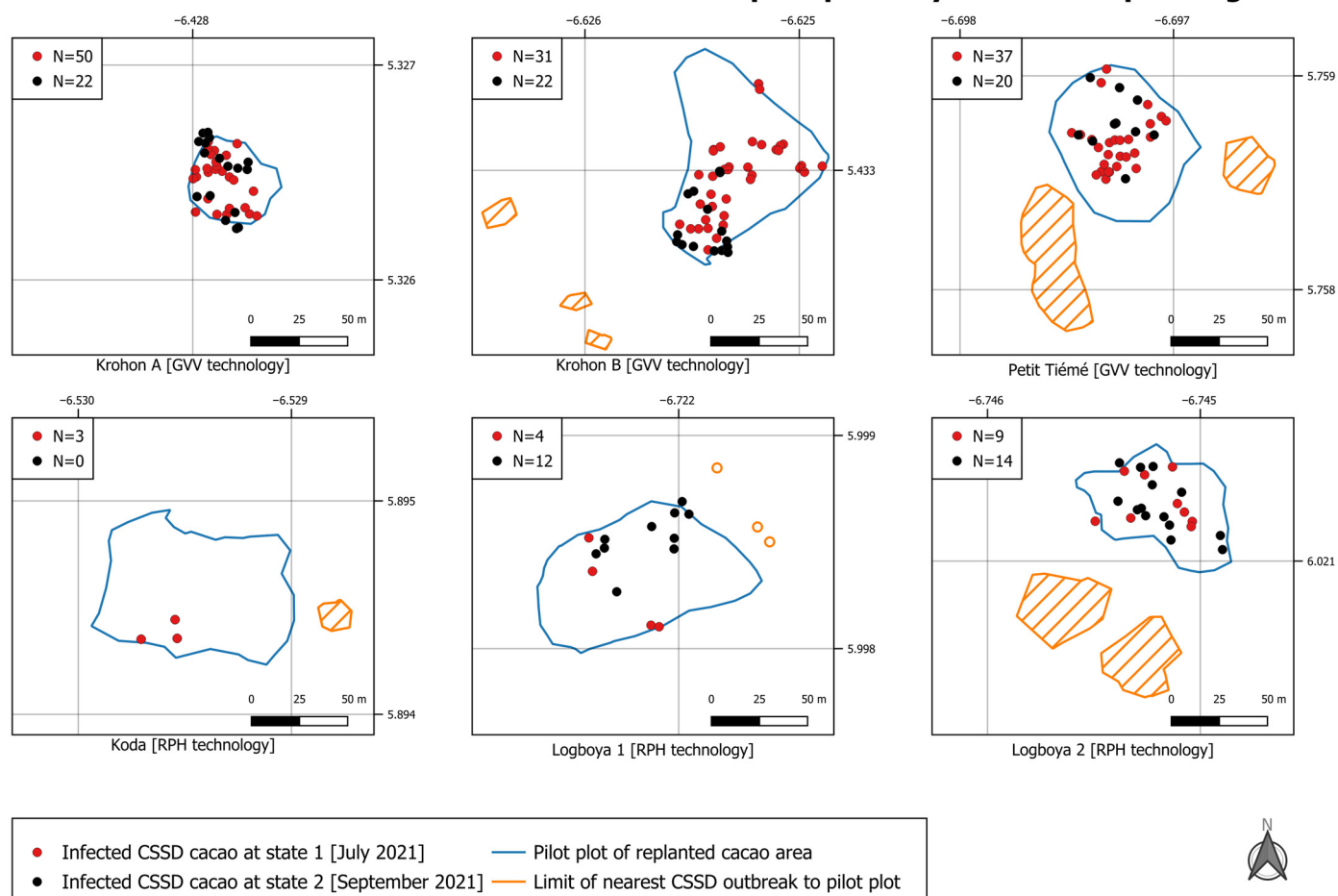


Figure 3. Distribution of CSSD-infected cocoa trees via GVV technology in the rehabilitation pilot plots in the Nawa region in Côte d'Ivoire.

3.2.3. Mealybug Abundance on Infected Farms

At the farm level, the results indicate a slightly increased number of mealybugs observed on the trunks of asymptomatic cocoa trees compared to infected cocoa trees (Figure 4).

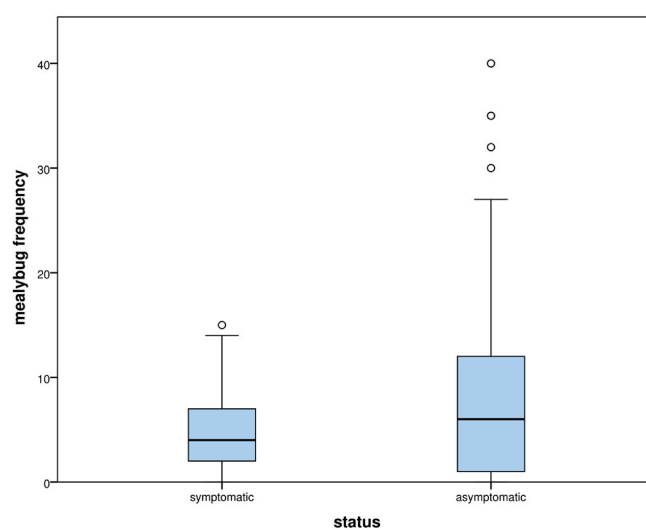
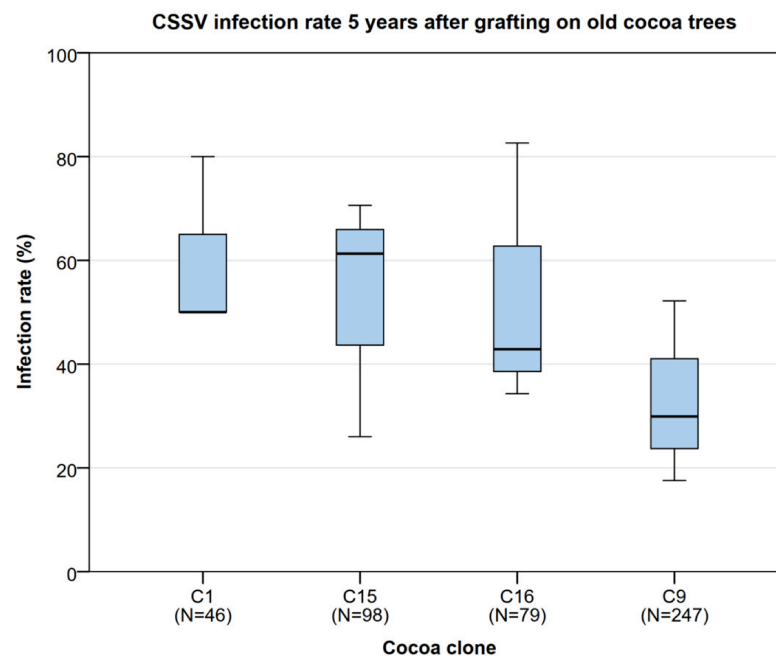


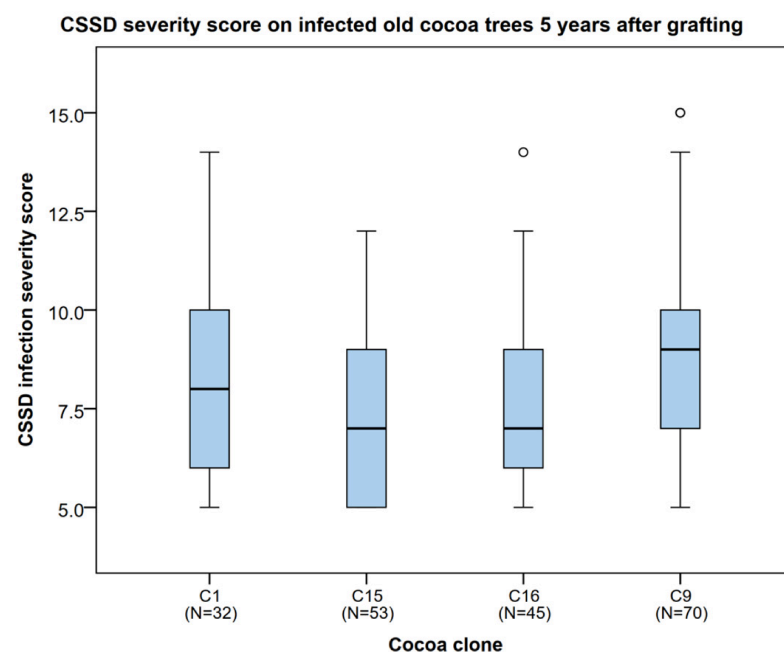
Figure 4. Mealybug abundance on CSSD-infected cocoa in the pilot.

3.2.4. Field Incidence of CSSD Across Cocoa Clones

In rehabilitation plots using grafting technology, all four clones (C1, C9, C15, and C16) showed high CSSD infection rates, although C9 was marginally less affected (Figure 5a). Severity scores indicated comparable susceptibility across all clones (Figure 5b).



(a)



(b)

Figure 5. CSSD infection rate and severity score for infected cocoa clones five years after field establishment: (a) CSSD infection rate for cocoa clones grafted on old trunks in the field; (b) CSSD severity score for cocoa clones grafted on old trunks in the field.

3.2.5. CSSD Infection in Hybrid Cocoa Varieties

Initially, CSSD outbreaks were observed for the rehabilitation farms with cocoa hybrids five years after seedlings were planted. The number of infected cocoa seedlings in the plots increased with the number of CSSD outbreaks (Figure 6).

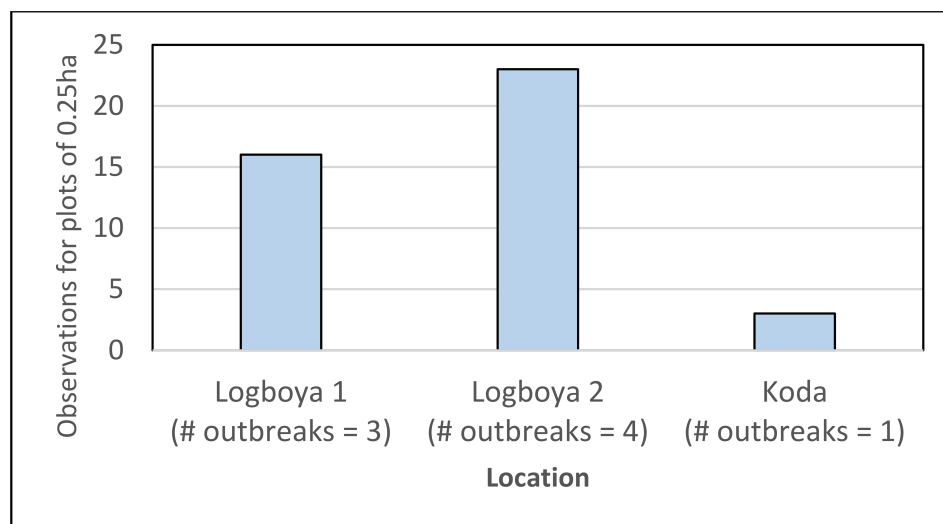


Figure 6. CSSV infection status on hybrid cocoa varieties after five years of planting on three farms in the Nawa region, Côte d'Ivoire.

3.3. Molecular Epidemiology of CSSD Around Disease Spots on Farm

The selected plots were categorized by visibly infected trees per outbreak, according to the official “cutting out” protocol. All three GVV plots had 11–100 infected trees. On these farms, the removal of trees within a 12 m diameter of infected trees is officially recommended to eliminate the virus. The three other RPH farms containing 1–10 infected trees per outbreak are categorized and grouped for cutting out within a 6 m diameter. The molecular PCR results (Figure 7) for symptomless trees adjacent to visibly infected trees showed CSSD infections with variable infection rates according to the distance around the outbreaks.

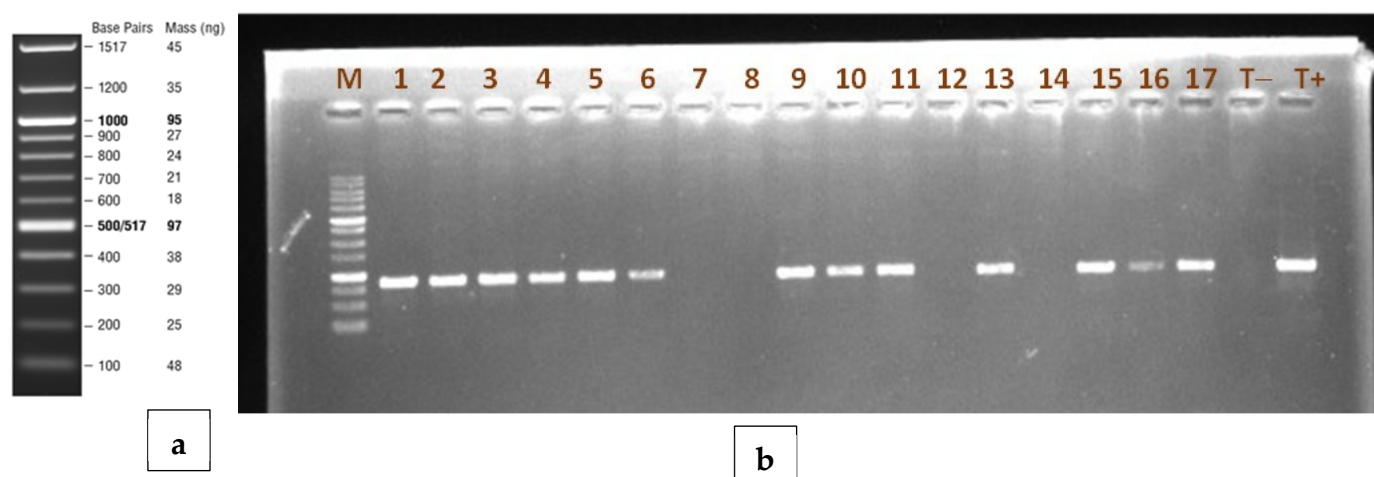


Figure 7. PCR results for asymptomatic samples of cocoa leaves collected from CSSD outbreaks in the fields in Soubré, Côte d'Ivoire: (a) ladder graduation; (b) electrophoresis 0.8% agarose gel with a light-spot at 400 bp indicating the presence of CSSV (M: ladder; # 1–17: containing the amplified DNA products from analyzed cocoa leaves samples; T–: negative control; T+: positive control).

For outbreaks containing 1–10 infected trees, PCR analysis of asymptomatic trees revealed infection rates of 87%, 80%, and 20% at the 6 m, 12 m, and 18 m buffer zones, respectively (Figure 8). Under the current control measures, infected trees in the 12 m and 18 m buffers would not be identified or removed, leaving latent infections untreated.

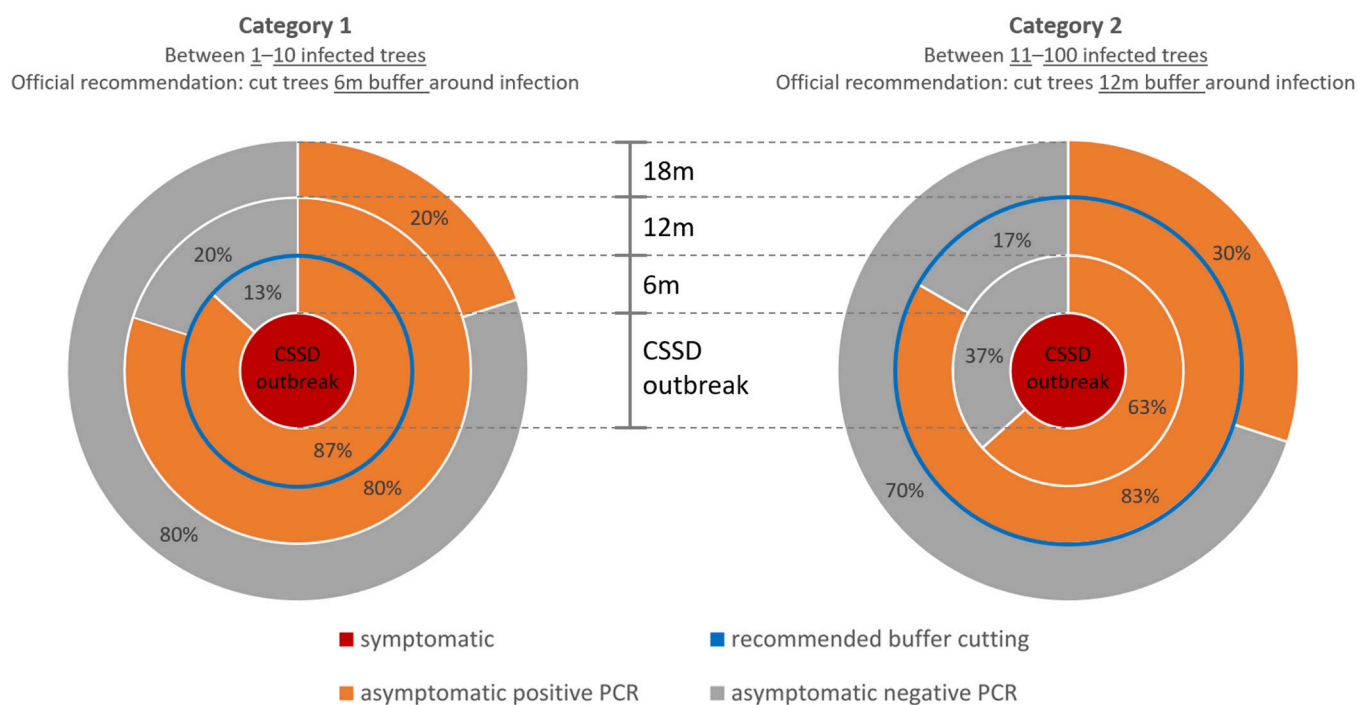


Figure 8. Latency area and missed trees in the cutting out process compared to the officially recommended cocoa tree removal area.

In the outbreaks containing 11–100 infected trees, the buffer zone of 6 to 12 m showed an 83% PCR-detected infection rate. This confirms the rationale of cutting out all trees within this radius when an infection outbreak occurs. However, the buffer of 18 m around the outbreaks still showed a 30% latency infection rate that is neglected by the official CSSD treatment control measure. The results indicate a high percentage of missed infections in small outbreaks (80%) compared to large outbreaks (30%).

4. Discussion

This study investigated the reinfection and temporal spread of cocoa swollen shoot disease across rehabilitation plots using three innovative propagating technologies. The data presented was based on a subsample of a pilot, as it was not possible to visit all 1200 plots across all farms. The random sampling approach ensures that the results are representative of field conditions. CSSD infection patterns in the pilot are discussed at the landscape and farm level.

4.1. CSSD Propagation at Landscape Level

The CSSD spread was mapped at the landscape level. Some areas, such as Gueyo, were still virus-free, while other localities, including Méagui and Buyo, showed the infection/reinfection of newly planted farms. These results confirm previous observations in the Soubré area, where less CSSD infection was observed in areas with diversified farm landscapes than in extensive cocoa monocultures [27]. The level of landscape diversity at Méagui, Soubré, and Buyo greatly facilitated the spread of CSSD. However, the lower rate of infection observed in the Gueyo area could be explained by the presence of palm oil plantations mixed with the cocoa farms [20].

4.2. CSSD Reinfection and Sustainability in Rehabilitated Cocoa Farms

This study was conducted in the Nawa region on cocoa rehabilitation pilots. The pilots were established in 2016 for the validation of the on-farm agronomic performance of small-scale innovative technologies. Results of the on-field survey indicate early CSSD infection/reinfection in this pilot, four years after the rehabilitation. The CSSD prevalence recorded in the pilot at the landscape level showed an exponential propagation incidence of up to 7%, which doubled between years 5 (2021) and 6 (2022). The lack of barriers around these trial plots, likely associated with the latency infection phase, facilitated the rapid infection observed. These observations are in agreement with similar works in Togo and Ghana [12,28,29] where, although initially involving the same planting material in the same physical environment, the distribution of the disease in the reinfected farms had very different dynamics due to the presence or absence of a plant barrier effect and the level of maintenance. For GVV trials, the initial selection of virus-free mature farms for rehabilitation by grafting was based on visual observations of the presence/absence of CSSD characteristic symptoms. The mapping of the disease spots inside those trials showed that most infected cocoa trees were located in the centers of the plots. This result indicates that some of the plots selected for grafting were infected at the beginning of the pilot but did not show any symptoms at the time of selection. The latency phase of CSSD constitutes one of the main challenges for on-farm inspections. GVV contributed to improving the cocoa yield at the farmer level but seemed to be detrimental during CSSD outbreaks. There was no significant difference between infected and healthy farms at the initial stage, but this is neither reliable nor sustainable for the future. Disease spreading from outbreaks in neighboring plots increased the viral pressure on the trial plots. An early detection tool is therefore essential for successful rehabilitation and the scaling up of improved planting material technologies [30].

For RPH technology with hybrid planting material, the selected infected farms were cut individually without treating the neighboring infected farms before the establishment of the pilot. Observations indicated the presence of disease outbreaks around the trials and the appearance of infections on seedlings along the border. This clearly indicates disease migration from infections originating outside the newly planted cocoa farms. The lack of barriers around these trials left the pilot more susceptible to disease reinfection, which greatly facilitated the spread of CSSD [20]. However, the sporadic occurrence of disease observed in the centers of the trial plots could be explained by poor application of the CSSD management risk protocol/guide in the rehabilitated farms. The early reinfection observed on those rehabilitated plots with improved planting material also indicates that partial or sporadic cutting out in areas of CSSD mass infection was not the appropriate measure to properly eliminate virus pressure and all sources of infection in the surrounding environment. The systematic elimination of viral inoculum from the surrounding environment before replanting in areas of CSSD mass infection, combined with farmer risk management capacity building, would help to mitigate the rapid spread of CSSD and to ensure the sustainability of replanted cocoa farms.

4.3. CSSD Infection and Planting Material Tolerance on Farm

The improved planting materials (clones and hybrids) in these trials were infected four years after their establishment under field conditions. They were therefore all susceptible to CSSD. This situation calls for the building of a research program for the development of CSSD-resistant cocoa varieties. A harmonized approach could combine field trials with molecular screening while considering other productivity challenges in West Africa [29]. Thus, the use of tolerant planting material without integrating any other control measure cannot adequately protect replanted farms against CSSD reinfection. Consequently, more

investigation into the selection of resistant cocoa varieties for CSSD control is needed. To date, the best approach to combating the disease remains integrated management combining cross-protection tools, agroforestry, barriers, tolerant planting material, and farmer capacity building.

4.4. Missed Infections in the Current Application of the CSSD Control Measures

PCR results from randomly selected asymptomatic trees around on-farm disease outbreaks show that the recommended buffer zone largely underestimates the true extent of the infection surrounding CSSD outbreaks. For category 1 (1–10 infected trees), with an officially recommended 6 m buffer, a substantial proportion of asymptomatic trees remain in the field. The results show 80% infection rates for asymptomatic trees in the 6–12 m buffer and 20% infection rates in the 12–18 m buffer. In category 2 (11–100 infected trees), with a recommended 12 m buffer, non-negligible proportions of asymptomatic trees remain outside the buffer zone. This remains true even if the largest proportion of asymptomatic trees are cut out with the recommended method. The recommended buffer for category 2 reflects the reality of greater CSSD infection. Even so, it underestimates the need to remove all infected trees around the outbreak. This finding can help refine the recommendations for categories 1 and 2 to improve the efficacy of CSSD control using the cutting out method. This is consistent with [31,32], which found 30–40% of asymptomatic trees surrounding a CSSD outbreak in the latency phase. This confirms that relying solely on visual inspection to delimit cutting out areas will leave latent infections untreated.

The latency rate was highest during the early stages of infection (1–10 symptomatic trees), highlighting the importance of farmer skill and experience in identifying early signs and symptoms before mass infection occurs. Detection strategies must therefore address both the asymptomatic phase and vector-mediated spread. According to [33] control measures are more efficient when the disease is detected early, underscoring the value of an in-field detection tool, especially for newly planted farms [30].

5. Conclusions

This study addressed the epidemiological characteristics of CSSD in newly planted, rehabilitated farms in regions such as Nawa that had existing CSSD infection pressure. Before rehabilitation, farmers should consider removing all trees on infected farms rather than the current practice of sporadically cutting in the infected areas only. Based on these results, the following recommendations are proposed for enhancing farmer resilience: (i) organizing a permanent capacity building scheme for stakeholders, including farmers, on the subjects of CSSD diagnostics, risk management, and best rehabilitation practices; (ii) harmonizing CSSD control intervention tools and protocols for mapping, rehabilitation, and surveillance; (iii) piloting a cocoa-based agroforestry system for rehabilitation with existing innovations and technologies; while (iv) developing a robust program for screening planting material for CSSD resistant or tolerance.

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