Comparing effectiveness, cost- and time-efficiency of control options for Xanthomonas wilt of banana under Rwandan agro-ecological conditions

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Abstract Xanthomonas wilt of banana (XW) is a major disease affecting banana throughout East and Central Africa (ECA). Initial control was through complete diseased mat uprooting (CDMU), which had limited adoption due to high labour demands and cost. Further research demonstrated single diseased stem removal (SDSR) was an effective, less labour intensive and less costly alternative to CDMU. A comparative assessment of the two control practices was needed to foster uptake by policy makers, especially in countries like Rwanda where SDSR had not been tested or scaled up. To test SDSR in Rwanda, a study was conducted in farmers' fields comparing the effectiveness, labour cost and time demands of CDMU and SDSR. SDSR was equally effective as CDMU for XW control, with initial XW incidences of 3.0 to 9.4% being reduced to <0.5% within 3 months of using either method. The major benefit of SDSR lies in its significantly lower resource requirements. The total time needed for applying SDSR on a single plant was 88% less, averaging 4.3 min (standard deviation, sd = 0.3) compared to 36.5 min (sd = 4.5) for CDMU on a complete mat. Accordingly, the cost of labour was significantly lower for SDSR. The main cost of CDMU (78% of total cost) arose from the need to replant with healthy banana plantlets. The total cost of SDSR (26 Rwandan Francs [Frw], sd = 2) was 96% lower than that for CDMU (619 Frw, sd = 27). Hence, the incentive to use SDSR for managing XW is very high. These findings will boost SDSR adoption by both policy makers and farmers in ECA.

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Introduction

Xanthomonas wilt (XW) of banana (*Musa* spp.) is a destructive disease caused by the bacterium *Xanthomonas vasicola* pv. *musacearum* (*Xvm*; previously *Xanthomonas campestris* pv. *musacearum*). The disease was first observed on enset (*Ensete ventricosum*) in the 1930's (Castellani 1939) and later by Yirgou and Bradbury (1968). On *Musa* spp. (banana and plantains, hereafter banana(s)), XW was first reported in Ethiopia in 1976 (Yirgou and Bradbury, 1974). In the East and Central African (ECA) region, it was first reported in Uganda in 2001 (Tushemereirwe et al. 2004), and has since spread to all highland banana growing regions in the ECA (Blomme et al. 2014; Carter et al. 2010; Mbaka et al. 2007; Ndungo et al. 2006; Reeder et al. 2007).

Infection in banana occurs when the *Xvm* bacterium enters a healthy plant's vascular system through an open wound on the male inflorescence or through wounds caused by tools on any part of the plant or mat (Blomme and Ocimati 2018). The disease is commonly spread by flying insect vectors (mainly bees), which transmit the inoculum from the inflorescence of a diseased plant to a healthy plant while sourcing nectar and pollen (Tinzaara et al. 2006). Contaminated farm tools and infected planting materials are also important modes for spread of XW (Eden-Green 2004). Spread via birds and bats, browsing cattle and small ruminants can also occur, although to a lesser extent (Blomme et al. 2017a; Blomme and Ocimati 2018; Buregyeya et al. 2014).

The disease has severe effects on food security and income of banana dependent households and production systems where banana predominates. Yield losses can be 100% when control of XW is delayed (Blomme et al. 2014). Muchuruza and Melchior (2013) reported yield and income losses of 84% and 64%, respectively, in Tanzania, while Nkuba et al. (2015) reported a 35% decline in sales and doubling of healthy bunch prices in Rwanda and Tanzania. The crop loss can result in land degradation as soil becomes exposed due to uprooting of infected plants and mats. Ecosystem services including erosion control and carbon sequestration can be impaired in severely affected areas (Ocimati et al. 2016, 2019). Thus, timely and effective management strategies are needed to combat XW.

Management of XW has relied entirely on cultural practices as all edible banana in the ECA are susceptible to the disease (Ssekiwoko et al. 2006; Kagezi et al. 2006; Tushmereirwe et al. 2006). During early stages of an XW epidemic several practices were advocated. These include complete uprooting of diseased mats (containing at least one diseased plant) and/or entire fields ('complete diseased mat uprooting', CDMU), followed by destruction of plant debris by burning, composting or burying, disinfection of farm tools between plants or after use on infected plants, early removal of male buds using a forked stick to prevent disease transmission by insect vectors, and use of clean planting materials (Karamura et al. 2008). Despite the promotion of these practices, XW continued to spread to new areas. Incomplete adoption of control practices by small-holder farmers has been identified as the major cause for the failed disease containment, due to the labour requirements and costs of uprooting entire diseased mats (Tushemereirwe et al. 2006; Bagamba et al. 2006; Jogo et al. 2013). Furthermore, CDMU results in significant yield reduction for up to 2 years due to the need to replant with healthy plants, which negatively affects food security and income of smallholder farmers (Jogo et al. 2013; Ocimati et al. 2013; Rietveld et al. 2014). Thus, determination of more efficient control strategies for XW was imperative.

Epidemiological studies of XW showed that *Xvm* does not colonize all lateral shoots within a diseased banana mat, a concept referred to as incomplete systemicity (Ocimati et al. 2013, 2015). The concept of incomplete systemic spread of *Xvm* gave rise to the practice of Single Diseased Stem Removal (SDSR), where only the symptomatic stems within an affected banana mat are removed, coupled with proper disposal of infected plant debris, sterilisation of garden tools and early removal of male buds (Blomme et al. 2014, 2019; Blomme et al. 2017b). In contrast to CDMU, SDSR has reduced labour need and less cost for implementation, and the yield losses that arise from losing all plants on a banana mat is averted. SDSR has been shown to reduce the incidence of XW to less than 2% within 3 months, irrespective of the initial incidence in pilot experiments in the eastern Democratic Republic of Congo (Blomme et al. 2019; Blomme et al. 2017b). In Uganda, a cost-benefit analysis to assess the adoption of the various elements of the SDSR package showed that the adoption of the full package resulted in financial benefits for farmers, with increases of approximately US$ 462/ha/year (Kikulwe et al. 2019).

In Rwanda, XW was first observed in Gisenyi province in 2002 (Reeder et al. 2007), and rapidly spread to all banana-producing regions of the country. The initial control strategy for XW was eradication (2005 to 2011) and was implemented through a government policy in Rwanda. Eradication focused on rogueing of complete plots and fields with diseased banana mats (CDMU), followed by planting annual crops (including maize and beans) for a period of at least one year (Rutikanga et al. 2016). Replanting with a selection of high-yielding banana cultivars (e.g., 'Mpologoma' [cooking; *Musa* AAA-EAH], 'Injagi' [cooking; *Musa* AAA-EAH], 'FHIA17' [tetraploid hybrid] and 'FHIA25' [tetraploid hybrid]) was advocated. However, XW has since reappeared in previously rogued and replanted areas (Gaidashova, personal communication, 2018; Okonya et al. 2019).

Landscape-wide rogueing has had a negative impact on the diversity of banana cultivars as only a limited selection of high yielding cultivars has been used as replants. CDMU continues to be promoted for control of XW. As in other affected countries of the region (Blomme et al. 2014; Jogo et al. 2013), the adoption of CDMU in Rwanda has been poor, with farmers often removing only the visibly diseased stems (Gaidashova, S. personal communication, 2019). Thus, determining SDSR as an alternative to CDMU in the agroecological zones of Rwanda where banana is cultivated is crucial to inform policy making for control of XW.

The objective was to determine whether SDSR and CDMU were preferable based on control of XW and the economics of the control measures under Rwandan agroecological conditions. Thus, we compared SDSR and CDMU for i) efficacy of XW control, and ii) impact on local farmers with respect to labour requirements and associated costs. We believe that the results will further guide XW control efforts across the ECA region.

Materials and methods

Study area

In January 2019, field experiments comparing SDSR and CDMU were initiated at four sites in Rwanda. Each site was in a different province, thus providing a range in agroecological factors for assessing the effectiveness of the two XW control approaches. The study sites were in the districts of Kayonza, Gisagara, Rubavu and Rulindo,

respectively located in the Eastern, Southern, Western and Northern provinces of Rwanda (Fig. 1 and Table 1). The study region was situated within the equatorial zone and is characterised by a moderate tropical climate due to elevation (Henninger 2013; Peel et al. 2007). Further site description (climate and soil characteristics) is provided in Table 1.

Experiment design

At each site, fields/plots with at least 50 banana mats and an incidence of plants exhibiting symptoms of XW ranging from 3.5 to 9.4% were selected for the experiments. Plots with a similar initial plant incidence of XW, but to which no treatments were applied, were included as controls (as reference for comparison to the SDSR/CDMU treatments). Banana mats consisted of one main stem and 2 to 3 suckers (lateral shoots that are physically connected to the main stem). In regard to mats, a mean of 19.5% of mats had symptoms of XW, with 12 to 33% of plants infected per mat. Additional plots with healthy plants (no symptoms of XW) were included as healthy controls. The two controls are referred to as the 'diseased control' and the 'healthy control'. The banana fields were comprised of a mixture of cultivars (dominated by AAA East African Highland types) and a mixture of young (planted within the past year) and mature (> 18 months) mats.

The CDMU treatment consisted of the immediate uprooting of entire diseased banana mats when at least one stem within a mat showed symptoms of XW. A hoe and/or a pickaxe were used for uprooting the mats. The mother plant and all attached lateral shoots, the underground corms and the roots within the upper 50 cm of soil and 60 cm laterally from the main banana stem were removed (Blomme 2000). Healthy suckers for replanting were sourced from fields with no prior history of XW within the trial village or district. Replanting was performed one month after removal to reduce yield losses that would have occurred if the recommended fallow period in Rwanda (6 to 12 months) was adhered to. Initially, Turyagyenda et al. (2007) and Sivirihauma et al. (2013) had recommended a 6- and 12-month fallow period, respectively, to allow all *Xvm* inoculum in the soil, and especially in remaining plant debris to be eliminated. However, subsequent field experience and insights into XW epidemiology showed that a shorter fallow period could also work, if all diseased mat rhizome pieces and roots were thoroughly removed.
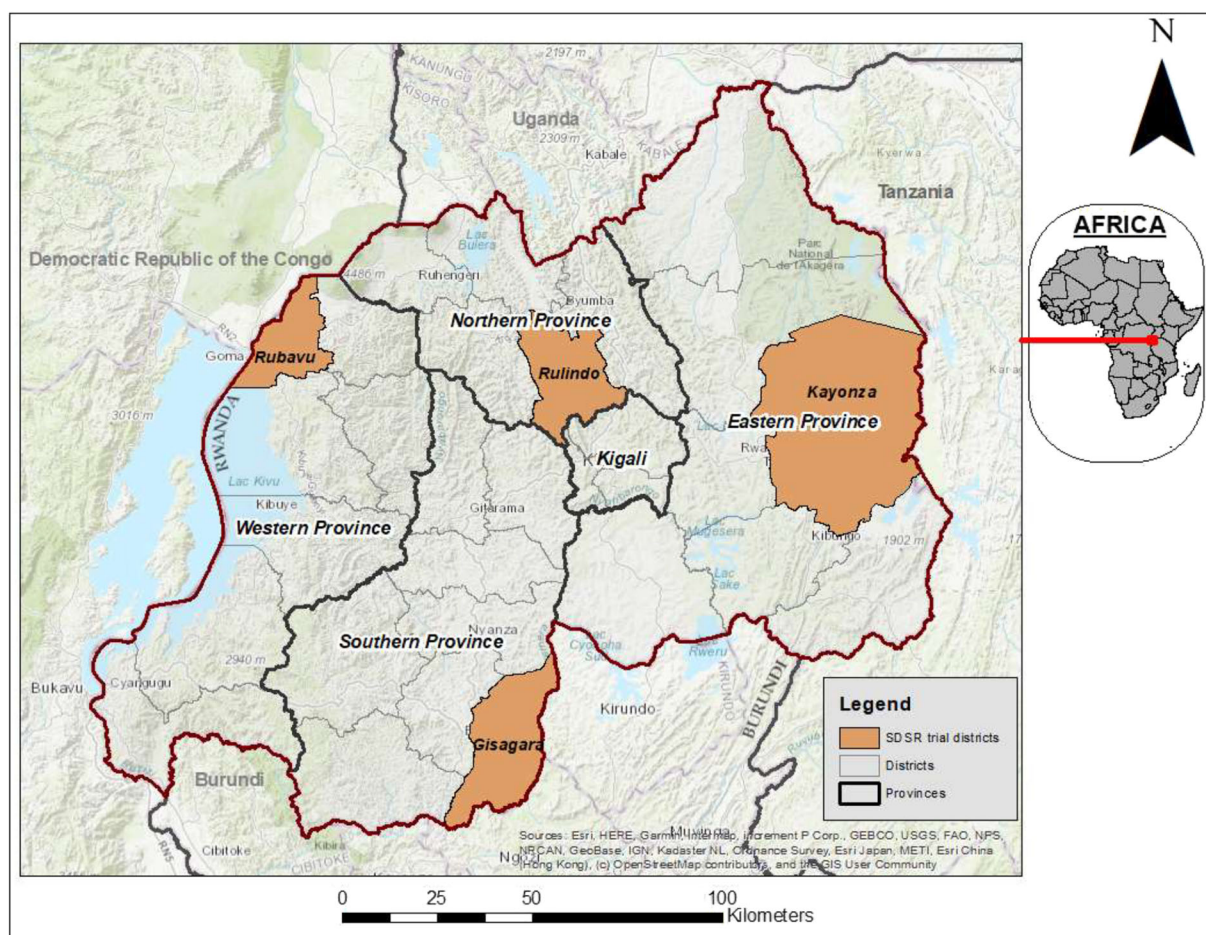
Fig. 1 Location of the four trial sites in the districts of Kayonza, Gisagara, Rulindo and Rubavu in Rwanda

Table 1 GPS coordinates, elevation, temperature, rainfall and edaphic descriptions for the four study sites in Rwanda

Site name	GPS Coordinates	Altitude (masl[a])	Average annual temperature (°C)	Annual rainfall (mm)	Soil type and characteristics
Rubavu	01° 6' S, 029° 28' E	1481	18.1	1377 (https://www.weather-atlas.com/en/rwanda/rubavu)	Shallow Andosols made up of weathered volcanic ash and lava.
Kayonza	02° 2.36' S, 030° 32.17' E	1557	22	1100 (Kayonza District Potentialities, 2013) and a bimodal rainfall pattern	Mixed patches of Oxisol and Ultisol and is predominantly clay and sand with some proportion of stones (UPCE Consult 2012).
Gisagara	2° 36' S, 028° 54' E	1592	19.4	1142 (https://www.weather-atlas.com/en/rwanda/Gisagara).	Dominated by Oxisol, which is a clay soil derived from shale (Minema 2019; Verdoodt and Van Ranst 2003).
Rulindo	01° 39' S, 029° 54' E	1792	16.5	1326 (Project brief Rulindo substation and transmission lines 2011).	Predominantly Ultisol and lateritic (Verdoodt and Van Ranst 2003).

[a] Meters above sea level

Mwebaze et al. (2006) reported *Xvm* to have limited survival of less than 3 months in the soil in the absence of suitable host tissue (roots, corm pieces). To avoid possible contact with any remaining *Xvm* in the soil, the clean sucker was re-planted adjacent (30–40 cm) to the location of the uprooted diseased mat.

The SDSR treatment was implemented by carefully cutting diseased stems at soil level (just above the corm using a machete) without injuring other plants on the mat, at first sight of symptoms and where necessary, destroying apical meristems of the vegetative stage stems using a machete. The remaining apparently healthy banana plants were left on the mat, and thus replanting was not necessary.

The CDMU and SDSR treatments were both supplemented with: i) tool sterilization after cutting and uprooting all diseased mats (CDMU) and cutting single diseased stems (SDSR) in a plot, or when moving between treatment and control plots, and ii) removal of male flower buds on healthy plants using forked wooden sticks after formation of the last hand on the bunch. Disinfection of tools was performed by holding the metal blade in a fire. Within a treatment plot, no disinfection of the digging or cutting tools was done when moving between diseased banana plants/mats. Finally, all diseased plant material cut or uprooted in the treatment plots was transported to the edge of the banana field, chopped up and deposited in a manure/compost pit. All tools were disinfected after completing the task.

At each of the four locations, experiments were established on five to seven farms depending on the size of the XW infected fields. At each site, four replicate plots each consisting of 50 banana mats were used for each treatment, making a total of 16 plots per site. The treatment plots with CDMU and SDSR were adjacent to each other. Diseased control plots were located at least 100 to 500 m from the CDMU/SDSR treatment plots to avoid cross-infection. The healthy control plots were located at least 200 to 1000 m from any diseased plot. Across all locations and treatments, and during the entire duration of the trials, harvesting of individual mature plants was allowed/continued, while weeding and de-leafing was suspended to minimise the risk of tool-mediated transmission of the disease. De-budding (removal of the male inflorescence using a forked stick) to prevent insect-mediated transmission, was performed in all treatments, except in the diseased control plots. Limited de-suckering was conducted in some plots, using sterilized cutting tools and under close supervision of a field technician in order to prevent any disease spread.

Data collection

The number of mats per plot, the number of plants in each mat, the number of diseased mats, and the number of diseased plants per mat were recorded. All the treatment and control plots were closely monitored on a weekly basis over a 13-month period between January 2019 and February 2020. The removal of diseased plants or mats in, respectively, the SDSR or CDMU plots was done immediately after a diseased plant was spotted. A trained farmer recruited within the village and a competent data collector recommended by the village chief, performed plot management activities and data collection, respectively. Both were supervised by a qualified scientist.

The impact of both treatment practices on yield potential was assessed based on the number of plants removed with either practice or lost due to disease in the diseased control plots, within the initial 6-month period of the trials. The disease was reduced to a very low incidence in both the SDSR and CDMU treatment plots and the percentage of cumulative plants lost was used as a proxy for the loss of potential bunch-bearing banana plants.

To quantify the time- and cost-effectiveness of the two treatments, the total time and costs invested in the application of the control practices over the entire trial period were recorded. More specifically, for the SDSR treatment the time to cut each single diseased stem was recorded, while for the CDMU treatment, the time needed for uprooting each entire mat was recorded. Mean values were calculated from all cut plants or uprooted mats, respectively. For the latter, the additional time needed for replanting a healthy sucker after uprooting each mat was recorded. Time needed for the destruction/processing of each diseased plant or mat debris and transport to a compost heap were also recorded and added to time needed for the SDSR or CDMU treatments, respectively. The cost (in Rwandan francs [Frw]) of the practices included the labour for cutting or uprooting, destruction of the diseased plant material, replanting and the cost of healthy suckers for replanting (in the case of CDMU) was calculated. The time and cost for de-

budding male flowers on healthy plants and mats was also included.

Data analysis

Prior to analysis, the residual plots were checked for deviations from linearity, homoscedasticity or normality. The percentage of plants lost due to Xanthomonas wilt (XW), treatment time, and treatment cost were analysed using a one-way analysis of variance to determine treatment effects. A post hoc Tukey HSD test was used for mean separation ($\alpha = 0.05$) of the four treatments. Simple linear regression, with time as the independent variable and incidence of XW as the dependent variable, were performed to assess the progress of XW in the diseased control plots over the one-year trial period. The analyses were performed using the R-packages 'stats' (R Core Team 2018) and 'agricolae' (Fde Mendiburu 2020), while post-processing and plotting was performed using the 'tidyverse' ecosystem (Wickham et al. 2019), 'dplyr' (Wickham et al. 2020) and 'ggthemes' (Arnold 2019) packages.

Results

Treatment effects on the incidence of XW

Both CDMU and SDSR were effective in reducing the incidence of XW (Fig. 2). Over all sites, incidence of XW declined significantly from 6.2% (standard deviation, sd = 2.5) for the CDMU, and 7.0% (sd = 1.1) for the SDSR treatments, respectively, to 0.3% (sd = 0.2) and 0.7% (sd = 0.4) (F = 22.5, $p < 0.001$ and F = 65.75; $p < 0.001$, respectively) within one month after the experiment commenced. After the initial decline, incidence of XW remained below 1% for both treatments over all sites. Continued management by both CDMU and SDSR during the consecutive months proved to be necessary and effective.

In the diseased control plots (plots in which the diseased banana plants were left untreated) the incidence of XW remained high or increased over the duration of the trial over all the sites (Fig. 2).

The relationship between time and incidence of XW was dependent on location, and ranged from moderate to weak: Gisagara ($R^2 = 0.49$; F = 13.48, $p < 0.001$),
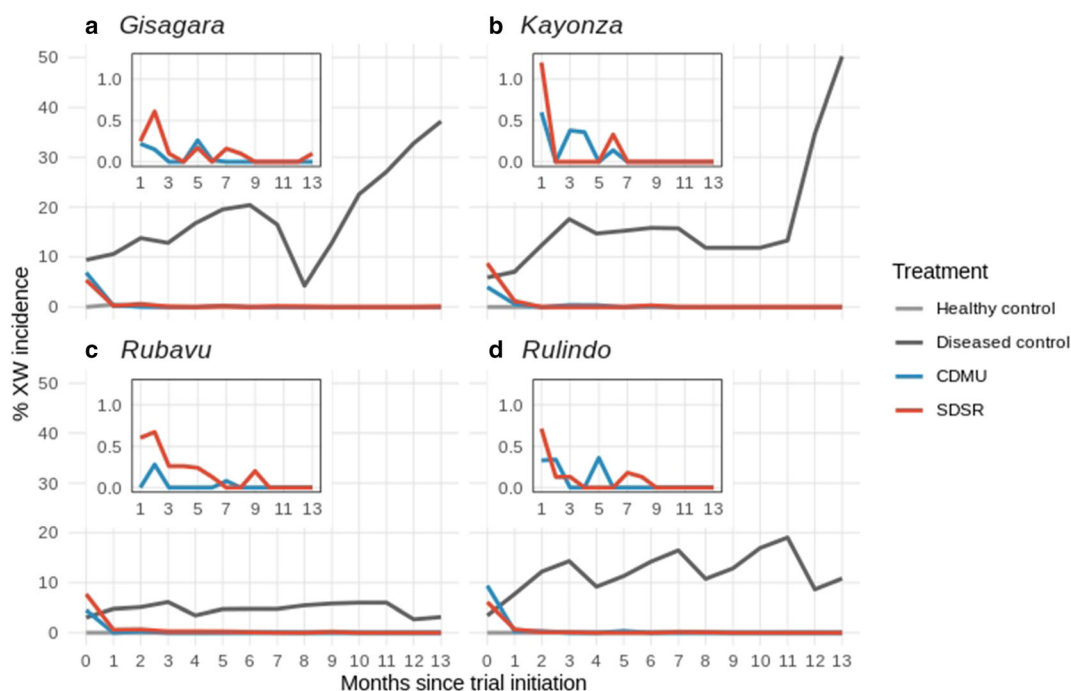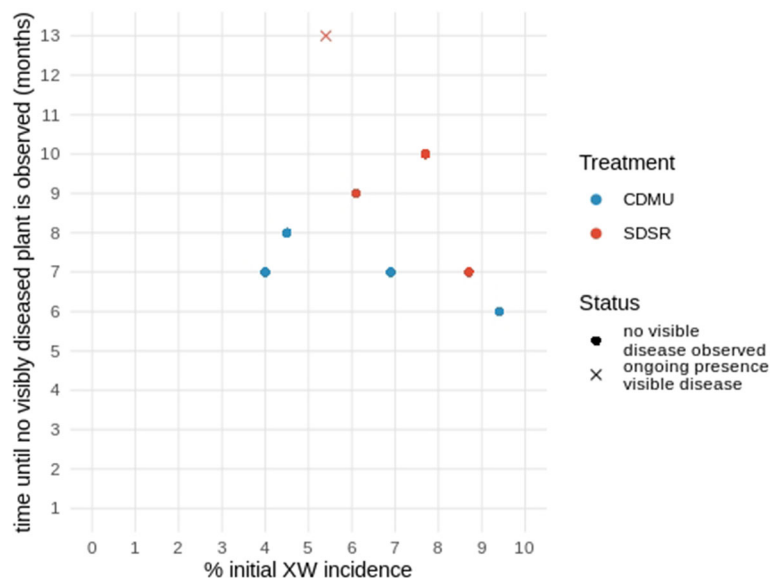

Fig. 2 Progress in the incidence of banana plants with symptoms of Xanthomonas wilt (XW) during a one-year trial in banana fields treated by complete diseased mat uprooting (CDMU) or by single diseased stem removal (SDSR) and in healthy and diseased control fields in (a) Gisagara, (b) Kayonza, (c) Rubavu, and (d) Rulindo.

Time 0 represents the initiation of the trials in January 2019, with disease progress shown in consecutive months since trial initiation. The inset figures present small fluctuations (0 to 1%) in the incidence of XW commencing one month after trial initiation

Kayonza ($R^2 = 0.37$; $F = 8.76$, $p < 0.05$) and Rulindo ($R^2 = 0.15$; $F = 3.21$, $p > 0.05$) in the diseased control plots. The incidence of XW in diseased controls increased from 9 to 37%, 6 to 50% and 3.5 to 11% in Gisagara, Kayonza and Rulindo, respectively. At Rubavu, there was no significant increase in incidence of XW in the diseased control: the incidence of XW was approximately constant at 4.7% (sd = 1.2).

Despite the effectiveness of both treatments (Fig. 2), the average time to the point no diseased banana plants were observed in the treated plots was shorter for the CDMU treatment compared to the SDSR treatment (Fig. 3). Time to no visibly diseased plant for the CDMU treatment was 6 to 8 months, depending on site, and was not dependent on the initial disease incidence. Although the time to no diseased plants for the SDSR treatment fell within the range observed for the CDMU treatment at Kayonza (7 months), longer recovery times of 9 to 10 months were recorded at Rubavu and Rulindo, while fields at Gisagara were not fully recovered (0.1% XW) at end of the trial (13th month), despite a low initial incidence of XW at the site. At all sites in treated plots, XW re-emerged periodically during the experiments (Fig. 2, inset plots). With the healthy control plots, only one plant at Gisagara developed symptoms of XW (one month after the experiment was commenced). The plant was removed. No further symptoms of XW developed on plants in any healthy control plots.

Impact of XW on productivity

Whilst both XW treatments effectively reduced disease incidence, the removal of single diseased stems (SDSR), or complete mats (CDMU) resulted in thinning of mats or mats in the fields, respectively, and thus reduced productivity. The cumulative number of stems removed over the initial 6-month period was significantly lower ($F = 20.35$, $p < 0.001$) for SDSR compared to the CDMU treatment (Fig. 4). Over all sites, 15% (6 to 29%) of the plants at the start of the trial were removed by the SDSR treatment compared to 35% (12 to 70%) for the CDMU treatment. During this initial 6-month period, the number of plants removed applying the CDMU treatment was comparable to a mean stem loss of 29% (7 to 64%) in the diseased control plots.

Some variability was observed in the proportion of stems lost between study sites. For example, there was no differences in the percentage of stems lost using the SDSR or CDMU treatments and the diseased control plots at Rulindo (Fig. 4d). This is due to the high within-site variability in the incidence of XW in the CDMU plots. At Rubavu (Fig. 4c), there was a significant difference ($F = 16.15$, $p < 0.01$) between the SDSR and CDMU treatments in the number of stems removed, while a limited number of stems were lost in the diseased control plots. At Rubavu there was a persistent low incidence of XW in the diseased control plots during the entire experiment (Fig. 4c), possibly due to the initial low incidence in these plots (Fig. 2).

Fig. 3 The time to eradication of Xanthomonas wilt (XW) in banana fields in Rwanda with different initial incidence of XW. Blue dots denote Complete Diseased Mat Uprooting (CDMU), while red dots denote Single Diseased Stem Removal (SDSR). The dots show the point at which no more diseased plants were observed for the remainder of the treatment period, while a cross denotes ongoing presence of XW disease at the end of the trial

Fig. 4 Percentage of plants lost due to Xanthomonas wilt (XW) over the initial 6-month period of the experiment in the Complete Diseased Mat Uprooting (CDMU) treatment plots, the Single Diseased Stem Removal (SDSR) treatment plots and the diseased control plots. During the first 6 months of the experiment the incidence of XW was reduced to very low values for both the CDMU and the SDSR treatments. Statistical differences between treatments within sites are indicated by different letters according to Tukey's HSD test ($\alpha = 0.05$). Whiskers indicate standard errors of the means
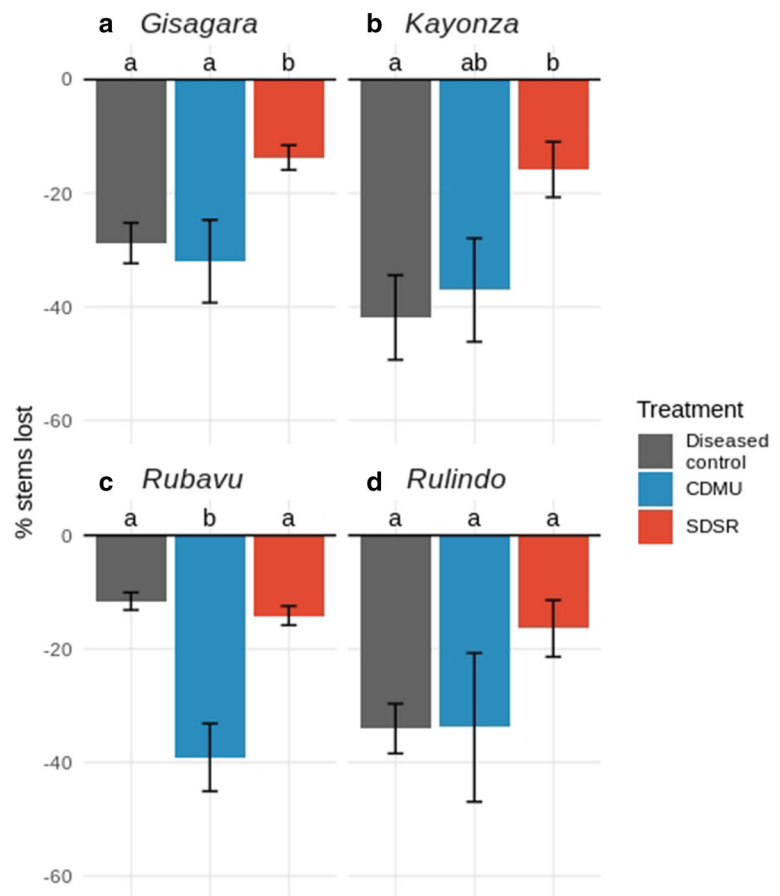
At Gisagara and Kayonza, the SDSR treatment was more productive than the CDMU and the diseased control treatments (Kayonza: F = 8.22, $p < 0.05$; Gisagara: F = 10.77, p < 0.05). Over all sites combined, the SDSR treatment consistently had a lower proportion of cut plants.

Labour and cost of XW control options

The SDSR treatment required less time and cost compared to the CDMU treatment for control of XW (Tables 2 and 3). Time needed for the removal of a single plant using SDSR was significantly less (0.4 min, sd = 0.2) compared to uprooting an entire banana mat using CDMU (15.8 min, sd = 4.4) (F = 117.2, $p < 0.001$). The time needed to uproot a diseased mat was significantly different between sites (F = 3.79, p < 0.05); mat removal took 10.1 min (sd = 4.4) at Gisagara compared to an average of 17.7 min (sd = 2.8) at the three other sites, Kayonza, Rulindo and Rubavu, combined. The difference in time is likely

due to a difference in banana cultivars and the size of the mats. The time to remove a single plant (SDSR) was similar across sites. The time taken to move and destroy (move plant debris to a compost heap) an entire infected banana mat (7.4 min, sd = 1.2) was significantly higher (F = 78.11, p < 0.001) than for a single plant (3.8 min, sd = 0.2). For CDMU, an additional time of 13.6 min (sd = 1.0) was needed for replanting. No replanting was needed using SDSR. Including all activities, the total time needed was 4.2 min (sd = 0.3) for the SDSR treatment and 36.4 (sd = 4.4) for the CDMU treatment.

The total cost for each treatment (the labour cost of uprooting a mat or cutting a stem, diseased plant or mat destruction, plus the cost of healthy plant material and replanting in the case of CDMU) followed a similar pattern to time needed (Table 3). On average, the total cost of the SDSR treatment per plant was 25 Frw (sd = 2), while the CDMU treatment cost 619 Frw (sd = 27) per mat. The total cost of CDMU was significantly (F = 4.07, p < 0.05) lower at Gisagara (581 Frw, sd = 27) compared to the other three sites

Table 2 Time required for treatments to control Xanthomonas wilt (XW) of banana in Rwanda. The Complete Diseased Mat Uprooting (CDMU) treatment and the Single Diseased Stem Removal (SDSR) treatment are standardized to one mat or plant, respectively. Time (minutes) for complete uprooting of an entire mat, or cutting of a single stem, removal of male buds, destruction of diseased plant material and replanting of healthy suckers after diseased mat removal are presented

Site	Treatment	Time per mat or plant (min)[a]			
		Time uprooting / cutting	Time destruction	Time replanting	Total time
Gisagara	CDMU	10.1c (4.4[b])	8.0a (0.8)	12.0	30.1b (4.5)
	SDSR	0.2d (0.1)	4.0c (0.8)	0	4.2c (0.8)
Kayonza	CDMU	17.0ab (2.0)	8.5a (1.3)	14.0	39.5a (2.0)
	SDSR	0.4d (0.1)	3.8c (1.0)	0	4.1c (0.9)
Rubavu	CDMU	20.8a (2.6)	5.8b (1.0)	13.0	39.5a (2.2)
	SDSR	0.4d (0.2)	3.5c (0.6)	0	3.9c (0.5)
Rulindo	CDMU	15.4b (7.3)	7.5a (1.3)	14.0	36.9a (7.0)
	SDSR	0.6d (0.4)	4.0c (0.8)	0	4.6c (1.0)
	F (P value)[c]	4.45 (0.014)	2.13 (0.127)	5.60 (0.001)	5.36 (0.007)

[a] Means in a column followed by the same letter are not significantly different from each other according to Tukey's HSD test ($p \leq 0.05$)

[b] Standard deviations are provided in parentheses

[c] The F-value (based on the F-distribution) is obtained from the analysis of variance, and the P value is the probability of obtaining an F-value at least as extreme as that observed, assuming that the null hypothesis is correct

combined (632 Frw, sd = 9) due to a shorter labour time linked to smaller mat sizes.

A major portion of the total cost of CDMU was the new planting material (400 Frw per sucker, or approximately 65% of the total cost). The cost of labour needed for replanting was also significant (80 Frw [sd = 6], or approximately 13% of the total cost). Replanting was not necessary with the SDSR treatment. The labor

Table 3 Treatment cost for strategies to control Xanthomonas wilt (XW) of banana in Rwanda. The Complete Diseased Mat Uprooting (CDMU) treatment and the Single Diseased Stem Removal (SDSR) treatment are standardized to one mat or plant, respectively. Labour cost (Rwandese Franc; Frw) for complete uprooting of an entire mat, or cutting of a single stem, removal of male buds, destruction of diseased plant material and replanting of healthy suckers after diseased mat removal are presented. Total cost based on labour and new planting material is provided

Site	Treatment	Cost per mat or plant (Frw) [a]				
		Labour cost uprooting / cutting	Labour cost destruction	Labour cost replanting	Cost planting material	Total cost
Gisagara	CDMU	60.5c (26.3 [b])	48.0a (4.9)	72	400	580.5b (26.7)
	SDSR	1.3d (0.7)	24.0c (4.9)	0	0	25.3c (4.9)
Kayonza	CDMU	101.8ab (12.1)	51.0a (7.8)	84	400	636.8a (12.3)
	SDSR	2.2d (0.6)	22.5c (5.8)	0	0	24.7c (5.6)
Rubavu	CDMU	124.5a (15.6)	34.5b (5.8)	78	400	637.0a (12.9)
	SDSR	2.6d (0.9)	21.0c (3.5)	0	0	23.6c (3.2)
Rulindo	CDMU	92.2b (43.5)	45.0a (7.8)	84	400	612.2a (41.9)
	SDSR	3.9d (2.6)	24.0c (4.9)	0	0	27.8c (5.9)
	F (P value)[c]	4.45 (0.014)	2.13 (0.127)	6.02 (0.001)	2.11 (0.129)	5.36 (0.07)

[a] Means in a column followed by the same letter are not significantly different from each other according to Tukey's HSD test ($p \leq 0.05$)

[b] Standard deviations are provided in parentheses

[c] The F-value (based on the F-distribution) is obtained from the analysis of variance, and the P value is the probability of obtaining an F-value at least as extreme as that observed, assuming that the null hypothesis is correct

cost for an entire banana mat with the CDMU treatment (95 Frw, sd = 27) was on average 40-fold higher than that for a single infected plant using the SDSR treatment (2.5 Frw, sd = 1). The labour cost for destroying a diseased mat (45 Frw, sd = 7) was approximately twice that for the destruction of a single plant (23 Frw, sd =1).

De-budding of the remaining healthy flowering plants was performed for both the SDSR and CDMU treatment plants and took on average 0.07 min (sd = 0.04) per plant for an average labour cost of 0.4 Frw (sd = 0.3) over all sites combined.

Discussion

Effectiveness of CDMU and SDSR for control of XW

The results of the study show that both CDMU and SDSR similarly reduced the incidence of XW. The incidence of XW declined to less than 0.5% within 3 months of initiating the treatments. However, the incidence of XW in the disease control plots (no CDMU or SDSR applied) remained high or increased during the 13-month study period. The decline in incidence of XW and recovery of the plant population in the SDSR treated plots is consistent with the results of Blomme, Ocimati, et al. (2017b); Blomme et al. (2019). The time to complete recovery of fields from XW was shorter with the CDMU treatment compared to the SDSR treatment, which may be attributed to differences in the mechanism of the two approaches. With both approaches, the reduction in incidence of XW and recovery of plant populations in fields is attributed to removal of diseased plants and a reduction or elimination of *Xvm* inoculum, and in the case of the CDMU treatment, replanting. With the SDSR treatment the chance exists that, apart from the visibly diseased plant or plants in a mat that were removed, other stems within the physically interconnected mat may be infected with *Xvm* but as yet the disease is latent (Blomme et al. 2014; Blomme et al. 2017b,b; Ocimati et al. 2015). Incursions of *Xvm* into lateral shoots most often results in latent infections that do not jeopardize growth and yield of the banana plant (Ocimati et al. 2013, 2015). However, a limited number of plants with latent infections can still develop symptoms, although the time for symptom development is not predictable. Ocimati et al. (2013, 2015) reported long incubation periods for XW (up to 24 months) in lateral shoots attached to mother plants that had been artificially inoculated through the inflorescence. Latency could also explain the outbreaks of XW that we observed after periods where no XW was observed in either the SDSR- or CDMU-treated plots (Fig. 2). The outbreaks of XW underline the need for regular assessments for XW in fields managed with SDSR, whether in the early stages of control or when there is no visible evidence of XW remaining, as small outbreaks are likely to occur at irregular intervals over a period of many months. In addition, Ntamwira et al. (2019) reported that timely application of SDSR (immediately after observing first symptom) was more effective for field recovery compared to a delayed application (2 weeks and 4 weeks) or no SDSR application. Timely application of SDSR not only reduces XW inoculum in diseased mats, it also prevents potential infection and/or build-up of *Xvm* in lateral shoots physically attached to the diseased plant. With CDMU, it is important to replant using clean planting materials. The additional components of both SDSR and CDMU, i.e., the early removal of male buds and the sterilization of farm tools most likely played an important role in preventing within mat and within field spread. If applied area-wide, both XW management approaches will reduce introductions from external sources through insect vectors, contaminated farm tools, or diseased planting material.

This study was conducted on farmers' fields, and the history of XW management in the plots was not available. It is possible that XW-management activities prior to the experiments could have influenced to the recovery of plant populations in experiment plots. However, this is unlikely when comparing the results from the control and treated plots at the different sites.

Impact of CDMU and SDSR on productivity

If left untreated, XW severely reduces banana production. Across the study sites in the diseased control plots there was a 29% reduction in productive banana plants over the 6-month period after trial initiation; the reduction in productive banana plants continued for the duration of the experiment. Other studies in the ECA report potential banana yield losses of up to 100% due to XW (Ssekiwoko et al. 2006; Kagezi et al. 2006; Tushemereirwe et al. 2006). It should be noted that other field operations including weeding, de-budding and de-leafing were halted for the duration of the trial in the diseased control plots. Limited de-suckering was performed in the diseased control plots at Rubavu under

close supervision of a field technician. Banana harvesting was conducted in all diseased control plots.

CDMU required uprooting entire mats comprised of symptomatic and asymptomatic plants which contributes to high yield losses. Potential yield loss in the CDMU plots, measured as mean number of plants lost or rogued in the 6 months after trial initiation, was 6% and 20% higher compared to that observed in the diseased control (29%) and the SDSR (15%) plots, respectively. The time needed to restore pre-infection yield levels using CDMU can be 18 to 20 months at the mid- to high-altitude sites in the ECA (Blomme et al. 2014). This prolonged recovery is attributed to the short fallow period between uprooting and replanting, and the time needed for a young sucker to grow into a mature plant (up to 18 months from planting to harvest). With the SDSR treatment, a mean of 15% of plants were removed, but because the banana mat was not removed, the remaining apparently healthy plants contributed to final yield. Thus, yield losses are lower using SDSR compared to CMDU, or to not applying any control measure. After applying CDMU, it is important to replant using clean planting materials.

Time and cost-efficiency

SDSR was more time and cost-efficient compared to CDMU. Using SDSR compared to CDMU reduced time to control XW by 88% and the cost of control by 96%. As expected, the cutting and disposal of single diseased plants by SDSR was less time consuming, less labour intensive and less costly. No additional time or cost related to replanting were incurred with SDSR. With CDMU, mats comprised of several plants had to be completely uprooted and disposed of. New, healthy planting materials had to be acquired and planted, leading to additional costs.

Rapid progress in XW is observed when sources of inoculum were not removed in a timely manner, when male buds are left on the plants, and garden tools used for de-leafing, de-budding, de-suckering and other farm operations are not sterilized after use (Blomme et al. 2017a, b; 2019; Ntamwira et al. 2019). So, both time and cost are also associated with the additional XW control operations of early de-budding of the male inflorescence part on healthy plants, and the sterilisation of tools. Both activities are crucial to prevent spread of XW under both SDSR and CDMU. With CDMU there may initially be fewer plants to de-

bud due to the uprooting of whole mats (comprising sick and healthy plants) and a delay in de-budding of the newly planted suckers. The overall difference in time and cost for de-budding between the two control practices is however expected to be minimal. Thus, the time and associated costs for both de-budding and tool sterilisation are not expected to affect the adoption of either management practice.

Reflections on adoption of CDMU and SDSR

Notwithstanding the importance of banana as a food and income source in the ECA, reports indicate that CDMU has been poorly adopted (Blomme et al. 2014; Jogo et al. 2013; Ocimati et al. 2019), which is thought to be due to the high labor demand and cost of CDMU. Blomme et al. (2017b) reported better adoption of CDMU in the market-oriented production systems (e.g. of south-western Uganda) compared to the subsistence-oriented production systems (e.g. of central Uganda). Kikulwe et al. (2018, 2019) reported that 'small' banana farmers have a low return on investment from XW control measures and is thus a reason why adoption is low in Uganda. Subsistence farmers dominate in the ECA, including in Rwanda, and SDSR is a suitable alternative to CDMU for the region. Adoption of agricultural innovations and disease control measures is dependent on multiple factors. These include the complexity of the proposed technique, compatibility with ongoing activities, the associated risks, the performance of the new technology and cultural and normative appropriateness (Sinja et al. 2004; Doss 2006; Pircher et al. 2013).

Adoption of XW control practices may also be influenced by gender relations and norms within households and communities. Kikulwe et al. (2018, 2019) found that women in male-led households had a lower adoption of XW control measures compared to their male partners. Since the authors did not differentiate between CDMU and SDSR, it is impossible to draw conclusions between control methods. However, Iradukunda et al. (2019) observed that labor constraints of women in female-led households limits their adoption of SDSR practices, and gender norms played a role in Burundi. For instance, norms that prescribe certain managerial tasks like digging and cutting the stems to be performed by men only (Rietveld and Farnworth 2018a, b; Kawarazuka et al. 2020) also affect adoption of control practices among women. Such norms can affect the adoption of both CDMU and SDSR. One aspect which is often ignored in adoption studies is the emotional component. Unlike

annual crops, or even some fruit trees, banana plantations in the ECA region tend to be long-lived. In a study conducted in Uganda (Kilwinger et al. 2019), farmers claimed that so long as new suckers keep on generating, a banana plantation can survive indefinitely. As such, the banana plantation presents inter-generational value and security to farming households, and farmers often feel an attachment to their plantation, and even to individual mats of specific cultivars which they have been collecting and growing over decades. In addition, banana is associated with traditional beliefs, ceremonies and rituals and presents spiritual value; *"the plantation is almost considered a living organism, which requires respect"* concluded Kilwinger et al. (2019). Thus, applying CDMU and uprooting XW diseased banana mats may have a psychological toll on farmers, making them perceive the control method as destruction rather than rescue. Access to healthy planting material may be an additional limiting factor to banana farmers in the ECA region; most farmers rely on suckers from their own or a neighbor's farm. Such suckers are potential sources of *Xvm*, or other pests and pathogens, thus perpetuating the problem.

Following these lines of reason, SDSR which is less destructive may be perceived as a more 'normal' and acceptable banana disease management technique in the sense that it prescribes only slight alterations to a common practice of cutting stems, irrespective of the associated labor and costs investment. However, when XW first appears on a new farm, and only a hand-full of mats are infected, the application of CDMU might be advised as it offers a greater probability to fully eradicate the disease. But, once the disease has spread over a larger geographical area and many banana mats are diseased, eradication becomes impossible and SDSR is the most rational approach.

Conclusions on adoption of XW control options

This is the first report quantifying and contrasting the time and labor demands associated with CDMU and SDSR. The results show CDMU and SDSR are effective at reducing the incidence of XW in banana farms over short periods, although production recovered more rapidly under SDSR. CDMU is associated with a large production loss over a long period, high labor and time costs, and a cost of replanting with healthy young plants. The costs and time needs are either lower or non-existent with SDSR. The evidence we present confirms

SDSR as the easier and cheaper control option for XW and explains the poor adoption of CDMU in the ECA. Based on these results, the SDSR package should be more widely accepted and adopted by farmers and policy makers in Rwanda, resulting in its promotion and acceptance as a superior alternative to the currently advocated CDMU. In addition, the results provide additional insights for countries or regions where SDSR is already widely practised.

compensated for potential losses in food and or income due to non-management of the disease on their fields.

Research involving human participants and/or animals   Not applicable.

Informed consent   Not applicable.

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