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ORIGINAL PAPER

Banana xanthomonas wilt continues to spread in Tanzania despite an intensive symptomatic plant removal campaign: an impending socio-economic and ecological disaster

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Abstract Banana Xanthomonas wilt (BXW), caused by the recently introduced pathogen *Xanthomonas campestris* pv. *musacearum* (Xcm), is a limiting factor for banana production in Kagera, Tanzania. A region-wide eradication campaign was initiated in 2013. The objectives were to gain insight into the spatial and seasonal occurrences of BXW and into field management practices. In 2015, 135 smallholder farmers were interviewed about BXW and management practices, and their farms were assessed for incidence of the disease. BXW incidence per ward in 2014, obtained from extension offices, and space-time cluster analysis was performed with SaTScan. BXW clusters were detected during rainy but not during dry seasons. These results agreed with the information provided by farmers that the highest incidence of BXW occurred during rainy seasons. Farmers recalled that BXW incidence increased exponentially between 2011 and 2013 but decreased steeply after 2013, coincident with the start of the BXW eradication campaign. However, pathogen transmission continued due to inconsistent sterilization of field tools and exposure of Xcm to rain. Fields of poor farmers are at greatest risk because they borrow tools and are unable to impose some recommended management practices. After the appearance of BXW in individual farms, the number of banana bunches consumed per family per month decreased significantly from 13.1 to 6.4 with a corresponding increase in areas planted to cassava and maize. Based on these findings, we suggest refining the BXW management recommendations, in particular limiting the cutting of BXW-affected plants to dry periods and sterilizing farm tools in fire.

Keywords East Africa · Emerging disease · Management · Food security · *Musa* species · *Xanthomonas campestris* pv. *musacearum*

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Introduction

Bananas and plantains (*Musa* spp.) are the most produced and consumed fruits worldwide (FAOSTAT 2011). The term banana refers to fruit bearing species and hybrids in the genus *Musa*, family *Musaceae*. Most edible bananas are hybrids that originated from two wild species: *M. acuminata* Colla and *M. balbisiana* Colla (Simmonds 1962). They are parthenocarpic and produce seedless fruit, and are multiplied vegetatively from suckers emerging from an underground rhizome (also called corm). Over time, a sucker develops into a fruit bearing plant, which together with new suckers forms a so-called mat. Bananas are best known as sweet dessert fruits, but many cultivars are grown for their starchy fruits that are roasted or cooked staple foods (Karamura et al. 2012). Some cultivars with bitter and astringent fruits are used for brewing beer.

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Tanzania produces about 3.7 million tons of bananas per year and is the second largest producer in Africa after Uganda (FAOSTAT 2011). Most of the bananas produced in the country are of the East Africa Highland Banana subgroup (EAHB) of AAA bananas (De Langhe et al. 2002), and 80 % of the total is grown in the highlands of the Kagera, Kilimanjaro, and Mbeya regions. Kagera is the leading region in banana production and consumption followed by Kilimanjaro and Mbeya regions. In Kagera, over 85 % of the population depends on agriculture, with over 600,000 ha under production of mixtures of food and cash crops, including bananas. Banana is by far the most widely grown food crop in Kagera, accounting for more than 45 % of the total cropped land (Baijukya and Folmer 1999; Baijukya et al. 2005). About 70 % of the population in Kagera depends on bananas as their daily source of energy (MAFC 2008).

In the past decade, banana production in Kagera has faced challenges from soil fertility decline, pests and diseases (Baijukya and Folmer 1999; Blomme et al. 2013). Most of these challenges have been managed with various cultural practices, applications of cow manure, and resistant hybrid cultivars (Edmeades et al. 2007; Mgenzi and Mbwana 1999). Despite reduced banana productivity a reasonable level of food and income security was maintained (Edmeades et al. 2007; Rugalema et al. 1994). However, since the introduction of banana Xanthomonas wilt (BXW) in Kagera in 2006, probably with infected plant materials, the livelihoods of thousands of smallholder farmers has been jeopardized (Nkuba et al. 2015). The disease affects all banana cultivars and ultimately kills infected plants and mats. Entire banana fields have been lost due to BXW in the region's Muleba, Karagwe and Bukoba districts. In late 2013, a BXW eradication campaign (operation Tokomeza, Swahili for eradication) was initiated, and in the first year of this campaign more than 2 million symptomatic plants were cut down and an additional 2 million since then (Mgenzi 2009; Mgenzi, personal communication).

BXW is caused by a Gram negative bacterium, *Xanthomonas campestris* pv. *musacearum* (Xcm), which invades the vascular system of banana causing wilting and death of the plant (Yirgou and Bradbury 1974). The primary mode of transmission of Xcm is via infected planting material, contaminated garden tools, traded infected bunches covered by banana leaves that are discarded in banana fields, and insect vectors (Yirgou and Bradbury 1974; Nakato et al. 2013). Of the insect vectors, stingless bees that are attracted to the male flower are particularly important (Tinzaara et al. 2006). Recently, the banana weevil (*Cosmopolites sordidus* Germar) was confirmed as a vector of Xcm (Were et al. 2015).

Control of BXW is challenging, as there are no resistant cultivars or effective chemical or biological measures. Sanitation and reducing Xcm transmission are the main measures to manage this disease. The main recommended management practices are: debudding (removing the male portion of the inflorescence); removing, burying or burning affected stems or whole mats; disinfesting farm tools after every use; and using pathogen-free planting materials (Yirgou and Bradbury 1974; Blomme et al. 2014). However, the most labor-intensive practices may not always be used by farmers, and recommendations like burying or burning of affected stems and mats have been abandoned in some countries (Kubiriba et al. 2014).

Effective and efficient disease intervention requires a good understanding of the disease's epidemiology and the pathogen's transmission dynamics in time and space (Bouwmeester et al. 2016; Shaw and Osborne 2011; Shimwela et al. 2016; Wu et al. 2005). Knowledge of the specifics that surround disease development is crucial for identifying risk factors, designing efficient surveillance methods and identifying control strategies (Shimwela et al. 2016). Shimwela et al. (2016) described spatiotemporal patterns of BXW in Kagera region from 2007 to 2011. Variable hotspots of BXW were identified in the Muleba, Karagwe, Bukoba and Misenyi districts of Kagera, and the disease was positively correlated with annual rainfall. However, the seasonality of epidemic development was not addressed in that or other studies, nor has the adoption of cultural management strategies for the disease in Tanzania (Blomme et al. 2014).

The main goal of this research was to gain insight into the distribution and seasonal development of BXW and the impact of field practices on the spread of BXW in Kagera. Ultimately, efficient surveillance methods and control strategies to curb BXW spread were sought. The specific objectives were: 1) to determine spatial clusters of BXW cases and the months when these occurred, 2) to relate the within-year temporal BXW distribution to monthly temperature and rainfall data, 3) to relate farm management practices to potential BXW spread, and 4) to estimate the socio-economic consequences of BXW management. To achieve these objectives, smallholder farmers were surveyed on their production and field management practices, months of year with the highest BXW incidence, and the impact the disease had on their livelihood. In addition, monthly symptomatic plant removal data collected by extension officers during the BXW eradication campaign between January and December 2014, was used to analyze BXW development in space and time.

Materials and methods

Description of the study area

Two studies were conducted in the Bukoba, Muleba, Misenyi and Karagwe districts of Kagera region. Each district contains 25–30 wards, and each ward 3–7 villages. The Kagera region is located in northwestern Tanzania between 1^{o}00' and 2^{o}45' latitude South and 30^{o}25' and 32^{o}40' longitude East (Fig. 1), and the altitude ranges from 790 m above sea level (masl) to 1874 masl. The banana growing areas in the four districts of this study have similar altitude ranges (Table 1). Kagera region has a tropical humid savanna climate with a bimodal rainfall pattern where the major and minor rainy seasons are from March to May and late September to December, respectively, and the rainfall ranges from 750 to 2000 mm $yr.^{-1}$. Most of the Karagwe and Misenyi districts receive low to medium rainfall (750–1250 mm $yr.^{-1}$), whereas most of the Muleba and Bukoba districts receive high rainfall (1000–2000 mm $yr.^{-1}$). The region has an average daily temperature of 20 °C, with an average minimum temperature of 15 °C and an average maximum temperature of 28.5 °C (Baijukya and Folmer 1999). The estimated annual temperature ranges (Shimwela et al. 2016) are similar for the four districts (Table 1).

Data collection

Banana plant removal records In 2013, the Kagera regional government launched an intensive banana removal campaign in an attempt to halt the spread of BXW. Visibly affected banana plants had to be cut by farmers, and fields were regularly inspected by extension officers. Farmers who had symptomatic plants at the time of inspection received hefty fines. Monthly records were kept by extension officers of all symptomatic plants cut in each ward and village. For the research described here, monthly records of 2014 were obtained from ward offices, district agricultural and livestock development offices (DALDOs) and the regional agricultural office. In total, data were obtained for 59 wards in the four districts mentioned above. Geographical coordinates of the extension offices in each ward were recorded using a hand-held Global Positioning System (GPS) (GARMIN International Inc) in 2015.

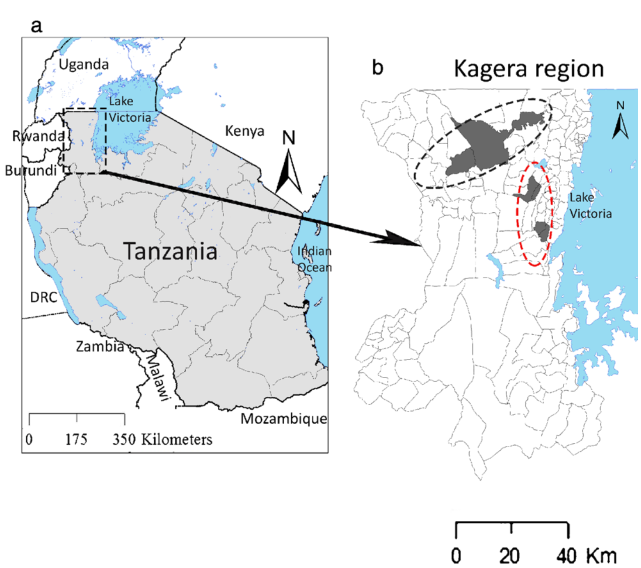

Fig. 1 **a** Geographical location of Kagera region, Tanzania and **b** location of four districts (dark gray) where the banana Xanthomonas wilt surveys were conducted in Kagera region in 2015. The black dashed ellipse contains Karagwe district (including 2 studied wards) and Misenyi district (with 1 studied ward) with medium and low rainfall, respectively, and the red dashed ellipse contains Bukoba and Muleba districts (including 2 studied wards each) with high rainfall

Household surveys In February and March 2015, household surveys were conducted in the Kikomelo and Rubale wards in Bukoba rural district, Biirabo and Kibanga wards in Muleba district, Kituntu and Kihanga wards in Karagwe district, and Kasambya ward in Misenyi district of Kagera region (Fig. 1). Kihanga ward is larger than the other wards, but less densely populated. A total of 135 evenly distributed households were selected throughout the seven wards, based on population density, banana production data and BXW records, and a structured household questionnaire was administered through face to-face interviews. Four researchers (three male and one female) went to the same wards simultaneously and divided the households randomly amongst themselves. The head of household was interviewed in each case. GPS coordinates of each field visited were recorded, and data were collected on household characteristics (Table 2), general field management practices and management practices for BXW. The year BXW was first observed, the year of peak occurrence, and the number of BXW-affected banana plants that were uprooted during the previous four years were recorded, as were numbers of banana bunches that were produced, sold and eaten. Also recorded were the sources of income from bananas and other activities, and areas under banana, maize and cassava before and after BXW arrived. In addition to administering the questionnaire on a farm, the number of banana mats with BXW affected plants (based on visual symptoms) were counted out of 30 mats by moving diagonally through each banana field. Finally, the farmers were classified in three prosperity categories. Farmers who owned 0.5–1.0 ha of land, two or more cows, goats and pigs, owned a business at the local market and/or received a remittance or pension were considered rich. Farmers who owned 0.2 to 0.5 ha of land, one cow, two goats, and a pig, owned a small business at the local market and/or received a remittance were considered medium prosperous, and farmers who had <0.2 ha of land, did not own livestock or have an extra source of income were considered poor.

Space-time analysis of banana plant removal records

Space-time statistical analyses were conducted using the SaTScan software version 9.4 (Kulldorff 2015) to identify geographic areas and periods of the year with BXW clusters based on the monthly banana removal records of 2014 collected from extension offices. Space-time cluster analysis is a widely used technique to examine how spatial patterns of disease change over time (Pfeiffer et al. 2008). The general

Table 1 Altitude, annual temperature and rainfall, and incidence of fields with symptoms of banana Xanthomonas wilt (BXW) in four districts at the time of a survey in Kagera region, Tanzania, in February and March of 2015

Districts	Altitude range (m)[1]	Mean annual temperature (°C)[2]	Mean annual rainfall (mm)[3]	Number of fields visited[4]	Number of fields infected with BXW[5]	Percentage of fields with BXW (%)[6]
Bukoba	1120–1500	18–22	1500–2000	42	30	71
Muleba	1140–1350	17–22	1000–1500	31	21	67
Karagwe	1180–1620	17–21	750–1250	29	20	68
Misenyi	1100–1600	19–22	750–1000	33	18	54

[1] Data collected during the survey in 2015

[2] Interpolated from Bioclim data as described in Shimwela et al. (2016)

[3] Data derived from Baijukya and Folmer (1999)

[4] Total number of fields visited per district

[5] Number of fields with at least one mat infected by BXW, based on visual symptoms

[6] Percentage of fields with at least one mat infected by BXW per district

statistical theory behind the spatial scan statistics has been described in detail in Kulldorff (1997). Briefly, we employed retrospective analysis using a space-time permutation model, as it requires only incidence (case) data with information about the spatial location and time for each occurrence (Kulldorff et al. 2005). Retrospective analysis was performed with the maximum temporal size of the window set to 50 % of the study period and the spatial window size set to 50 % of the wards with banana fields in Kagera. The analysis was performed using area-based data aggregated at the ward level in the Bukoba, Karagwe, Muleba and Misenyi districts. Latitude and longitude coordinates of ward extension offices were used as geographical locations. Monthly diseased plant removal data were analyzed for January to December 2014.

The significance test for the most likely and secondary clusters was based on comparing the size of the log likelihood ratio against a null distribution obtained from 999 Monte Carlo replications (Kulldorff 1997). The circle with the maximum likelihood ratio, containing more cases than expected from random distribution, was identified as the most likely (primary) cluster that least likely occurred by chance. For this study the most likely clusters with a significance level of P value <0.05 were considered. ArcGIS 10.3.1 was used to extract and represent the SaTScan results.

Statistical analysis of survey data

Descriptive frequencies and percentages were calculated for the first year BXW was observed on each farm, the year with highest BXW incidence, and the practices used to control BXW in each district. The incidence of fields in each district that had BXW in 2015 was also calculated.

The following field management practices were evaluated among different demographic groups of farmers: de-suckering, removing affected plants, corm removal (for any purpose), de-budding, de-trashing of dead leaves, leaf harvesting (for wrapping material or other purposes), weeding, bunch harvesting, and use and sterilization of farm tools. Chi-

Table 2 Household characteristics of interviewed farmers in four districts of Kagera region, Tanzania, in February and March of 2015

Characteristic		Districts			
		Bukoba	Muleba	Misenyi	Karagwe
Head of household	Female	13	9	10	10
	Male	29	23	22	19
Age (years)		24–80	24–77	22–78	34–68
Wealth category	Poor	13	10	8	7
	Medium	24	15	17	14
	Rich	5	7	7	8
Household size (persons)		1–6	1–10	1–19	1–11
Plantation age (years)		4–150	3–100	4–100	3–85
Banana farming experience (years)		4–65	3–50	4–58	3–45
Total farm size (ha)		0.2–4.5	0.2–9.0	0.2–5.7	0.2–6.7
Area under banana (ha)		0.1–2.2	0.1–0.8	0.04–1.1	0.2–1.4

square tests were used to determine whether there were differences among different wealth classes, age categories (20–35, 35–50, and >50), and female and male heads of households. Chi-square tests were also used to compare BXW incidence in different seasons in high rainfall (Bukoba and Muleba) versus medium and low rainfall (Karagwe and Misenyi) districts.

The independent t-test method was used to determine whether there were significant differences in banana production before and after the appearance of BXW in each farmer's field between 2006 and 2015. Differences in production data that were recalled by farmers were the areas under banana production, the numbers of bunches harvested, the numbers of bunches consumed, the numbers of banana plants uprooted after being affected by BXW, and the areas under maize and cassava. All chi-square and t-tests were performed in Excel 2013, and the results were considered significant if the *P*-value was less than 0.05.

Results

In all districts, the ages of interviewed heads of households ranged from 22 to 80 years, and about one third were women (Table 2). Similar numbers of farmers in the different prosperity categories were interviewed in all districts. Farm sizes and areas under banana cultivation were mostly small, and although household sizes, plantation ages, and years of banana farming experience varied widely, they did not differ among districts. With the exception of a few farmers with a college degree (retired school teachers or government officers), the educational levels of the interviewees were at least seven grades of primary school.

The majority of the interviewed farmers in the high-rainfall Bukoba and Muleba districts observed BXW symptoms in their fields for the first time between 2010 and 2011, while the majority of farmers in the dryer Karagwe and Misenyi districts observed BXW in their field for the first time between 2010 and 2012 (Fig. 2). Only six of the interviewed farmers never had BXW in their fields. All farmers considered 2013 as the year with the highest incidence of BXW in their area, regardless of district (Fig. 3). During the 2015 surveys, BXW was observed in 71 %, 67 %, 68 %, and 54 % of the fields visited in, respectively, the Bukoba, Muleba, Karagwe and Misenyi districts (Table 1). There was a positive correlation between the percentage of fields with BXW and average annual rainfall in the four districts ($r = 0.73$, $P = 0.05$). When asked in which months of the year most plants displayed BXW symptoms, most farmers mentioned those during the short or long rainy seasons (Table 3). The distribution of farmer responses over the seasons differed significantly between the high-rainfall districts, Bukoba and Muleba, and the medium/low rainfall districts, Karagwe and Misenyi, (chi-square = 8.74, df = 3, $P = 0.033$). This difference was partly due to the relatively large number of farmers in Karagwe and Misenyi who did not know which season had the highest incidence, but also due to the relatively large number of respondents in Bukoba and Muleba who thought that the dry season (which is not absolutely dry) in their district was also conducive for the disease (chi-square = 3.96, df = 1, $P = 0.059$).

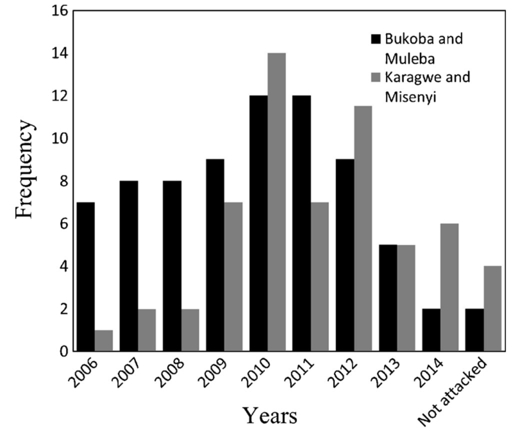

Fig. 2 Numbers of farms where BXW symptoms were observed by the interviewees for the first time in a particular year between 2006 and 2015 in Bukoba, Muleba, Karagwe and Misenyi districts of Kagera region, Tanzania. Bukoba and Muleba districts have high annual rainfall, while Misenyi and Karagwe districts have low to moderate rainfall (Table 1)

The association of rainy seasons with BXW spread was corroborated with space-time analyses of data on diseased banana plant removal obtained from extension offices (Table 4 and Fig. 4). SaTScan identified the presence of four most likely, statistically significant clusters in Kagera region (*P* value <0.001). The clusters varied in size and time period (ranging from 1 to 4 months). In the first half of 2014, two clusters were identified in the long rainy season, one with a radius of 38.5 km between 1 March and 31

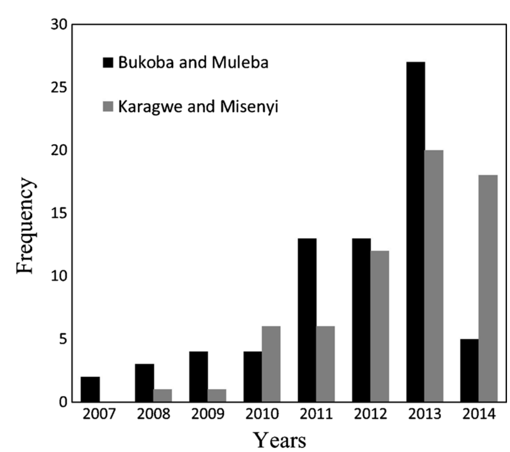

Fig. 3 Frequency distribution of farmers over the years when they observed the highest incidence of banana Xanthomonas wilt in their village in Kagera region, Tanzania. Bukoba and Muleba districts have high annual rainfall, while Misenyi and Karagwe districts have low to moderate rainfall (Table 1)

Table 3 Number of farms in Bukoba and Muleba districts versus Karagwe and Misenyi districts, where banana Xanthomonas wilt (BXW) was most prevalent in a particular season over the period from 2006 to 2015. Interactions between the two district groups and seasons of main BXW occurrence were determined by chi-square tests

Seasons/ Months	Bukoba and Muleba[1]	Karagwe and Misenyi[2]	Chi square test	Chi square *P* value
Short rain	35	24	Overall interaction	0.033
Long rain	15	19	Interaction between district group and short vs long rainy season	0.157
Dry season	14	4	Interaction between district group and rainy vs dry season	0.059
Do not know	9	15		
Total	73	62		

[1] High rainfall region

[2] Low to medium rainfall region

May 2014, and another smaller cluster (0.1 km radius) during the same period. These two clusters covered a large part of Karagwe district plus some wards of Misenyi and Bukoba districts, and the Kasambya ward of Misenyi district, respectively. In the second half of the year, two clusters with a radius of 51.2 km and a radius of 25 km occurred in the short rainy season (1 to 30 November and 1 September to 31 December, respectively). The latter clusters covered all four districts of Kagera region and a large part of Muleba district, respectively. No cluster was detected during dry seasons in 2014 (January to February and June to August).

Based on the 2014 weather data obtained from the Ari Maruku agricultural research station in Bukoba, the only agricultural weather station in Kagera region, the rainy seasons occurred from March to May and October to December (Table 5). There were significant positive correlations (Spearman's rho = 0.95 and 0.68, respectively) between number of rain days and rain amount per month and the numbers of BXW cases in the same months in five wards surrounding the Ari Maruku station (Table 5).

Survey data indicated that the extent and timing of BXW management practices like the removal of symptomatic plants and male flower buds varied among farmers. In Bukoba, Karagwe, and Misenyi districts, most interviewed farmers cut single stems (52, 60, and 56 %, respectively), and fewer farmers removed whole mats in the same districts (33, 34, and 40 %, respectively). However, in the Muleba district 67 % of the farmers removed whole mats compared to the 32 % that cut single stems (Tables 6 and 7). The remaining farmers either did not cut infected plants or did not have the disease.

Many farmers who used 'single-stem removal' of BXW-affected plants cut them 1 m above the ground to avoid destroying understory crops. This resulted in a profuse Xcm-laden yellow ooze developing on the cut surfaces (Fig. 5a). In general, single stem or whole mat removal was delayed for several weeks after BXW symptoms appeared. Although more than 95 % of the interviewed farmers removed all male flowers in their fields, many did not do it in time to avoid infection via insect vectors (Fig. 5b). Forked sticks are recommended for male flower removal rather than cutting tools such as slashers and pangas (=machetes) (Karamura et al. 2008), but 48 % of the interviewed farmers used non-sterilized cutting tools for this purpose (Table 7).

Various farm tools were used for other practices, such as de-suckering, leaf harvesting, de-trashing and bunch harvesting; all of these practices are capable of transmitting Xcm (Table 7). Tools were sterilized by fire, but inconsistently and only before starting field operations in the morning. Only 20 % of the interviewed farmers did so before bunch

Table 4 Most likely, statistically significant clusters in Kagera region, Tanzania, identified by SaTScan (Kulldorff 2015) using a maximum spatial window size of 50 % of the banana fields in Kagera and a temporal window size of 50 % of the season studied in 2014

Season	Time period	Cluster radius (km)	Observed cases	Expected cases	Wards and districts covered
Long rainy season	1 Mar to 31 May	38.5	18,492	9312	Karagwe district and some wards of Misenyi and Bukoba districts
Long rainy season	1 Mar to 31 May	0.1	824	278	Kasambya ward of Misenyi district
Short rainy season	1 to 30 Nov	51.2	53,184	37,950	All four districts of Kagera region
Short rainy season	1 Sep. to 31 Dec	25.0	17,283	4326	Most of Muleba district
Dry season	1 Jan. to 28 Feb	-[1]	-	-	-
Dry season	1 Jun to 31 Aug	-	-	-	-

[1] No clusters were detected in the dry seasons

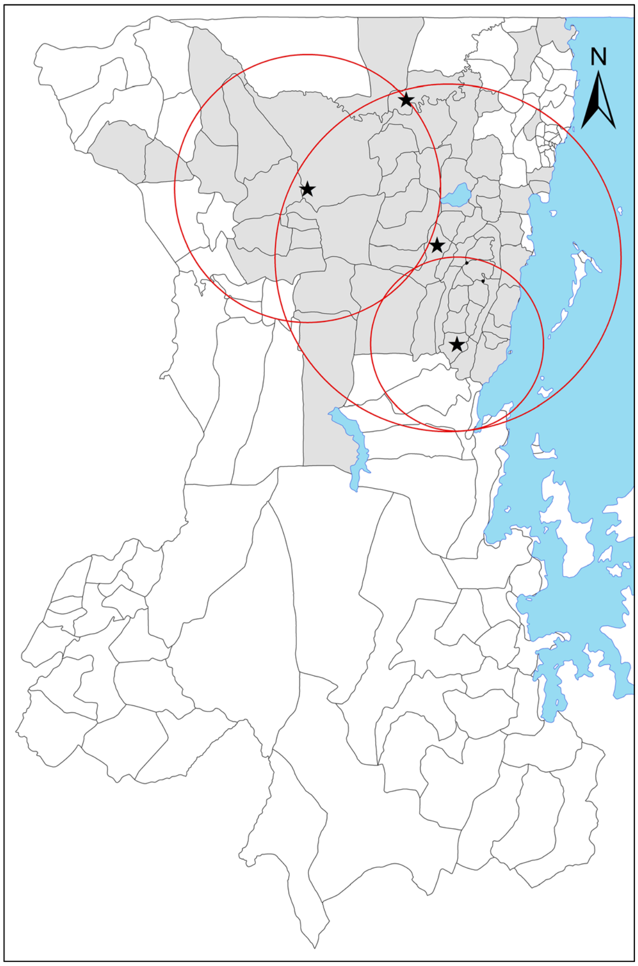

Fig. 4 Results of the space-time analysis of banana Xanthomonas wilt incidence using data obtained from the ward and district extension offices collected from January to December, 2014, in Kagera region, Tanzania. Clusters with a radius of 25 km or 51.2 km, covering all four districts of Kagera, were detected in the data of October through December (short rainy season). Clusters with a radius of 0.1 km and 38.5 km, covering part of Misenyi and Misenyi and Karagwe districts, respectively, were detected from March through May (long rainy season). No significant clusters were detected during the dry season (Table 4). The 59 wards used for the space-time analysis are indicated in grey

harvesting, 55 % before de-trashing, 71 % before de-suckering, and 75 % after removal of BXW-affected plants (Table 7). In addition to cutting and slashing tools, hoes were frequently used for weeding. Although they could also contribute to disease spread, none of the interviewed famers sterilized hoes before and/or after weeding (Table 7).

Several farm practices differed among wealth classes of farmers (Table 8). Fewer poor farmers (53 %) removed corms (for any purpose) compared to those who were moderately prosperous (96 %) or rich (86 %) (chi-square = 32.3, df = 2, $P < 0.0001$). Digging spears and hoes were used for corm removal (Table 7). Of those farmers who practiced corm removal (111 farmers) 83 % sterilized their tools before corm removal (Table 7). Leaf harvesting for household use, with non-sterilized pangas/knives or slashers (Table 7), was practiced by 58 % of the poor farmers and 26 % of the moderately prosperous farmers (chi-square = 7.7, df = 1, $P = 0.001$) (Table 8). None of the rich farmers removed leaves for this purpose. In addition, more farmers with medium wealth (61 %) weeded their fields than rich or poor farmers (40 %) (chi-square = 6.2, df = 2, $P = 0.045$) (Table 8). All other banana field management practices (de-suckering, de-trashing, bunch harvesting, male flower removal, and removal of BXW-affected plants) did not differ significantly among wealth classes. Although most farmers used their own tools, several poor and medium wealth farmers borrowed tools from neighbors. Significantly more poor farmers (24 %) than medium wealth farmers (7 %) borrowed farm tools (chi-square = 6.0, df = 1, $P = 0.015$) (Table 8).

No significant differences in management practices were found among the three age categories of the respondents (20–35, 35–50, and >50), but significantly more women sterilized farm tools (92 %) than men (71 %) (chi-square = 6.9, df = 1, $P = 0.009$) (Table 9).

More banana bunches were consumed per family before (13.1 bunches per month) than after (6.4 bunches per month) BXW was observed on a given farm ($t = 10.51$, $P < 0.001$). To compensate for reduced banana production after the appearance of BXW, larger areas were planted to cassava (0.059 ha vs 0.097 ha) ($t = -2.677$, $P < 0.001$) to provide calories for the household. Likewise, the area under maize increased significantly (0.094 ha vs 0.221 ha) ($t = -7.278$, $P < 0.001$).

Discussion

The present study integrated BXW incidence data, derived from the banana plant removal records collected by extension officers during the BXW eradication campaign in 2014, and farm survey data of 2015 to describe the spatiotemporal spread of BXW in the Kagera region of Tanzania. The plant removal records showed a tremendous variation among wards (administrative units) and months of the year. The number of plants removed varied from 0 to 20,000 per month per ward (data not shown). Application of the SaTScan method identified BXW clusters in all 59 wards and the periods (months/seasons) when they occurred. Clusters were also detected in the same region by Getis and Ord (G_i) statistics in an earlier study (Shimwela et al. 2016), but a distinction among months and seasons was not made in that study. This is the first study in which the spatial-temporal scan technique has been used to investigate geographical clustering of BXW. The SaTScan results corroborated farmer observations that BXW symptoms increased and were more noticeable during and soon after wet

Table 5 Average monthly rainfall and temperature data at the Agricultural Research Institute Maruku (ARI-Maruku) in Bukoba district in 2014[1]

Months	Rainfall days[2]	Rainfall amount (mm)[2]	Temperature maximum (°C)	Temperature minimum (°C)	Temperature average (°C)
January	8	113.2	28.0	16.7	22.4
February	4	42.5	28.3	16.8	22.6
March	14	246.7	28.2	16.1	22.2
April	16	341.6	28.2	16.3	22.2
May	14	316.9	27.9	16.6	22.2
June	6	183.9	27.9	16.9	22.4
July	2	10.8	27.5	16.2	21.8
August	7	148.6	27.2	16.1	21.6
September	7	135	27.0	16.5	21.7
October	11	157	27.7	16.1	21.9
November	16	165.5	28.1	16.2	22.2
December	12	214.6	28.1	16.6	22.3

[1] This is the only weather station in Kagera region besides the weather station at the Bukoba airport

[2] The Spearman correlations (rho) between rainfall days and amount and incidence of BXW in Bukoba district were 0.95 ($P < 0.0001$) and 0.68 ($P = 0.02$), respectively

[3] There were no significant correlations between temperature and BXW incidence in Bukoba district

seasons (Blomme et al. 2007; Biruma et al. 2007; Tripathi et al. 2009; Shimwela et al. 2016). The incubation period between Xcm infection and BXW symptom development can be fairly short (2 weeks up to 3 months) (Blomme et al. 2007; Nakato et al. 2014; Ocimati et al. 2013). Thus, infection likely took place in the rainy season and symptoms appeared either in that same rainy season or soon afterwards.

Bacteria such as *Xanthomonas* require either wounds or natural openings such as hydathodes and stomata to enter a plant (Gu et al. 2013; Hugouvieux et al. 1998; Ryan et al. 2011). Mwangi et al. (2006) showed that Xcm infects banana leaves from the margins (typical for hydathode entry) when kept under moist conditions for 72 h. We hypothesize that natural openings on banana leaves or wounds that are caused by management practices or other factors may provide access for Xcm during periods of prolonged leaf wetness. Once inside, rainfall may increase xylem flow and spread of Xcm within the infected mother plant and connected suckers. The extent to which bacterial ooze exuding from cut leaves or stems is dispersed by wind-driven rain and infects the above infection courts should be investigated as it may represent a significant means by which this pathogen and disease spread in Kagera region.

Table 6 Percentage of farmers practicing single stem, whole mat, or male flower removal to control banana Xanthomonas wilt in Kagera region, Tanzania

District	Single stem removal (%)	Whole mat removal (%)	Male flower removal (%)
Bukoba	52	33	92
Muleba	32	67	96
Karagwe	60	34	100
Misenyi	56	40	100
Overall	53	38	97

Farmers are required to remove symptomatic plants throughout the year in order to curb the spread of BXW. Although the incidence of BXW declined sharply after 2013, a longer evaluation than was conducted in the present study would be needed to determine if the epidemic slowed after the eradication campaign started. The mandatory recommendation of symptomatic plant removal is carried out by all farmers who had plants with BXW symptoms. Although not mandatory, many farmers also removed male flower buds. However, other recommendations such as mat removal and sterilization of farm tools were used less frequently as they were more difficult to implement. For example, regular sterilization of farm tools in the kitchen fire would be time consuming. Although jik (sodium hypochloride) has been recommended for sterilization of farm tools (Karamura et al. 2008), none of the interviewed farmers in Kagera used jik as a disinfectant due to its relatively high cost.

Based on the findings of this study the recommendations to control BXW should be refined. Most importantly, plant removal should be limited to the dry season to reduce the risk of spread of the pathogen by wind-driven rain or farm tools. Second, cut surfaces could possibly be covered by soil (Mwebaze et al. 2006) promoting competition from native bacterial species against Xcm and diminishing splash

Table 7 Number of banana farmers in three wealth categories using various agronomic management practices, frequency of each of these practices used, tools used for each of these practices, and sterilization of farm tools after each of these farm practices by banana farmers who participated in surveys in Kagera region, Tanzania, in 2015 (n=135)

Management practices	Farmer wealth			Frequency of practices			Tools used						Sterilization of farm tools	
	Rich	Medium	Poor	Regularly	Rarely	Not used	Digging spear	Hoe	Hand	Pangas[1]/ Knife	Slasher	Forked stick	Sterilized	Not used
Corm removal	24	67	20	83	28	24	94	17	0	0	0	0	92	19
Removal of BXW symptomatic stems	25	69	38	122	8	5	73	10	0	18	0	0	101	31
Removal of male flowers	27	70	34	123	8	4	0	0	0	44	21	66	14	117
De-suckering	27	70	38	110	25	0	127	8	0	0	0	0	96	39
Leaf harvesting	0	18	22	0	40	95	0	0	0	36	4	0	0	40
De-trashing	27	70	38	113	22	0	0	0	0	125	4	6	74	61
Bunch harvesting	27	70	38	135	0	0	0	0	0	135	0	0	26	109
Weeding	27	70	38	69	66	0	0	118	17	0	0	0	0	135

[1] panga = machete

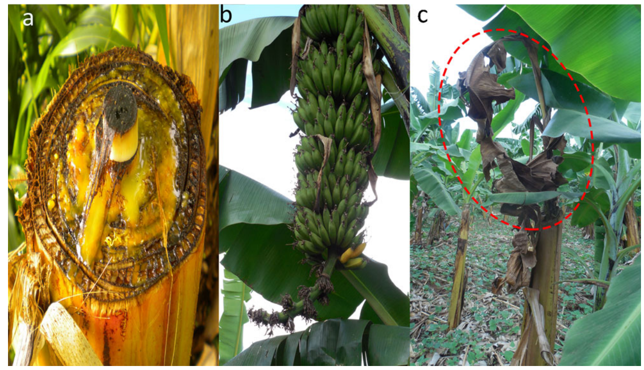

Fig. 5 Symptoms of banana Xanthomonas wilt (BXW) observed during surveys in Kagera region, Tanzania, in 2015. **a** Cut pseudostem surface with yellow bacterial ooze left uncovered after cutting a wilted plant; **b** uneven and premature ripening of the banana fingers, resulting from late removal of the male bud; and **c** new sprout with wilted leaves after the wilted mother plant was cut

dispersal of the pathogen (Cevallos-Cevallos et al. 2012). Survival of Xcm in dry soil is limited (Mwebaze et al. 2006). Although extensive training of farmers has occurred through village meetings, seminars, leaflets, and posters, the BXW recommendations they receive do not recognize the labor, time and capital farmers have for implementation. For instance, whole mat removal is not feasible for most farmers and single stem removal at ground level and stump coverage by soil as practiced in Uganda and Kenya (Kubiriba et al. 2014) is arduous and undesirable in the presence of annual understory crops. However, covering above-ground stem cuts with soil would be feasible. Also, garden tools should be sterilized more frequently before and after each use. Using fire for disinfection of farm tools is more realistic if brick fire kilns are present in the middle of the field. Thus, the recommendations for BXW control need to be adjusted, and conveyed to farmers in a more effective way, for example through farmer field schools (Ochola et al. 2015).

Insufficient farmer knowledge about disease control, a lack of capital and resistant varieties, and an increased movement of people across countries and regions have been associated with increased disease problems worldwide (Beed 2014). BXW incidence has increased in the Kagera region since 2006 (Shimwela et al. 2016), but ignorance of management recommendations may not be the main reason. Many farmers know that contaminated farm tools contribute to the rapid spread of Xcm (Ocimati et al. 2013; Tinzaara et al. 2013), but recommendations such as the use of jik are not practical in Kagera region, especially for poor farmers, although they are used in Uganda (Kubiriba et al. 2014). Moreover, banana traders who move among farms and harvest with nonsterile tools may contribute significantly to BXW spread. Thus, traders must also be trained in and are expected to use safe harvesting practices.

The rapid spread of BXW has had significant socio-economic impacts wherever the disease occurs (Karamura

Table 8 Frequencies of rich, medium and poor farmers using different management practices in banana fields in Kagera region, Tanzania, in 2015

Practices	Rich ($n = 27$)	Medium ($n = 70$)	Poor ($n = 38$)	Chi-square test	Chi square *P* value
Corm removal	24	67	20	Corm removal (yes/no) by wealth category	<0.0001
Leaf harvesting	0	18	22	Leaf harvesting (yes/no) by wealth category	0.0009
Weeding	11	43	15	Weeding (yes/no) by wealth category	0.0449
Borrowing tools	0	5	9	Borrowing (yes/no) by wealth category	0.0145

2006; Karamura et al. 2010; Ploetz et al. 2015). The effects can include total crop loss in the field, the cost of disease management and cost to switch to other crops (Karamura 2006; Karamura et al. 2010). For many years banana was the dominant crop in the Kagera region, while cassava, sweet potatoes, and maize were considered minor crops (Maruo 2002; Baijukya et al. 2005). In the past, people who consumed maize, sweet potatoes or cassava were considered poor (Mgenzi and Mbwana 1999). However, in recent years, especially after the outbreak of BXW, farmers have expanded maize and cassava production in Kagera region. Nkuba et al. (2015) reported that 70 % of the farmers in this region reduced their consumption of bananas due to BXW, and the present study indicated that the area under maize and cassava increased significantly in recent years. The same trend was observed in Uganda (Karamura 2006; Karamura et al. 2010). Maize fields on hillsides are especially prone to erosion (Thierfelder and Wall 2009). If shade-providing banana plants are removed on a large scale, erosion can be expected to increase, leading to reduced agricultural, ecological and economic sustainability.

In conclusion, the results of this research clearly demonstrated that BXW incidence was highest in the rainy seasons in Kagera. Based on these findings it is suggested that management of BXW should be concentrated during the January/February and June/July dry seasons. These and other practices, such as leaf removal throughout the year, should be accompanied by tool sterilization in a fire pit inside the field. BXW recommendations need to consider what farmers are capable of doing given their resources. Clearly, farmers and banana traders must be trained in realistic strategies for managing this important disease.

Table 9 Sterilization of garden tools after removing plants with symptoms of banana Xanthomonas wilt (BXW) by female and male heads of households in Kagera region, Tanzania[1]

Gender	Sterilization of tools in fire	No sterilization of tools	Chi square P value
Female	35	3	0.0088
Male	63	26	
Total	98	29	

[1] Six farmers who did not have BXW in their fields and two farmers who had not used BXW management practices were not included in this table

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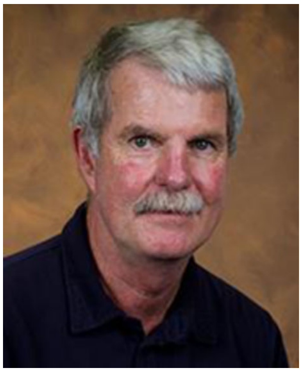

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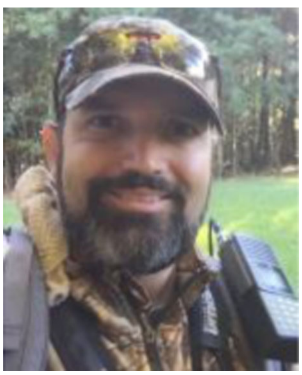

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