Vol. 16(9), pp. 1253-1269, September, 2020
DOI: 10.5897/AJAR2020.15023
Article Number: 5FDB28964797
ISSN: 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Banana pest risk assessment along banana trade axes running from low to high altitude sites, in the Eastern DR Congo and in Burundi

Guy Blomme[1]*, Walter Ocimati[2], Serge Amato[3], Alexandra zum Felde[4], Muller Kamira[5], Mariam Bumba[5], Liliane Bahati[5], Daniel Amini[5] and Jules Ntamwira[5]

[1]Bioversity International, P.O. Box 5689; Addis Ababa Ethiopia.
[2]Bioversity International, P.O. Box 24384, Kampala, Uganda.
[3]International Institute of Tropical Agriculture, Kalambo Research Station, Bukavu, South Kivu Province, Democratic Republic of Congo.
[4]Independent Consultant, Germany.
[5]Bioversity International, Bukavu, South Kivu Province, Democratic Republic of Congo..

Received 16 June, 2020; Accepted 27 July, 2020

Pests and diseases greatly contribute to the decline in banana yields, food and income insecurity in the Great Lakes region of Africa. Understanding people's role in pest and disease spread at landscape level is crucial for effective pest and disease management. To determine this, focus group discussions (FGDs) targeting 10 experienced farmers (50% female and 50% male) were conducted in 27 villages along four banana trade routes in western Burundi and eastern DR Congo. FGDs determined the presence and risk of spread of key banana pests and diseases via the movement of banana bunches, planting material and other products, labourers, traders and farm tools. Black leaf streak (BLS), Fusarium wilt and banana bunchy top disease (BBTD) were reported to have been in the landscape for over 40 years while Xanthomonas wilt (XW) was a more recent introduction (1-7 years). BBTD, XW and weevils were the most prevalent constraints. BBTD was observed at previously unsuitable high-altitude zones, which should be a cause of concern, especially with the current risk of climate change. Climate change, and linked temperature increases, could also worsen the prevalence of XW, weevils, nematodes and BLS. Movement of farming tools by labourers and traders, of planting material/suckers and banana bunches emerged as the most common human practices potentially responsible for the spread and/or build-up of banana pests/diseases. Strengthening farmer's knowledge and institutional capacities of actors on these different modes of disease spread in banana value chains in the region is recommended.

Key words: Black leaf streak, bunchy top disease, Fusarium wilt, nematodes, weevils, Xanthomonas wilt.

INTRODUCTION

In the African Great Lakes Region (AGLR), bananas and plantains (hereafter banana) play a very important social

*Corresponding author. E-mail: G.Blomme@cgiar.org. Tel: +251-921927808.

and economic role (Baret and Van Damme, 2010). In the Democratic Republic of the Congo (DR Congo), banana production area covered about 1.2 million ha, with a total production of 5.1 million tonnes of banana in 2018 (FAO, 2019). In Eastern DR Congo, representing one of the main banana production zones, bananas are consumed daily by about 70% of the population in various forms, including traditional banana beer (Mukwa et al., 2015). In Burundi, banana is the most widely produced crop, with an annual production of 1.7 million tonnes on an estimated production area of 208,603 ha in 2018 (FAO, 2019), accounting for 17 to 20% of arable land and about 45% of Burundian crop production (FAO, 2019).

Grown on small areas around homesteads, bananas play a multifunctional role for banana-based households in the AGLR (Ndungo et al., 2008; Kamira et al., 2014; Ocimati et al., 2018a). In the DR Congo and Burundi, bananas contribute enormously to food security and nutrition of millions of people. They are an important source of vitamins and minerals, while providing more than half of calories consumed daily in these countries (IITA, 2015). Bananas also represent a vital source of regular income to households in the east and central African region. This income helps farmers cover important expenses such as school fees and health-care related costs (Baret and Van Damme, 2010) and enables the rural poor to take on a greater number of social roles in their communities (IITA, 2015).

However, in recent years, banana production and area planted have declined between 20 and 60% in DR Congo (Mobambo et al., 2010) and between 20 and 50% in Burundi (Actualitix, 2016). Pests and diseases greatly contribute to these declines (Kamira et al., 2013; Blomme et al., 2014; Niyongere et al., 2015). The main pests include nematodes, particularly endo-parasitic ones, like *Radopholus similis* and *Pratylenchus* species and weevils (*Cosmopolites sordidus*) (Kamira et al., 2013). The common diseases include Xanthomonas wilt of banana (caused by the bacteria *Xanthomonas vasicola* pv. *musacearum*, Xcm), black sigatoka or black leaf streak (BLS) (a foliar disease caused by the fungus *Pseudocercospora fijiensis,* formerly: *Mycosphaerella fijiensis*), Banana Bunchy Top Disease (BBTD) caused by the banana bunchy top virus (BBTV) and transmitted by the banana aphid (*Pentalonia nigronervosa*), Fusarium wilt or Panama disease (a wilt disease caused by the fungus *Fusarium oxysporum* f. sp. *cubense*) and Banana Streak Virus (BSV).

These pests and diseases represent significant threats to banana production and have the potential to devastate entire plantations, which equates to crippling reliable livelihood(s) with serious consequences on household incomes and food security. Preventing losses due to pests and diseases can be achieved if the importance of various mechanisms of spread is known.

Given the importance of banana, banana products are regularly traded across the region. While some banana diseases are spread abiotically (e.g. black leaf streak/black sigatoka ascospores being blown from plant to plant in a field by the wind (Ploetz, 2001) or Fusarium wilt spores travelling in surface water from an infected area to new areas along drainage ditches (Hwang and Ko, 2004), most diseases and pests can and are readily spread by other factors. Contaminated planting material or plant parts (e.g. banana leaves used to wrap foods) as well as tools or footwear of workers exiting contaminated fields, can carry pathogens, their spores or pests directly or in soil adhering to them. Pest and disease spread through infected planting materials is also common in the region. Environmental factors such as altitude and/or temperature effects, precipitation and vegetation cover have also been reported to directly or indirectly impact on the severity of these pests and diseases in the region. For example, above 1,600 m, the banana weevil (*C. sordidus*) does not multiply well (Gold and Messiaen, 2000) while the banana aphid (*P. nigronervosa*) has been reported not to transmit the banana bunchy top virus as efficiently as it does at lower altitudes (Niyongere et al., 2012). Insect vector transmission of Xcm also declines with increasing elevation (Shimelash et al., 2008; Rutikanga et al., 2015), as insect populations and levels of insect activity significantly decline. The nematode *R. similis* is known to thrive at altitudes below 1,400 m, but their numbers and vigour drop off at higher altitudes (Speijer and De Waele, 1997). Climate change is thus likely to influence disease and pest spread, prevalence and incidence levels. For example, an increase in temperature could increase, at higher elevations, aphid transmission of BBTV and insect-mediated spread of Xcm. The potential interaction of human activities with changes in the climate could thus profoundly undermine the current benefits of low disease pressure and/or slower disease spread in the high-altitude sites.

Against this background, there is an outstanding need to assess the potential risk for the spread of these pests and diseases across banana production landscapes in the AGLR, especially in zones with altitude gradients. This need arises from the experience of outbreaks of many banana diseases over the last decades and their persistence in the affected landscapes. Information on banana pest and disease spread at a landscape level and the extent of the role of human agents in this spread is not well known. This study assessed the risk of banana pests and diseases spreading along four banana trade routes in western Burundi and eastern DR Congo. More specifically, the objectives were to: (i) identify the banana pests and diseases present in the study area and (ii) assess their potential to spread via the movement of: banana products along trade routes, labourers and their tools, taking into account the possible effect of altitude on their presence and spread.

These case studies are expected to provide reliable evidence on current disease/pest presence and an understanding of the risk of spread through human

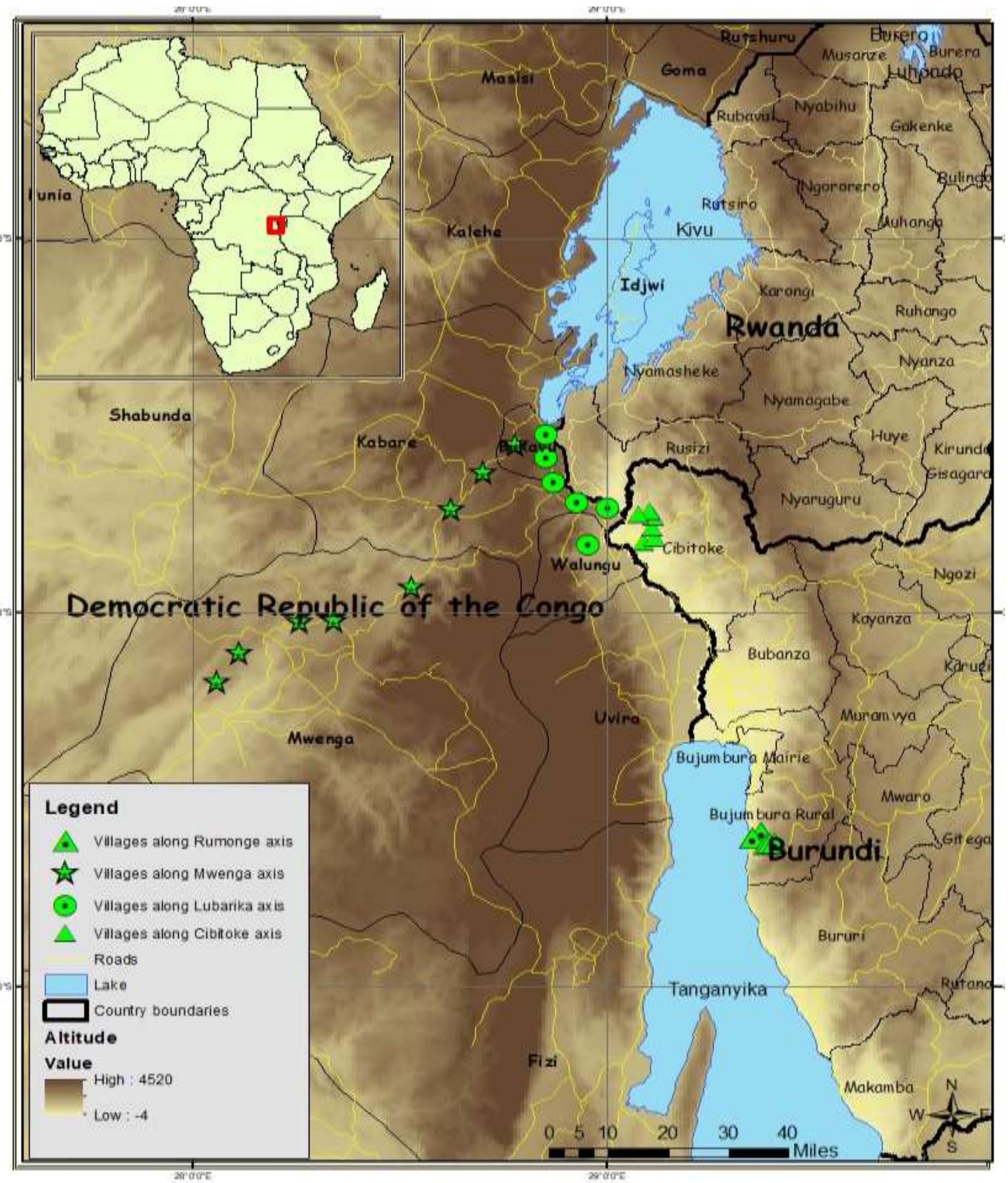

Figure 1. Map of study area with villages along the banana trade axes marked.

agents at landscape level in western Burundi and eastern DR Congo. The findings of the study will serve as a basis for suggesting management options which can reduce the risks of pest and disease spread across banana producing landscapes in the AGLR.

MATERIALS AND METHODS

This study was carried out along four banana trade axes, two in western Burundi and two in eastern DR Congo (Figure 1). This study determined the presence and the risk of spread of the most common and important banana pests and diseases, via the movement of banana bunches, other banana products (e.g. leaves for packaging, suckers for planting), labourers, traders and farm tools.

In eastern DR Congo, the pest risk assessment was conducted along two trade axes that run from lowland production regions in South Kivu Province towards the town of Bukavu (1,498 m) – the main banana consumption centre. In South Kivu, bananas are an important crop and cover 20 to 30% of cultivated land (Neyrinck, 2011). The first axis *Mwenga-Bukavu* starts from the village of Kibe (685 m) in Mwenga territory and moves towards Kasiru (1,996 m) in

Kabare territory; the *Lubarika-Bukavu* axis goes from the village of Lubarika (927 m) in Uvira territory to Mabijo (1,740 m) in Kabare territory (Figure 1).

In contrast, in Burundi, the two banana trade axes ran from high to low altitude production areas. These 2 axes are at a distance from the main market of Bujumbura, though products of the high-altitude zones are transported to Bujumbura through the lowland zones along Lake Tanganyika and the Rusizi valley. The *Rumonge* axis goes from the village of Gabaniro (799 m) to Muhowe (1,841 m), both in Muhuta province. The *Cibitoke* axis goes from the village of Munyika-1 (906 m) in Rugombo province to Mpinga (1,713 m) in Mabayi province (Figure 1). These 2 axes in Burundi, in contrast to the DR Congo axes, are located along shorter but very steep altitude gradients. The gradients for *Cibitoke* and *Rumonge* axes are 32.1 and 172 m/km, respectively, compared with -13.7 and -5.6 m/km for *Lubarika* and *Mwenga*, respectively.

Focus group discussions (FGDs) were carried out in a total of 27 villages along the 4 trade axes and the average distance between the villages was 15 km. The location (country and territory/province; axis) and altitude of these villages are presented in Supplementary Table S1 and Figure 1. In each village, 10 farmers (50% female; 50% male) who had been active in banana production and/or trade and aged between 30 and 80 years were selected to participate in the FGDs. It was assumed that these farmers had a rich experience and good knowledge of banana production and marketing activities in their respective regions. The geographical position of each village/ FGD was recorded using a hand-held GPS at a precision of approximately 10 m (Figure 1 and Supplementary Table S1).

Structured questionnaires were used to guide the FGDs. In addition, the FGD facilitators used a checklist to elicit information on the characteristics and management of their banana farms, key biotic constraints and trade related practices. Where necessary, participants were probed to triangulate responses and caution was taken to foster participation of all FGD participants. With respect to farm characteristics and management, farmers provided information on whether banana was predominantly intercropped or grown as sole crops across the village; grown for food or sold on the market, or both; and the role of men and women in banana farming. FGDs also provided information on the type and sources of labour used within villages; distance labourers travel; use in space and time of farm tools and associated tool sanitation practices; banana cultivars grown, and planting material types used. For the biotic stresses, the FGD participants were presented with images of disease/pest symptoms and/or illustrations of common pests, and were asked to confirm their presence in their landscapes. In addition, they were asked when a biotic constraint was first observed or reported. The FGDs also reported on the key management practices used within their landscapes for managing the abiotic constraints and their access to extension services. Through the FGDs, the risk of disease spread through trade was also explored. The FGD participants reported about the banana products traded, frequency of trade, distance to markets, and sanitation practices applied by farmers and traders on farm.

The actual presence of diseases and pests in the village was confirmed by experienced and trained researchers through on farm assessments on randomly selected farms. FGD participants were not informed in advance of the subsequent field assessments to avoid bias in the responses. In each of the villages, small plots of fifty banana mats made known to have these constraints were selected and examined, depending on reported presence, for visible symptoms of Fusarium wilt, BBTD, black sigatoka and XW. The number of infected mats was recorded and used to compute the percentage of infected mats per plot. Nematode and weevil damage was assessed on 5 mats per village. Nematode damage was assessed following the procedure described by Speijer and De Waele (1997) to calculate the root necrosis index. Banana roots in a 25 × 25 × 25 cm cube section, 10 cm from the plant pseudostem were dug out for nematode cord root damage assessment. Five functional cord roots were randomly selected per sampled plant, trimmed to 10 cm length, sliced lengthwise and percentage root necrosis in the exposed cortical tissue scored. Each of the five 10 cm root piece accounted for a maximum necrosis score of 20%, thus totaling to a necrosis score of 100% (Speijer and De Waele, 1997).

Banana weevil rhizome/corm damage was assessed on 5 harvest-ready mats, using a scale of 0 to 3, where 0: no damage, 1: slight damage (<10% rhizome cross section covered with weevil larvae tunnels), 2: moderate damage (11-30%) and 3: severe damage (>30% tunnel coverage).

The risk of the spread or introduction (entry and establishment) of pests and diseases in the study area was assessed using information related to the movement of banana products, labourers and traders, distances products move or people travel from infected areas, as well as presence and importance of hosts and other possible pathways by which pests and diseases can spread.

Quantitative information provided during FGDs or collected through on farm assessments to quantify the prevalence and damage levels of banana pests and diseases was directly analyzed to generate descriptive statistics using STATA version 14 (StataCorp, 2015). The qualitative information was used to explain the quantitative information after being summarized/synthesized with MS Excel. Regressions of the dependent variables (disease/pest incidence and prevalence) against altitude were conducted using the MS excel package.

RESULTS

Importance of banana

The importance of banana varied greatly from axis to axis, with banana ranked as the main crop in most of the villages along the *Lubarika* (67%) and *Cibitoke* axes (83%) compared with only 22% and 17% of villages along the *Mwenga* and *Rumonge* axes, respectively. In the study region, bananas are grown on a semi-commercial scale and are often produced for both cash (sale of bunches and banana beer) and food. In *Lubarika* and *Cibitoke*, 100% of the villages grew banana for both food and income. In *Mwenga*, 22% of the villages solely grew bananas for food, with the others growing for both food and income. In *Rumonge*, in contrast, 33% grew bananas solely as a cash crop, with the other 77% growing the crop for both food and income.

Banana pests and diseases

The key banana diseases that include BBTD, XW and two fungal diseases (BLS and Fusarium wilt) were encountered in nearly all the studied axes. Pests encountered included the banana weevil and nematodes. Nematodes were not identified to the species level in this survey, though *Pratylenchus goodeyi* is known to dominate in East African Highland banana production systems (Gaidashova et al., 2009; Kamira et al., 2013). For all pest and disease constraints, no significant associations (R^2 <0.1) were observed with the altitude. The oldest banana disease in the area in accordance with farmers' reports was BLS (64 years), followed by

Table 1. Pests and diseases as recognized by farmers and in brackets the time they have been present on their farms or landscape. Data were collected through Focus Group Discussions (FGDs) in villages located in different altitude ranges along four banana trade axes in eastern DR Congo and western Burundi.

Road axis	Altitude range (m)	No. of FGDs	Banana pests and diseases (% villages/FGDs reporting)					
			BBTD*	XW*	BLS*	Fusarium wilt	Banana weevils	Nematodes**
Mwenga	<900	2	100.0 #(20.5)	0.0	0.0	100.0 (19.5)	100.0 (22.0)	0.0
	900-1200	2	100.0 (30.0)	0.0	0.0	50.0 (44.0)	100.0 (18.5)	50.0
	1200-1500	3	100.0 (18.0)	0.0	33.3 (9.0)	33.3 (54.0)	66.7 (12.5)	33.3
	>1500	2	100.0 (14.0)	50.0 (1.0)	100.0 (64.0)	50.0 (14.0)	0.0 (-)	0.0
	Mean	9	100	12.5	33.3	58.3	66.7	20.8
Lubarika	<900	0	-	-	-	-	-	-
	900-1200	2	100.0 (45.0)	100.0 (1.5)	50.0	0.0	0.0 (50.0)	0.0
	1200-1500	1	100.0 (26.5)	100.0 (1.0)	0.0	0.0	0.0	0.0
	>1500	3	100.0 (21.5)	66.7 (4.5)	0.0	33.3 (5.0)	33.3 (36.3)	0.0
	Mean	6	100.0	88.9	16.7	11.1	11.1	0.0
Rumonge	<900	1	100.0 (39.0)	100.0 (5.0)	0.0	0.0	100.0 (43.0)	0.0
	900-1200	1	100.0 (15.0)	100.0 (3.0)	100.0	0.0	100.0 (50.0)	0.0
	1200-1500	0	100.0 (25.0)	100.0 (7.0)	0.0	0.0	100.0 (30.0)	0.0
	>1500	4	100.0 (17.3)	100.0 (2.7)	0.0	0.0	100.0 (36.3)	33.3 (41.0)
	Mean	6	100.0	100.0	25.0	0.0	100.0	8.3
Cibitoke	<900	0	-	-	-	-	-	-
	900-1200	4	100.0 (29.3)	100.0 (3.7)	0.0	25.0 (19.0)	50.0 (26.0)	0.0
	1200-1500	0	-	-	-	-	-	-
	>1500	2	100.0 (40.0)	100.0 (3.5)	0.0	50.0 (40.0)	0.0	0.0
	Mean	6	100.0	100.0	0.0	37.5	25.0	0.0
Overall mean		27	100.0	75.4	18.7	26.7	50.7	7.3

**Nematodes were not identified to genus or species level. *BBTD: Banana Bunchy Top Disease; XW: Xanthomonas wilt of banana; BLS: Black Leaf Streak. "-": no observation as there were no villages within this altitude range along the axis.

Fusarium wilt (54 years) and BBTD (45 years). XW was a more recent introduction in the area (1-7 years) (Table 1). Based on FGDs, BBTD was the most widespread disease (100% of the villages visited (Table 1). XW and weevils were also frequently mentioned. Fusarium wilt, black sigatoka and nematodes were much less frequently reported (Table 1). Along the *Mwenga axis*, XW was reported only for sites above 1500 m. This can be attributed to the fact that the XW outbreak in DR Congo first occurred in the eastern high-altitude areas around Masisi and is currently spreading westwards in the direction of the low-lying altitudes (Ocimati et al., 2019). In contrast, XW was reported at all sites along the *Lubarika*, *Rumonge* and *Cibitoke* axes (Table 1). In the DR Congo, BLS was reported in villages above 1200 m along the *Mwenga axis*, and only in those below 1200 m along the *Lubarika axis*. In Burundi, black sigatoka was only reported in villages between 900 and 1200 m in the *Rumonge* axis, and not at all along the *Cibitoke* axis. Fusarium wilt was reported in all altitude ranges along the *Mwenga* and *Cibitoke axes*, but only above 1500 m along the *Lubarika* axis and not at all along the *Rumonge axis* (Table 1). Banana weevils were reported in all villages along the *Rumonge axis,* in those below 1200 m and two thirds of those at 1200 to 1500 m along the *Mwenga axis,* and to a much lesser degree along the two other axes. On average, less than 8% of villages reported having observed the symptoms of nematodes, with only farmers located in villages between 900 and 1500 m along the *Mwenga axis* and those above 1500 m along the *Rumonge axis* reporting having observed nematode characteristic symptoms (that is, plant toppling) (Table 1).

Field assessments revealed BBTD to be present throughout the sites, within every altitude range though not in every village (Table 2). No XW infected plants were observed on farms in the villages along the *Mwenga axis*, while incidences ranging from 1 to 50%, were recorded in villages along the *Lubarika*, *Rumonge* and *Cibitoke axes* (Table 2). For the most part, FGD results and field observations of diseases such as BBTD, black sigatoka

Table 2. Pests and diseases recorded during researcher-led field assessments in villages located within different altitude ranges along the studied banana trade axes in eastern DR Congo and western Burundi. Field assessments in a landscape were conducted after the focus group discussions.

Road axis	Altitude range (m)	No. of Villages	Banana pests and disease incidence (%)					Nematode root necrosis index**
			BBTV*	XW*	BLS*	Fusarium wilt	Banana weevils	
	<900	2	35.0	0.0	0.0	15.0	20.0	0.1
	900-1200	2	70.0	0.0	0.0	70.0	60.0	0.6
Mwenga	1200-1500	3	31.7	0.0	30.0	5.0	65.0	3.6
	>1500	2	27.5	0.0	10.0	20.0	-	3.3
	Mean	9	41.1	0.0	10.0	27.5	48.3	1.9
	<900	0	-	-	-	-	-	-
	900-1200	2	25.0	25.0	5.0	0.0	0.0	2.0
Lubarika	1200-1500	1	10.0	1.0	0.0	0.0	0.0	2.5
	>1500	3	11.3	1.0	0.0	1.0	20.0	4.5
	Mean	6	15.4	9.0	1.7	0.3	6.7	3.0
	<900	1	5.0	15.0	0.0	0.0	10.0	7.4
	900-1200	1	10.0	50.0	40.0	5.0	20.0	1.0
Rumonge	1200-1500	0	20.0	40.0	0.0	0.0	5.0	0.6
	>1500	4	18.3	28.3	0.0	0.0	11.7	1.0
	Mean	6	13.3	33.3	10.0	1.3	11.7	2.5
	<900	0	-	-	-	-	-	-
	900-1200	4	11.3	5.0	0.0	20.0	12.0	2.0
Cibitoke	1200-1500	0	-	-	-	-	-	-
	>1500	2	5.0	50.0	0.0	15.0	0.0	2.0
	Mean	6	8.2	27.5	0.0	17.5	6.0	2.0
Overall mean			19.5	17.5	5.4	11.6	18.2	2.4

**Nematode presence was inferred from the Root Necrosis Index, as described in Speijer and De Waele (1997). *BBTD: Banana Bunchy Top Disease; XW: Xanthomonas wilt of banana; BLS: Black Leaf Streak. "-": No observation as there were no villages within this altitude range along the axis.

and Fusarium wilt overlapped, though the proportion reported by the FGDs was always greater than that observed in the field by scientists across all the sites and altitude ranges. Banana weevils were observed on plots across sites, including in areas where farmers had not reported seeing them in the past (Table 3). Mean nematode damage varied between 0.1 and 7.4% across the transects, with the highest nematode damage observed along the *Rumonge* axis (Table 2). No nematode damage was observed in *Lubarika*. Along the two other axes, nematodes were only found in a few plots within a single altitude range (Table 2). As for the reports given by farmers during the FGDs, the field pest and disease prevalence and incidence values were not influenced by the altitude (R^2 <0.1).

Risks of pest and disease spread and establishment due to human practices

Disease and pest spread, and establishment can be influenced by several agronomic practices that include: planting material type and movement, crop mixtures, cultivar diversity on farms and the use and management of farming tools.

Planting material type and movement

Planting materials play a critical role in the spread of banana pests and diseases. Access to clean and safe planting material was found to be a challenge across all the axes studied. Farmers predominantly used suckers to establish new fields or fill gaps in established fields, and no nurseries producing clean planting materials were present in the study area. Most farmers obtained suckers from their own farm (Table 3), though many farmers also obtained suckers in exchange for other goods, especially those in villages along the *Cibitoke axis*. Only in villages along the *Rumonge* and *Mwenga* axes do farmers buy suckers, with farmers in *Mwenga* purchasing suckers of all four banana types. The farmer's willingness to pay for

Table 3. Percentage of communities (represented by FGD groups) along the banana trade axes in eastern DR Congo and western Burundi who obtain suckers of various banana types from different sources, are willing to pay for clean planting material and the price they would pay for that material.

Road axis (n)	Banana type	% of communities who obtain suckers: From own farm	As a gift	In exchange	From merchant	% of communities willing to pay for clean planting material	Price farmers are willing to pay for a clean planting material (US$)
Mwenga (9)	Beer	77.7	55.5	44.4	0.6	44.4	0.59
	Cooking	77.7	22.2	55.5	1.3	55.5	1.33
	Dessert	55.5	77.7	44.4	1.0	44.4	1.03
	Plantain	55.5	55.5	22.2	1.0	22.2	1.03
Lubarika (6)	Beer	100.0	0.0	50.0	0.6	50.0	0.58
	Cooking	83.3	0.0	50.0	0.4	50.0	0.36
	Dessert	100.0	0.0	33.3	0.4	33.3	0.36
	Plantain	100.0	0.0	33.3	0.4	33.3	0.36
Rumonge (6)	Beer	83.3	0.0	16.7	0.2	16.7	0.19
	Cooking	66.7	16.7	16.7	0.4	16.7	0.41
	Dessert	83.3	0.0	16.7	0.2	16.7	0.19
	Plantain	33.3	16.7	0.0	0.0	0.0	0.0
Cibitoke (6)	Beer	50.0	0.0	83.3	0.2	83.3	0.20
	Cooking	83.3	0.0	83.3	0.2	83.3	0.20
	Dessert	50.0	0.0	83.3	0.6	83.3	0.55
	Plantain	50.0	0.0	66.7	1.8	66.7	1.75

clean banana planting material was very high in *Cibitoke* (67-83%), moderate in *Mwenga* (22-56%) and *Lubarika* (33-50%) and low in the *Rumonge* (0-17%) axis (Table 3). Along the *Mwenga* axis, farmers were willing to pay from $0.59 to $1.33 for a clean planting material, depending on the banana type. The highest price for clean planting material was recorded for plantains ($1.75) along the *Cibitoke* axis. Elsewhere, farmers were only willing to pay lower prices for clean banana planting material, varying from $0.19 to $0.60 (Table 3).

About 81% of the Focus Groups reported that the planting material used came from within the village in which the farmers live (Table 4), while 25% reported that planting materials were obtained from within their parish, 11% from within their district, 4% from within the province and 3% from a neighbouring country. Though the 4 axes were located close to the border between Burundi and the DR Congo (Figure 1), not much cross-border sucker trade occurred. Some farmers travelled considerable distances to acquire suckers of specific banana types (e.g. *Mwenga* farmers travelled up to 50 km for beer banana suckers), while others barely travel at all, sourcing their suckers mostly from their own fields or neighbours in the village (e.g. farmers living along the *Lubarika axis*) (Table 4). The size of the area (from village to country) from which planting material is obtained greatly increases the chances of spreading diseases and pests over large distances.

Risk factors related to crop mixtures

On average, 76% of villages reported to intercrop banana with other crops (89% in *Mwenga*, 50% in *Lubarika*, 67% in *Rumonge* and 100% along the *Cibitoke* axis). The crops most frequently intercropped with bananas along the trade axes were legumes (71%) and tuber crops (68%) (Figure 2). No relationship was however observed between the intercropping practices and the prevalence of the pests and diseases.

Diversity of cultivars grown

Communities in visited villages grew a wide diversity of banana and plantain cultivars. The total number of cultivars grown varied between 20 and 58 across the axes (Table 5), while it varied between 6 and 18 per sampled village. In east DR Congo, the number of banana cultivars grown along the two axes was very dissimilar (58 in Mwenga vs. 21 in Lubarika). Of the banana cultivars grown in the DR Congo, plantains (36%) and beer types (38%) were the dominant banana types in Mwenga and Lubarika, respectively.

Along the *Rumonge* and *Cibitoke* axes, the beer (50%) and cooking (38%) banana cultivars, respectively, were the most abundant (Table 5). The green cooking cultivars are predominantly east African highland (*Musa* AAA) types. The predominant beer types comprised of the east

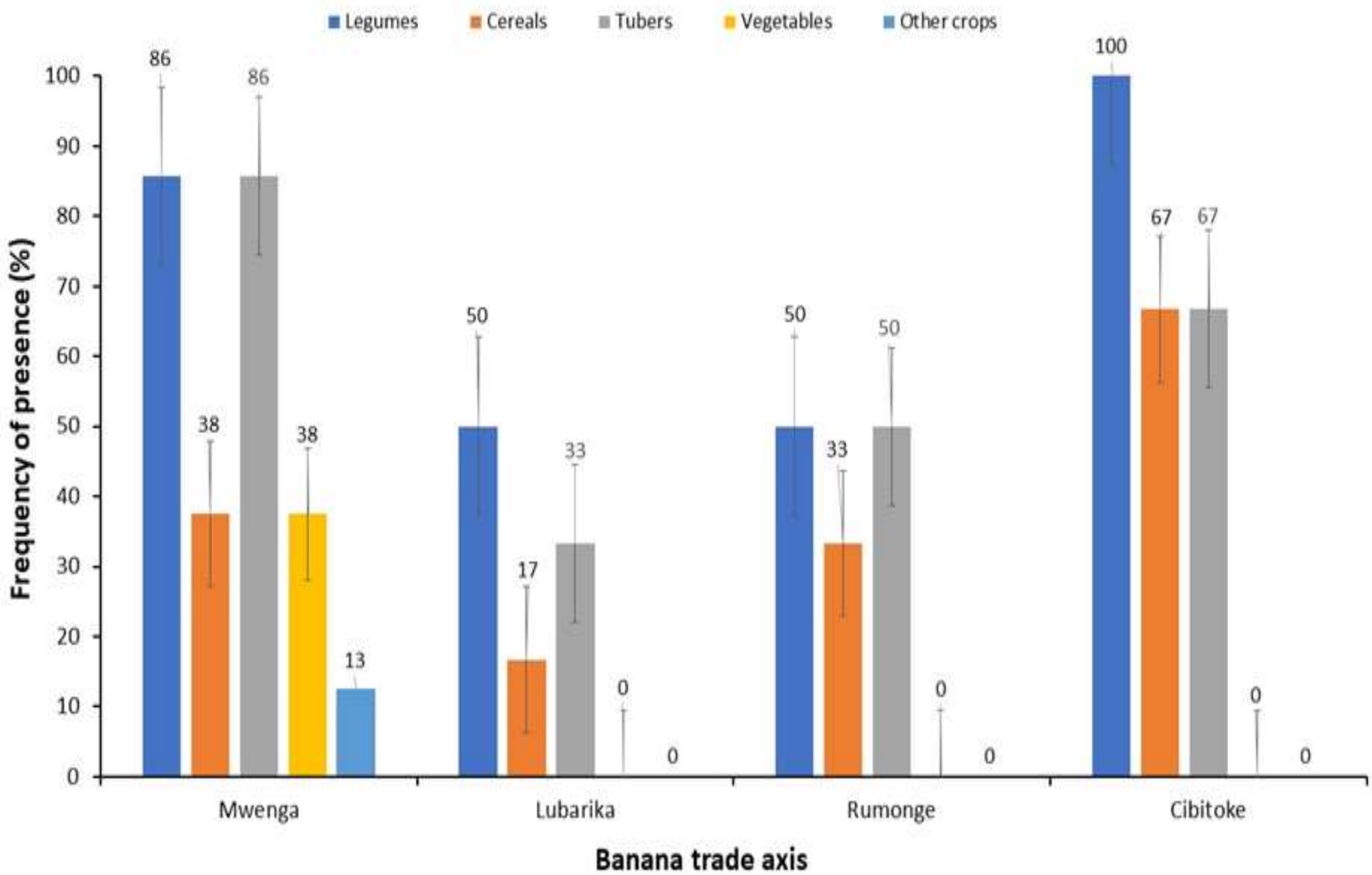

Figure 2. Occurrence (%) of various crops intercropped with bananas in plots along four studied banana trade axes in eastern DR Congo and western Burundi.

African highland banana types (in the high-altitude areas of *Mwenga, Lubarika, Rumonge* and *Cibitoke* axes), *Musa* ABB types (low altitude sites of *Rumonge* and *Cibitoke* axes) and km5 (*Musa* AAA) in the *Cibitoke* axes. The common dessert types included the Cavendish (*Musa* AAA), Gros Michel (*Musa* AAA) and apple bananas (*Musa* AAB).

Risks related to labourer and tool movements

Labour types (family or hired) varied across all the four axes. Only 33.3% of communities along the *Mwenga* axis reported using hired labour exclusively. Family labour exclusively and/or both types of labour sources combined were more prevalent across the road axes. Exclusive use of family labour occurred in 67, 50 and 17% of landscapes in *Mwenga*, *Rumonge* and *Lubarika*, respectively, while a combination of both family and hired labour occurred in 100%, 83% and 50% of the landscapes in *Lubarika*, *Cibitoke* and *Rumonge*.

The type (family or hired), source and movement of labour can increase the probability of spreading some diseases and pests, especially as labourers often move with their own tools from infected to non-infected areas. Between 33 and 100% of villages across the 4 study transects used hired labour from other villages/ communities in their banana plots (Table 6). The furthest distance the hired labourers travelled varied between 10 and 35 km. Risky practices of lending farming tools (83-100%) and joining labour groups (50-100%) were common across all the sites and can potentially expose non-infested plots to contamination.

Pest and disease risks related to banana product trade

The analysis of the movement of banana products via trade transactions focused on suckers, bunches, leaves, fibres, as well as handicrafts with attention to the way pathogens can be spread. Results revealed that banana bunches (100% of sites) and suckers (0-33%) were the main banana products traded (Table 7). Banana leaves, fibres and handicrafts were not found for sale or traded in the local markets or at the farm gate. The local markets within villages and parishes were the main destination of the banana bunches and suckers (Table 7).

The distance of markets for banana bunches were on average (56% of the villages) within one km of the villages (Table 8). Longer distances were travelled along the *Mwenga* and *Rumonge* transects to sell banana bunches (Table 8). Banana suckers were only traded along the *Mwenga* and *Lubarika* road axes, with all the trade occurring within a 0 to 5 km radius of the villages.

Even though banana is traditionally a man's crop in the study area, both men and women are involved in banana product marketing (Table 9). For example, in the eastern DR Congo transects, between 50 and 100% of villages reported that women play an important role in marketing bunches, compared to between 33 and 50% in Burundi. As for suckers only women were involved along the *Mwenga* transect whereas few men traded suckers in the *Lubarika* transect (Table 9).

The frequency of transactions was high for banana bunches while very low for suckers (Table 10). Between 67 and 83% of the communities reported trade in banana bunches once or twice in a week across the four transects. In contrast, 85% of the communities did not trade in suckers, with half of those that reported to trade in suckers, transacting once over the period in which suckers are actively planted. This is probably explained by the fact that commercialization of suckers is still limited, with most farmers being reliant on suckers from their own farms or from within their village (c.f. Table 3). It is also not common for small-scale farmers in the highland zones to sell or buy planting materials. At low elevation sites along the *Mwenga* axis cooking and plantain suckers were traded, while in the lowland sites along the *Lubarika* axis plantain and FHIA suckers were the predominant planting materials traded.

Potential role of traders in disease spread

Trade through either the movement of products and/or harvesting of bunches and suckers by traders have been reported to also contribute to disease spread. Along the four transects in this study, 33, 66.7, 100 and 66.7% of the communities in *Mwenga, Lubarika, Rumonge* and *Cibitoke* axes, respectively reported that traders use own tools to harvest banana bunches and to a much lesser extent suckers from their farms. More still, traders were reported to most often not sterilize their tools in between farm visits, a measure that is crucial for the control of XW spread.

Access to extension support

Access to knowledge and information on disease epidemiology and management is very important for minimising the risks associated with spread of pests and diseases. Access to extension services was low in Mwenga (33%) and very high in the other three road axes (83-100%) (Table 11). However, the frequency of access within a year was generally very low (2-5 times a year), with the highest frequency recorded for the Mwenga axis. Some of the communities along the Mwenga axis (22%) also had community by-laws, action plans and disease control committees. The presence of several international NGOs along the Mwenga axis might have contributed to the higher-level of contact with extension bodies and the use of by-laws/action plans and committees (Table 11). Except for Lubarika (11 km), distances to offices of extension bodies were short (1-3 km).

DISCUSSION

Pest and disease prevalence across four trade axes along low-high altitude gradients

BBTD which arrived in the central African rift valley region over 60 years ago (initially at the INEAC Lubarika Research Station in eastern DR Congo) (Blomme et al., 2013) is omnipresent in the study regions, including the high-altitude sites above 1500 m. This is supported by the low regression observed in the study between BBDT incidence and altitude. For long it had only been reported at low- to mid-elevation sites (<1500 m). The observed high prevalence of the disease at the high elevation sites above 1500 m in this study is of concern as the disease may gradually invade the high-altitude banana production zones of east and central Africa adjacent to the rift valley depression, especially under changing climatic conditions. BBTD is mainly spread through banana aphids and planting materials (Niyongere et al., 2012, 2015). Aphid-mediated spread at high altitudes is reported to be negligible (Niyongere et al., 2012, 2015). Given that the disease has been present in the study sites for 15 to 45 years, the observed spread to and within the high altitudes could be mainly attributed to short distance spread through infected planting materials which must have gradually occurred over numerous years. The weak extension support in the study locations over past decades could have only contributed to this spread. Farmers in the study region relied entirely on planting material from their own farms or their neighbourhood (on average 9 km) (cf. Table 4). Labour exchange between communities was common and labourers often move around with suckers from high-yielding cultivars that are not yet present on their farms or from highly-marketable cultivars. Xanthomonas wilt disease, though a more recent introduction (between 1 and 7 years), is already widely spread across most sections of all axes in the study region and is a cause of great concern. The rapid spread of XW can be attributed to its complex/multiple modes of spread that include: movement of infected planting materials, cross farm/cross village use of farm tools, and insect, bird and bat vectors that visit diseased and healthy banana

Table 4. Percentage of communities (represented by FGD groups) along the studied banana trade axes in eastern DR Congo and western Burundi who used various sources of suckers and their estimated travel distances irrespective of administrative boundaries to obtain planting material based on banana type.

Road axis (n)	Banana type	Sources of banana planting material used by farmers					Average distance farmers travel (km)
		Village	Parish	District	Province	Out of the country	
Mwenga (9)	Beer	77.7	55.5	44.4	11.1	0.0	51.2
	Cooking	88.8	33.3	11.1	0.0	0.0	11.4
	Dessert	100.0	33.3	22.2	11.1	11.1	18.5
	Plantain	55.5	33.3	11.1	0.0	0.0	26.3
	Mean	80.5	38.9	22.2	5.6	2.8	26.9
Lubarika (6)	Beer	100.0	0.0	0.0	0.0	0.0	1
	Cooking	100.0	0.0	0.0	0.0	0.0	1
	Dessert	83.3	0.0	0.0	0.0	0.0	1.2
	Plantain	100.0	0.0	0.0	0.0	0.0	1.2
	Mean	95.8	0.0	0.0	0.0	0.0	1.1
Rumonge (6)	Beer	100.0	33.3	0.0	0.0	0.0	1.7
	Cooking	66.7	0.0	0.0	0.0	16.7	13
	Dessert	83.3	16.7	0.0	0.0	0.0	1.2
	Plantain	16.7	33.3	0.0	0.0	0.0	1.8
	Mean	66.7	20.8	0.0	0.0	4.2	4.4
Cibitoke (6)	Beer	83.8	33.3	16.7	0.0	0.0	5
	Cooking	66.7	50.0	33.3	16.7	0.0	0.8
	Dessert	100.0	33.3	16.7	16.7	16.7	6
	Plantain	66.7	50.0	16.7	0.0	0.0	3.0
	Mean	79.3	41.7	20.9	8.4	4.2	3.0
Overall average		80.6	25.3	10.8	3.5	2.8	8.9

Table 5. Number and types of banana cultivars grown along the four banana trade axes studied in eastern DR Congo and western Burundi.

Road axis	Number (%) of banana cultivars by type/use group				Total number of cultivars	Range of N° of cultivars by axis
	Green cooking (%)	Beer (%)	Dessert (%)	Plantain (%)		
Mwenga	12 (21)	18 (31)	7 (12)	21 (36)	58	7 - 16
Lubarika	6 (29)	8 (38)	5 (24)	2 (10)	21	6 - 11
Rumonge	4 (20)	10 (50)	5 (25)	1 (5)	20	6 - 14
Cibitoke	13 (38)	11 (32)	8 (24)	2 (6)	34	6 - 18

In brackets, cultivar numbers are expressed as a percentage of the total number of cultivars for a given axis.

Table 6. Labour practices that can influence the spread of pests and diseases along the studied banana road axes in east DR Congo and Burundi.

Road axis	Hired labourers from other villages (%)	Furthest distance labourers travel to work (km)	Lending of farm tools (%)	Joining group labour (%)
Mwenga (9)	88.8	27.1	100.0	100.0
Lubarika (6)	100.0	35.2	83.3	100.0
Rumonge (6)	33.0	10.3	100.0	50.0
Cibitoke (6)	83.3	34.3	100.0	50.0
Mean (27)	76.3	26.7	95.8	75.0

Values represent averages calculated from responses given during Focus Group Discussions.

Table 7. Banana products traded in villages along the banana road axes studied in the DR Congo and Burundi.

Road axis (n)	Banana bunches		Banana suckers		
	Local market	Farm gate	No trade	Local market	Farm gate
Mwenga (9)	88.9	11.1	66.7	33.3	0.0
Lubarika (6)	100.0	0.0	83.3	0.0	16.7
Rumonge (6)	100.0	0.0	100.0	0.0	0.0
Cibitoke (6)	100.0	0.0	100.0	0.0	0.0
Mean (27)	95.2	4.8	85.2	11.1	3.7

Table 8. Percentage of villages that sell their banana products at local markets along the banana road axes studied in east DR Congo and Burundi.

Road axis (n)	Banana bunches				Banana suckers				
	0-1 km	>1-5 km	>5-10 km	>10 km	No sales	0-1 km	>1-5 km	>5-10 km	>10 km
Mwenga (9)	44.4	44.4	0.0	11.2	66.7	11.1	22.2	0.0	0.0
Lubarika (6)	83.3	0.0	0.0	16.7	83.3	16.7	0.0	0.0	0.0
Rumonge (6)	33.3	50.0	16.7	0.0	100	0.0	0.0	0.0	0.0
Cibitoke (6)	66.7	16.7	16.7	0.0	100	0.0	0.0	0.0	0.0
Mean (27)	55.6	29.6	7.4	7.4	85.2	7.4	7.4	0.0	0.0

Table 9. Household members involved in marketing banana bunches and suckers across villages along four road axes studied in east DR Congo and Burundi.

Road axis	Bunches			Suckers			
	Man	Woman	Both	No marketing	Man	Woman	Both
Mwenga	0.0	77.8	22.2	66.7	0.0	33.3	0.0
Lubarika	50.0	33.3	16.7	83.3	16.7	0.0	0.0
Rumonge	66.7	0.0	33.3	100	0.0	0.0	0.0
Cibitoke	50.0	0.0	50	100	0.0	0.0	0.0
Mean	37.0	33.3	29.6	85.2	3.7	11.1	0.0

Table 10. Frequency of banana trade transactions along the banana road axes studied in the DR Congo and Burundi.

Road axis	Banana bunches				Banana suckers			
	Twice per week	Once a week	Twice a month	Once a month	No trading	Twice a week	Once a week	Once a month
Mwenga	44.4	33.3	0.0	22.2	67.7	0.0	11.1	22.2
Lubarika	50.0	33.3	16.7	0.0	83.3	16.7	0.0	0.0
Rumonge	16.7	50.0	33.3	0.0	100	0.0	0.0	0.0
Cibitoke	83.3	0.0	16.7	0.0	100	0.0	0.0	0.0
Overall	48.2	29.6	14.8	7.4	85.2	3.7	3.7	7.4

Trading in suckers reflects transactions within rainy seasons when suckers are planted (planting takes place in the highlands dominated by AAA-EAH type bananas from September till March, while planting in the lowland plantain-dominated zones takes place during September and October).

inflorescences (Blomme et al., 2017, Blomme and Ocimati, 2018; Ocimati et al., 2019). For example, farmers entirely relied on planting material from own or neighbours' fields, the latter potentially contributing to cross-farm disease spread. Sharing and cross-farm use of farm tools was also common. These practices play

Table 11. Community access to extension services along four transects in eastern DR Congo and Burundi.

Road axis	Access to extension services (government, local and int. NGOs)	Number of contacts with extension agents over the past year	Presence of community by-laws, action plans, control committees	Distance to nearest extension office
Mwenga	33.3	5.0	22.0	3.0
Lubarika	83.3	2.0	0.0	10.7
Rumonge	100.0	2.0	0.0	1.0
Cibitoke	83.3	2.0	0.0	1.1
Overall	75.0	2.7	5.5	4.0

crucial role in XW spread. XW spread through trade, mainly by banana traders that harvest bunches indiscriminately across villages and farms using their own tools without sterilization has also been reported (Blomme et al., 2014; Nakato et al., 2013). However, trade in bunches was predominantly over short distances (that is, local markets) and this could have contributed to short distance and local spread of diseases, e.g. XW disease through infected crop residues (that is, fruit peels and peduncles).

Black leaf streak, Fusarium wilt, banana weevils and nematodes were present across most study axes. This agrees with Blomme et al. (2013) who reported the omnipresence of these biotic constraints across the whole of east and central African production zones. However, farmers' report of year of first observation of BLS (that is, as early as 1962) contradicts the first scientific reports that place the introduction of the disease in the AGLR in the 1980s (Sebasigari, 1990; Blomme et al., 2013). Farmers could have potentially confused the symptoms of BLS to yellow sigatoka (*Mycospharella musicola*). In Africa, *M. musicola* was reported in Uganda in 1938 (Stover, 1962). Six months from the first report in Uganda, separate outbreaks, about 160 to 320 km apart were reported along the East African coast. In 1941, *M.* musicola was also reported in Cameroon, West Africa, about 2,400 km away (Stover, 1962). BLS prevalence has been reported to be high at hot and humid lower altitude sites (Erima et al., 2017). The fact that no BLS was observed in lowland zones (<1200 m) along the Mwenga axis in eastern DR Congo can be explained by the short lifespan of plantains caused by poor suckering and weevil damage. Farmers mainly harvest the parent plant and sometimes the first ratoon. Regular plantain replanting is the norm in these production zones, which prevents disease build up. The omnipresence of the BLS-resistant 'km5' cultivar along the Lubarika and both Burundi axes might explain the often low BLS incidence values that were reported/observed.

Farmers' report of when they first observed Fusarium wilt (that is, as early as 1962) also contradicts the official scientific reports that place its introduction to a much later period, that is, before the 1980's (Blomme et al., 2013). However, already in the 1950s Fusarium wilt was reported in countries neighbouring DR Congo, Burundi and Rwanda (Blomme et al., 2013), suggesting that the disease could have arrived in DR Congo at an earlier date than what was officially reported. *Fusarium* species is commonly spread through planting materials and infected soils (adhered to e.g. shoes/boots, tools, motorcycle and car tires) (Ploetz, 2015; Dita et al., 2018).

Risk factors for pest and disease spread and build-up

Planting materials are an excellent means for the spread of banana pests and diseases and have been reported to play a major role in the spread of XW, BBTD, Fusarium wilt, nematodes and weevils in banana (Jacobsen et al., 2019). The short distance household members travelled to obtain banana planting materials (mean furthest distance of 9 km) suggests a possibly limited long distance spread of diseases and pests through planting materials. This suggests that planting material-borne diseases will only gradually spread over time. However, within short distance disease and pest spread (e.g. within villages) and build up through exchange or recycling of planting materials within fields would be high given most households mainly relied on suckers from own fields or from neighbouring fields.

Access to clean planting materials was limited across all the study sites due to the complete absence of tissue culture or macro-propagation facilities producing clean planting materials in eastern DR Congo and a long distance to such facilities in Burundi. Farmers' willingness to buy clean planting materials was however very variable (16-83%) and high along the *Cibitoke* axis, moderate along *Mwenga* and *Lubarika* axes while low at *Rumonge* axis. The high variation in farmers' willingness to invest in planting material could be influenced by agro-ecological conditions at their farms and villages, prevalence of pests and diseases and access to markets. For example, the demand for clean planting material in the *Cibitoke*, *Lubarika* and *Rumonge* axes was mainly attributed to the need for clean material to replant fields devastated by BBTD. In contrast, in the low elevation hot and humid forested regions of *Mwenga*, bananas were reported to have a short plantation life, thus farmers have to regularly re-establish banana plantations, thus the high demand for clean planting material. This short plantation life span can be attributed to the low suckering ability of plantains at this altitude and the high banana weevil burden observed in the study site compared with the other axes. Earlier studies by e.g. Sikyolo et al. (2013), have also reported low suckering, especially for plantains planted at low altitudes in eastern DR Congo, meanwhile in Uganda, the high weevil burden at the low elevation sites of central Uganda has been reported to primarily be responsible for the historical shift of banana production into the then pest-free south-western highland zones of Uganda (Gold et al., 1999). Despite the expressed demand for clean planting material, with the exception of Mwenga where farmers were willing to pay up to $1 per clean planting material, farmers in the other three axes were mainly willing to pay lesser amounts that may not attract or sustain investments in the production of clean planting materials in these regions.

A high banana cultivar diversity was reported across the four axes. The diversity of cultivars on farms can affect the spread and establishment of pests and diseases. Ocimati et al. (2018b) observed a lower XW incidence and prevalence with increasing number of banana cultivars, especially in mixtures consisting of the ABB cultivars (e.g. 'Pisang Awak') that are susceptible to insect mediated infections and cultivars with traits that escape insect-mediated infection (e.g. the east African highland banana 'Mbwazirume'). The cultivars with these traits have either persistent or semi persistent non-fruit forming/male flowers and male-bud bracts. Banana cultivar mixtures have also been shown to reduce the incidence of black sigatoka, banana weevils and nematodes (Mulumba et al., 2012). Although some genome groups in the study sites have a good level of tolerance or resistance to some of the pests and diseases, no clear patterns were observed between the level of pest and disease presence and the predominant *Musa* genome groups in a site.

Intercropping of bananas was predominant across the four axes. Intercropping with non-host crops has been reported to slow down the spread of some pests and diseases within fields and reduce disease incidence and severity (Mukiibi, 1982; Allen et al., 1989; Poeydebat et al., 2016; Vidal et al., 2017). The depression of pest and disease incidence in cultivar and or crop mixtures can be attributed to factors such as physical barriers to vectors and aerial pathogens, altered microclimate, a dilution effect, pathogen inhibition and host alteration (Sumner et al., 1981; Boudreau, 2013; Vidal et al., 2017). In contrast, banana intercropping with annual crops and other root and tuber crops in the study regions has often been associated with cutting of banana leaves to allow for more light to the understory crops (e.g. beans) and weeding/ earthing up using farm tools that often damage banana roots. These practices have been shown to potentially spread XW disease within banana fields (Ocimati et al., 2013, 2019; Blomme et al., 2017).

Hiring of external labour was a common practice across the study sites, with these labourers coming from other villages in 76% of cases. These labourers were reported to mainly move around with their own farm tools, boots and clothes. This can potentially allow for spread of soil borne nematodes and disease pathogens e.g. *Fusarium* spp. (in case of tools and boots) (Dita et al., 2018), fungal diseases e.g. black leaf streak (boots and clothes) (IICA, 2006) and XW disease (farm tools) (Blomme et al., 2017; Blomme and Ocimati, 2018). Labour was hired from or sold to an average distance of 27 km from the farms, suggesting that labourers can contribute to disease spread over low to moderate distances. Other risky practices included lending of farm tools and provision of labour in groups on a rotational basis. In both cases, the tools used, boots and clothes worn can spread diseases as described above.

Banana bunches and to a small extent suckers were the main banana products traded, mainly at the local markets that were between 1 and 10 km from the farm gate. The potential role of trade in disease spread through asymptomatic banana bunches containing ooze or traders tool used across farms has been reported for XW (Nakato et al., 2013). For example, the disease can be introduced into a farm if the buyer peels an infected fruit with a knife and thereafter uses it for e.g. pruning on own farm. The scope of the effect of sale of banana products is likely to vary from within the villages to as far as 100 km, though farmers had no knowledge of the exact distance their buyers travelled. For example, Bukavu which is 120 km from *Mwenga* is one of the destinations for banana bunches from *Mwenga*. Traders, in 33 to 100% of cases used their own tools to harvest bunches on banana fields. This practice has been reported to play an important role in XW spread in east and central Africa (Blomme et al., 2017).

Access to knowledge extension services was generally low across all study sites. Access to information on management and epidemiology of diseases is crucial for containment (Ocimati et al., 2019; Kikulwe et al., 2019), thus needs to be fostered.

This study points to various modes of disease/pest spread, which most likely also occurred over past decades. Regression analysis did not show a significant link between pest/disease presence and altitude, mainly due to the current omnipresence of the pest/diseases in the landscapes. Except for XW that is a more recent introduction but nevertheless spreads rapidly, the other pests and diseases were reported to be present in the region since several decades, over which time they have gradually spread. This has not been helped by the weak extension service support and interlinked low farmer knowledge on pest/disease control and prevented spread, over past decades, in both Burundi and eastern DR Congo.

Data for this study were collected through FGDs at landscape level. This limited/constrained the analysis to a landscape level. As such, further data exploration through a multivariate statistical analysis did not yield any relevant information. A regression analysis was carried out to determine the relations between disease and pest variables and altitude.

Information generated through this study is however relevant for the study sites and other banana growing locations in e.g. east and central Africa. This study could contribute to insights on the timely management of new pests and diseases of banana and could even provide useful insights applicable to other vegetatively propagated crops.

Climate change vs. pests and diseases

The observed prevalence of banana weevils and BBTD at the high-altitude sites raises a huge concern with respect to the current trends in climate change. Warming conditions with increasing rainfall and humidity could improve conditions for the survival of weevils at the high-altitude sites, previously known to be unfavourable for the multiplication of banana weevils. Though present at the high elevation banana production zones, the aphid that spreads BBTV has been known to be inefficient in BBTD spread at the high-altitude areas with lower temperatures. The acquisition and inoculation of banana bunchy top virus (BBTV) by the aphid *P. nigronervosa* has been shown to be affected by temperature (Wu and Su, 1990; Anhalt and Almeida, 2008). Wu and Su (1990) observed no BBTV transmission at 16°C and a maximum transmission efficiency at 27°C. Anhalt and Almeida (2008) observed a higher transmission efficiency of BBTV by the aphids at 25 and 30°C but a low efficiency a 20°C. Anhalt and Almeida (2008) also observed similar temperature effects on aphid fecundity and hypothesized a longer latent period at the lower temperature of 20°C. Given the current prevalence of BBTD at the cooler high elevations (presumed to be gradually and mainly spreading through planting materials), increasing temperatures at the high altitudes would create conducive conditions for the transmission of BBTV and increase the rate of disease spread and overall BBTD burden. This could also, gradually, place the highland production zones in eastern Africa at modest to high risk.

Warming of conditions at the high altitudes will also create a more conducive environment for the development and spread of BLS. BLS has in the past not been found at altitudes above 1350 m (Erima et al., 2017). However, more recent studies in the East and Central African region have reported *P. fijiensis* the causal agent of BLS at higher and cooler altitudes and this has been attributed to increasing temperatures (Erima et al., 2017; Kimunye et al., 2020). Higher altitude eco-regions are cool, favouring the reproduction of *P. goodeyi* (Pinochet et al., 1995; Gaidashova et al., 2009). A reduction in the area occupied by *P. goodeyi* and an increase in other nematode spp. (e.g. *R. similis*) currently limited to lowland zones could also be expected under increasing temperature regimes.

Currently the spread of XW at high elevation sites can be predominantly attributed to movement of contaminated farm tools and infected planting materials. At these altitudes, the activities of the insect vectors of XW are low (Rutikanga et al., 2015; Shimelash et al., 2008). Warmer climates would increasingly support insect-mediated spread of XW and thus increase its prevalence and severity at higher altitudes.

Conclusions

The present study identified key banana pests and diseases and several potential risk factors responsible for their spread and build up across different axes, with due consideration of altitude effects. The key banana pests of concern included nematodes and weevils while the diseases included XW, BBTD, Fusarium wilt and BLS. This study also provides insights in modes of spread that most likely already contributed to disease/pest spread over past decades in the study region. The main potential pathways of pest and disease spread included the movement of farming tools by labourers and traders (respectively, 10-35 km and often over 100 km), planting material/suckers (often less than 5 km) and banana products, especially bunches (mainly less than 5 km, but occasionally over 10 km; traders can transport bunches over larger distances to main urban markets).

Apart from Cibitoke (>65%) the willingness to buy clean banana planting materials was low (<50%). With the exception of Mwenga (for all cultivars), in the Cibitoke (dessert and plantains) and Lubarika axis (beer types only), farmers were willing to pay between $0.6 and $1.75 per clean planting material. The current price for clean planting materials in the region varies between $0.6 and $0.7 (Ntamwira Jules, personal communication, 2018) and values less than this could be a disincentive to the development of banana planting material enterprises in the study regions and a major bottleneck towards the management of pests and diseases. Use of crop or cultivar mixtures was common and could be harnessed to reduce the spread and build-up of pests and diseases. Envisaged changes in climate are likely to affect pest and disease build up and spread, and in case of warmer and more humid conditions, will lead to increased spread of BBTD, XW, BLS, weevils and some damaging nematode species at higher altitude zones. Fostering knowledge extension on pest and disease epidemiology and management can also help improve the demand for clean planting material and overall management of the biotic constraints, thus reducing further spread and/or build-up of these pests and diseases. This may also necessitate strengthening institutional capacities of actors (such as farmer institutions, labour associations, trader association) and stakeholders intervening in banana value chains in the region.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENT

This study was supported by funds from the CGIAR Research Program on Roots, Tubers and Bananas, and the CGIAR Fund Donors.

REFERENCES

Actualitix (2016). Burundi: Ranking - Banana - Production (Tons). https://en.actualitix.com/country/bdi/burundi-banana-production.php (accessed on 1 August 2019).

Allen DJ, Dessert M, Trutmann P, Voss J (1989). Common beans in Africa and their constraints. pp. 9-31. In: Schwartz, H.F. and Pastor-Corrales. Bean production problems in the Tropics. CIAT, Cali, Colombia.

Anhalt MD, Almeida RPP (2008). Effect of temperature, vector life stage, and plant access period on transmission of Banana bunchy top virus to banana. Phytopathology 98(6):743-748.

Baret P, Van Damme J (2010). La culture bananière. Réponse à la sécurité alimentaire. Louvain P 184.

Blomme G, Dita M, Jacobsen KS, Pérez Vicente L, Molina A, Ocimati W, Poussier S, Prior P (2017). Bacterial Diseases of Bananas and Enset: Current State of Knowledge and Integrated Approaches toward Sustainable Management. Frontiers in Plant Science 8:1290. doi:10.3389/fpls.2017.01290.

Blomme G, Jacobsen K, Ocimati W, Beed F, Ntamwira J, Sivirihauma C, Ssekiwoko F, Nakato V, Kubiriba J, Tripathi L, Tinzaara W, Mbolela F, Lutete L, Karamura E (2014). Fine-tuning banana Xanthomonas wilt control options over the past decade in East and Central Africa. European Journal of Plant Pathology 139:265-281.

Blomme G, Ocimati W (2018). Xanthomonas bacterial wilt. Chapter 5: Diseases caused by bacteria and phytoplasmas. Handbook of diseases of banana, abacá and enset. (Ed. Jones, D.R.). CAB International pp. 296-313.

Blomme G, Ploetz R, Jones D, De Langhe E, Price N, Gold C, Geering A, Viljoen A, Karamura D, Pillay M, Tinzaara W, Teycheney PY, Lepoint P, Karamura E, Buddenhagen I (2013). A historical overview of the appearance and spread of Musa pests and pathogens on the African continent: highlighting the importance of clean Musa planting materials and quarantine measures. Annals of Applied Biology 162:4-26.

Boudreau MA (2013). Diseases in intercropping systems. Annual Review of Phytopathology 51:499-519.

Dita M, Barquero M, Heck D, Mizubuti E, Staver C (2018). Fusarium Wilt of Banana: Current Knowledge on Epidemiology and Research Needs Toward Sustainable Disease Management. Frontiers in Plant Science 9:1468.

Erima R, Kubiriba J, Komutunga E, Nowakunda K, Namanya P, Seruga R, Nabulya G, Ahumuza E, Tushemereirwe WK (2017). Banana pests and diseases spread to higher altitudes due to increasing temperature over the last 20 years. African Journal of Environmental Science and Technology 11:601-608.

Food and Agriculture Organization (FAO) (2019). Crops. [http://www.fao.org/faostat/en/#data/QC]. (Accessed on 6 June 2018).

Gaidashova S, Delvaux B, van Asten P, De Waele D (2009). Relationship between soil properties, crop management, plant growth and vigour, nematode occurrence and root damage in East African Highland banana-cropping systems: a case study in Rwanda. Nematology 11(6):883-894.

Gold CS, Karamura EB, Kiggundu A, Bagamba F, Abera AMK (1999). Monograph on geographic shifts in highland cooking banana (*Musa*, group AAA-EA) production in Uganda. African Crop Science Journal 7(3):223-298.

Gold CS, Messiaen S (2000). The Banana Weevil Cosmopolites Sordidus. Musa Pest Fact Sheet No. 4. pp.4. https://www.bioversityinternational.org/fileadmin/_migrated/uploads/tx_news/The_banana_weevil_Cosmopolites_sordidus_696.pdf (accessed on 28 March 2020).

Hwang SC, Ko WH (2004). Cavendish Banana Cultivars Resistant to Fusarium Wilt Acquired through Somaclonal Variation in Taiwan. Plant Disease 88(6):580-588.

IICA (2006). Action Plan for Black Sigatoka *Mycosphaerella fijiensis* (Morelet). Miscellaneous Publications ISSN-0534-5391 CaRC/LC-06-004., Saint Lucia. P. 23. http://orton.catie.ac.cr/REPDOC/A0967I/A0967I.PDF (accessed on 24 July 2019).

IITA (2015). Value Chain Analysis of Major Food Crops in South Kivu and North Katanga. DR Congo. http://www.gcp21.org/wcrtc/ppt/S17presentation/S17-10.DontsopNguezetPaul.SIGNED.ID4625.424.pdf. (accessed on 30 March 2020).

Jacobsen K, Omondi BA, Almekinders C, Alvarez E, Blomme G, Dita M, Iskra-Caruana ML, Ocimati W, Tinzaara W, Kumar PL, Staver C (2019). Seed degeneration of banana planting materials: strategies for improved farmer access to healthy seed. Plant Pathology 68:207-228.

Kamira M, Hauser S, van Asten P, Coyne D, Talwana HL (2013). Plant parasitic nematodes associated with banana and plantain in eastern and western Democratic Republic of Congo. Nematropica 43:216-225.

Kamira M, Sivirihauma C, Ntamwira J, Ocimati W, Katungu MG, Bigabwa JB, Vutseme L, Blomme G (2014). Household uses of the banana plant in eastern Democratic Republic of Congo. Journal of Applied Biosciences 94:8915-8929.

Kikulwe EM, Kyanjo JL, Kato E, Ssali RT, Erima R, Mpiira S, Ocimati W, Tinzaara W, Kubiriba J, Gotor E, Stoian D, Karamura E (2019). Management of Banana Xanthomonas Wilt: Evidence from Impact of Adoption of Cultural Control Practices in Uganda. Sustainability 11(9):2610.

Kimunye JN, Were E, Mussa F, Tazuba A, Jomanga K, Viljoen A, Swennen R, Muthoni FK, Mahuku G (2020). Distribution of *Pseudocercospora* species causing Sigatoka leaf diseases of banana in Uganda and Tanzania. Plant Pathology 69(1):50-59.

Mobambo P, Staver C, Hauser S, Dheda B, Vangu G (2010). An innovation capacity analysis to identify strategies for improving plantain and banana (*Musa* spp.) productivity and value addition in the Democratic Republic of Congo. Acta Horticulturae 879:821-828.

Mukiibi JK (1982). Effects of intercropping on some diseases of beans and groundnuts. pp. 110-114. In: Keswani, C.L. and Ndunguru, B.J. ed., Proc. Second Symp. on Intercropping in Semi-Arid Areas. IDRC – 186e. IDRC, Ottawa.

Mukwa LFT, Muengula M, Zinga I, Kalonji A, Iskra Caruana ML, Bragard C (2015). Occurrence and distribution of Banana bunchy top virus related agro-ecosystem in South Western. Democratic Republic of Congo. American Journal of Plant Sciences 5(5):647-658.

Mulumba JW, Nankya R, Adokorach J, Kiwuka C, Fadda C, De Santis P, Jarvis DI (2012). A risk-minimizing argument for traditional crop varietal diversity use to reduce pest and disease damage in agricultural ecosystems of Uganda. Agriculture, Ecosystems and Environment 157:70-86.

Nakato GV, Beed F, Ramathani I, Rwomushana I, Opio F (2013). Risk of banana Xanthomonas wilt spread through trade. Journal of Crop Protection 2(2):151-161.

Ndungo V, Fiaboe KKM, Mwangi M (2008). Banana Xanthomonas Wilt in the DR Congo: Impact. spread and management. Journal of Applied Biosciences 1(1):1-7.

Neyrinck C (2011). L'impact du paillage et du non labour sur le ruissellement et l'érosion dans les systèmes bananes haricots dans la région du Sud-Kivu. Master Thesis. Université Catholique de Louvain. Belgium.

Niyongere C, Losenge T, Ateka EM, Nkezabahizi D, Blomme G, Lepoint P (2012). Occurrence and Distribution of Banana Bunchy Top Disease in the Great Lakes Region of Africa. Tree and Forestry Science and Biotechnology 6(1):102-107.

Niyongere C, Omondi AB, Blomme G (2015). The Banana bunchy top disease. In: Tennant P. and Fermin G. (eds). *Virus diseases of tropical and subtropical crops*. CAB International Plant Protection Series 12/2015. Wallingford, United Kingdom. pp. 17-26. http://www.cabi.org/bookshop/book/9781780644264

Ocimati W, Bouwmeester H, Groot JC, Tittonell P, Brown D, Blomme G (2019). The risk posed by Xanthomonas wilt disease of banana: Mapping of disease hotspots, fronts and vulnerable landscapes. PloS ONE 14(4):e0213691.

Ocimati W, Groot JCJ, Tittonell P, Taulya G, Blomme G (2018a). Effects of Xanthomonas wilt and other banana diseases on ecosystem services in banana-based agroecosystems. In: *International Symposium on Banana/ISHS-ProMusa symposium: Agroecological approaches to promote innovative banana production systems.* International Society for Horticultural Science pp. 19-32.

Ocimati W, Ssekiwoko F, Karamura EB, Tinzaara W, Blomme G (2013). Does *Xanthomonas campestris* pv. *musacearum* colonize banana cord root tissue? Acta Horticulturae 986:103-109.

Ocimati W, Were E, Groot JC, Tittonell P, Nakato GV, Blomme G (2018b). Risks posed by intercrops and weeds as alternative hosts to *Xanthomonas campestris* pv. *musacearum* in banana fields. Frontiers in Plant Science 9:1471.

Pinochet J, Fernandez C, Sarah JL (1995). Influence of temperature of *in vitro* reproduction of *Pratylenchus coffeae*, *P. goodeyi*, and *Radopholus similis*. Fundamental and Applied Nematology 18(4):391-392.

Ploetz RC (2001). Black Sigatoka of Banana: The most important disease of a most important fruit. The Plant Health Instructor P. 7. https://www.apsnet.org/edcenter/apsnetfeatures/Pages/BlackSigatoka.aspx

Ploetz RC (2015). Fusarium wilt of banana. Phytopathology 105:1512-1521.

Poeydebat C, Carval D, De Lapeyre de Bellaire L, Tixier P (2016). Balancing competition for resources with multiple pest regulation in diversified agroecosystems: a process-based approach to reconcile diversification and productivity. Ecology and Evolution 6(23):8607-8616.

Rutikanga A, Night G, Tusiime G, Ocimati W, Blomme G (2015). Spatial and temporal distribution of insect vectors of *Xanthomonas campestris* pv. *musacearum* and their activity across banana cultivars grown in Rwanda. In Proceedings of the 7th Congress on Plant Protection" Integrated Plant Protection- a Knowledge-Based Step Towards Sustainable Agriculture. Forestry and Landscape Architecture". November 24-28. 2014. Zlatibor. Serbia (pp. 139-153). Plant Protection Society of Serbia (PPSS).

Sebasigari K (1990). Effect of black Sigatoka (*Mycosphaerella fijiensis* Morelet) on bananas and plantains in the Imbo Plain in Rwanda and Burundi. In: Sigatoka leaf spot diseases of bananas: Proceedings of an international workshop'. Costa Rica. (Eds RA Fullerton, RH Stover). (INIBAP).

Shimelash D, Alemu T, Addis T, Turyagyenda FL, Blomme G (2008). Banana Xanthomonas wilt in Ethiopia: occurrence and insect vector transmission. African Crop Science Journal 16:75-87.

Sikyolo I, Sivirihauma C, Ndungo V, De Langhe E, Ocimati W, Blomme G (2013). Growth and Yield of Plantain Cultivars at Four Sites of Differing Altitude in North Kivu, Eastern Democratic Republic of Congo. In: Blomme, G., van Asten, P. & Vanlauwe, B. (eds.): Banana systems in the humid highlands of sub-Saharan Africa: Enhancing resilience and productivity. CABI, Wallingford, Oxfordshire, UK. pp. 48-57.

Speijer PR, De Waele D (1997). Screening of Musa germplasm for resistance and tolerance to nematodes (Vol. 1). IITA.

StataCorp (2015). Stata Statistical Software: Release 14. College Station, TX: StataCorp LP.

Stover RH (1962). Intercontinental spread of banana leaf spot (*Mycosphaerella musicola* Leach). Tropical Agriculture (Trinidad) 39:327-338.

Sumner DR, Doupnik Jr B, Boosalis MG (1981). Effects of reduced tillage and multiple cropping on plant diseases. Annual Review of Phytopathology 19:167-187.

Vidal T, Boixel A, Durand B, de Vallavieille-Pope C, Huber L, Saint-Jean S (2017). Reduction of fungal disease spread in cultivar mixtures: Impact of canopy architecture on rain-splash dispersal and on crop microclimate. Agricultural and Forest Meteorology 246:154-161.

Wu RY, Su HJ (1990). Transmission of banana bunchy top virus by aphids to banana plantlets from tissue culture. Botanical Bulletin of Academia Sinica 31(1):7-10.

Table S1. Location of villages in which focus group discussions were held along the four banana trade axes studied in western Burundi and eastern DR Congo, and distances along a straight axis from the main markets (that is, Bukavu for DR Congo and Bujumbura for Burundi).

Country	Banana trade axis	Territory / province	Village name	Village altitude (m)	Distance along a straight axis from main market (km)
DR Congo	*Mwenga*	Mwenga	Kibe	685	114.1
			Tukenga	689	116.4
			Kilungutwe	1032	-
			Ngenje	1146	60.5
			Kibanja	1203	81.7
			Kalole	1310	90.0
		Walungu	Bwahungu	1454	34.9
			Cikamba	1641	22.7
		Kabare	Kasiru	1996	10.7
	Lubarika	Uvira	Lubarika	927	43.0
		Walungu	Kashenyi	980	28.7
			Rushebeyi	1260	27.4
			Nyamurabwe	1611	19.5
		Kabare	Cihugi-1	1657	10.8
			Mabijo	1740	3.7
Burundi	*Rumonge*	Muhuta	Gabaniro	799	27.2
		Kabezi	Ceri	1062	25.3
		Muhuta	Muhuta-2	1603	26.7
			Gatwenzi	1713	28.8
			Muhuta-1	1765	28.5
			Muhow	1841	28.6
	Cibitoke	Rugombo	Munyika-1	906	67.5
			Rugerere	1088	67.9
			Kinama	1167	73.6
		Mugina	Muyange	1199	71.9
		Mabayi	Kirinzi	1582	75.4
			Mpinga	1713	76.2