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Research article

Influence of altitude as a proxy for temperature on key *Musa* pests and diseases in watershed areas of Burundi and Rwanda

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A R T I C L E I N F O

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A B S T R A C T

Pests and diseases are key biotic constraints limiting banana production among smallholder farmers in Eastern and Central Africa. Climate changemay favour pest and disease development and further exacerbate the vulnerability of smallholder farming systems to biotic constraints. Information on effects of climate change on pests and pathogens of banana is required by policy makers and researchers in designing control strategies and adaptation plans. Since altitude is inversely related to temperature, this study used the occurrence of key banana pests and diseases along an altitude gradient as a proxy for the potential impact of changes in temperature associated with global warming on pests and diseases. We assessed the occurrence of banana pests and diseases in 93 banana fields across three altitude ranges in Burundi and 99 fields distributed in two altitude ranges in Rwanda watersheds. Incidence and prevalence of Banana Bunchy Top Disease (BBTD) and Fusarium wilt (FW) was significantly associated with temperature and altitude in Burundi, revealing that increasing temperatures may lead to upward movement of banana diseases. No significant associations with temperature and altitude were observed for weevils, nematodes and Xanthomonas wilt of banana (BXW). Data collected in this study provides a baseline to verify and guide modelling work to predict future pest and disease distribution according to climate change scenarios. Such information is useful in informing policy makers and designing appropriate management strategies.

1. Introduction

Farming communities within the East and Central African (ECA) region have consistently ranked *Musa* spp. (comprising bananas and plantains) as an important food and cash crop [1, 2, 3]. The cultivated area in the region is estimated to be approximately 4.2 million sq. km with an annual production of about 17 million tonnes [1,4]. On the scale of smallholder farms, banana is often intercropped with perennial and annual crops such as coffee (*Coffea arabica* L. and *Coffea robusta* L. Linden), cassava (*Manihot esculenta*

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Crantz), sweet potato (*Ipomoea batatas* L. Lam), beans (*Phaseolus vulgaris* L.) and yams (*Dioscorea* spp.) [1, 4, 5, 6]. The East African highland cooking bananas (EAHB; *Musa* AAA genome group) and plantains (AAB genome group) are the predominant *Musa* groups cultivated in the ECA region [7]. Other cultivars grown in the ECA region include dessert types (e.g., AABs such as 'Sukari Ndizi' and AAAs such as 'Cavendish' and 'Gros Michel'), the ABB cooking and beer types (e.g., 'Bluggoe' and 'Pisang Awak') and multipurpose FHIA types (hybrids).

Altitude has been reported to affect both growth and yield of *Musa* cultivars [4,8], meaning that changes in temperature can potentially impact *Musa* production and distribution. For example, the AAA-EAHB cultivars are known to perform well at cooler temperatures thus production of this cultivar group could shift to higher altitude areas as ground temperatures increase because of global warming [4]. Current plantain growing zones are mainly limited to lower altitudes with humid conditions [8, 9, 10, 11] and could possibly expand to higher altitudes under rising temperature and decreasing rainfall scenarios. Numerous abiotic and biotic factors have been reported to affect banana production in the ECA region [12,13]. Key biotic constraints include diseases such as Xanthomonas wilt of banana (BXW), banana bunchy top disease (BBTD) caused by the banana bunchy top virus (BBTV) and Fusarium wilt (FW), and pests such as banana weevils (*Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) and plant parasitic nematodes (PPNs) (e.g., *Pratylenchus goodeyi* (Cobb) (Nematoda; Pratylenchidae) Sher and Allen, *Helicotylenchus multicinctus* (Cobb) (Tylenchida; Hoplolaimidae) Golden and *Radopholus similis* (Cobb) Thorne) (Rhabditida: Pratylenchidae) [14,15]. The impact of these biotic constraints is influenced by a range of factors including cultivar susceptibility, crop management, weather, and climatic conditions [16, 17, 18, 19, 20, 21]. Changes in crop production practices, landscapes and environmental conditions thus greatly influence the spread and impact of pests and diseases [22, 23, 24, 25, 26].

In this study, we aimed to improve our understanding of how the incidence and prevalence of banana pests and diseases varies across altitude in major production areas in Burundi and Rwanda. This requires an understanding of the management and environment factors that influence the variability of pest populations, disease prevalence and incidence. A study by German Calberto et al (2015) predicted an increase of up to 50% in land suitable for banana production based on projected rainfall and temperature in the next 10–50 years in Africa. The increase will provide suitable conditions for banana production in the tropics; however, in parallel, it may also accelerate pest and disease development and spread. Therefore, a strong understanding of the potential effect of changes in weather patterns on these key pests and pathogens of banana is crucial for guiding decision-making on management strategies. This study was therefore undertaken to understand the temporal and spatial occurrence of various banana pests and diseases along several altitude gradients with varying climatic conditions (temperature and rainfall). The altitude gradients were proxies for different climate scenarios (with lower elevations corresponding to higher temperature scenarios) and used to assess the potential effect of climate change in ECA region on banana pests and diseases. A strong correlation has been observed between altitude and temperature, i.e., in the study regions, the more the altitude the lower the temperature pattern [8]. In addition, [8] also reported higher precipitation at the mid to high altitude sites in the same watersheds. Incidence and/or prevalence of banana pests (weevils, PPNs) and diseases (BXW, BBTD, Fusarium) were assessed within different altitude gradients. These five biotic constraints have existed in the studied watersheds for a long time and as such, altitude effects and temperature linked patterns on pest and disease distribution should be visible. It has been postulated that differences in incidence and prevalence of pests and diseases observed across altitudinal/temperature gradients could be extrapolated to simulate expected impacts of global warming. The findings of this study will contribute towards the development of cohesive and proactive pest and disease management strategies under the prevailing conditions of global warming. Other factors influencing plant growth that are possibly affected by the altitude gradient such as atmospheric pressure, oxygen, carbon dioxide concentrations, sunlight, nutrient movement in the soil were not explored.

2. Materials and methods

2.1. Field selection

Banana fields (<2 years old) with a minimum of 60 mats (clump of shoots and their rhizomes which are physically interconnected) were randomly selected at intervals of 3–5 km during two growing cycles of 2015 and 2016 in the watershed areas of Rusizi in Burundi and Ruhengeri in Rwanda. The assessment period coincided with the planting and harvesting of the annual crops that are commonly intercropped with banana. In Burundi, data were collected mid-way through the planting and harvesting period of March 2015 and July 2016, respectively. For Rwanda, data were collected in the middle of the harvesting and planting period of July 2015 and November 2016, respectively. Automatic weather stations with data loggers (HOBO Pro v2 U23-001 - Temperature/RH Data Logger, Onset Computer Corp., MA, USA) were set up to record daily temperature (°C) and rainfall (mm) within the target watersheds covering three altitude ranges/gradients (i.e., low, 700–1200); mid, >1200–1700 and high, >1700 - >2200 m) in Burundi and two (mid and high) altitude gradients in Rwanda (Fig. 1). All assessed banana fields in Rwanda were within the two altitude ranges. The weather stations recorded data on an hourly basis. Monthly mean temperature and rainfall for each altitude range was computed over the study period. For each assessed field, coordinates and altitude were recorded using a handheld GPS (GARMIN eTrex 12 channel GPS) at <10 m navigation accuracy (Fig. 1). Global Positioning System (GPS) data were used to generate maps using ArcGIS software to indicate the exact locations of the assessed farms. The 192 farm households assessed during the two growing cycles (93 in Burundi and 99 in Rwanda) are shown in Fig. 1. Dominating cultivars on farmer fields in both countries are shown in Table 1 below.

2.2. Pest and disease assessments

Incidence and/or prevalence of the major banana diseases (BBTD, BXW and FW) and pests (*C. sordidus* and nematodes) were

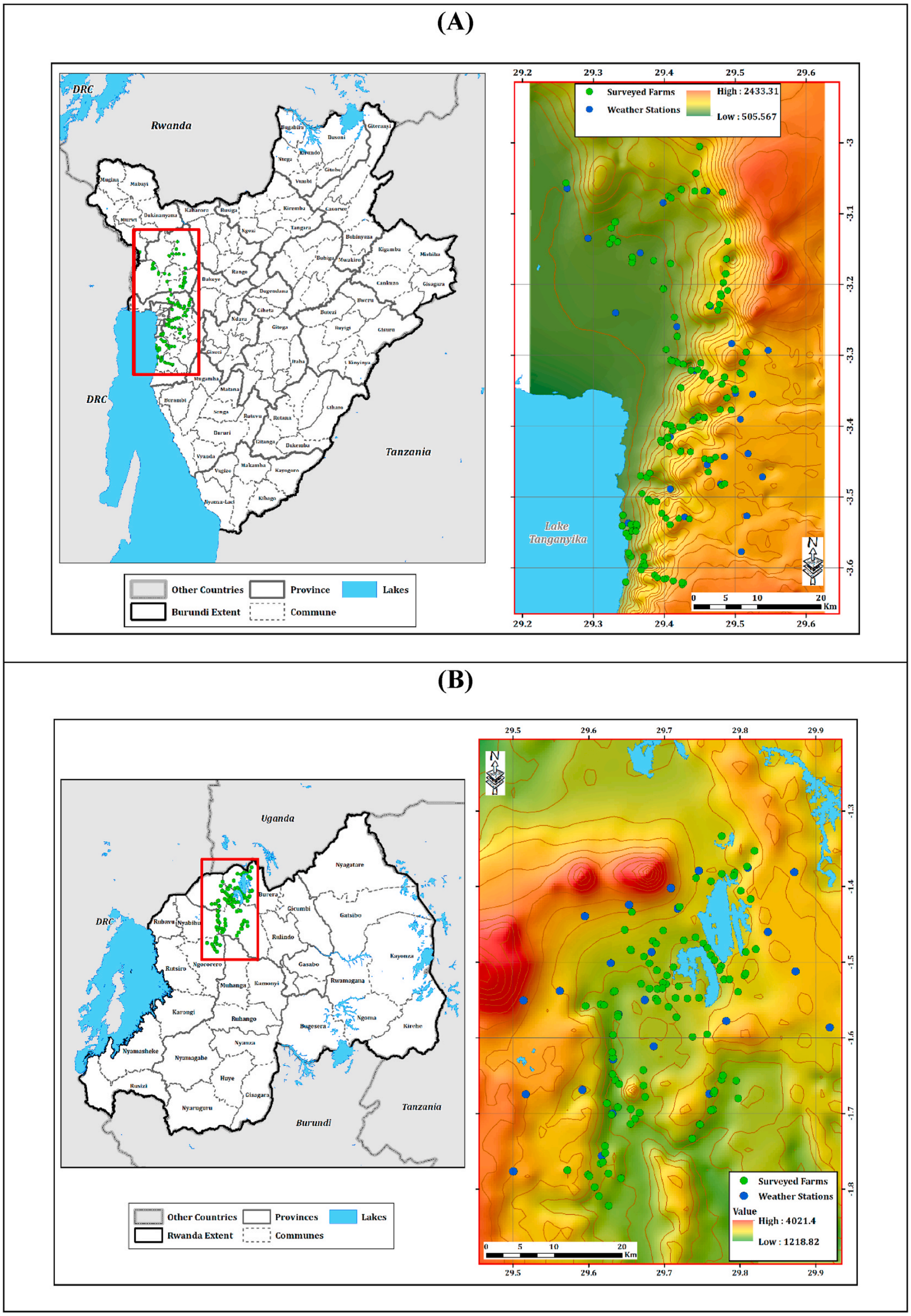

Fig. 1. Map of the two study areas; Rusizi watershed in Burundi (A) and the Ruhengeri watershed in Rwanda (B). The blue and green dots, respectively, represent the locations of the weather stations and farms assessed during the two growing cycles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Summary of the banana genotypes grown at the different altitude bands in the Burundi and Rwanda watersheds.

Country	Altitude gradient	Dominant genotypes	Use	Ploidy	Other genotypes	Use	Ploidy
Burundi	700–1200 m	Km5	Beer	AAA	Igitsirye	Beer	EAHB
		FHIA 17	Dessert	AAAA	Bluggoe	Beer	ABB
		Pisang Awak	Beer	ABB	Igisahira	Cooking	EAHB
					FHIA 23	Beer	AAAA
	>1200–1700 m	Km5	Beer	AAA	Igitsirye	Beer	EAHB
		FHIA 17	Dessert	AAAA	Bluggoe	Beer	ABB
		Pisang Awak	Beer	ABB	FHIA 23	Beer	AAAA
		Igisahira	Cooking	EAHB	Pisang Awak	Beer	ABB
					Ikiyove	Beer	EAHB
					Mubira	Beer	EAHB
	>1700 - <2200 m	Igisahira	Cooking	EAHB	Bluggoe	Beer	ABB
		FHIA 17	Dessert	AAAA	Pisang Awak	Beer	ABB
		Km5	Beer	AAA	FHIA 23	Beer	AAAA
					Ikiyove	Beer	EAHB
Rwanda	>1200–1700 m	EAHB	Cooking	AAA-EA	Pisang Awak	Beer	ABB
		EAHB	Beer	AAA-EA	Ney Poovan	Dessert	AAB
					Prata	Dessert	AAB
	>1700–<2200 m	EAHB	Cooking	AAA-EA	Pisang Awak	Beer	ABB
		EAHB	Beer	AAA-EA	Ney Poovan	Dessert	AAB
					Prata	Dessert	AAB

assessed on randomly sampled farmers' fields across the three (for Burundi) or two (for Rwanda) altitude ranges. Incidence of the three banana diseases was visually assessed by observing all the plants on a mat and in a field for symptoms characteristic of each disease Nelson_2004 [11,27, 28, 29]. Mat-level incidence was calculated as the proportion of sampled mats containing at least one infected plant and expressed as a percentage. Disease and pest prevalence data was recorded as presence or absence of the diseases and pests on the assessed farms. A short and structured interview was used to obtain information from farmers (caretakers/owners of the sampled fields) on the trend in incidence (increasing, decreasing or stable) for the three diseases over the period 2012–2016 on each assessed field. *C. sordidus* damage was assessed by cutting off the pseudo-stem stump of at least five recently harvested plants to expose rhizome tissue [30]. The exposed rhizome tissue was examined for *C. sordidus* larvae damage by dividing the exposed rhizome surface into eight cross-sections; the number of sections with *C. sordidus* damage was divided by eight and multiplied by 100 to calculate the percentage damaged area [31]. Assessment for nematodes was done on ten plants per field following a zigzag transect, according to the procedure described by [32].

2.3. Data analysis

The relationship between altitude and incidence and/or prevalence of diseases and pests was explored through the production of maps using ArcGIS (ESRI 2018; version 10.7). Scatter plots of altitude against disease incidence and monthly mean temperatures were produced to further explore this relationship. GenStat 19th Edition [VSN International Ltd 2014] was used for data analysis. A chi-square test of independence was performed to examine the relationship between temperature and disease and pest prevalence. Significant effects were reported at the 95% confidence level. The trend in disease presence for the period 2012–2016 was recorded as a percentage of respondents on whose farm diseases were increasing, decreasing, or remained stable, based on information provided by the farmer. Minimum and maximum temperature variation between assessments and at different altitudes for each country are presented in Table 2.

Table 2
Minimum and maximum temperature variation between growing cycles and at different altitudes for the Rusizi and Ruhengeri watersheds in Burundi and Rwanda, respectively.

Country	Altitude gradients	Average altitude	Temperature (°C)			
			2015		2016	
			Min	Max	Min	Max
Burundi	700–1200	914	20.3	29.4	19.2	29.6
	1201–1700	1434	17.7	28	18.4	28.2
	1701–2200	1927	15.9	26.7	15.8	26.6
Rwanda	1201–1700	1576	14.3	26.6	13.9	26.2
	1701–2200	1966	13.7	26	13.5	25.9

3. Results

3.1. Disease incidence

In Rwanda, no BBTD was observed in the target watershed whereas in Burundi, mat level incidence went over 50% (Fig. 2). While over 40% of the farms were infected with FW in Rwanda, the mat level incidences remained below 25% whereas in Burundi FW mat level incidence went over 50% (Fig. 3). In Rwanda, only a quarter of the surveyed farms were affected by BXW with mat level incidences remaining below 25%. (Fig. 4). By contrast, BXW mat level incidence varied from <25% to greater than 50% in Burundi (Fig. 4). No significant interactions ($P < 0.05$) were observed for mat level incidence of FW, BXW (Burundi and Rwanda) and BBTD (Burundi) with altitude range.

A scatter plot of altitude against mat level disease incidence showed high incidence levels for all the three targeted diseases at low (700–1200 m) and mid (>1200–1700 m) altitudes in Kabezi, Kayonsha, Isale and Mutimbuzi communes of Burundi; and towards the high end of the mid-altitude category and the low end of the high-altitude category (>1700 - >2200 m) in Musanze and Ngororero districts of Rwanda for BXW and FW (Fig. 5). Whereas farms with BXW infected banana plants were found more at the mid- and high-

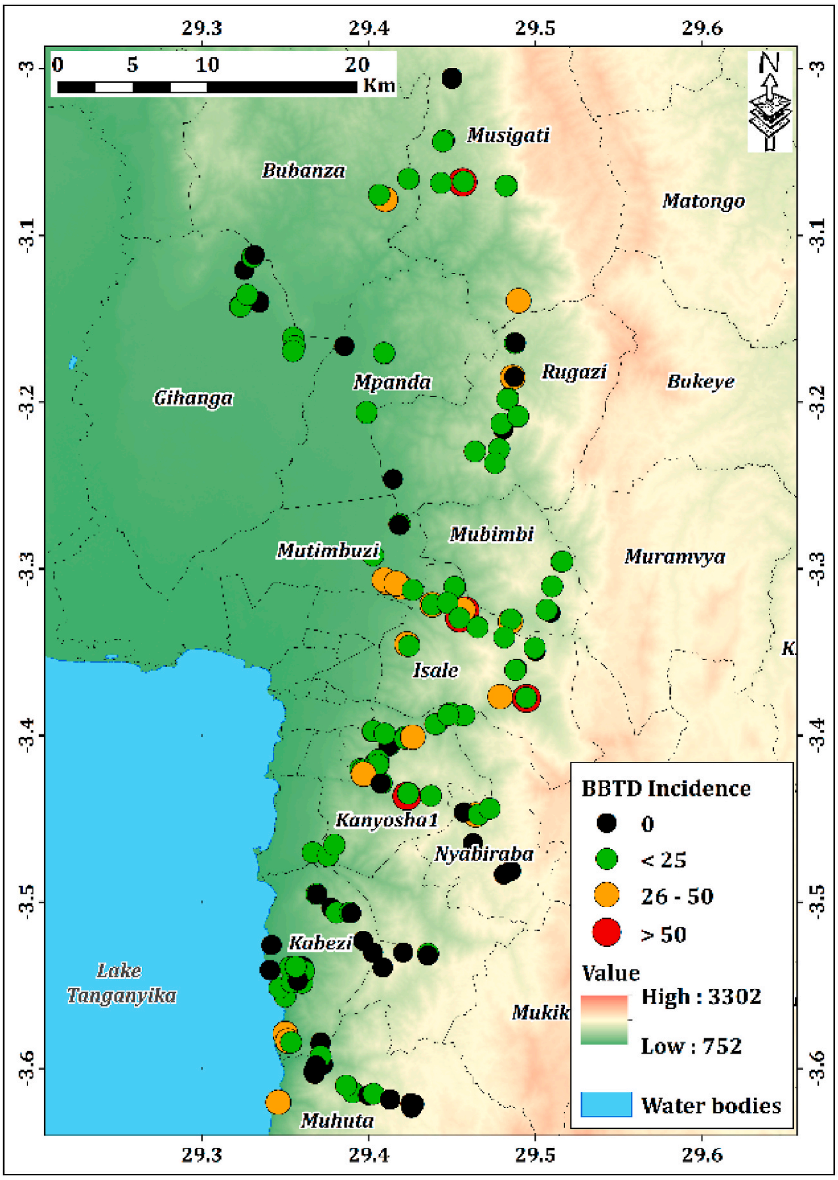

Fig. 2. Mat level incidence of Banana Bunchy Top Disease (BBTD) in the Rusizi watershed area of Burundi. Each dot represents a farm where assessments took place.

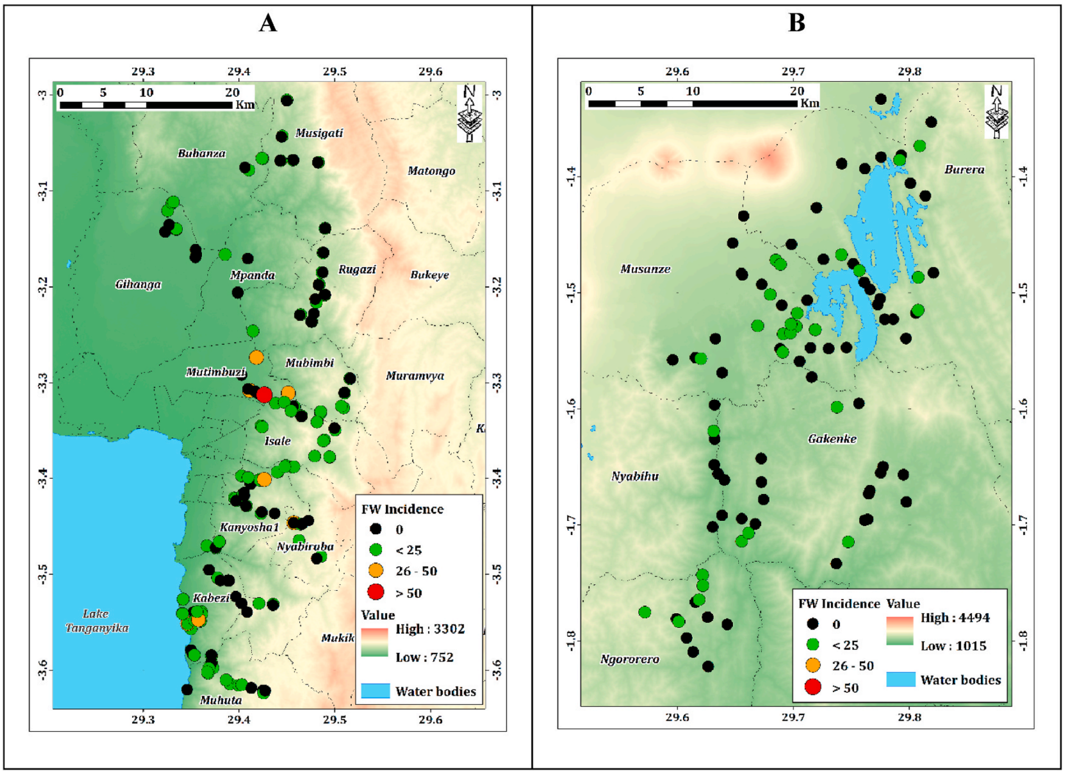

Fig. 3. Mat level incidence of Fusarium wilt of banana in the (A) Rusizi watershed area of Burundi and (B) the Ruhengeri watershed area of Rwanda. Each dot represents a farm where assessments took place.

altitudes in Burundi; FW incidence was highest at the low altitudes (Fig. 5). In Rwanda, BXW and FW incidences were higher in the high altitudes (mid-way the mid and high altitudes) (Fig. 5).

3.2. Disease and pest prevalence

Analyses of prevalence data with the different altitudes showed significant differences for BBTD and FW in Burundi only (Fig. 6). As the lowest prevalence pattern of BBTD was noticed at the high altitude (39%), the highest pattern got detected at the mid altitude level (78%), which didnot significantly differ from the low altitude (64%). The number of FW infected farms showed gradual decrease from the low to the high altitude (Fig. 6) and the effect of altitude variation on pest prevalence showed non-significant pattern in both Burundi and Rwanda (Fig. 6). No significant altitude effects were found on pest prevalence in either Burundi or Rwanda.

3.3. Correlation of pest and disease variables with average temperature

Results of chi-square tests of independence were not significant for disease and pest prevalence in Burundi and Rwanda, except for Fusarium wilt in Burundi, X^2 $(1, N = 186) = 41.64$, $p < 0.001$ (Table 3). This implies that in this study temperature did not significantly influence prevalence of diseases and pests.

3.4. Trend in disease incidence

In Burundi, 51% of the farmers as well as 11% in Rwanda reported banana diseases on their farms to have increased over the period 2012–2016 (Fig. 7). In contrast, 19% and 16% of the farmers in Burundi and Rwanda, respectively, reported a decrease in the occurrence of banana diseases over this period (Fig. 7). 7% and 14% of the farmers in Burundi and Rwanda, respectively, indicated that once they applied the recommended management practices, the incidence of banana diseases within their fields stabilized (Fig. 7). In Burundi, close to 23% of the farmers had no knowledge of trends on incidence of banana diseases on their farms (Fig. 7). One percent of farmers in Burundi and 12% in Rwanda did not report any banana disease on their farms (Fig. 7). None of the farmers mentioned banana weevils or banana nematodes as pests of concern.

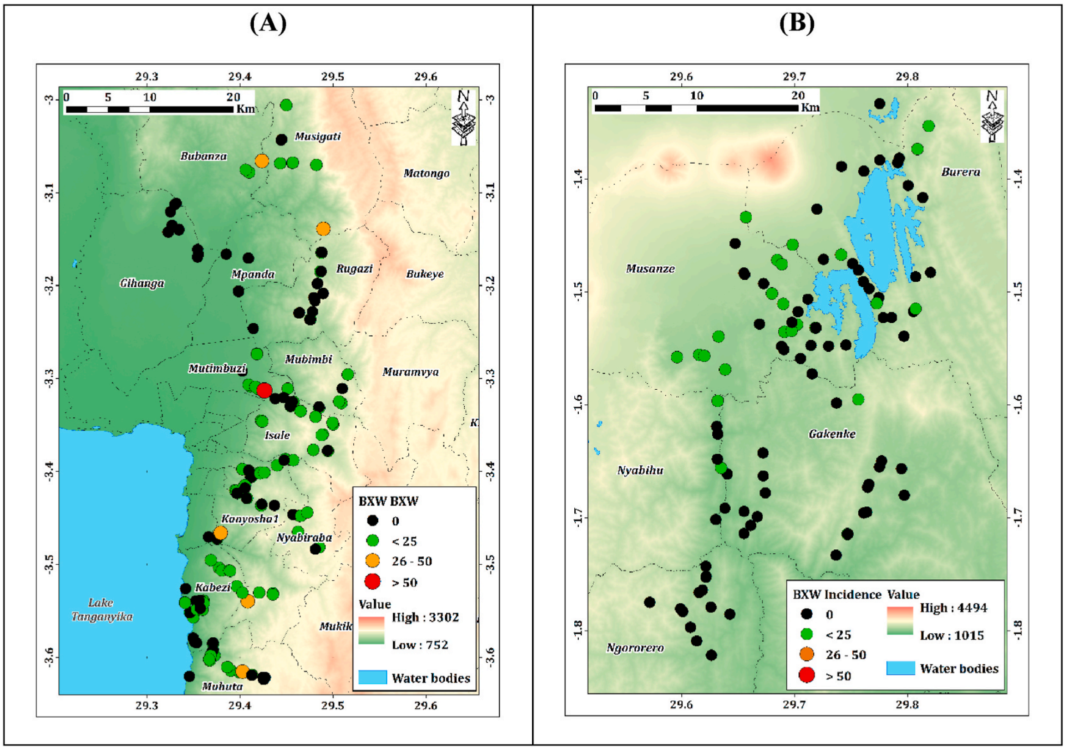

Fig. 4. Mat level incidence of Xanthomonas wilt of banana (BXW) in the (A) Rusizi watershed area of Burundi and (B) the Ruhengeri watershed area of Rwanda. Each dot represents a farm where assessments took place.

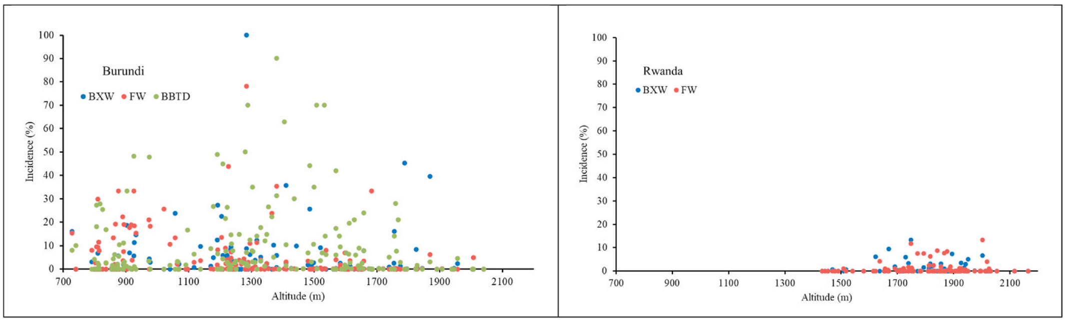

Fig. 5. Scatterplot of mat level disease incidence against altitude for the surveyed farms in the Rusizi watershed in Burundi and the Ruhengeri watershed in Rwanda during the 2015 and 2016 assessment periods.

4. Discussion

BBTD was not found in the targeted Rwanda watershed despite the presence of the disease in the Rusizi district of Rwanda, and in nearby Burundi and eastern DR Congo [33,34]. Long-distance spread of BBTV occurs through transportation of infected suckers, whilst spreading from the affected farms to neighbouring ones is exacerbated by winged *Pentalonia nigronervosa* (Coquerel) (Hemiptera: Aphididae) aphids [33]. This means that to decrease the likelihood of infection spreading, banana suckers (planting material) should be carefully inspected in order to exclude the infected ones. For farmers who can afford pesticides, we recommend the safe use of insecticides to control aphids and uprooting of all infected mats. Periodic inspection of should be practiced to identify and uproot infected material.

Prevalence and incidence of diseases varied between countries. The success of banana disease control in Rwanda, especially for Xanthomonas wilt, is attributed to community ownership of the problem [35, 36, 37]. Also, the Ministry of Agriculture through the Rwanda Agriculture Board (RAB) put in place effective measures to control Xanthomonas wilt, under the arrangement dubbed Community Mobilization Campaigns and setting up of field schools to enhance awareness of farmers in affected areas. Such government initiatives were not evident in Burundi, which might provide reasonable justification for the higher disease incidences

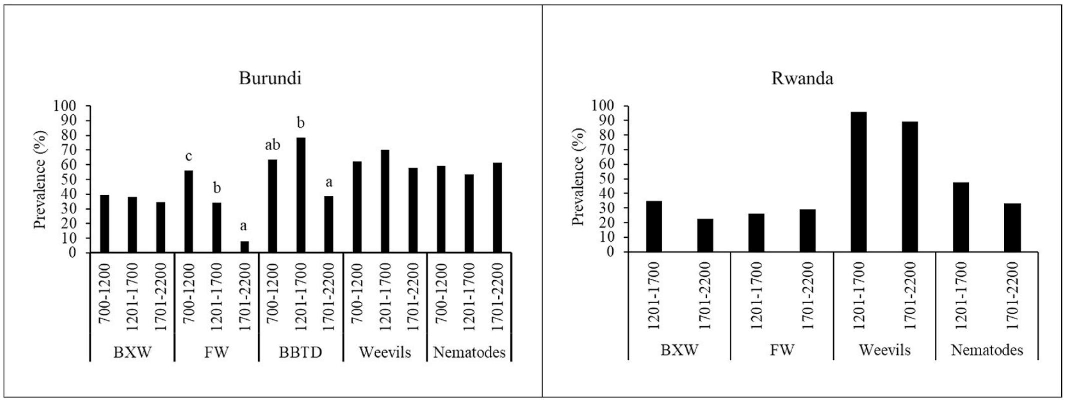

Fig. 6. Comparison of overall percentage pest and disease prevalence at different altitude gradients for Burundi and Rwanda. Letters were only added when significant differences were reported.

Table 3
Chi-Square test of significance between farm-level prevalence of banana pest and disease with average monthly temperature for the Rusizi and Ruhengeri watersheds in Burundi and Rwanda, respectively.

Farm level prevalence	Burundi		Rwanda	
	Chi-square (X^2)	p-value	Chi-square (X^2)	p-value
Nematode	11.92	0.750	15.07	0.373
Weevil	17.09	0.380	18.89	0.169
Xanthomonas wilt	24.84	0.073	13.02	0.525
Fusarium wilt	41.64	<0.001	14.53	0.411
Banana Bunchy Top Disease	23.06	0.112	–	–

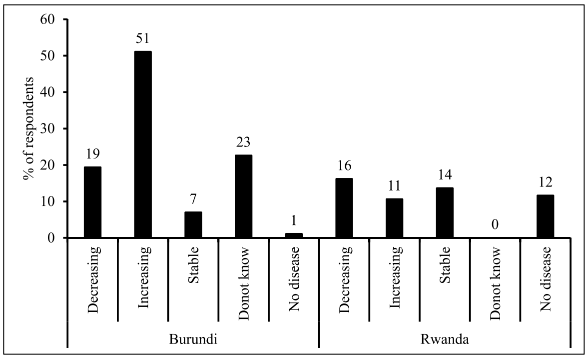

Fig. 7. Trends in incidence of banana diseases in Burundi and Rwanda focusing on the period 2012–2016 assessed through farmer interviews.

observed there.

On most of the surveyed farms, mixed genotypes/cultivars were grown. A high crop species or cultivar diversity on banana farms has been reported to reduce BXW incidence and/or severity [21,38]. Similar observations have been reported for diseases of other crops [39,40]. The incidence of Fusarium wilt is also reduced when susceptible banana genotypes are mixed with resistant/tolerant genotypes. This suppressive effect of mixtures arises from their dilution effect as well as an alteration of the microclimate which affects pathogen or vector survival and dispersal rate [40].

Decrease in temperature (low temperatures) and rainfall (low rainfall) will result in less diseases and less crop losses. Any change in these two environmental factors may escalate crop losses due to pest [41] and pathogen [42] damage, although the reverse can also happen. To understand the effects of climate change on the risk posed by diseases and pests to field grown crops, it is imperative to look at the distribution of the diseases and pests along an altitude gradient, representing a range of environmental temperatures. Such information is useful to track any shifts resulting from responses to climate change [43], since pest and disease compositions may change along an altitude/temperature gradient. For example, several studies concluded that the occurrence of BXW and BBTD was mainly limited to the lower and mid-altitude zones as the presence of the insect vectors of BBTV and BXW was negatively affected by cooler temperatures found at higher altitudes [27,34,44–51]. In line with these findings, the results from our study indicate that BXW and FW prevalence were lowest at high-altitude sites in Burundi. Limited prevalence of BXW, this is attributed to fewer floral infections due to a reduced insect vector activity at altitudes above 1700 m.a.s.l [27,44,45]. Insect vectored transmission of *Xanthomonas vasicola* pv. *musacearum* (Xvm), the pathogen causing BXW, is more prevalent in areas dominated by cultivars with dehiscent bracts on the male peduncle section (such as 'Pisang awak'; ABB genome group) and in production zones at altitudes below 1500 m.a.s.l where insect populations are large and very active [45].

Hodkinson [52] noted that thermal requirements for growth rather than temperature tolerance seemed to set spreading limits for insect species along altitude gradients. This was determined by the insect species' capacity to match their thermal tolerance range to the altitudinal temperature profile of their habitat. This implies that an increase in temperature with ultimate increase in insect vector activity in higher-altitude areas could potentially increase insect mediated infections for BXW. Similarly, higher temperatures at lower altitudes encourage the development of FW [49,53,54]. For Burundi, this would lead to a predicted increase in FW prevalence due to rising temperature associated with climate change and enhanced by periods of drought [55,56]. For Rwanda, however, data obtained during the current study provided no clear evidence for a temperature effect (using the altitude proxy) on BXW. Strong correlations have been observed between precipitation and BXW infection, with regions having higher rainfall levels being more prone [20,57].

BBTD was more observed at mid altitudes and less at the high and low altitudes. BBTD occurrence has been reported at altitudes between 780 and 2090 m.a.s.l. [34,51], with incidence levels reducing as altitude increases [34] also noted that higher temperatures coupled with poorly managed banana fields may enhance the spread of BBTD to higher elevations in Burundi [33] reported the presence of aphids at high altitudes, however, specific observations to evaluate a possible relationship between aphids and altitude were not made [58] linked incidence and prevalence of BBTD to the quantity of winged aphids that habitually develop after many generations of wingless aphids. They observed winged aphids at all altitude levels with the highest winged aphid numbers reported during the dry weather conditions in Burundi and recommended that cultural practices such as deleafing and desuckering, usually practiced during the rainy season because of intercropping (possibly contribute to reduction of aphid numbers) should be sustained in the dry season. Low incidence of BBTD at the highest altitudes could be attributed to reduced insect vector activity resulting from reduced temperatures as previously explained.

According to [59]; any change in temperature is significant enough to influence the pest populations and their distribution [30] noted that damage from banana weevils is influenced by cultivar and altitude, with noticed reduction in reproduction levels at altitudes above 1500–1600 m.a.s.l. In Burundi, no significant differences for weevil prevalence were observed at the different altitudes despite the differences in minimum and maximum temperature. Average minimum and maximum temperature differences between the mid- and high-altitude locations in Rwanda during the two growing cycles were similar. This could explain in part why no significant differences were observed in the prevalence of banana pests/diseases in Rwanda. Although temperature did not influence farm-level prevalence of the pests in the current study [60] observed that the more the increment in temperature pattern, the more developmental acceleration in certain pests, resulting in more cycles of generations and crop damage per year. Increasing temperatures at higher altitudes will favour banana production but will increase prevalence of pests and diseases. Hence, there is an urgent need to develop predictive models to forecast incidence of important banana pathogens under changing climate. According to [61]; data on pest and disease occurrence is useful to demonstrate the role of environmental and socioeconomic variables in determination of their occurrence.

The measurement of awareness and understanding of farmers' knowledge of Musa pests and diseases could put us in the right track to design and implement appropriate disease management practices [62,63]. Unlike in Burundi, most farmers in Rwanda were aware of the common banana diseases and how to manage them, which could explain the lower observed incidence in Rwanda. The success of banana disease control in Rwanda, especially for BXW, is attributed to community ownership of the problem Ndaihanzamaso et al. 2016 [36,37]. Unfortunately, this is not the case for pests such as nematodes as these continue to be neglected or go unnoticed by farmers, extension agents and policy makers all over the world, sub Saharan Africa (SSA) being no exception, despite the significant economic losses they cause [64]. Our results are in line with other studies that have emphasized the low awareness levels and poor understanding of nematodes in SSA [65]. Considering the results obtained from our pest and disease survey, the lack of knowledge by farmers about the importance of banana weevils and nematodes as pests threatening banana fields, can be likely attributed to a lack of awareness about these pests rather than to their absence, as both banana weevils and banana nematodes were highly prevalent in all the sampled areas.

Further research should consider a larger number of growing cycles with different temperature and rainfall distribution patterns. From this study, we realize the need for a multidisciplinary approach to comprehensively analyse the severity of banana pests and diseases under future climates and not simply tracking the problem from a pathology and climate perspective. Although the data generated during this study is not sufficient to make conclusions on effects of climate change on banana pests and diseases, it highlights the need to adopt climate-smart integrated pest and disease management practices to ensure that smallholder farmers are resilient and able to mitigate climate change [66,67]. This will require the development of effective climate-smart management practices, (such as, breeding for pest tolerant and disease resistant cultivars, drip or furrow irrigation, crop rotation, manure application and application of biological pesticides) while engaging multiple stakeholders to build and strengthen the necessary linkages. Involving multiple stakeholders will provide a suitable environment to ensure farmer resilience to existing impacts as well as preparedness for future impacts. The development of climate-smart management strategies will also require quantitative modelling to investigate multiple interactions simultaneously. It will then be possible to interpret results from such models alongside social and ecological model outputs to support the development of appropriate responses to future outbreaks. Continuous monitoring and evaluation are required to allow the re-evaluation of tools and approaches. We also acknowledge that factors other than temperature affect abundance of pests and diseases. This could have favoured population build-up for aphid transmitting aphids at mid elevation.

Author contribution statement

Gloria Valentine Nakato; Joshua Sikhu Okonya: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Deo Kantungeko: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Walter Ocimati: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. George Mahuku: Contributed reagents, materials, analysis tools or data; Wrote the paper. James Legg: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Guy Blomme: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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