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Research paper

Xanthomonas Wilt of Banana (BXW) in Central Africa: Opportunities, challenges, and pathways for citizen science and ICT-based control and prevention strategies

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ABSTRACT

Xanthomonas Wilt of Banana (BXW) is a complex problem in the African Great Lakes Region that is affecting the livelihoods of millions of smallholder farmers. Since the first disease reports from Uganda and the Democratic Republic of Congo in 2001, BXW has been studied widely. The majority of these studies focus on the technological or biophysical dimensions, while aspects and influence of socio-cultural, economic and institutional dimensions only recently started to gain attention. This paper provides an in-depth analysis of the broader BXW problem using a systems perspective, with the aim to add to the understanding about reasons for poor uptake of appropriate disease management practices, and limited ability to prevent rather than control BXW in the region. We comprehensively describe and analyse the various problem dimensions, and determine relations with data, information, knowledge, and connectivity. Building on this, the paper explores and discusses entry-points for the use of Information and Communication Technologies (ICT) and citizen science tools to better address BXW in banana production systems.

1. Introduction

Infectious crop diseases continue to cause large yield losses with underestimated social and economic impacts in developing countries (Vurro et al., 2010). Xanthomonas Wilt of Banana (BXW), caused by the bacterium *Xanthomonas campestris* pv. *musacearum*, affects production of all types of bananas, in all major production regions in East and Central Africa (Tripathi et al., 2009). The disease is detrimental to banana-based farming systems, due to easy spread, rapid in-plant development, absence of resistant cultivars, and inevitable death of infected plants (but not the whole physically interconnected mat due to incomplete systemicity) in absence of disease resistant varieties (Tripathi et al., 2009). Banana is an important source of livelihood for millions of farmers, providing food and income, as well as playing an important role in the social life of populations in the African Great Lakes Region (i.e. Burundi, the Democratic Republic of the Congo, Kenya, Rwanda, Tanzania, and Uganda) (Van Damme et al., 2014). For example, 30% of the cultivated land in the region is occupied by banana (Van Asten et al., 2004), and in a country like Rwanda banana contributes to approximately 50% of the diet of 32% of the households (Nkuba et al., 2015). Hence production declines not only impact household income but also food and nutrition security, and social and cultural wellbeing.

BXW is a complex problem that is rooted in a multitude of challenges, embedded and cross-cutting in six different system dimensions, and has shown to be persistent and recurrent. Since the first disease reports from central Uganda and east DR Congo in 2001, BXW has been studied widely. Most studies focus on the technological or biophysical dimensions (Biruma et al., 2007; Shimwela et al., 2016; Tinzaara et al., 2016) and cultural practices. Key practices are the originally

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Box 1
Description of managing BXW, the traditional and the alternative way.

The initial way: Complete Mat Uprooting (CMU)

Uprooting of an entire banana mat after diagnosis of BXW, even if only one plant in the mat shows symptoms, has long been the recommended control BXW practice. Although very effective in removing most of the inoculum causing BXW, Complete Mat Uprooting (CMU) is tedious, labour intensive, time consuming. A side-effect is that asymptomatic plants are removed too. It requires from farmers to replace the removed mats with new planting material. This need makes CMU costly, further aggregated by high labour demand and long-term impact on production. Moreover, for optimal impact, i.e. reduce risk of reinfection, CMU should be practiced by all infected farmers in an area. Farmers are often reluctant to remove an entire banana mat when disease symptoms are minor and symptomless shoots could potentially still bear an edible bunch. Nevertheless, Blomme et al. (2017) suggest that in regions with intensive, market-oriented banana systems, where the goal is to eradicate BXW from the field, CMU could be a preferred management option. In addition, CMU would be applied where the disease appears for the first time in a location and is still limited to a few mats. Unfortunately, CMU cannot guarantee long term eradication of BXW, as there is always a risk of reinfection under small-scale farming conditions (Tinzaara et al., 2013).

The alternative way Single Diseased Stem Removal (SDSR)

Single Diseased Stem Removal (SDSR) technology is based on understanding that adjacent/physically attached shoots of an infected mother stem/plant are often disease free. SDSR is a less intensive alternative to CMU. Continuous removal of symptomatic plants, cutting them at soil level when observing first symptoms, can drastically reduce inoculum levels and disease incidence over time (from up to 80% to below 2% within 3 months, and below 1% within 5–10 months) (Blomme et al., 2017). Advantages of SDSR over CMU are low cost, and simple and easy applicability. Additionally, farmers can individually control BXW in highland settings with highland type bananas [AAA-EAH genome group] (van Schagen et al., 2016). This lessens need for collective action in AAA-EAH dominated systems in high elevation settings, allowing for effective out-scaling of the technology by targeting individual households. Nevertheless, a collective approach is preferable to prevent the incursion of inoculum from neighbouring infected farms. In lowland areas and in ABB dominated systems where insect vector mediated transmission is rampant, early male bud removal should be rigorously applied too. With SDSR there is no need for replanting and productivity of a BXW infected field can be restored in a relatively short time with non-removed shoots that reach their harvest stage. This makes SDSR a suitable management strategy for subsistence banana systems that target management of BXW at acceptable levels (< 1%) (Blomme et al., 2017). However, SDSR does not remove all inoculum and requires rigorous application for as long as disease is present on or near a farm. Practice alongside other cultural management practices is critical (e.g. male bud removal, and tool sterilization), making BXW management still knowledge and labour intensive and necessitating continuous training and extension efforts.

recommended Complete Mat Uprooting technology (CMU), and the increasingly suggested Single Disease Stem Removal technology (SDSR) (Box 1). CMU and SDSR should be combined/applied with other endorsed practices, e.g. early removal of the male bud using a forked stick, disinfection of tools, selection of clean planting material, in order to be most effective. Aspects and impacts of the non-technological dimensions (i.e. socio-cultural, economic, institutional, and political) only recently started to gain attention. Yet, addressing a complex problem like BXW requires an integrated approach with attention for both technological and non-technological dimensions (Schut et al., 2014a). In other words, a focus on solving individual (technological) challenges will likely be ineffective when failing to simultaneously understand and address interrelationships with (non-technological/socio-cultural, economic, institutional, and political) challenges, and the roles of different actors, and different system levels.

As amplified by Cieslik et al. (2018) in this issue, opportunities to collect and exchange data, information, and knowledge emerge from the enhanced availability of mobile/smart phones, smart Information and Communication Technologies (ICT), and internet in low and middle income countries. Moreover, these innovations give prospect to resolve communication and connectivity related challenges in rural areas. The emergent robust, affordable and low maintenance sensing, data processing, visualization and other ICT enabled features have also led to growth in the number of so called citizen science initiatives (Buytaert et al., 2014). Citizen science (also referred to as environmental or participatory monitoring) was introduced by Irwin (1995) more than two decades ago as a concept that enables active involvement of non-scientists in research design, data collection and data interpretation (Buytaert et al., 2014). Until now, most citizen science initiatives occurred in high-income countries where volunteers engaged in monitoring and reporting of environmental aspects (e.g. counting birds or insects, monitoring spread of communicable diseases). However, similar initiatives start to take off in developing countries too. Wageningen University and Research's Environmental Virtual Observatories for Connective Action (EVOCA) programme explores the potential of such ICT-based citizen science platforms for tackling complex socio-ecological problems in six case studies in Africa. The complex problem of BXW that we focus on in this paper represents one of those case studies.

In this paper, we contribute to two strategic gaps in the scientific literature: (i) comprehensive understanding of both the technological and non-technological BXW problem dimensions (ii) how problem dimensions are related to (the lack of) data, information, knowledge, and connectivity. In doing so, the paper has three main objectives: (i) to comprehensively describe and analyse BXW in the Great Lakes Region, thereby contributing to a deeper understanding of the complex problem, (ii) to determine the potential role of data, information, knowledge, and connectivity in addressing the problem, and (iii) to explore whether and how citizen science and ICT-based platforms can contribute to overcoming specific BXW problems in Central Africa.

The next section provides a short historical background on banana farming and BXW in the Great Lakes Region (Section 2). A conceptual and methodological framework is presented in Section 3. Thereafter, the main characteristics of the BXW problem in the region are identified and discussed per system dimension (Section 4). In Section 5, we explore how these characteristics are interlinked with data, information, knowledge, and connectivity challenges. In the same section, we analyse how citizen science and ICT could offer appropriate intervention mechanisms for the identified problem characteristics. Lastly, Section 6 provides a reflection on our findings and some practical recommendations.

2. Historical overview and gaps in our understanding of BXW and its management in the Great Lakes Region

2.1. History, symptoms and spread of BXW

Bananas form an important staple crop in East and Central Africa.

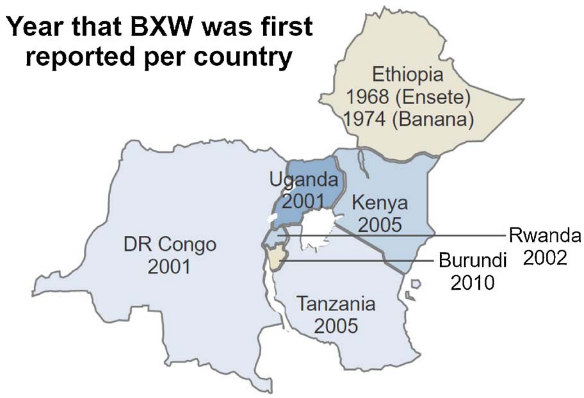

Fig. 1. Schematic overview of historical spread of Xanthomonas Wilt of Banana (BXW) in the Great Lakes Region, with the year in which BXW was first reported (map developed based on data from Yirgou and Bradbury, 1974; Karamura et al., 2005; Niko et al., 2011; Tushemereirwe et al., 2003; Yirgou and Bradbury, 1968; Castellani, 1939).

Among the worlds' top ten producers of cooking bananas, Uganda ranks first, and DR Congo holds the 8th position (FAO and FAOSTAT, 2014). For production of dessert bananas Tanzania is the world's 8th largest producer, and Rwanda the 10th (FAO and FAOSTAT, 2014). More than 50% of Sub-Saharan Africa's production takes place in the African Great Lakes Region (Frison and Sharrock, 1998; Blomme et al., 2014). Bananas are of major economic importance in this region, forming an important part of peoples' daily diet and providing income and food security to millions of smallholder households.

BXW was first reported in Ethiopia on enset (*Ensete ventricosum*), a relative of banana, in 1968 (Yirgou and Bradbury, 1968) and hereafter on banana in 1974 (Yirgou and Bradbury, 1974) (Fig. 1). BXW was recognized as a thread for banana production in the entire region, but remained confined to Ethiopia until first outbreaks were observed in Central Uganda in 2001 (Tushemereirwe et al., 2003). Since then BXW has spread through to DR Congo (2001), Rwanda (2002), Tanzania, Kenya (2005) and Burundi (2010) respectively (Karamura et al., 2005; Niko et al., 2011; Tushemereirwe et al., 2003). Trans-boundary transmission of the disease has been reported. For example, in Rwanda, BXW was first identified in the North-Western region around Rubavu district, where local farmers mentioned seeing first symptoms around 2002–2003. BXW most likely spread into Rwanda from DR Congo's Kivu region due to continuous exchange of people and goods across the Rubavu-Goma border and the fact that first outbreaks of BXW in DR Congo were confirmed near this border in the Masisi region north of Goma (Reeder et al., 2007).

Several governments took rigorous actions in an attempt to eradicate BXW. For example, Uganda installed task forces assigned with the mission to cut down and destroy infected plantations/fields, remove male buds to prevent insect vector transmission, and control cutting of bunches with non-sterilized tools (Tushemereiwe et al., 2006). These types of interventions are rigorous and have had effect in reducing disease incidence (Bouwmeester et al., 2016). However, the invasive nature of uprooting entire plantations received little support from farmers (Blomme et al., 2017). Although disease eradication has been achieved in some sites, BXW has reached endemic status in other sites where resurgence is observed after a period of control, often due to a less rigorous application of control measures (Tinzaara et al., 2014). Additionally, endemicity of BXW is sometimes attributed to lack of awareness and knowledge about disease transmission, diagnosis, and disease management by stakeholders across the value chain. Alternatively, reluctance of farmers to actively apply awareness and knowledge due to the invasive/time-consuming nature of recommended practices can be a cause. As complete eradication of the disease has proven difficult to achieve, the focus has shifted towards development of strategies that use SDSR and complementary approaches to reach a situation in which BXW is manageable and disease incidence minimized to economically acceptable levels.

2.2. Gaps in understanding the disease and its management

Since the first reports of BXW in the Great Lakes Region in 2001, there have been numerous publications analysing the disease. Initial focus of academic literature was on improving understanding about the disease's epidemiology and control (mainly building on existing knowledge from banana bacterial wilts in Asia and Latin America), and later on strategies to develop BXW resistant banana cultivars, mostly through genetic engineering (Tripathi et al., 2009; Biruma et al., 2007). This contributed to considerable progress in terms of knowledge about the technological and biophysical dimensions of BXW, including disease epidemiology, bio-engineering of resistant varieties and, updating/fine-tuning cultural control practices. Based on increased understanding of e.g. within plant and mat systemicity and disease spread/dissemination, cultural control practices were developed and updated. The concentration on understanding the biophysical and technological dimensions of the crop protection problem corresponds with findings by Schut et al. (2014c), who concluded that there is generally much less attention for other problem dimensions (e.g. socio-cultural (e.g. stakeholder beliefs, or locally preferred practices), economic (e.g. costs of disease management), and institutional (e.g. trade policies, or disease control strategies)). Capturing the impact of these system dimensions, e.g. on BXW transmission at farm and regional scales, as well as the role of surveillance and control mechanisms, and their impact on combating BXW (Tinzaara et al., 2016; Markham, 2009), becomes gradually more important now that focus shifts from developing knowledge to developing suitable interventions. This includes investigating (i) diversity among farmers, their production objectives and barriers for adopting (BXW) technologies, (ii) effective strategies of information provision and capacity development for farmers, (iii) information needs and communication preferences to better understand and address constraints and challenges, and (iv) how multi-stakeholder processes can support joint problem identification, analysis and collective action (Schut et al., 2014c). This diagnostics paper does not offer such an investigation, yet it conveys the importance of each problem dimension by providing a comprehensive assessment of their contribution to the persistence of BXW.

3. Conceptual and methodological framework

3.1. Conceptual framework

The conceptual framework for this study is rooted in three coherent theoretical concepts that fit the study's purpose: (i) systems perspective on complex agricultural problems, (ii) ICT for agriculture and citizen science, and (iii) theoretical understanding of data, knowledge, information, and connectivity. Each of these concepts responds to one of the study objectives. We use systems perspective to frame our analysis of BXW in Section 4. Theory on ICT for agriculture and citizen science informs our assessment and discussion of potential contributions of ICT in addressing BXW. Furthermore, the four intervention categories presented in the discussion section build on the notion that ICT for agriculture and citizen science are approaches for generating and exchanging various classes of content, as well as connecting people. The concepts of data, knowledge, information, and connectivity additionally help to perceive differences between the categories.

3.1.1. Complex problems and systems perspectives

Complex agricultural problems are problems in the agricultural domain that cannot be resolved but rather have to be managed. Complex agricultural problems are typically unstructured, embedded in the agricultural system and therefore persistent, relentless, and cross-cutting (Weber and Khademian, 2014). BXW can be considered a complex problem as it too is persistent, unresolvable, and embedded and cross-cutting in the banana system. BXW is rooted in a multitude of challenges in various system dimensions (i.e. biophysical, technological, social, cultural, economic, institutional, and political) (Markham, 2009), and as past experiences have shown that technology-based solutions do not necessarily provide the full answer, an alternative approach, which is more integrated and knowledge-based, is required (Markham, 2009). Addressing such problems rather requires collaboration between different actors (e.g. farmers, extensionists, researchers), at different levels (e.g. local, regional, national) to address challenges in different dimensions (e.g. social, economic, institutional) (Schut et al., 2014d). Improving understanding of the interplay of various system dimensions is important, given that current efforts to out-scale interventions and technologies, which gave promising results at local or farm level, mostly yield unsatisfying success rates (Tinzaara et al., 2016). This associates with the notion that interventions aiming to solve crop disease issues must be tailored to a specific crop production system (Jogo et al., 2013), and that farmers should be offered management options fitting with their local and individual context (Blomme et al., 2017).

3.1.2. ICT for agriculture and citizen science

With their strength to allow for co-creation of knowledge and joint reflection, contemporary ICTs offer immense potential for addressing a variety of today's complex agricultural problems. For example, interventions in which contemporary ICTs such as mobile phones complement or replace face-to-face agricultural service delivery are increasingly observed (FAO, 2017). As much as ICTs can be useful, they should not be seen as a panacea for solving all complex agricultural problems, or for providing all pieces of the puzzle that are required to manage complex problems (Deichmann et al., 2016; Nelson, 2010).

Contemporary ICTs (e.g. mobile phones, tablets) are a key driver for the recent boom in citizen science initiatives. Citizen science initiatives focus on crowd-sourcing data from citizens, often in conjunction with an online, ICT-based platform (Fradera et al., 2015). The term citizen science represents (i) a science that assists the needs and concerns of citizens and, (ii) a form of science developed and enacted by citizens themselves. Most citizen science platforms aim to monitor the environment and foster collaborative research, learning, and action (Cieslik et al., 2018). Citizen science emerged from the observed need for an approach to enhance dialogue between scientific and citizen groups, as well as to recognize the added value of building on expertise and understandings possessed by citizen in decision making processes (Irwin, 1995). Benefits include increased awareness and knowledge, and a more participatory and democratic research process for citizens, while scientists profit from faster access to larger data sets for studying complex problems at lower costs (Fradera et al., 2015). Identified challenges with citizen science include the potential difference between who participates and the population targeted, reliability of data collected, and communication of models developed based on citizen science data (Buytaert et al., 2012).

3.1.3. Framing data, knowledge, information, and connectivity

Deployment of ICT tools and citizen science-based interventions in agriculture are only useful when they mediate in generating and sharing content or connecting people in the agricultural system. It has been argued that ICT-based platforms can enhance connectivity between disassociated populations, enabling participatory monitoring (collection and exchange of data), broad accessibility of information, and dialogue about scientific-based models (knowledge creation) (Jalbert and Kinchy, 2016). To further conceptualize this, we first look at the understanding of, and differences between, data, information, and knowledge. These have been described widely (Alavi and Leidner, 2001; Leeuwis and van den Ban, 2004; Ackoff, 1999) and the difference between the two concepts can be subtle (Alavi and Leidner, 2001; Leeuwis and van den Ban, 2004). Given the scope of this paper we use broader definitions of the three terms. In this study, we understand data as raw facts and numbers from observations or measurements (for example outputs from measurements of the number of banana mats infected with BXW); information as processed or interpreted data made tangible in useful descriptions (for example a message informing extensionists that 20% of all banana mats in a region are infected with BXW and need to be managed with appropriate cultural control practices) that turn it into something that is accessible and actionable; and knowledge as interpreted and personalized data and information (for example the knowledge that with a 20% plant incidence rate SDSR is the most effective management strategy for farmers operating in that region) (Alavi and Leidner, 2001; Leeuwis and van den Ban, 2004; Ackoff, 1999).

Knowledge is influenced by and influences for example mindset, behaviour, and learning processes (Leeuwis and van den Ban, 2004). It also informs people's capacity to understand patterns to which they can take action (Alavi and Leidner, 2001; Ackoff, 1999). Data, information, and knowledge are connected through a forward flow: data is processed into information, which is then assimilated into knowledge. A reverse flow is possible too, when knowledge explains information and filters and processes data (Heeks, 2018).

The difference between information and knowledge is that the first entails processed data useful to its recipient, while the second aggregates information to a higher level by assimilating it into a coherent framework of understanding (Heeks, 2018). This brings us to the additional description of knowledge as the sum of what has been perceived, discovered and learned (6).

Alavi and Leidner (2001) make two important points to take into account for exchanging information and knowledge that is actionable to a receiver: (i) most information has little value to a user unless it goes through a process of reflection, enlightenment, or learning, and (ii) knowledge is individual and to be useful for someone else it needs to be expressed and communicated in such way to a receiver that it is interpretable. This links with the notion that uncontextualized knowledge, that is analysed and interpreted by experts and then projected back to a locality, is likely inappropriate for utilization (Cieslik et al., 2018; Leeuwis and van den Ban, 2004).

Lastly, we understand connectivity as the ability of and opportunity for stakeholders to interact and collaborate, as well as to coordinate and organize themselves (Bennett and Segerberg, 2012). Connectivity relates to how people interact, and who interacts with who, and can therefore influence collection and exchange of data, information, and knowledge. The absence of effective stakeholder collaboration and connectivity can form a bottleneck for agricultural system development (Schut et al., 2014a), is often related to heterogeneity in communities and weak leadership and control arrangements, power imbalances and information asymmetries (Poteete et al., 2010; Olson, 1965), and a limiting factor to solving complex agricultural problems (Schut et al., 2014b). For example, banana farmers excluded from interactions with extension officers and operating individually are more likely to lack access to information about BXW management. According to Bennett and Segerberg (2012) digital innovations foster opportunities for communicative ways of organizing that do not rely on formal organizational coordination but rather on self-organizing networks, thereby creating new spaces of interaction that can be accessed by many. Cieslik et al. (2018) argue that this may be of relevance in the context of environmental management in developing countries, hence for an agricultural challenge like BXW.

3.2. Methodological framework

3.2.1. Study location

Although much of the data presented in this paper apply broadly across the Great Lakes Region, we sometimes focus on specific BXW-related issues in Rwanda. This is for three reasons. First, BXW has been a recurring problem in Rwanda since the initial identification in 2002,

Table 1
Overview of problem descriptions and causes per problem dimension.

Problem dimension	Biophysical	Technological	Socio-cultural	Economic	Institutional	Political
Description of the problem	Relatively small genetic variability of banana (mostly ABB and AAA-AE) in a densely populated region in combination with an environment that is suitable for insect vector transmission	Costly, time consuming and complicated process to unravel disease epidemiology, screen genepool for resistance, develop transgenic varieties, and develop and update control practices	Poor targeting of diverse smallholder farmers who base decisions on their direct cost-benefit ratio	(Cost) Inefficient control and prevention of BXW by farmers and extension services (including e.g. labour, time, access to in- and outputs)	Diversity in policies and their implementation and performance in the African Great Lakes Region	Top-down nature of the agricultural sector in general and extension services in particular (in Rwanda) and/or ineffective formal organization of extension services
Causing challenges	– Lack of BXW-resistant cultivars (Tripathi et al., 2009) – (Long-distance) disease transmission through airborne (insect) vectors, bats and birds, and contaminated planting material (Tinzaara et al., 2013; Blomme et al., 2014) – Resurgence of BXW after a period of control due to continued vector pressure and reduced control intensity (Tinzaara et al., 2013)	– Absence of BXW-resistant (transgenic) cultivars (Tinzaara et al., 2016) – Insufficient understanding of disease epidemiology (Tinzaara et al., 2016) – Low availability of clean plant material – Single Disease Stem Removal (SDSR) technology does not remove all inoculum (Tinzaara et al., 2016)	– Farmers not enough involved in finding solutions with positive cost-benefit ratio (Mwangi and Nakato, 2009) – Awareness campaigns and trainings not targeted to vulnerable farmer groups (e.g. women, youth) (Blomme et al., 2014) – Low adoption of control technologies limiting sustainability of disease control efforts (Ndayihanzamaso et al., 2016) – Low farmer awareness of BXW (Ndayihanzamaso et al., 2016) – Limited attention for influence of gender roles on adoption of control and prevention strategies in the household (Blomme et al., 2017). E.g. gender roles can limit women's decision making/agency/access to information – Insect-vector transmission susceptible 'Pisang Awak' or 'Kayinja' (ABB) variety culturally popular among smallholder farmers (Nkuba et al., 2015) – Lack of collective action among farmers and other stakeholders	– No accurate predictive system for early disease diagnosis and action (Bouwmeester et al., 2016) – Lack of reliable data on economic losses (Vurro et al., 2010) – Cumbersome and expensive nature of traditional management techniques (e.g. Complete Mat Uprooting (CMU) (Blomme et al., 2017) – Often lack of income generating alternatives that majority of farmers can rely one when banana production is reduced – Priority setting for continuous investment lacking in small number of farmers with off-farm jobs (Okech et al., 2005) – Fundamental research expensive, time consuming and complex	– Absence of appropriate institutional frameworks for policy guidance and byelaws (e.g. on quarantine measures) (Tinzaara et al., 2013) – Low buy-in of technologies due to unknown interests and incentives for stakeholders (Mwangi and Nakato, 2009; Kubiriba et al., 2012) – Ineffective surveillance methods leading to untimely actions (Tinzaara et al., 2016) – Differences in the institutional environment in various Great Lakes countries (Vurro et al., 2010) – Lack of a working formal seed system (Tinzaara et al., 2013) – Lack of adequate knowhow and sensitization about BXW among extensionists and other stakeholders along the value chain (Tinzaara et al., 2013)	– Lack of participatory and demand driven approach (Nkuba et al., 2015; Kubiriba et al., 2012) – Inadequate mobilization and sensitization of key stakeholders (Tinzaara et al., 2016) – National level political actors determine allocation of funds and efforts for crop extension services (Cioffo et al., 2016)

despite attempts to control it. Officials in the Ministry of Agriculture and Animal Resources articulated existence of keen interest for innovations providing a lasting solution (Ministry of Agriculture, personal communication, July 2017). Second, Rwanda has the most ambitious objectives for use of ICT in rural and agricultural transformation in the African Great Lakes Region. The country profiles itself as the ICT hub in Africa and adopted several policies and strategies to enhance the use of ICT among which the 'National ICT for Rwandan Agriculture Strategy' (Ministry of Agriculture and Animal Resources, 2016). Third, Rwanda is the main focus country of the EVOCA case study that was the entry-point for our diagnostics study.

3.2.2. Data collection and analysis

Data for this qualitative paper were gathered through various methods: literature and secondary data review, scoping field visits, semi-structured interviews, and semi-structured group interviews. The methods' focus on BXW was stronger than on ICT and citizen science in response to our research objectives. This mixed approach was appropriate since it (i) allowed for a broad assessment of scientific and field level knowledge and understanding about BXW, (ii) provided the necessary input to unravel the research problem across all system dimensions both technologically and socially in Section 4, and (iii) supported development of suitable pathways for interventions in Section 5. More specifically, Table 1 in Section 4 was developed based on review of literature and secondary data, while Table 2 in Section 5.1 emerged from synthesizing information from Section 4 and linking this with the data, information, knowledge and connectivity concepts as laid out in the conceptual framework.

First, literature and secondary data were reviewed. For the BXW, banana systems, and citizen science related literature snowball sampling was used, tracing references in articles to identify additional relevant peer-reviewed articles and grey-literature. Advancements in understanding of technological and biophysical aspects, that led to changing/fine-tuned ideas about appropriate BXW control strategies, and recently developed interest for social aspects were considered. Therefore, recent publications (from 2015 to 2017) were consulted first and supported identification of older relevant publications. ICT for agriculture related literature was purposively selected from a set of articles retrieved through search queries in Web of Science, Scopus and CAB-abstract. Selection took place based on relevance in relation to the study objectives. Catering for developments in the research field, focus was on recent publications (after 2007). Second, scoping visits to banana production areas in Rwanda's Eastern Province (Kayonza District, 2 areas visited) and Southern Province (Kamonyi District, 1 area visited) took place between January and June 2017, and Burundi's Muyinga District (August 2017, 2 areas visited). Sampling was purposive, based on presence of existing projects from IITA (CIALCA, in Rwanda) and Bioversity International (DFAP-AMASHIGA, in Burundi). Third, aforementioned visits facilitated semi-structured interviews in Rwanda. We purposively selected 2 lead farmers who represented members of a banana innovation platform in Kayonza, covering experiences with BXW, disease incidence in the area, and management strategies. Fourth, four semi-structured group interviews were organized with in total approximately 50 smallholder farmers (mixed male, female, age) in Muyinga, Burundi, focusing on experiences with different control strategies and use of mobile technologies. These interviews asked a regular set of questions used by project staff during routine visits with the addition of questions about mobile technology by the researcher.

4. Results: unravelling dimensions of the BXW problem

This section unravels the different dimensions of BXW as a complex problem and identifies different challenges under each of the six system dimensions. Table 1 summarizes for each dimension a problem description and characteristics that are discussed in detail in adjacent paragraphs. We build on findings and interpretations from scientific literature and secondary data, and supplement by input retrieved from field visits and focus group discussions.

4.1. Biophysical dimension

Biophysical characteristics refer to issues of biological nature that may or may not be controlled. Roughly, edible bananas are divided into four categories, each with their own varieties and purposes: (i) dessert (sweet yellow banana, eaten ripe), (ii) cooking (unripe green bananas for cooking, also known as matoke), (ii) plantain (for cooking and frying), and (iv) juicing (also called beer banana, used for production of local brews) (Vurro et al., 2010). Another means of categorization is in different subgroups: East African highland cooking and brewing cultivars (AAA-EA), exotic brewing, dessert and roasting types (AB, AAA, AAB, ABB) and hybrids (Nkuba et al., 2015). No resistant cultivars have been identified (Tripathi et al., 2009), and the locally popular and widely spread ABB cultivars (*'Pisang Awak' or 'Kayinja')* are particularly prone to insect vectored transmission of Xcm (BXW) (Nkuba et al., 2015). This cultivar is particularly common in non-commercial, low-management areas further which adds to risk for disease transmission. Susceptibility of banana to BXW and infection risk are intensified by the large and, especially in Rwanda, densely populated banana growing areas in the Great Lakes Region. Different vectors for BXW transmission are: airborne (insects, bats, or nectar sucking and fruit pulp eating birds), contaminated garden tools, infected planting material and browsing animals. Especially airborne vectors are a typical biophysical challenge. The Great Lakes region is specifically suitable for this type of transmission (Mwangi and Nakato, 2009), due to – for example – insect favourable climatological conditions and, the aforementioned human population density and pressure on land. The resulting lowered ability to predict and control disease spread clarifies why BXW can suddenly pop-up in previously unaffected areas.

BXW symptoms appear as early as 3–4 weeks (Tripathi et al., 2009) and up to 16 months (Ocimati et al., 2013) after infection, depending on conditions. Recent studies confirmed that BXW does not necessarily infect or cause symptoms in all shoots physically attached to an infected (mother) plant in a mat, a condition that is referred to as incomplete systemicity (Ocimati et al., 2015). Symptoms of BXW are progressive yellowing, withering and necrosis of leaves; fruits that rapidly and prematurely ripen and show internal browning; shrivelling/rotting male flowers and bracts, stem and bunches; withering and rotting of the entire plant (Biruma et al., 2007).

The lack of BXW resistant cultivars necessitates use of cultural management practices. Survival of the inoculum on tools used in such practices and presence of e.g. free roaming animals (Tinzaara et al., 2013; Blomme et al., 2014) increases the complexity to prevent transmission within fields and over (long) distances. Biophysical characteristics impact chances of BXW resurgence after a disease-free period. Tendency is to reduce rigour after incidence levels reduced significantly, while in fact continuous field monitoring and application of appropriate management practices are needed (Tinzaara et al., 2013). This makes fighting BXW labour intensive both nationally and locally however. Our discussions with farmers showed that farmers indeed tend to reduce monitoring practices when disease pressure is low, especially for fields further away from the homestead. Additionally, farmers critiqued impact of neighbours who fail to appropriately maintain their bananas and thereby increase disease infection risks.

4.2. Technological dimension

Technological characteristics relate to the role technological advances play in solving agricultural issues. For example, technological advances like improved diagnostics, disease management strategies, and generally improved agronomic practices can all reduce risk of major disease outbreaks. Research on BXW led to improved diagnostics and increased knowledge about epidemiology, as well as the development of different technologica options for e.g. diagnostics, management and control. These options however face limitations, e.g. SDSR does not completely remove inoculum and CMU is labour intensive and requires replanting of uprooted mats.

Absence of BXW resistant cultivars forms a, partially, technical issue too. Efforts to develop transgenic cultivars with resistance are in an advanced stage, however not yet to the point of marketability. Additionally, transgenic cultivars are (1) only available for some popular cultivars, and (2) not or limitedly acceptable within existing regional bio-control policies. Also, clean planting material is perceived as expensive while its availability is low. Correspondingly, we observed that farmers mostly sourced unscreened material (i.e. suckers/lateral shoots) from own or neighbouring farms, a practice posing the risk of disease spread/(re)introduction (Tinzaara et al., 2013).

4.3. Socio-cultural dimension

Socio-cultural challenges are mostly the result of common one-size-fits-all approaches that insufficiently respect needs and interests of diverse groups of farmers. Despite advances made, the epidemiological knowledgeability of extensionists and farmers is still insufficient to address the problem effectively (Tinzaara et al., 2016). For example, our interviews with trained farmers in Burundi revealed that some still struggled with recognizing the disease. Also, not all respondents applied regular or proper tool disinfection mostly due to limited awareness of the most appropriate practice. Incomplete knowhow/understanding and subsequent suboptimal implementation of appropriate control and prevention strategies leads to new and resurging BXW epidemics.

Farmers of different gender, age and socio-economic groups pursue different livelihood strategies to ensure food, income and nutrition security, and face different land, labour and other resource constraints (Klapwijk et al., 2014). Information about and access to markets forms an output constraint (Okello et al., 2012). Smallholder, including banana-based, farming systems are thus diverse and complex. For example, van Damme et al. (2013) found three distinct categories of banana producers in the Great Lakes Region based on characteristics such as land-size and productivity. Analysis of the largest group of farmers, those with medium-sized farms, showed additional heterogeneity (e.g. in number of crops and crop management practices) which the authors attributed to varying risk coping strategies. This contributes to system resilience but impedes rapid transitions towards increased productivity (van Damme et al., 2013). Next to typologies based on farming system and livelihood characteristics, it is useful to differentiate according to the willingness of a farmer to invest and change practices. Hence, 'Silver bullet' solutions to production constraints are an illusion given the system's complexity (Giller et al., 2011), and thus technologies and service provisions like awareness campaigns and trainings, need to target the specific challenges and opportunities of vulnerable farmer groups (Blomme et al., 2017; Blomme et al., 2014).

Current farmer involvement in the search for innovations with positive cost-benefit ratio is limited (Mwangi and Nakato, 2009). This may impact local awareness about BXW and understanding of disease severity and spread (Tinzaara et al., 2016; Tinzaara et al., 2013) despite the many campaigns aiming to inform farmers. The result is disease transmission through, for example, non-disinfected farm tools or browsing domestic animals (Tripathi et al., 2009). Moreover, information provision about disease transmission, spread and control is ambiguous, inducing beliefs that BXW cannot be controlled effectively (Ndayihanzamaso et al., 2016). The resultant is low adoption of control and prevention technologies, limited collective action, late disease diagnosis, and ultimately poor sustainability of disease control efforts (Ndayihanzamaso et al., 2016).

Literature makes note of other persisting mindset issues and, indeed, during our scoping field visits and group interviews many of following challenges came to the surface. Farmers largely base decisions about disease control mechanisms on the economic risk involved, i.e. the estimated cost of controlling BXW needs to outweigh the estimated cost of losing the crop (Gent et al., 2013). In addition, perceptions of control technique effectiveness determine adoption decisions (Blomme et al., 2017). For BXW this mindset proves problematic as initial symptoms are mild with limited impact on plant mat productivity. Farmers are hence hesitant to quickly act as benefits of traditional control mechanisms, such as CMU, have no short-term visibility (Blomme et al., 2017), while the effort required to apply them and the negative trade-offs are immediately visible. Additionally, the perception exists that individual efforts are ineffective due to the high chance of reinfection if neighbours do not manage their fields (Blomme et al., 2017). Hence, most interventions have a curative control character and are implemented when disease manifestation and crop losses are visible in a large portion of a field.

The lack of considering gender issues when designing and disseminating interventions to control BXW is problematic as technology uptake affects and is affected by gender relations (Blomme et al., 2017). For example, gender roles influence success of management practices such as SDSR. Blomme et al. (2017) discuss potential conflicts between male (usually managing the perennial banana) and female (usually managing annual (inter) crops) household members during the application of SDSR. This is the case when SDSR is practiced during the growth period of the intercropped annual crop, which can then be disrupted/damaged by people walking in the field for monitoring or cutting and falling of (especially large) diseased stems. Consequently, annual cropping seasons should be considered when planning SDSR activities, for example by the removal of all visibly diseased plants before onset of the annual cropping season as to match labour demand by men and women, and limit movement in the field during the growth period of annual crops.

4.4. Economic dimension

Economic characteristics relate to the devastating impacts of BXW on household food, nutrition and income security, and the inefficient attempts to prevent and control it. From a scientific point of view, fundamental research is expensive, time consuming and complex. Economic impact and thus return on investment are not fully understood (Biruma et al., 2007), though its impact on food security is likely substantial. Accurate data on the short- and long-term economic impact of BXW are limited and mostly assumption based (Vurro et al., 2010; Nkuba et al., 2015). However, without effective control BXW certainly causes yield losses up to 100% (Nkuba et al., 2015) especially in ABB-dominated production systems. The initial control measure to drastically reduce field inoculum levels (CMU) is cumbersome as it is time and labour intensive, and therefore expensive. Also, replanting is inadvisable before 6 months of fallowing (Blomme et al., 2014) and, adding time until first bunch production (approx. 18 months), production losses entail about 24 months. All along households' food, income and nutrition security are disrupted. Understandably, farmer willingness to control BXW with such cost-ineffective techniques is low (Blomme et al., 2017). Additionally, lack of sufficient strategies/timely intervention approaches to prevent large-scale, and severe outbreaks induce unnecessary high control costs both locally, nationally, and regionally. Although SDSR technology is more farmer friendly, it still requires significant time and labour investments, especially in the initial application phase with high incidence levels. Consequently, farmers may perceive reason to opt for more economic coping strategies, e.g. switching other crops. Lastly, a dichotomy exists between farmers with and without off-farm income generating activities. The first has low motivation for continuous investment in banana management as it is not the main source of income. In group interviews this was mentioned as a concern and nuisance. The latter lacks room for financial manoeuvre both for managing the crop and when BXW affects the production while bananas provide an important income source.

4.5. Institutional dimension

Institutional challenges relate to the diverse appearances and performance of the institutional environment in the Great Lakes Region that affect ability to implement BXW control and prevention strategies at scale. Appropriate frameworks, guiding policies and byelaws (e.g. quarantine measures) are largely absent (Tinzaara et al., 2013). The institutional situation moreover differs per country (Vurro et al., 2010) complicating potential for and willingness to engage in regional action.

Trans-boundary pathogen transmission is difficult to prevent since both banana produce and planting material travel across borders without restraint. Additionally, surveillance methods are ineffective (Tinzaara et al., 2016), due to a common lack of organization, regularity or accuracy. Although Rwanda currently conducts a country-wide BXW mapping exercise, the absence of national and regional strategies and collaborations for continuous surveillance and intervention decreases ability to forecast disease spread. This affects potential for timely disease diagnosis and action, thereby impacting infection rates and crop yields. Interventions hence largely have a curative character due to limited research and developments for BXW prevention, and absence of predictive early-warning systems for BXW spread/resurgence hotspots (Bouwmeester et al., 2016) to inform governments about targeted investments.

Extension services, including those for control and prevention of pests and diseases, in the Great Lakes Region are generally the responsibility of national agricultural research institutes. Research and (extension) service providers have a role in finding solutions that can increase development of and access to agricultural services by all farmers (Poulton et al., 2010). Continuous interaction between farmers and service providers to make extension services more demand-driven, inclusive, and widely available can contribute to increasing benefits from rural development for all farmer categories. However, Government extension systems are often incapable to provide farmers with adequate support. Traditional extension services are usually expensive, ineffective or both, and more efficient extension models are required to improve this situation (Kabunga et al., 2011).

Indeed, we observed that Rwanda's Twigire Muhinzi extension programme aims to follow an approach that is demand-drive and participatory. Yet, Cioffo et al. (2016) noted that local actors, like sector and district agronomists, who assumedly are the most important providers of such demand-driven extension services often lack budgetary and decisional autonomy, and instead rely on top-down decisions and actions that may or may not match local realities. Although our primary data did not capture it, the nature of Rwanda's agricultural system tells that this issue may apply here too.

An important challenge in the fight against BXW is the lack of healthy planting material. This is both a technological, socio-cultural, and an institutional constraint. The lack of a working formal seed-system forms an obstacle for reestablishment of uprooted fields. In absence of sufficient high-quality planting material from micro- (tissue culture) or macro-propagation (suckers or suckers-derived plantlets), farmers rely on unregulated sources. The socio-cultural practice to obtain planting material free of cost rather than purchasing it aggregates the issue. Most farmers source suckers from their own fields (60%) or neighbouring fields (30%) (Tripathi et al., 2009) thereby risking obtainment of BXW contaminated planting material (Tinzaara et al., 2013), a habit that was confirmed by farmers during group interviews.

4.6. Political dimension

Political characteristics result from top-down structures in some of the Great Lakes countries (e.g. Rwanda), and lack of collaboration and coordinated efforts between key stakeholders within and across different levels. Additionally, mobilization and sensitization of stakeholders along the value chain is inadequate (Tinzaara et al., 2016). The result is that current capacities and efforts to out-scale interventions and technologies often have unsatisfying results.

Most extension services still have a strong top-down, linear, and technological orientation, and focus on the development, transfer, adoption and diffusion of crop (protection) technologies to farmers (Schut et al., 2014b). This despite the alleged shift of extension services towards a more systemic and participatory approach. A bottleneck is that decisions about fund allocation and priority crops are made by political actors at national level, thereby limiting agenda-setting and bargaining power of local actors.

The lack of participatory and demand-driven approaches (Van Asten et al., 2004; Kubiriba et al., 2012; Nkuba et al., 2015) results in poor understanding of local agro-ecological and socio-economic context and related challenges, and has caused low adoption of technologies by farmers and relatively low buy-in of governments in scaling BXW prevention and control measures. The result is low stakeholder awareness about the BXW problem and its impact, with negative impact on interest for participation and investment in collective control and prevention initiatives. This translates in lack of regional mechanisms for surveillance and monitoring, and limited collaboration between stakeholders in the different affected countries (Tinzaara et al., 2013). This on the one hand complicates introduction of suitable regional institutional frameworks, and on the other hand prevents scaling of effective control strategies.

5. Analysis and discussion

5.1. The role of data, information, knowledge, and connectivity in overcoming BXW

The previous section presented an extensive series of findings based on our review of the literature, and interactions with farmers and banana experts. These provide a starting point to analyse how BXW challenges are related to data, information, knowledge, and connectivity constraints, and how ICT and citizen science can play a role in overcoming such BXW challenges (Table 2).

Relationships with knowledge and connectivity dominate, while data and information score lower. This confirms not necessarily the absence of data or information, but rather their relevance and reliability, as well as inclusive access form an issue (Bruce, 2016; Walsham, 2017). Regardless of some successful intervention approaches (e.g. through the use of Farmer Field Schools in Uganda (Tinzaara et al., 2016; Kubiriba et al., 2012)), communication related problems are present for BXW. Concerning data, we see limitations in the amount of reliable and up-to-date data about disease diffusion patterns, severity of outbreaks, and effect of control measures, as well as socio-economic and socio-cultural data that could feed into farmer decision-making tools and an early warning system. Development of informed policies and prevention strategies is also hindered by the absence of large-scale accurate data. Another data problem is the missing link between data collection and action-oriented research. The diversity of stakeholders causes two problems that we link to information. Firstly, the use of one-size-fits all approaches results in a lack of actionable information, customized to the perceptions, practices, and resources of diverse target groups. Secondly, available information is not up-to-date (e.g. about current disease incidence) nor adapted to the local context (e.g. on use of preferred cultural management practices), fails to link technological and socio-economic data, and therefore either inaccessible or non-useful for various target groups. Knowledge problems include gaps in understanding of long- and short-term disease impact, and poor awareness of both the problem and suitable solutions for BXW by farmers and extension agents, causing negligence to take timely action. Additionally, both horizontal (between farmers, and between extension agents) and vertical (across value chain, and across innovation system)

Table 2
Linkages between challenges in each dimension and data, information, knowledge, and connectivity.

Problem dimension	Specific BXW related challenges	Type of problem where ICT and citizen science can support			
		Data related problems	Information related problems	Knowledge related problems	Connectivity related problems
Biophysical	Long distance transmission through variety of vectors	√	√	√	√
	Resurgence after period of control	√	√	√	√
Technological	Absence of resistant (transgenic) cultivars			√	√
	Insufficient epidemiologic understanding	√		√	√
	Low availability of clean plant material		√	√	√
	SDSR technology leaves some inoculum			√	
Socio-cultural	Farmers not involved in finding solutions			√	√
	Campaigns and trainings not inclusive		√	√	√
	Low adoption of control technologies		√	√	√
	Low farmer awareness of the disease		√	√	√
	No attention for gender			√	√
Economic	No accurate predictive system	√	√	√	√
	Lack of reliable data on economic losses	√	√	√	√
	Cumbersome and expensive nature of traditional management techniques				√
Institutional	Absence of appropriate institutional frameworks	√	√		√
	Ineffective surveillance methods	√	√	√	√
	Different institutional environments				√
	No formal seed system				√
	Lack of disease knowhow at institutional level		√	√	√
	Stakeholder incentives and interests unknown	√	√		√
Political	Inadequate mobilization of key actors at all levels				√
	National level policy actors determine allocation of funds and activities				√

exchange of information that is translatable into actionable knowledge is limited. Absence of connections and collaborations between stakeholders at all levels is a cross-cutting problem that prevents effective exchange of data, information, and knowledge.

5.2. The potential of citizen science and ICT-based tools for overcoming data-, information, knowledge- and connectivity-related BXW challenges

Based on our findings we have developed four different intervention pathways: (1) data for prevention of new outbreaks, (2) information for BXW control, (3) knowledge for enhanced capacity to act timely and influence decision making and, (4) connectivity for connective action. These pathways build on the impression that citizen science and ICT enabled collection of data, exchange of information and knowledge, and stakeholder connectivity could positively contribute to addressing BXW. In summary, large scale data from citizen science would support timely diagnosis of new and recurrent/re-emerging (i.e. resurgence) disease outbreaks. Information exchanged through a digital platform could help farmers and extensionists to make decisions about actionable control strategies. Knowledge developed by engaged stakeholders can enhance capacity to act timely and increase dialogue. Lastly, connectivity between stakeholders would allow building of self-organized networks.

5.2.1. Data-related interventions: citizen science and ICT for prevention of new BXW outbreaks

Current efforts to manage BXW are mostly targeting control of the disease after it has been diagnosed in a farm or area. Adoption of preventive measures such as male bud removal, and tool sterilisation has been limited. More successful results have been obtained by task-forces that surveyed an area for disease outbreaks and enforced rigorous action when disease was diagnosed. However, such measures meet farmer reluctance for impracticability (Blomme et al., 2014) and are reported as too costly to be sustainable for smallholders (Tushemereiwe et al., 2006). Yet, the need for monitoring does not end with the control of BXW in a region given the high risk of resurgence and continuation of surveillance activities is critical. Thus, there is need for cost-efficient and effective interventions that enhance the ability to identify disease outbreaks early on thereby reducing necessity to control severe outbreaks in a late(r) stage. A system in which citizen science and ICT tools are used to crowd-source environmental data (e.g. about disease spread, incidence and severity), and that links existing (scientific) data with field level observations from farmers and extension service providers could be helpful here, possibly combined with historical and real-time data from satellite images or collected by drones. In such a system, farmers would play a leading role, sharing data (e.g. on location, BXW incidence and severity) that can support real-time monitoring and prediction of disease spread and incidence that would then provide decision support to farmers about accurate management strategies, to extensionists about hotspots for monitoring and training, and governments about where to focus investments.

5.2.2. Information-related interventions: reliable and real-time data to improve BXW control

Citizen science and ICT tools can support better access to information and in a far timelier manner, as well as increase meaningfulness and interpretability of information. This can positively affect farmer decision-making, and in turn be a first step towards improved technology adoption rates, more sustainable disease control, and increased prevention. Farmers base decisions on local conditions, and this needs to be considered when providing farmers with decision support (Wood et al., 2014). For example, enforcing the practice of CMU to control BXW spread in a region where bananas are mostly grown as a subsistence crop resulted in farmers rejecting/poorly adopting the practice due to its expensive and cumbersome nature (Blomme et al., 2014; Tushemereiwe et al., 2006). Albeit from a scientific perspective CMU may be the preferred technology for most effective disease eradication (or reduction in overall field inoculum level), technologies like SDSR could be more appropriate in a specific farming context and therefore better meet farmer needs and demands resulting in better uptake and impact. Digital innovations may support gathering and assessing appropriate information and control strategies for a specific farmer in a specific locality. For example, app or SMS based services could be combined with more conventional forms of communication used in the banana system to gather, process, and exchange information relevant to individual farmers or farmer communities. Experiments with the use of mobile phones for multiway interaction between science and practice for the control of BXW in Uganda showed opportunities for more cost-effective disease control and surveillance in the region (Nakato et al., 2016). This is promising given the lack of strong national and regional surveillance and monitoring mechanisms necessary for management of BXW (Tinzaara et al., 2014). Other examples of existing initiatives that provide farmers and extensionists with a tool for rapid diagnostics and control advice on crop pests and disease diagnosis are PEAT's Plantix and Penn State University's PlantVillage. Examples of crop specific tools are Africa Rice's Rice Advice, and ICAR-National Rice Research Institutes' RiceXpert. Thus, we observe opportunities to – for example – provide decision-support on suitable BXW control strategies to different groups of farmers, including those who normally have difficulties to access information, such as women. This could include sensitizing farmers about risks of locally sourced plant material or, providing information about locally available clean seed resources. Bringing together all information needed for informed decision-making enhances the reliability and consistency of that information for farmers or other end-users.

5.2.3. Knowledge-related interventions: enhanced knowledge, knowhow and capacity to act and influence

Knowledge is critical for addressing complex problems as they are intertwined with peoples' actions and processes of change (Leeuwis and van den Ban, 2004). Not knowledge about BXW as such is key, but rather knowledge that can enhance the capacity of stakeholders in terms of understanding, defining and strategizing the broad range of existing and new challenges for addressing BXW. This also builds on stakeholder perceptions and beliefs about effective BXW management (Blomme et al., 2017; Blomme et al., 2014).

However, for knowledge to become actionable it needs to be interpretable, something difficult to achieve with one-size-fits-all knowledge. ICT and citizen science could support here, integrating local and scientific knowledge and experiences. A suitable intervention would be the introduction of a digital platform (based on existing digital technologies and platforms such as WhatsApp, SMS, and Unstructured Simplified Service Data (USSD)) to exchange data, information, knowledge and expertise. Integration with a wide variety of digital technologies and platforms makes the platform inclusive for a larger variety of stakeholders. This way ICT and citizen science can enhance availability, accessibility, accuracy, and actionability of the knowledge and knowhow needed to make informed decisions at individual, household and institutional levels by assembling existing knowledge and translating it into new knowledge that is adjusted to the needs and context of its user. Additionally, it allows for collection of scientific and practical evidence of BXW's spread and impact (e.g. data on crop and economic losses) that can convince policy makers to engage in national and regional action.

5.2.4. Connectivity-related interventions: connective action among stakeholders

Although newer management practices such as SDSR make individual level control of BXW very effective under certain conditions (e.g. at highland sites with AAA-EA type bananas), stakeholder collaboration and connectivity remain an important bottleneck when aiming for BXW prevention rather than control. General absence of well-functioning networks providing assistance in monitoring, surveying and controlling crop diseases in developing countries results in incomplete data and provides a hurdle to effective disease control and prevention (Vurro et al., 2010). Hence, there is a need for scientists and farmers to collaborate and turn available information into relevant, actionable farming knowledge (Bruce, 2016). This especially for knowledge-intensive agricultural problems, like BXW, that require intensive training and extension efforts and close collaboration between trainers and learners (Kabunga et al., 2011).

Experimentation with new forms of social mechanisms and exchange of contextualized information through ICT and citizen science provides an entry-point for engaging farmers in research and development activities, creating opportunities for targeted, multi-way, multi-level interaction. Citizen science and ICT can enhance such multi-way information exchange by collecting the feedback from farmers to the research community that can shape new research questions and improve service delivery to farmers (Kindred, 2015; Phillipson et al., 2012). Additionally, ICT provides opportunities for more inclusive services that benefit a larger number and broader variety of stakeholders (Bruce, 2016), and can support improved understanding and communication about best-bet practices according to science, and best-fit practices following farmers' context. Already some banana technologies stem from such a participatory, collective approach (e.g. SDSR and cost-effective macro-propagation). Although face-to-face interactions with experts will still be needed, citizen science and ICT can enable, complement, or accelerate these approaches.

6. Conclusions

This paper contributes to a deeper understanding about BXW in the Great Lakes Region by unravelling this complex agricultural problem. We found that the BXW epidemic/constraint is a resultant of numerous challenges across various system dimensions and is not only caused by biophysical and technological challenges. Identified challenges sequentially link with data, information, knowledge, and stakeholder connectivity challenges. This finding has largely been neglected in studies and interventions this far, potentially contributing to meagre results of efforts to control existing and prevent new or recurrent disease outbreaks. Literature on ICT and citizen science innovations suggests that these could potentially be put to effective deployment for addressing such information and communication related challenges. Related to this we identified four action pathways: (1) Data-related interventions: Citizen science for BXW prevention (e.g. involving farmers to collect large scale data on disease transmission patterns); (2) Information-related interventions: Reliable and real-time data to improve disease control (e.g. sharing personal(ized) and contextualized information to facilitate translation into applicable knowledge); (3) Knowledge-related interventions: Enhanced knowledge, knowhow and capacity to act and influence (e.g. establishing a digital platform for sharing of expertise on knowledge-based interventions) and (4) Connectivity-related interventions: Collective action among stakeholders (e.g. creation of a virtual platform for connective action).

Citizen science and ICT innovations based on these pathways are likely more cost-efficient and have an ability to reach larger groups of farmers than current extension services and interventions for disease management. However, ICTs nor citizen science alone will offer the panacea to a longstanding agricultural problem like BXW. Alternatively, they should be considered useful new modalities that support tackling such problems. We recommend that research and development efforts to address BXW in the Great Lakes Region should not primarily focus on the development of new tools and applications. Instead the focus should be on the identification of best-fit options for combining face-to-face interactions with ICT and citizen science-based innovations for problem solving.

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