Epidemic networks and potential sources of bacterial wilt infection in a potato seed network in Kenya

Sospeter Gachamba[1,2*], Yanru Xing[3,4,5*], Kelsey F. Andersen Onofre[3,4,5], Karen A. Garrett[3,4,5], Douglas W. Miano[2], Agnes Mwangombe[2], Kalpana Sharma[6]

*Both authors contributed equally.

[1]Kenya Plant Health Inspectorate Service, Nairobi, Kenya

[2]Department of Plant Science and Crop Protection, University of Nairobi, Kenya

[3]Plant Pathology Department, University of Florida, Gainesville, FL, United States

[4]Food Systems Institute, University of Florida, Gainesville, FL, United States

[5]Emerging Pathogens Institute, University of Florida, Gainesville, FL, United States

[6]International Potato Center, Nairobi, Kenya

Corresponding authors:

Karen A. Garrett, karengarrett@ufl.edu

Kalpana Sharma, kalpana.sharma@cgiar.org

Abstract

Potato seed systems in Kenya are largely informal, characterized by high seed degeneration due to the buildup of seed- and soil-borne diseases, including bacterial wilt caused by *Ralstonia solanacearum*. Informal sources of seed include neighbors, local markets and farmer-saved seed, and present a risk for spread and establishment of disease. To understand the larger context of potato disease risk in Kenya, we used network analysis to evaluate (1) epidemic risk through potato trade networks centered around East Africa, and (2) locations in East Africa likely to be particularly important for epidemic management because of their high potato cropland connectivity. We evaluated the interactions of the key stakeholders in a potato seed system and used network analysis to identify locations that are likely to be important for the spread of infection of *R. solanacearum* in a potato seed distribution network in Meru, Kenya. Household details, seed sources, quantities sold, pest incidence and management practices, knowledge about seed degeneration and farmers' sources of information on potato production were obtained and analyzed. The survey revealed that self-saved, neighbors, seed companies, friends, exchange, and markets are the main seed sources. Only 43% of total seed transacted was certified. Users of uncertified seeds have high disease risk, and this is an especially important risk if their roles in the network give them the potential to be 'superspreaders' of disease.

Introduction

Potato is an important food security crop and a major source of household income for smallholder farmers in Kenya (MOALF, 2016). The country's area under potato production is 145,967 ha with an annual production of approximately 2 million tons (FAOSTAT, 2019). The crop grows well between 1500 masl and 3000 masl; Meru, Nakuru, and Nyandarua are the main potato producing counties in Kenya, accounting for 80% of the total potato production (Kaguongo et al., 2014; 2010; Muthoni et al., 2013; Were et al., 2013). The most preferred potato varieties are Shangi, Dutch Robjn, and Kenya Karibu (Daniel et al., 2016), and the average tuber yield is 8–15 t ha^{-1} which is more than three times lower than the 30–40 t ha^{-1} that are achievable under field conditions (Gitari et al., 2018; Muthoni et al., 2013). The low productivity is mainly attributed to the erratic rainfall patterns, lack of high yielding varieties, unavailability of and limited access to certified seed potatoes, and pest and diseases such as late blight (caused by *Phytophthora infestans*), bacterial wilt (caused by *Ralstonia solanacearum*) and viruses (Potato virus X, Potato virus Y and Potato leafroll virus) (Gildemacher et al., 2009; Kaguongo et al., 2014). Lack of adequate certified potato seed has increased the seed and soil borne disease problem in Kenya (Muthoni et al., 2013).

Potato seed systems in Kenya are largely informal (96%), about 3% semiformal and 1% formal (Kaguongo et al., 2014). In formal seed systems, seed is officially produced following a seed certification scheme of the Kenya Plant Health Inspectorate Services (KEPHIS) under the Chapter 326 of Seed and Plant Varieties Act of 2012 (National Council for Law Reporting, 2012). The semi-formal seed system is made up of seed producers who use certified seed as their planting material, and multiply further following good agricultural practices guidelines but without the seed certification scheme of KEPHIS. In informal seed systems, seed is produced without KEPHIS guidelines. Seed is sourced from neighbors, local markets, and previous harvests (Gildemacher et al., 2009), therefore seed quality is not assured. Most smallholder farmers rely on the informal seed system as a source of seed (Kaguongo et al., 2014), and this poses a risk in pest and pathogen spread through contaminated tubers.

Improving seed security is vital for improved livelihoods for smallholder farmers, where both informal and formal seed systems coexist. Seed systems are composed of farmers, multipliers, traders, NGOs, companies, breeding organizations, and communities. The connections among those stakeholders represent formal and informal interactions that are complex, and analyses that address this complexity can help in evaluating how systems can be improved. A seed system network can be defined as a set of individuals or actors (nodes) - such as individual farmers, entities or groups involved in the movement of seed in a certain locality or area – connected together by their relations (links), such as exchange of seed (Garrett et al. 2018). Seed networks provide a framework to identify the significance of each actor in the system and the relationships between nodes. Social networks of trade or knowledge sharing are an important factor in the spread of seedborne diseases (Buddenhagen *et al.*, 2017; Pautasso and Jeger 2014).

Network analysis can be used to evaluate how plant diseases spread and establish, in studies of the influence of landscape topology on disease dynamics, climate and edaphic characters predisposing plants to disease risk and genetic variation of host and pathogen across their geographical distribution (Andersen et al., 2019; Pautasso and Jeger, 2014; Xing et al., 2020). Because seed networks can function as epidemic networks, network analysis has also been used to analyze networks of seed distribution and to identify geographical points for interventions (Abay et al., 2011; Andersen et al., 2019; Andersen Onofre et al., 2021; Buddenhagen et al., 2017; Hernandez Nopsa et al., 2015; Poudel et al., 2015). Characterizing seed systems as networks allows us to consider multiple scenarios for system management, including the impact of epidemic spread or variety deployment (Andersen et al., 2019; Garrett, 2021). As Jeger et al. (2007) describe, control of pathogen spread in epidemic networks should emphasize highly connected individuals. Such individuals, by having many network links, can act as sources, sinks, and bridges for pathogen movement (Buddenhagen *et al.*, 2017). Models of disease spread can be used to evaluate the relationships among various actors, environments and pathogens (Moslonka-Lefebvre *et al.*, 2011), potentially using tools such as exponential random graph models (ERGM) to characterize networks (Buddenhagen *et al.*, 2017), and to identify geographical locations for effective interventions. Scaling up of epidemic network analysis can address networks of susceptible host patches in landscapes (e.g., Xing et al., 2020) and movement of host materials and potential associated pathogens through trade.

Understanding potential sources of infection by *R. solanacearum* in the potato seed network in Meru, Kenya will be vital for identifying the most important points for intervention and informing best management approaches to the management of the disease. The objectives of this study were to (1) evaluate the potential role of cropland connectivity in disease risk and the risk of disease spread through trade networks, (2) characterize the seed distribution network in four potato growing wards in Meru, Kenya and to identify important nodes for interventions, (3) compare the likely performance of strategies for managing diseases in this seed system in scenario analyses, and (4) identify influential actors for communicating interventions. Understanding seed network structures can support the functioning of local seed distribution systems, build the capacity and resilience of seed sectors as well as provide evidence-based guidelines and recommendations for policy and institutional support mechanisms for clonally propagated crops in Kenya and other countries developing improved seed systems.

METHODS

Cropland connectivity analysis. We evaluated the connectivity of the potato cropland network using a cropland connectivity risk index (CCRI) (Xing et al., 2020) in Sub-Saharan Africa, using the harvested potato area data in SPAM 2017 v2.1 (International Food Policy Research, 2020) by converting grid harvested area values in hectare as grid fraction of harvested area, with a 5 x 5 minute grid unit (without aggregation and disaggregation of raw data resolution) of cropland as a geographic node and the probability of pathogen spread between pairs of nodes as link weights. In these and following analyses we used the R programming environment (R Core Team, 2020) and R packages igraph (Csardi and Nepusz, 2006), raster (Hijmans et al., 2020), sf (Pebesma, 2018), tmap (Tennekes, 2018), and INA (Garrett, 2021), with code examples in Supplemental Material 1. The uncertainty quantification analysis of the CCRI for countries in Sub-Saharan Africa was performed applying the same model parameter values and link weight thresholds as in Xing et al. (2020), but three different thresholds for inclusion (0.015, 0.02, 0.025) were used.

Potato trade network analysis. We evaluated the potato international trade dataset from 2015 to 2019 from the Food and Agriculture Organization of the United Nations (FAO) potato trade database. The yearly mean of trade in tons between pairs of countries was summarized, with an analysis limited to trade transactions involving the six countries of Kenya, United Republic of Tanzania, Burundi, Rwanda, Uganda, and Democratic Republic of the Congo as export countries or import countries, separated for the potato trade network analysis. The trade network was plotted using the R package igraph (Csardi and Nepusz, 2006), with each country as a node and with the links between countries denoting the trade transactions. The network was plotted on the potato mean CCRI map from Xing et al. (2020). Plant disease distribution data from CABI (www.cabi.org) was integrated in the trade network, and each country was represented as a pie chart to show the status of eight priority diseases and pests: *Globodera pallida*, *Globodera rostochiensis*, potato virus X, potato virus Y, potato leafroll virus, *Ralstonia solanacearum* race 3, *Phytophthora infestans*, and *Pectobacterium parmentieri*.

Survey study area. A survey was conducted in four potato growing wards of Meru County, Kenya in 2018 (Fig.1). Meru county is one of the major potato production areas in Kenya and was chosen for the study due to its proximity to the certified seed producer and the potato seed network supported by the International Potato Center (Leung et al., 2015) with the objective to improve seed security and potato productivity via community-based seed potato production. Meru County is located in Eastern Kenya to the east of Mount Kenya. It shares border with five other counties: Isiolo County to the north, Nithi County to the east, Nyeri County to the southwest and Laikipia County to the west. Meru receives rainfall ranging from 500 mm to 2500 mm per annum, and the temperature ranging from 8°C to 32°C. Potato is grown mainly in Buuri, Imenti South, and Imenti Central sub-Counties.

Survey to characterize seed distribution network. Our seed network analysis targeted four potato growing wards in Meru County, namely, Nkuene in South Imenti sub-County, Athoboguchi West and Kibirichia in Central Imenti sub-County and Kiirua in Buuri sub-County. First, key stakeholders (actors) were identified from a preliminary survey of the potato seed distribution system in this region by the International Potato Center (Leung et al., 2015), which helped to identify the types of stakeholders who had roles in the seed distribution network (Table 1).

All potato farmers were clustered into their respective groups with the assistance of the Village Based Advisors (VBAs). VBAs are nominated village leaders who offer agronomic advice and disseminate quality declared seed. There were 20 VBAs in total across the four wards representing 5 VBAs per ward. From each VBA, four beneficiaries (recipients of quality declared seed), were identified and surveyed. Various actors in these networks represented important nodes for the flow of potato seed (**Fig. 2**). Farmers were surveyed using a snowball sampling technique, beginning with the VBAs, and beneficiaries who received seed from VBAs. In total there were eighty beneficiaries directly connected with the VBAs. Fifty-three (53) more indirect beneficiaries of seeds, either from the VBAs or other sources (friends, neighbors), were also included because of their role in the flow of seed in the region (**Table 1**). The seed produced by VBAs is categorized as quality declared seed since it was produced in plots monitored and maintained to control pests and diseases.

Four enumerators were trained to collect data from each ward. The enumerators were involved in collection of data in the respective ward using a structured questionnaire to obtain details of households, location of farms, level of education, seed sources, seed sales, ware potato sales, pest prevalence, pest control practices, farmers' knowledge of seed degeneration, and sources of information related to potato production. A total of 100 farmers, directly linked in the network either by being recipients or givers of seed, were interviewed.

Seed flow information was important for evaluating the primary node as a source of *R. solanacearum* infection in the seed network, and to understand farmer's behavior in these wards for plant health management prospective. Potato tuber samples from VBAs and their direct beneficiaries were collected and tested for *R. solanacearum* latent infection using NCM-ELISA (enzyme-linked immunosorbent assay on nitrocellulose membranes) kit following the protocol of Priou et al. (2001) at Kenya Plant Health Inspection Service (KEPHIS).

Seed network analysis. Data about sources of seed and respective beneficiaries (nodes) and the paths of exchange (edges), was analyzed by creating the seed distribution lists between pairs of nodes. Edges were weighted based on the total quantity of seed exchanged. The edge and node lists were then populated in R using the igraph package (Csardi and Nepusz, 2006) and Gephi software v. 0.9.2. Graphs were visualized using the ForceAtlas Algorithm. Degree centrality was calculated in Gephi. To identify important nodes, the in-degree and out-degree of the nodes and the edge weights were calculated and tabulated. Major sources, sinks and bridges for potato seed, which could constitute a high risk node for the spread of *R. solanacearum*, were identified.

Network analysis: Evaluating the importance of nodes for surveillance. After constructing the seed exchange network, we applied the smartsurv function from the INA package in R (Garrett, 2021) to ask which nodes in the system would be the best to monitor for disease, for a scenario in which each node has the same likelihood of being an introduction point for a pathogen. In this seed distribution network, we also investigated the BW disease symptom distribution pattern and the network of farmers by gender and potato farming practice.

In the smartsurv simulation, we considered the case of bacterial wilt, which would primarily be spread through the exchange of infested seed potato material. We considered the scenario where each node is considered a potential starting point and determined the number of nodes uninfected by the time the pathogen would be detected at each potential sampling node. In a second version of this analysis, we included “ward” nodes in the network, where individuals who reside in the same ward would be linked by a common node with probability P = 0.1, representing their higher chance of exchanging material because of geographic proximity. Network links reported in the survey were assigned a probability p = 0.3 of experiencing potato movement in each season in this scenario. Each simulation experiment described above was evaluated for 500 realizations to understand the range of potential outcomes from the stochastic model. This type of analysis is available in the INA R package (Garrett, 2021) and illustrated in two previous studies of seed systems in Ecuador (Buddenhagen et al., 2017) and Uganda (Andersen et al., 2019). In a third scenario analysis we considered locations where BW was detected in surveys as potential starting points for the infection and determined the best location for detection (or those most likely to become infected) other than those already infected. Finally, we performed this analysis with nodes weighted by the management practices reported by each farm during the survey (such as use of certified seed, positive selection, and information source about pest and disease and IPM), where locations reporting better practices were less likely to be entry points for disease.

Management scenario evaluating management differences for VBAs and general farmers. One of the potential benefits of VBAs is their tendency to have more links than general farmers, and we evaluated the benefit in the seed system reported here, if project management efforts focus on the influence of VBAs compared to general farmers. We applied the INAscene function from the INA package in R (Garrett, 2021) to simulate the possible management benefit. We compared scenarios in which VBAs had improved management to reduce the risk of BW, compared to scenarios in which general farmers had improved management. The outcome from the scenarios was evaluated in terms of the proportion of locations (nodes) with disease present after two time steps of simulated disease spread. We also evaluated a scenario in which status of a node as a VBA was reassigned to the nodes with greatest node degree, to reflect a situation where VBAs were 'perfectly' selected among farmers to represent the greatest benefit to the system in terms of reduced BW risk.

RESULTS

Cropland connectivity analysis and trade network structure, The uncertainty quantification analysis of the CCRI for potato production in Sub-Saharan Africa indicates locations that are likely to be particularly important in epidemics, in terms of the potential for pathogen spread through the landscape (Fig. 1). The trade network shows the reported locations for key pathogens and pests of potato in the region, and the links between countries (Fig. 3).

Seed network. Network visualization of the four seed networks in the study area showed directed flow of seed potato within the four networks (Figs. 4 A, B and C). VBAs sourced certified seed from Kisima Farm, a certified seed producer. Kisima Farm is the central node distributor for certified seeds to the VBAs and other actors within the network accounting for 34% of total seed distributed in the network. The bulk of the seed was moved by VBAs who provided 64% of the seed in the form of quality declared seed for the next planting season. Within the network VBAs acted as the main actors connecting the certified seed producers and the beneficiaries, thus forming key nodes with higher in-degrees and out-degrees. While the major role of VBAs was to distribute quality declared seed to farmers within their networks, they also sourced seeds from other sources including neighbors and markets, at the same time utilizing previously saved potato seeds for planting.

In the seed system network, the connectivity between actors plays a major role in seed distribution. These included three VBA's who provided seed to actors in the network under study. Degree centrality is the number of edges a node has. In the seed network, Kisima Farm had the highest out-degree, with 41 edges. In a directed network a node with higher degree centrality has the potential to be an important source of infection due to the higher number of nodes connected to it. Since its source of seed could not be reliably obtained, it had zero in-degree. Kisima Farm undergoes a stringent inspection regime to guarantee freedom from pests. Betweenness centrality is a measure of a node's capacity to affect other nodes in the network as a bridge between different parts of the seed system. In the network an actor with a high betweenness centrality would tend to have greater influence over the flow of seed or information. In our study case VBA5 and Beneficiary 14 are the most important in terms of having the highest betweenness centrality in the network.

Seed exchange. Fifty-four percent of the farmers reported planting certified seed, while 56% had never used certified seeds. Certified seed accounted for 43% of sourced seed and Quality seed accounted for 57% of the entire seed sourced from various suppliers (26% from neighbors, 19% from friends, 8% from markets and 5% farm saved seed). Certified seed was preferred compared to seed from other sources. In the network, only 26% of farmers from Kibirichia, Kiirua and Athoboguchi were involved in sale of seed, and 3300 kg of seed was exchanged by purchase from one node to another.

Pest and disease prevalence. Late blight and bacterial wilt were reported as the most important diseases in the survey area (Table S.2). Bacterial wilt was confirmed on 30 beneficiaries and 5 VBAs by ELISA tests (Table S.3). Moreover, bacterial wilt incidence was high in those farms that had been using farm-saved seed each planting season (Table 2) due to the high cost of certified seed.

Disease management practices implemented by farmers. Most of the farmers reported preferring chemical control methods over cultural methods for the management of pests and disease. However, the preference varied with the type of disease reported by the farmers (Table S.1, Table S.4, Table S.5). For the management of bacterial wilt, crop rotation was preferred by 46% of the respondents, 5% preferred roguing (five times during growing seasons), and only 1% practiced positive selection. Late blight was controlled by use of fungicides (94%), and very few practiced positive selection (1%), crop rotation (1%) and roguing (1%). About 42% of the farmers did not practice any measure to manage viral diseases, whereas some practice crop rotation (7%,) roguing (3%), chemical treatment of the vectors (9%) and positive selection (1%).

The importance of nodes for surveillance, and distribution of gender in the seed system network. Based on epidemic simulations, we identified the nodes in the system that would be most important for monitoring for disease, for a scenario in which each node has the same likelihood of being an introduction point for a pathogen (Fig. 4A). In this seed distribution network, we also investigated the BW disease symptom distribution pattern and the network of farmers by gender and potato farming practice (Fig. 4B, 4C). The risks and benefits in the system appear similarly distributed for men and women.

Management scenario evaluating management differences for VBAs and general farmers. In the scenario analysis based on the reported network, there was a small increase in the system efficiency for simulated scenarios in which VBAs had greater management effects versus general farmers having greater management effects. When assignment of VBAs was simulated as being for the farmer nodes with highest degree, there were still limited effects of VBA selection compared to general farmer selection, based on the limited number of farmers in the survey. It could also be that more extensive sampling would reveal greater system-level effects of VBA positioning in the network.

Farmers' knowledge about seed quality, purity and degeneration. The majority of farmers in Nkuene and Kiirua had knowledge and understanding of seed quality, seed purity and seed degeneration, and (Table 3). Similarly, the government extension service had the highest number of ties (node degree) for all information related to crop production, i.e., fertilizer use, selection and use of pesticides, integrated management practices, emerging potato pests, current pests and diseases, benefits of using certified seed, new potato varieties and general potato production practices to the farmer (Fig. 5).

DISCUSSION

We used network analysis to identify locations that are likely to be particularly important for the spread of seedborne pathogens such as the bacterial wilt pathogen, *Ralstonia solanacearum*, in a potato seed distribution network in Meru, Kenya. Network analysis can identify interactions among actors in a network and enable identification of particularly important actors for channeling of interventions (Pautasso *et al.*, 2007; Jeger et al, 2007; Shaw and Pautasso, 2014; Anderson *et al*., 2019). Network and information theories have enhanced knowledge of disease epidemiology and in designing tactical and strategic interventions for disease control and management (Ojiambo *et al.*, 2017). Links may be weighted to indicate the number of interactions that occur between nodes to further inform the importance of each node in disease spread. Our study network was composed of a main seed producer in the region, village based advisors, general farmers and friends to whom seed was sourced and distributed. We evaluated disease incidence in the farms and obtained samples for pathological analysis to identify which diseases were prevalent in the farms. We identified 32 nodes infected by the bacterial wilt pathogen *Ralstonia solanacearum* (Fig. 4). Bacterial wilt disease is a major constraint to production of potato in Kenya affecting 77% of farms (Kaguongo *et al.*, 2010). Infected nodes represent important risk factors as sources of infection and disease spread in the network. These nodes can be ranked and prioritized for interventions. Suggested interventions include provision of clean seed potato, crop rotation, selection, training and awareness on disease control and management.

Seed system network analysis can be used to evaluate the importance of particular nodes for disease surveillance and to evaluate how people experience the system as a function of their gender or other demographic traits. In this reported seed system, disease risk and the importance of nodes was similar for men and women. Supporting VBAs is an option for strengthening seed systems. In a scenario analysis based on the reported seed system network, the position of VBAs in the network resulted in a small benefit in simulations of project investments, compared to investments in general farmers. Selection of VBAs taking into account both their skills and knowledge as farmers, and also their positions in seed systems, has the potential to improve project efforts to improve seed systems and management of diseases in them. Caution is needed when interpreting smaller snowball samples, in terms of extrapolation to larger systems structures (Newman 2018). When there are opportunities to sample over a larger share of a seed system, more aspects of the roles of individuals in the system may be revealed.

At larger scales, the analysis of potato cropland connectivity shows locations likely to be particularly important in epidemics, based on the geographic distribution of potato and its importance for the local spread of vectors and windborne spores, and for informal potato seed trade. Cropland connectivity is one component of risk and can be combined with other risk factors such as conducive weather and use of susceptible varieties to evaluate locations key for surveillance and mitigation. Understanding of the geographic distribution of risk and of management efficacy, and of farmer needs, can also be used to inform decisions about where to invest projects efforts, such as training for use of positive selection, for greater benefits (Buddenhagen et al., 2021, Garrett et al., 2020). At the scale of international trade, countries where pathogens and pests expanding their ranges have been reported are a particular risk, especially if countries have limited phytosanitary capacity to detect and mitigate invasions. One caveat for interpreting the risks of pathogen spread through these trade networks is the potential for under-reporting about which countries already have a pathogen or pest present.

The survey revealed a substantial lack of knowledge and lack of implementation of other disease management practices beyond chemical control. Most farmers did not understand positive or negative selection and this was lacking as a management option by the farmers. Many farmers preferred chemicals sprays for the control of late blight, against easy to implement cultural practices, e.g., crop rotation, roguing, and positive or negative seed selection. The frequency of sprays during growing season was unusually high, 6-7 times in a growing season. These findings are consistent with observations made by Nyankanga *et al.* (2004) and Njoroge et al. (2019), highlighting the overreliance on application of fungicides for the control of late blight by Kenyan farmers. This suggests misapplication of the fungicides either due to lack of knowledge about disease infection stages or poor mix volume ratio for subsequent sprays.

The Kenyan government through the Ministry of Agriculture Livestock and Fisheries (MOALF) developed the National Potato Strategy 2016-2020, outlining key stakeholders and their roles in improving the productivity of potato in the country. The stakeholders' roles range from research and regulation to finance. While this is a positive move by the government, our study revealed low information uptake by farmers about, for example, positive selection, roguing out of volunteer crops and use of certified seed. This information is readily provided by the extension department of the Ministry of Agriculture. Certified seed is viewed as expensive by smallholder farmers, making the advantages of using healthy seeds less common. Our study was conducted in a seed distribution network where quality declared seeds are used under the conceptual model of using village based advisors (VBAs) to provide guidance about production and crop management to farmers. Interviewed farmers alluded to an increase in production from previous cropping seasons. This demonstrates further gains can be made if quality declared seeds are used and would reduce the burden of purchasing certified seed, which was cited as expensive by the majority of smallholder farmers.

Information type and source is an essential component of a social system. Information access shapes how farmers react to risk (Parmar *et al.*, 2019). Farmers are confronted by many challenges, including lack of resources, pests and diseases, drought, crop loss, low fertility levels, and lack of knowledge about best agronomic practices. We assessed the type and sources of information available to farmers. Various actors were involved in the dissemination or source of different information types to the farmers. In the study, government extension service was observed to be the main source of all categories of information (fertilizer use, pesticide use, integrated pest management, current and emerging pests and diseases, certified seed producers and new varieties (Fig. 6). Information types varied with the type of mandate an individual organization executes. Since the extension service was represented in every administrative ward and there was easy contact with the farmers, extension officers thereby became the most important sources of information. Where interventions are required, extension officers are suggested as the best actors to disseminate proposed interventions.

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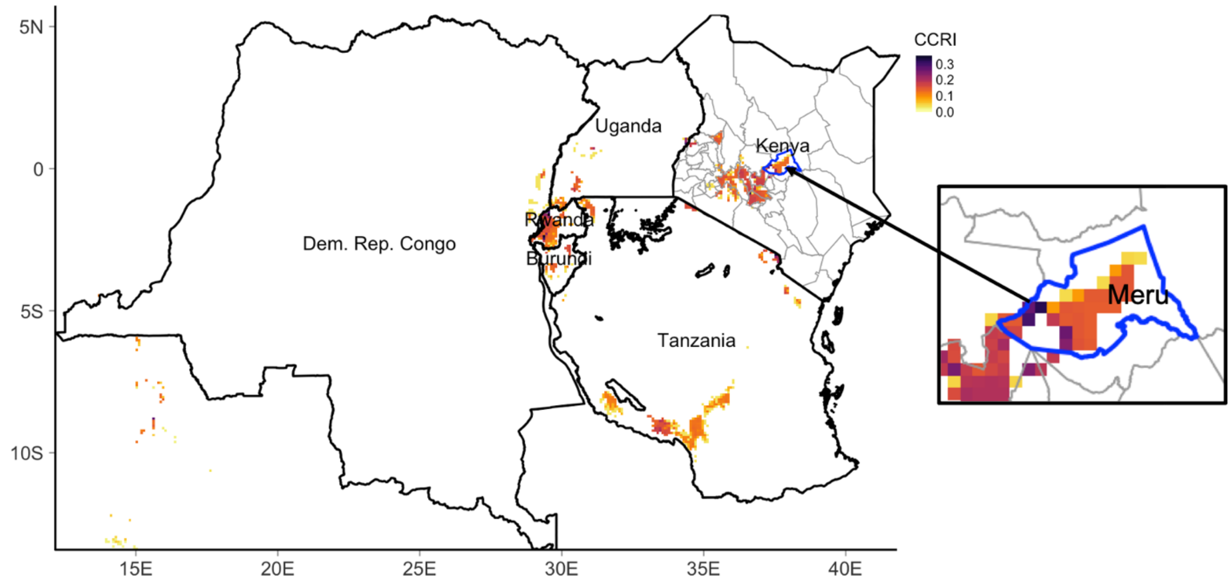

Figure 1. Map of a potato cropland connectivity risk index (Xing et al. 2020) calculated using Sub-Saharan Africa potato harvested area data (International Food Policy Research 2020), focused on Kenya and neighboring countries. A detailed potato seed system survey was conducted in Meru County of Kenya, demarcated by a blue border.

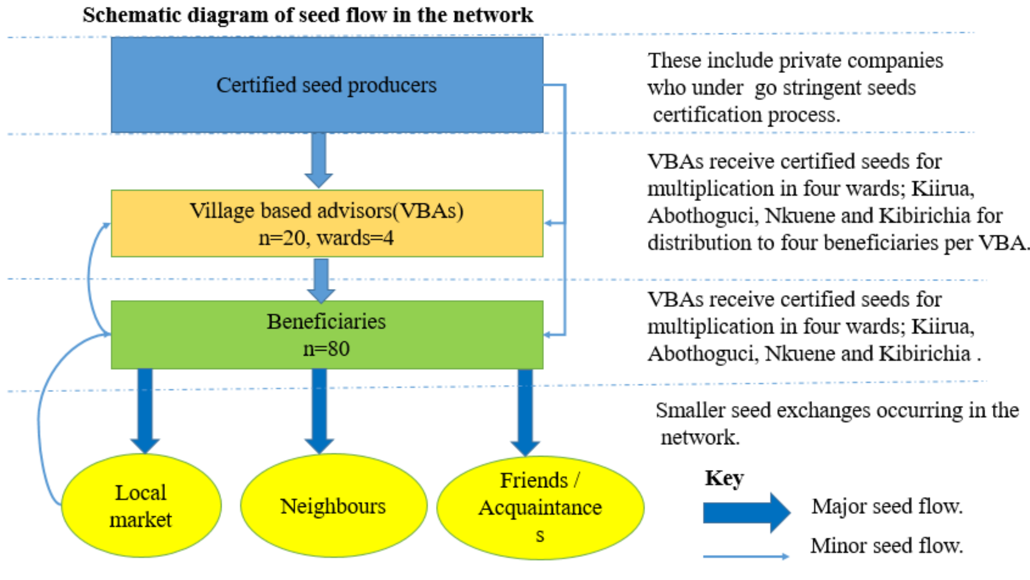

Figure 2. Schematic flow of potato seed in the network. Seed was obtained from certified seed producers and supplied to the village based advisors (VBA) for multiplication under a quality enhanced production system. Once harvested seed was distributed to beneficiaries within the four wards. Seed exchange (in which seed health status could not be ascertained) was also noted to occur from groups highlighted in yellow in the diagram.

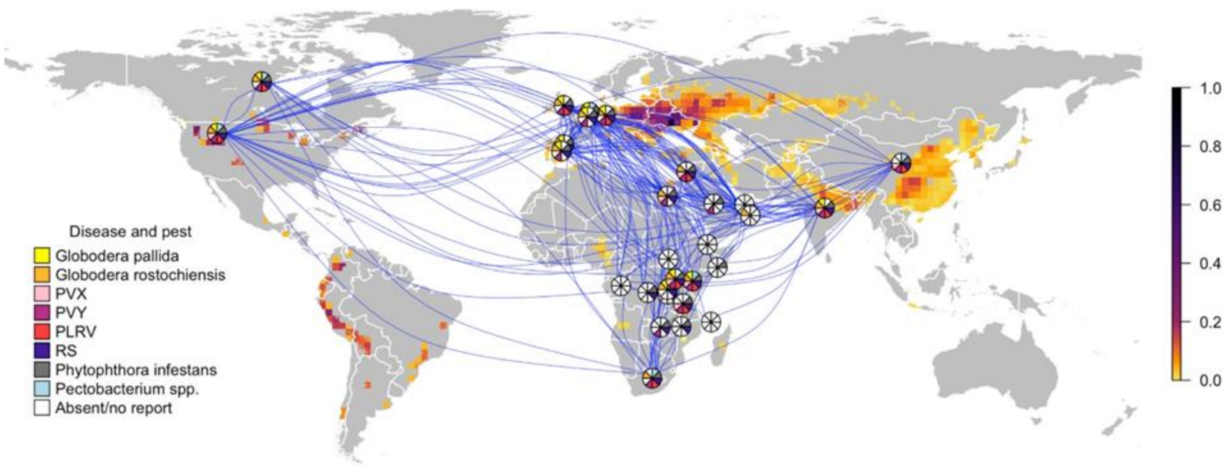

Figure 3. Potato trade transactions for countries exporting directly to, or importing directly from, Kenya, Tanzania, Burundi, Rwanda, Uganda, and the Democratic Republic of the Congo (and transactions among their direct trading partners), presented as a trade network overlaid on a world map of potato cropland connectivity risk index (CCRIL Xing et al. 2020). Each node represents a country and the partitions of the pie chart at each node indicate the presence or absence of eight priority diseases and pests, each represented by a distinct color. The corresponding pie partition is colorless if a pest or disease is absent. The weights of the links between the country nodes, represented by link width, indicate the yearly mean potato trade transactions from 2015 to 2019 (FAO) between the corresponding countries.

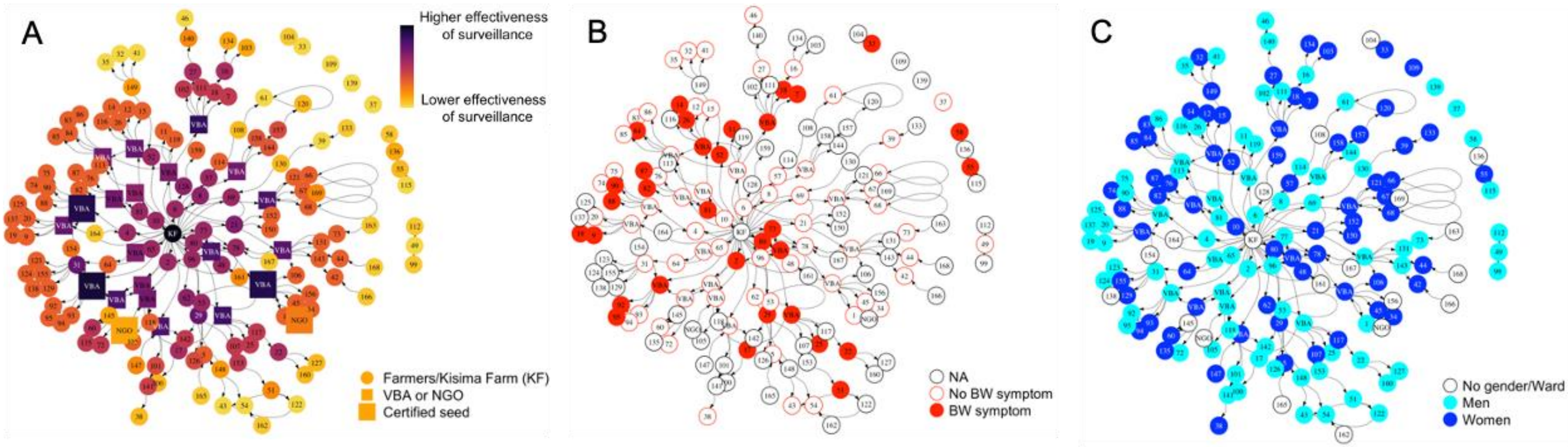

Figure 4. Three views of the potato seed distribution network. **A**. Nodes shaded darker colors are the most important for sampling as smart surveillance locations, based on an analysis of simulated epidemics in the network. Circle nodes denote individual farmers or Kisima Farm, and square nodes denote VBAs or NGOs, and distributers of certified seeds are indicated by larger square nodes. **B.** A survey of bacterial wilt (BW) symptoms was conducted, where red-filled nodes had observed BW symptoms, unfilled red-framed nodes had no BW symptoms observed, and unfilled black-framed nodes indicate missing information. **C.** Dark blue nodes indicate women, light blue nodes indicate men, and empty nodes indicate no gender information or nodes without gender. Access to seed, and risk in epidemic simulations, was comparable for both men and women.

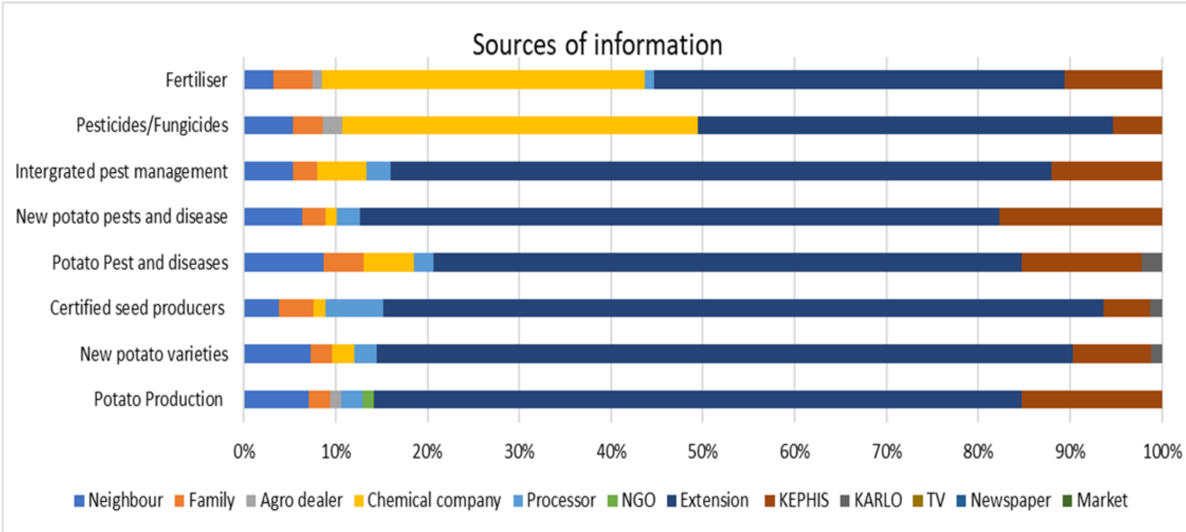

Figure 5. The types and sources of information reported by potato farmers

List of tables

Table 1. Characteristics and number of stakeholders identified in the survey regions from the preliminary survey

Stakeholder type	Stakeholder characteristics	Number of stakeholders
Certified seed producer	Registered seed producer whose production system undergoes certification process by KEPHIS.	2
Semi-formal seed producers	Seed producers who use certified seed as their planting material and produce more seed by following provided agronomic guidelines including scouting for disease but without inspection by KEPHIS	20
Informal seed potato producers	Small scale potato farmers with limited to no access to certified seeds.	100
Local villages market	Sale points for potato seeds in the community	3
Neighbors	Acquaintances benefiting from seed exchange due to the proximity to the source/giver.	33
Friends	Acquaintances benefiting from seed exchange due to relations with source/giver	25
Government body	County government or other government agency that supplied seed to members of the group.	1

Table 2. Frequency of seed re-use on the incidence of bacterial wilt in the survey area

Seed recycling	Number of respondents	Number of farms with bacterial wilt
Every planting season	31	16
After two planting seasons	18	10
After three planting seasons	30	5
After four planting seasons	8	3
After three years	13	0

Table 3. Percentage of famer (respondent) with seed quality, purity, and degeneration knowledge

Ward	Seed quality			Seed purity			Seed degeneration		
	Yes	Limited	No	Yes	Limited	No	Yes	Limited	No
Nkuene	100	0	0	92	0	8	80	20	0
Athoboguchi	8	44	48	0	9	64	8	16	76
Kibirichia	16	50	24	12	17	20	20	60	20
Kiirua	92	4	4	100	0	0	96	0	4