

Guide for using clean seed to help slow the spread of crop pathogens

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Invasive pathogens and seed degeneration. When a crop pathogen is invading a country, it is particularly important to use pathogen-free seed to keep the pathogen from establishing in more locations. There are two considerations for invasive pathogens: each farmer's short-term economic considerations and the benefit that all farmers in a location gain if the pathogen can be kept out longer.

Characterizing networks of invasion: seed networks. In seed systems, informal seed trade is one major pathway for the movement of pathogens. A first step in understanding invasive risk is understanding patterns of seed movement.

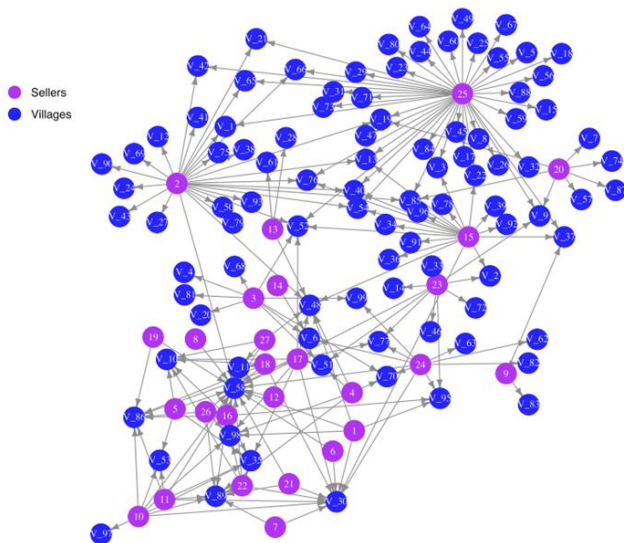


Fig. 2. Network structure of sweet potato vine transactions reported in the 2014 growing season in northern Uganda with both sellers (lighter nodes) and villages (darker nodes). Links represent the occurrence of at least one transaction in the 2014 growing season. The graph layout was generated with the Davidson–Harel layout algorithm and does not represent the geographic locations of villages.

Figure A. A sweetpotato vine transaction network reported in northern Uganda (figure 2 from Andersen *et al.* (2019)). Characterizing the network shows which locations are key to slowing the spread of pathogens (and increasing the movement of good varieties).

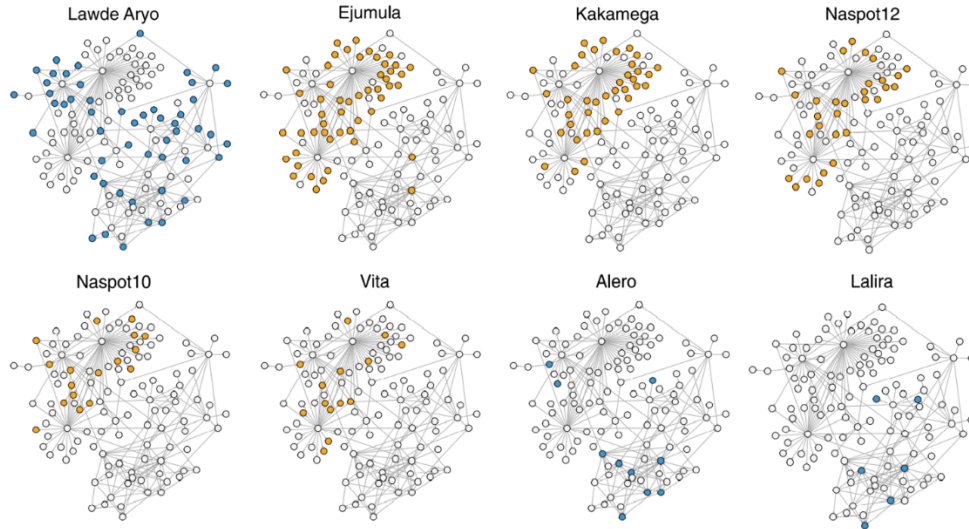


Fig. 4. Networks of dissemination of the top eight cultivars sold during the 2014 growing season in terms of number of transactions reported. All sellers and villages surveyed are represented in each network, whereas filled nodes represent sellers and villages involved in the sale or purchase of the specified cultivar. Unfilled villages did not access a given variety in 2014 through this surveyed seed network. Node shade indicates white-fleshed landraces (darker) and orange-fleshed sweet potato (lighter) cultivars.

Figure B. The Ugandan sweetpotato vine transaction network evaluated for individual varieties (figure 4 from Andersen et al. (2019)). Separating analyses by variety can be important for understanding the spread of materials discovered to be infected by an invasive pathogen, and also for understanding the potential spread of resistant varieties that can combat the impacts of pathogen invasion.

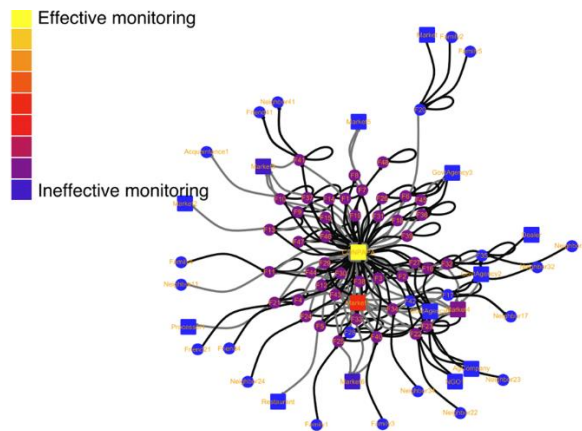


Figure C. A small network of potato seed movement in Ecuador (figure from Buddenhagen *et al.* (2017)). This network representation also includes information about the importance of each node (farm or institution) in the network for monitoring potential spread of a pathogen in the system.

Characterizing networks of invasion: spread of vectors and propagules outside seed trade. Vectors can also spread pathogens, and wind can spread pathogen propagules such as spores. Combining these two types of potential movement can capture more of the features of an invasion network.

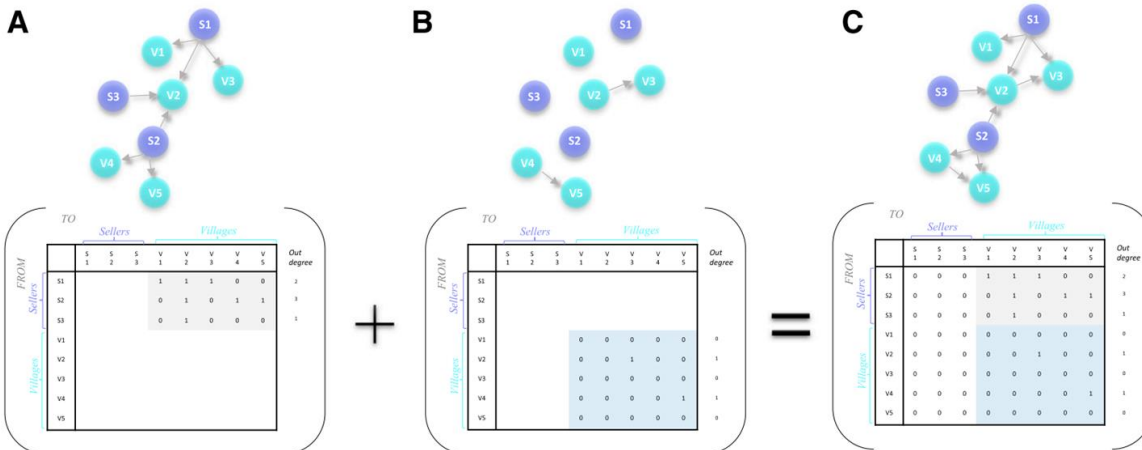


Fig. 3. Schematic illustrating how two types of data were combined: **A**, seller-to-village links reported in the 2014 vine seller survey and **B**, village-to-village links estimated based on the distance between villages using an inverse power law or negative exponential model of the probability of movement. The schematic represents a hypothetical network of three sellers and five villages, each represented as a node in the network. A link between nodes is represented as a one in the matrix, and absence of a link is indicated by a zero. Matrices were combined in **C**, a “supranetwork” with both seller-to-village and village-to-village links. Note that, in this study, all potential seller-to-seller links and village-to-seller links were set to zero, with no transactions taking place in this direction. A “supranetwork” based on the Ugandan sweet potato data was used in the simulation experiments presented in this study.

Figure D. Combining adjacency matrices based on both trade and potential spread among villages by vectors, etc. (figure 3 from Andersen et al. (2019)). Adjacency matrices represent the potential for moving between each pair of people, locations, or institutions. The combined adjacency matrix can be used to evaluate potential paths for invasion through the cropping areas being evaluated.

Clean seed to slow invasions. National programs that produce pathogen-free seed in response to a pathogen invasion will often not be able to produce enough seed for every farmer, especially at the beginning of an invasion. When the program wants to use pathogen-free seed to ‘fight’ an invasive pathogen, it can consider both individual farmer benefits and general benefits from slowing invasions. Any farmer could benefit from pathogen-free seed. Pathogen-free seed for farmers in particular locations may also have a bigger effect for slowing the invasion.

Integrated seed health strategy. To complement use of pathogen-free seed, disease resistant varieties and on-farm management are critical components of regional management (Thomas-Sharma *et al.*, 2017, Thomas-Sharma *et al.*, 2016). Capacity building for farmers in on-farm and post-harvest management strategies will help individual farmers and help to slow the invasion.

Decisions about where to distribute clean seed. There may be two ‘extremes’ where distributing pathogen-free seed is less useful. In one extreme, if there is so much disease in the area that a plant grown from pathogen-free seed will immediately get infected from outside sources, there is only a momentary benefit. In the other extreme, if there is no disease in the area and everyone uses seed without the disease, anyway, bringing pathogen-free seed may be redundant. In between these two extremes, there are many potential situations where pathogen-free seed will be most useful to farmers and have the biggest impact for slowing the pathogen invasion.

Characterizing locations in terms of their importance in an invasion network: **before** invasions. Understanding the structure of a potential invasion network supports regional management planning. Important locations can be prioritized in surveillance to detect initial occurrence of the pathogen in a region

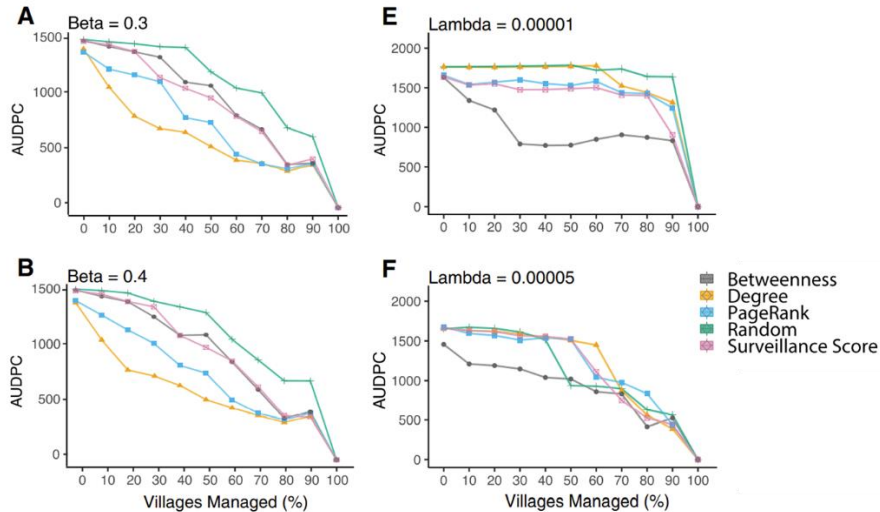


Fig. 8. Sensitivity analysis results across four intermediate values of the spread parameters, for both the **A to D**, inverse power law and **E to H**, negative exponential models of link formation. Mean AUDPC values were calculated across five scenarios where 0 to 100% of villages were intensively managed, in increments of 10. Managed nodes were selected based on five methods: node betweenness centrality, degree centrality, PageRank centrality, surveillance score (calculated in experiment 1), and random selection. Each point represents mean AUDPC based on the percentage of nodes infected out of those not quarantined over the course of 20 time steps across 1,000 realizations. There were 97 villages total in the system and 27 sellers. The seller that served as the starting point for the epidemic in each simulation was drawn at random. The slight increase in mean AUDPC for the case where 90% of nodes are quarantined is a function of the small number of nodes (~10) remaining with the potential for infection. When these do become infected, it leads to a larger percentage of potential nodes infected (illustrated in Supplementary Fig. S15). Values for the treatment where 100% of nodes were quarantined, although undefined, are represented as zero.

Figure E. For deciding where in a network is most important for management before an invasion, measures of the importance (centrality) of individual nodes can be used, such as betweenness, degree, pagerank, and epidemic surveillance scores (Garrett, 2021a) from epidemic simulation (figure 8 from Andersen et al. (2019)). In this example, a range of percentage locations (villages) are managed to remove disease, such as by complete and effective replacement of seed with pathogen-free seed. The area under the disease progress curve (AUDPC) measures how much of the region is infected. Different beta and lambda parameter values correspond to different likelihoods of moving greater distances in the landscape for two dispersal models. For these specific scenarios, degree centrality is useful for identifying locations to manage in the cases on the left, and betweenness centrality for cases on the right.

Potential strategies for distribution. The most useful locations for pathogen-free seed to slow a pathogen invasion will often be near the ‘front wave’ of the epidemic, where the disease is recently present and may not be widely established. Deciding where exactly to target with pathogen-free seed will generally require data to characterize the epidemic.

Characterizing locations in terms of their importance in an invasion network: **after an invasion begins.** Once locations where the pathogen is present have been identified, epidemic simulations can take this into account and evaluate where the pathogen is likely to move next. The ‘frontiers’ for disease expansion in the invasion network can be identified, along with potentially using other measures of the centrality of locations.

Developing decision support for a particular epidemic. Policy makers who are deciding how to distribute pathogen-free seed can benefit from input about the likely outcomes from potential choices. Given a scenario for pathogen-free seed distribution, what are the likely epidemic outcomes?

Simulating epidemic outcomes and the effects of pathogen-free seed. Taking into account the current locations of disease and the structure of the invasion network, the most important locations for management such as pathogen-free seed use can be identified. Although the quantity of pathogen-free seed may be limited, pathogen-free seed can be supplemented by use of resistant varieties (when available) and capacity-building for on-farm management.

Data needs for decision support. The first type of data is characterization of where disease is currently present. Second, characteristics of epidemics that will influence the value of a given seed distribution choice include the following. (1) The speed at which the epidemic is moving. A slower epidemic may be better managed by pathogen-free seed near the front line, while a fast-moving epidemic may be better managed by pathogen-free seed further ahead of the front line. (2) The role of each location in spread of the disease, through trade or vector/spore movement. (3) The importance of long-distance movement, such as through trade, where long-distance trade makes planning more challenging.

Pathogen spread and the speed of epidemic movement. Two types of dispersal need to be considered: dispersal through trade and dispersal outside trade, such as by vector or spore movement. For well-studied pathogens, approximate dispersal parameter estimates may be available. Sensitivity analyses may be used to see if better management strategies are the same regardless of the underlying dispersal parameters.

The role of locations. Locations may be more or less important for epidemic spread, based on factors such as environmental conduciveness and host availability (and cropland connectivity).

The likelihood of long-distance movement. Identification of long-distance trade routes, and potential long-distance movement through weather patterns, is likely to be very important for planning management where key new invasion locations will be.

Potential use of expert knowledge elicitation. Expert knowledge elicitation may be used to characterize some aspects of invasion networks. For example, experts may have valuable insights into the likelihood of informal trade between particular regions (Andersen Onofre *et al.*, 2021) or the likelihood that farmers use a particular type of management (Thomas-Sharma *et al.*, 2017). The R2M (rapid risk assessment to support mitigation) includes a meta-tool for generating expert knowledge elicitation tools (garrettlab.com/r2m).

Dealing with uncertainty about the system characteristics. Sensitivity analysis (or uncertainty quantification) can be used to evaluate how the best management strategies vary with values of a particular set of parameters, such as parameters describing dispersal. With luck, the best strategy may be the same across a range of parameter values. If the selection of the best strategy is sensitive to a particular parameter, that indicates that collecting more data to estimate that parameter better. Another type of uncertainty is about the likelihood of each type of potential long-distance movement. Sensitivity analysis could also evaluate the implications for strategies if particular long-distance movement occurs, even if that movement is apparently unlikely.

Finding the appropriate spatial and temporal resolution for analyses. Another decision for identifying important locations is the resolution needed. Another type of sensitivity analyses may address this point.

Other considerations. Policy makers need to balance a number of considerations, in addition to prioritizing slowing the spread of invasive pathogens. Choices of where to distribute pathogen-free seed may be driven by farmer need, as well. If disease does not spread quickly from one field to another, pathogen-free seed may be particularly important and effective for individual farmers in locations where disease is now widespread. But if farmer need is equal, and disease can spread quickly from field to neighboring field, distributing pathogen-free seed following a strategy to slow an epidemic will benefit all farmers where the disease is not yet present.

Examples of related studies

Characterizing potato seed networks in Ecuador and the importance of locations in potential epidemics (Buddenhagen *et al.*, 2017)

Characterizing sweetpotato seed networks in Uganda, linking trade networks and other dispersal networks, and the importance of locations in potential epidemics (Andersen *et al.*, 2019)

Characterizing banana seed networks in Burundi, and the importance of locations in potential epidemics (Nduwimana *et al.*, 2022)

Management performance mapping to identify where particular management approaches work well (Buddenhagen *et al.*, 2022)

Integrating network analysis, cropland connectivity, and trade network analysis, incorporating expert knowledge elicitation, for potato in the Republic of Georgia (Andersen Onofre *et al.*, 2021)

Characterizing cassava seed networks in Vietnam (Delaquis *et al.*, 2018) and integrating weather-conduciveness in invasion networks to evaluate strategies for managing cassava mosaic disease in SE Asia (Andersen Onofre *et al.*, 2024).

Overview of network analysis in plant disease management and approaches for linking data types for regional management (Garrett *et al.*, 2018, Garrett *et al.*, 2022)

Characterizing postharvest wheat networks (Hernandez Nopsa *et al.*, 2015)

Characterizing soybean rust epidemic networks to identifying strategies for surveillance (Sutrave *et al.*, 2012, Sanatkar *et al.*, 2015)

Impact network analysis to evaluate regional management strategies (Garrett, 2021a, Garrett, 2021b)

Cropland connectivity analysis as a tool for characterizing invasion networks through landscapes (Xing *et al.*, 2020, Keshav *et al.*, 2024)

Characterizing seed degeneration rates at a particular location based on key parameters (Thomas-Sharma *et al.*, 2016, Thomas-Sharma *et al.*, 2017)

Understanding the effects of policies on regional management outcomes (Etherton *et al.*, 2023, Etherton *et al.*, 2025, Etherton *et al.*, 2024, Mouafo-Tchinda *et al.*, 2024)

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