Epidemic network analysis for mitigation of invasive pathogens in seed systems: Potato in Ecuador

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ABSTRACT

Seed system structure defines pathways for the spread of pathogens involved in seed degeneration and influences their ability to supply high quality seed to farmers. We evaluated seed system networks defined by a regional potato farmer consortium (CONPAPA) in Tungurahua, Ecuador. The structure of networks of farmer seed and potato transactions, and the linked network of information about pest and disease management, were estimated based on surveys. We performed a scenario analysis of disease spread in this multilayer network to identify key nodes for sampling and mitigation. The centrality of CONPAPA's leadership group in the network means that disease management interventions, such as training, monitoring and variety dissemination, should target CONPAPA staff and facilities. A market in the largest nearby town, Ambato, was the next most important node. Farmers reported receiving advice about disease and pest management through trusted CONPAPA technical staff. Advice from agrochemical stores was common but viewed as significantly less reliable. Farmer access to information (number and quality of sources) was similar for both genders. Women had a smaller amount of the market share, however. Understanding seed system networks provides a window into options for system improvement that include environmental and societal concerns.

Additional keywords: complex systems, multilayer networks, pests and diseases, seed degeneration, seed networks

Networks of crop seed distribution are an important factor in determining the ecology and spatial distribution of crop plant genotypes (cultivars or landraces), and disease resistance genes, as well as determining the potential for the spread of seedborne disease. Seed systems are human mediated seed distribution networks that encompass biophysical elements as well as all the stakeholders and activities that support the system, including interacting scientific (e.g., breeding, extension), management (e.g., agricultural practices, integrated pest management) and regulatory aspects (e.g., legally certified seed standards; Almekinders et al. 2007; Devaux et al. 2014; Jaffee et al. 1992; Kromann et al. 2017; Thiele 1999; Thiele et al. 2011). Thus, seed systems are best understood as a network of interacting biophysical and socioeconomic elements (Leeuwis and Aarts 2011). Only the state regulated aspects of a system would be considered a "formal" system (Sperling et al. 2013). Seed systems share many traits with other managed ecological systems in which there are larger-scale human institutions driving some system components and individual land managers who make choices about smaller units in the landscape (e.g., farmers or conservation managers). Institutional interventions –or lack thereof– can affect systems indirectly and directly via policy, training, funding or direct management. The relationship between institutional interventions and on the ground management may be more or less predictable, depending on adoption by land managers.

Ideally seed systems provide disease free, disease resistant, high quality seed to farmers, through improved seed processing, multiplication, storage and distribution. Scientists also contribute to seed systems by developing more disease resistant varieties with other positive traits for dissemination through the system. Understanding seed systems can help scientists make meaningful links among epidemiological patterns and socioeconomic factors across a range of scales. While seed transaction networks have sometimes been studied and characterized, there is great potential for developing new approaches to predict the spread of seedborne diseases and help target disease detection efforts, training, treatments and other interventions (Andersen et al. 2017; Hernandez Nopsa et al. 2015; Pautasso et al. 2013; Tadesse et al. 2016). Here we use epidemiological network analysis (Shaw and Pautasso 2014) of a seed potato network to understand and predict disease risk, developing a new type of scenario analysis for interpreting epidemic risk in seed systems.

Efforts to create new seed systems may be only partially successful, especially in developing countries (Devaux et al. 2014; Devaux et al. 2010; Hirpa et al. 2010; Jaffee et al. 1992; Kromann et al. 2017; Panchi et al. 2012; Thiele et al. 2011; Thomas-Sharma et al. 2016). Understanding the structure and function of formal, informal, and mixed seed systems can support the development of more sustainable seed systems. Aspects that determine the degree of seed system utility, sustainability, and resilience include access to and availability of seed, seed quality, cultivar quality (e.g., adapted, disease resistance, and matching user preferences), affordability, and profitability (Sperling et al. 2013). There are tradeoffs in connectivity for farmers, where high connectivity is good for getting access to new varieties and training, but can increase the risk of being exposed to disease. Managing connectivity can help to increase system resilience (Biggs et al. 2012).

Seed system resilience is tested when there are significant stressors or crises, be they environmental (Violon et al. 2016), biotic (e.g. pathogen or pest outbreaks) or socioeconomic (McGuire and Sperling 2013). Though broad categories of threats are predictable, some events may be viewed as crises because they are spatially varied, temporally unpredictable, and may have multiple distinct drivers (e.g. pathogen, drought, conflict and economic crises). Formal seed systems can be “static and bureaucratic” (Lybbert and Sumner 2012) while farmers and markets may be quite adaptable. Single optimal solutions are unlikely. Many development agencies orient their interventions toward the development of demand-driven systems that support a for-profit model of seed supply, believing them more sustainable and resilient (McGuire and Sperling 2013; Sperling et al. 2013), but governments and aid agencies continue to play important roles in subsidized seed systems. A common belief is that diversity improves resilience, in terms of crops and cultivars, or supply channels (McGuire and Sperling 2013). A frontier for plant epidemiology is to better incorporate human decision making about disease management (McRoberts et al. 2011). Seed system development efforts often attempt to foster equitable access by stakeholders to services (Ricciardi 2015), although more needs to be understood about gender effects on access. Epidemiological network analyses can help to identify systemic vulnerabilities related to gender access to quality planting materials, integrated pest management information, and the market for products (Tadesse et al. 2016). Clearly short- and long-term planning could be required to meet challenges, and stakeholders need to be flexible to strike a good balance between sustaining and transforming systems. Trade-offs are likely, with interventions under one scenario or set of stressors potentially being counter indicative in another scenario, or for some stakeholders.

There is always a risk that pathogens can move through a seed system network. Detection of pathogens in the network in a timely manner could allow for mitigation measures to be implemented. Important hubs in the network are obvious points of risk for disease spread, but peripheral nodes could be the entry point for an invasion (Xing et al. 2017). Strategies for dissemination of resistant varieties may need to change depending on network properties. In addition, the spread of endemic pathogens like *Rhizoctonia* spp., or the potential arrival of emerging diseases from distant locations (e.g., *Dickeya* spp.; Czajkowski et al. 2015;

Czajkowski et al. 2011; van der Wolf et al. 2014) can be modeled and mitigation strategies tested using a multilayer network analysis (Garrett 2012, 2017). Our objectives in the analysis presented here are as follows: (a) characterize cultivar dispersal through a potato seed system in Ecuador defined by the potato consortium CONPAPA; (b) determine whether gender is associated with different types of network transactions or access to information; (c) develop a risk assessment for disease vulnerability of individual network nodes and examine their utility as control points for pathogen mitigation measures; and (d) explore a scenario where the CONPAPA leadership group no longer plays an organizing role in the seed system, and existing seed multipliers must compensate for its absence.

MATERIALS AND METHODS

Study system: the CONPAPA potato seed system in Tungurahua, Ecuador. There are approximately 50,000 ha of potato production in Ecuador, with 97% of this area located in the Andes, and 87.5% of farms being less than 10 ha in size (Devaux et al. 2010). It is possible to produce tubers all year, which has created a market that expects fresh potatoes for consumption year round (Devaux et al. 2010). Seed is typically reused, i.e., tubers from the previous season are planted in the next. This makes potato subject to seed degeneration and associated yield loss (Thomas-Sharma et al. 2016). Seed degeneration refers to the reduction in yield or quality caused by an accumulation of pathogens and pests in planting material over successive cycles of vegetative propagation. The national agricultural research institute, INIAP (*Instituto Nacional de Investigaciones Agropecuarias*) is the only agency in Ecuador registered to produce formal basic seed potato. However, according to a 2012 estimate, less than 3% of the seed potato used in Ecuador is from the formal system (Thomas-Sharma et al. 2016). Two preferred cultivars for farmers in the Ecuadorian Andes are INIAP-*Fripapa* and *Superchola*. However, farmers also grow many other cultivars, such as INIAP-*Gabriela*, INIAP-*Catalina*, and *Diacol-Capiro*. Seed is produced by INIAP from pre-basic seed, which are mini-tubers produced from *in-vitro* plants. Basic seed, the next generation, is multiplied in the field by INIAP or associated farmers. The next three generations of seed include the following three seed categories; registered seed (*semilla calidad I*), certified seed (*semilla calidad II*), and selected seed (*semilla calidad III*), and are produced in the field by seed producers. Trained seed producers form a part of the Consortium of Potato Producers (CONPAPA) and produce seed for member farmers (Fig. 1). The yield increase associated with each of these three categories has been reported to be 17%, 11% and 6%, respectively, compared to the seed produced by the farmers in the informal system (Devaux et al. 2010), although these estimates are low compared to the potential (30%) yield increases reported globally from the use of quality seed potato (Thomas-Sharma et al. 2016).

Viruses such as *Potato virus Y* (PVY), *Potato virus X* (PVX) and *Potato leafroll virus* (PLRV), are major causes of seed degeneration in many parts of the world (Frost et al. 2013; Salazar 1996). Additionally, depending on the geographic region, fungi, bacteria, nematodes, phytoplasmas, and insects can also play important roles in potato seed degeneration (Thomas-Sharma et al. 2016). In high-elevation potato production regions of Ecuador, *Rhizoctonia solani* is a major cause of seed degeneration (Fankhauser 2000), while in many other tropical and subtropical countries *Ralstonia solanacearum* is a major concern (Mwangi et al. 2008). Adding to this complex etiology, the rate of degeneration is also highly variable across geographical regions. Factors such as host physiology, vector dynamics, environmental variability, and the choice and success of management strategies can affect the rate of degeneration (Thomas-Sharma et al. 2017; Thomas-Sharma et al. 2016). In high elevation regions, for example, lower temperatures can limit vector activity and pathogen multiplication while also influencing host physiology that limits pathogen transmission into daughter tubers (Bertschinger 1992; Navarrete et al. 2017). In at least one case the presence of *Potato yellow vein virus* (PYVV) was associated with small yield *improvements*, possibly via some sort of competitive interaction with other viruses (Navarrete et al. 2017). In the Andes, evidence suggests virus transmission to daughter tubers is usually incomplete with between 30 and 75% of tubers being infected (Bertschinger et al. 2017). Similarly, the application of management strategies such as resistant cultivars, certified seed material and other on-farm management strategies, individually and/or collectively, can affect the spread of disease epidemics in a region (Thomas-Sharma et al. 2017). A better understanding of these inter-related factors could contribute to the design of an integrated seed health strategy for a geographic region (Thomas-Sharma et al. 2016).

Established in 2006, CONPAPA has a membership of ca. 300 farmers in central Ecuador (principally in Tungurahua, Chimborazo and Bolivar Provinces). This organization is the current realization of various aid and governmental efforts to improve livelihoods for small-scale potato farmers (Kromann et al. 2017). It aims to support small-scale farmer associations that produce seed potato and potato for consumption, through training, provision of quality assessed seed, and by processing and marketing produce. It cleans and processes produce (e.g., for chips and fresh potato) in regional processing facilities. It also sells potato on behalf of members. Annual mean, production yield of table potato in CONPAPA (Tungurahua) ranges between 15 and 20 metric tons per hectare, with production levels being influenced by management, variety, time of year, and the number of generations since the seed was sourced from basic seed. Average production reported by CONPAPA is higher than the 9.5 metric tons per hectare that has been reported for Ecuador as a whole (Devaux et al. 2010). CONPAPA in Tungurahua reported (www.conpapa.org) that it supplies more than 25 tons of potato for consumption per week to meet market demand. Importantly, CONPAPA has trained seed multipliers who provide seed for redistribution to member farmers.

Survey methods. This study focuses on 48 farmers who are members of CONPAPA in the Tungurahua province. This is 66% of the 72 heads of households registered as members in this region (Montesdeoca, pers. comm.). However, the 48 farmers in this study represent a census of all the active farmers at the time of this study. Farmer network sizes and farmer activity can change as farmers opportunistically pursue a variety of alternative livelihoods from year to year, e.g., construction or service jobs, in response to changing conditions (in good and bad years; Violon et al. 2016). A questionnaire was completed by scientists via on-farm voluntary interviews of 48 farmers in the CONPAPA district of Tungurahua over three weeks in November and December, 2015. In addition to demographic information, the questionnaire documented the seed sources, cultivars planted, volume bought, and price paid for the last three planting periods, as reported by farmers. Information was also collected about the sale or use of potato for food, including destination, cultivar, volume, and price received. Information was recorded about the principal pests and diseases that the farmers reported. Farmers were also asked to describe their sources of advice regarding integrated pest management, and the confidence they had in that advice. In some cases, there was missing data related to volume or price information.

Data analysis and modeling. Networks of seed and potato transactions between the farmers and other stakeholders were analyzed using igraph (Csárdi and Nepusz 2006) in the R programming environment (R Core Team 2016). For cases where farmers reported a transaction but did not give volume information, links were depicted in the network as dotted lines and given a minimum visible width. Missing price and volume data were not treated as zeroes, but were omitted from the calculation of means and percentages. Missing volume and price data are reported in the results. An adjacency matrix based on reported sales was constructed, as well as an adjacency matrix based on reported information flow. Transaction counts, volumes and prices were compared with respect to potato cultivar and farmer gender, based on percentages, means, and one-sided Wilcox tests (using the wilcox.text function in R). The frequency with which common pests and diseases were reported by farmers, including diseases responsible for seed degeneration, is reported overall and by gender (where gender differences were tested using chi-squared tests).

Rating the importance of nodes for sampling efforts. An important question for optimizing management of potential invasive pathogens in a seed system, is where the most important geographic nodes are for sampling to detect disease (both in the field and in the harvested tubers). Sampling some nodes will result in rapid detection of the pathogen, while sampling other nodes will only detect the pathogen when it has already spread widely in the network. In a scenario analysis, disease spread was simulated across the seed and table potato distribution network, where the network was based on reports aggregated across the last three plantings (and actual or anticipated harvest dates ranged from May 2014 to May 2016). In the simplest version of the analysis, each node was considered equally likely to be the point of initial introduction of a pathogen into the seed system network. Another version of the analysis drew on the structure of the communication network. In this case, the probability that a pathogen would be introduced into the network by a given farmer was weighted by a farmer's access to information about pest and disease management (IPM), as a proxy for farmer ability to respond effectively. During the survey interviews, farmers described their sources of information for pest and disease management, and the trust that they placed in these. The probability that infection would be introduced into the network by a given farmer was weighted by a function of the number and quality of information sources about IPM. The idea is that a well-informed farmer (with high node in-degree in communication networks, or with highly trusted sources) will be less likely to be a point of disease establishment (with the probability of disease entering the network at a node set to 0.8 to the power of the number of sources for that node). “In-degree” is the number of directed links that point toward a node. In this case, it indicates the number of sources of information that a farmer reports. This simulation generates an estimate of the number of nodes infected before the disease will be detected at each potential sampling node, given that each potential starting node has a weighted probability of being the initial source. The output allows us to estimate relative risk in terms of the number of nodes that would be infected if only the node in question were monitored.

Scenario analysis where the CONPAPA leadership group does not supply seed. The CONPAPA leadership group is clearly central to this seed system, a key “cutpoint”, or node whose removal creates multiple disconnected components in the network. We explore how resilient the seed system might be if the CONPAPA leadership group were removed. How would other nodes need to compensate for its absence? We compared the scenario where the CONPAPA leadership group provides seed to farmers and multipliers with a scenario where it does not have a role in seed provision. For this alternative scenario we evaluated the reported volumes for seed transactions over three plantings. Then where the CONPAPA leadership group provided basic seed to multipliers we replaced these transactions with INIAP, the government agency that provides basic seed to CONPAPA (GovtAgency1 in the Figures). Finally, where farmers sourced their seed from the CONPAPA leadership group, they instead sourced their seed from the geographically nearest multiplier (Farmers 7, 27, 34 and 46). The alternative scenario thus maintains the same transaction volumes that were reported but removes the CONPAPA leadership group as the go-between replacing these with the most plausible alternative. We evaluate the structure of this new network.

RESULTS

Seed system: overview. The seed system in this study is centered around the CONPAPA leadership group in Tungurahua, which provides and receives seed and table potato from member farmers (Fig. 2). A total of 1157 quintals (100 lb bags), or 52 *t* (metric tons), of seed was reported as used by farmers in the most recent planting, where CONPAPA provided 47%, and 36% was self-supplied or reused seed, while the remaining 16% came from other sources. CONPAPA was reported as receiving only 7 *t* of seed from trained (male) seed multipliers. Only two women (F7 and F46) reported providing seed (Puca, Fripapa and Superchola) to CONPAPA during this interval, although farmers 7, 8, 10, 19, 36, 40, 46, and 47 are women trained to be seed multipliers. Of the 48 farmers that reported buying or selling potato or seed, 16 (33%) were women. Farmers reported a total of 503.9 *t* potato being sold, with CONPAPA buying 414.7 *t* (82%) of potato (where 28% of this was from women). Farmers reported selling 85.3 *t* directly to local markets, and one farmer reported selling 3.2 *t* directly to a restaurant. It is important to note that 262 transactions were reported in the most recent season but interviewees did not provide volume for 71 transactions or price information for 58 transactions (including self-supplied seed transactions). On a per transaction basis there was a difference between the volume of potato product sold by women (mean=97 quintals) and men (mean=165 quintals; Wilcox test (one sided alternative=less), W=1159 p-value = 0.03). There was also evidence for a difference in per transaction volume for seed between women and men, with means of 5.6 and 16.2 quintals respectively (Wilcox test, one sided alternative=less, W = 127.5, p-value = 0.003). There was not evidence for a difference in per transaction prices for table potato for women and men, with means of \$13.5 and \$12.5 USD, respectively (Wilcox test (one sided alternative=greater), W=1456 p-value = 0.16). Prices were infrequently reported. These analyses are based on the most recent season. Unreported here is the movement of pre-basic seed to CONPAPA from INIAP. CONPAPA in Tungurahua may also receive seed from CONPAPA multipliers outside of the region. Farmers reported replacing seed every 3-4 seasons. The evidence here is that improved or healthy seed is bought but grown alongside seed saved from previous plantings.

Seed system: analysis by variety. Overall, while farmers planted on average two cultivars, the median use was just one. In other words, about half of the farmers planted a single cultivar, while the other half planted 2 to 5 different cultivars. Ranking the use of cultivars by the numbers of farmers using them matches almost exactly the ranking by number of transactions per cultivar (Table 1), which suggests that the high number of transactions for the main cultivars is driven by their overall popularity. The 3 most commonly planted cultivars, according to these criteria, are Superchola (33% of farmers planted it, its product transactions represent 36% of all transactions, and its seed transactions 32%), Fripapa (17%, 20%, 22%) and Puca (13%, 10%, 10%), in respective order of ranking.

A second comparison of the total volume of transactions by cultivar, shows that the three most frequently exchanged cultivars are also the ones with most transacted volume (Table 2). Indeed, Superchola's transacted volume represents 40% of all volume transacted in terms of product and 35% in terms of seed. Fripapa's seed volume transacted is higher than the product volume transacted 26% vs. 21%. Finally, Puca variety volume represents 9% in terms of product and 7% in seed. Interestingly, two varieties that are not used by a majority of farmers —Carrizo and Victoria—represent 8 and 7% in terms of volume transacted, almost as much as Puca. This related to a few farmers providing large volumes of product to a few non-CONPAPA buyers. Finally, the percentage of volume transacted of Unica's seed is larger than Puca's seed volume (9%) and Natividad is as large as Puca's (7%).

IPM information. Farmers largely reported obtaining information about integrated pest and disease management (IPM) from the CONPAPA leadership group (mean in-degree for information received by farmers was 3.5 overall; Fig. 3). There was not evidence for a difference (t-test, p-value=0.39) between male (3.7) and female (3.2) in-degree with respect to number of information sources reported. Importantly, farmers frequently reported receiving information from agrichemical stores (green squares in Fig. 3). Family members also provided important sources of information about IPM (Fig. 3). A quarter of the women reported their husband as a source of information for IPM, but no men reported that their wife was a source of IPM information. Farmer assessed trust levels could range between zero and five. There was some evidence for a difference in mean trust levels reported by men (3.4) and women (3.8) (t-test, p-value=0.08). The main sources of information were CONPAPA and agrochemical stores, where the mean trust level farmers reported for all stores was 3.01 compared to 4.4 for CONPAPA (t-test, p-value=1.873e-07). Only one farmer reported the internet as an important source of information about management.

The most frequently reported diseases and pests were potato late blight, Andean potato weevil, and potato black leg. Despite prompting, viruses were reported by only one percent of farmers (Table 3). Slugs and leaf miners were more frequently reported as a problem by women than men, though rates were low (Table 3).

Disease risk in the system. Under the scenarios we evaluated (Fig. 4A-C), the CONPAPA leadership group is obviously the most effective place to monitor in order to detect a disease before it has spread far. This reflects its central role in the network. Similarly, several stakeholders and farmers at the periphery of the seed and potato network tend to be poor locations for detecting potential disease in every simulation. This is because they only provided seed rather than receiving seed or product (yellow) in this network, or had low in-degree (orange or light orange; Fig. 4A-C). Weighting risk of establishment based on the quality of the information sources about IPM causes some nodes at the periphery to become more important for monitoring (colors are yellow in the equal weight scenario (Fig. 4A) versus darker orange (Fig. 4B-C). In the scenario where farmer ability to prevent establishment was weighted by the number of sources of information (Fig. 4C), we find that sampling “Market1” will lead to relatively rapid detection of an incipient disease. This is the market in Ambato, the largest town in the region, which has the highest reported in-degree of any of the five markets.

Scenario analysis where the CONPAPA leadership group does not supply seed. We compared the scenario where the CONPAPA leadership group provides seed to farmers and multipliers, and multipliers sell their seed to CONPAPA (Fig. 5A), with a scenario where the CONPAPA leadership group does not have a role in seed provision (Fig. 5B). In this analysis, based on a role of geographic proximity to multipliers, we see that multipliers do not have equal access to all the seed buying farmers in the market (Fig. 5B). CONPAPA’s role as distributor and organizer of seed distribution (Fig. 5A) may result in all farmers having access to seed from any of the multipliers.

DISCUSSION

In this analysis, we demonstrate an approach for identifying priorities for monitoring plant health in seed systems. In this relatively small and centralized seed system, disease monitoring at CONPAPA processing facilities is obviously a high priority for detection of incipient disease, because it receives high quantities of table potato (it has high in-degree), and is the source of most of the improved seed (it has high out-degree). Monitoring at the market in Ambato could also be relatively effective. Similarly, mitigation measures during a disease outbreak – such as dissemination of new resistant cultivars, training, or treatment of fields – would best focus on these nodes in the network. Secondarily, the analysis identifies other nodes in the network that can play a role in sampling and mitigation, offering a method to prioritize among these nodes for sampling in the field and postharvest. Network models provide a window into the epidemiology of plant diseases and strategies for efficient sampling for plant epidemic surveillance (Chadès et al. 2011; Harwood et al. 2009; Hernandez Nopsa et al. 2015; Sanatkar et al. 2015; Sutrave et al. 2012). We find that the CONPAPA leadership group and the Ambato market (Market1 in the Figs. 2, 4 and 5) would be effective points for monitoring. By this we mean that if an invasive disease entered the network from any node, it would tend to spread less through the network before it was detected if sampling was at these key nodes (Fig. 4). Secondary nodes identified as having some sampling value could also be ranked and prioritized to supplement sampling of the two key nodes. An undetected disease at the CONPAPA leadership group or the Ambato market would spread relatively quickly through the network.

Information about the dispersal of particular cultivars through the seed network can provide insights into the likelihood of disease transmission, if cultivars have resistance to a particular disease or if seed of a new cultivar is inadvertently a source of an introduced pathogen. Good information is available about cultivar susceptibility to *Phytophthora infestans* (e.g., Forbes 2012; Kromann et al. 2009), but studies of viral infection rates for cultivars used in Ecuador rarely consider more than a few varieties. Seed born viral incidence, especially PYVV, PVS, and PVX were reported in one study for some of the cultivars used by CONPAPA farmers, (from lowest to highest incidence: Fripapa, Gabriela, Yana, Unica, Dolores and Chaucha), but per plant yield effects were negligible (Navarrete et al. 2017). High levels of PVY infection have been reported occasionally in Ecuador for Superchola and Fripapa, but viral incidence seems to depend on complex interactions between ecological conditions, on-farm management practices, vector biology, seed sources and cultivar (Navarrete et al. 2017). Yana was reported as extremely resistant to PLRV and PVY, while Unica was resistant to PVY but susceptible to PLRV (Acquisition and Distribution Unit 2009).

In Ecuador seed degeneration, mostly attributable to viruses, can have important effects on yield (7-17% loss, or even *gains* in the case of PYVV), but virus incidence is often low at high altitude, even if levels vary widely from site to site (Peter Kromann unpublished; Devaux et al. 2010; Navarrete et al. 2017; Panchi et al. 2012). It appears that the problem is still understudied, under-appreciated or rarely recognized. For example, only one farmer reported viruses as concern in this study. Yield losses of ±30% are common elsewhere in the world (Thomas-Sharma et al. 2017). A large share of farmers report that they draw on advice from agrochemical stores. Importantly, and perhaps with good reason, farmers do not report trusting them highly as a source of information compared to technical staff working for CONPAPA. Clearly training these store owners about disease and pest management has the potential to be an effective measure to improve management outcomes for farmers inside and outside of the consortium. However, it is unclear if training store owners would result in improved advice and the sale of appropriate pesticides, or if potential economic conflicts of interest would influence the quality of their advice. We modelled disease spread as a function of farmer information quality and sources with respect to IPM. This usefully joins the network for the spread of information about management with the biophysical network (seed network and disease epidemiological models).

Women made up a third of the farmers and reported selling smaller volumes of potato product on average. Clearly, they are making less money from potato farming than their male counterparts. There were limited differences in gender access in terms of the number of information sources, or the trust they placed in their information sources. It would be interesting to determine if this is typical, or if less formal seed system networks in the region reveal larger gender effects.

Modeling disease spread in seed and potato transaction networks can indicate the structural effects of seed degeneration. In the case of viruses, most are transmitted to daughter tubers and will be hitchhikers for each transaction of seed or potato. It is clear that some spread can always occur via the seed system. Network dynamics change from year to year, so scenarios should consider temporal dynamics (e.g., the different effects of wet and dry years; Violon et al. 2016). A more nuanced approach would also take into account different suites of viruses, and the way their transmission rates from infected mother plants to daughter tubers vary depending on varietal and environmental conditions (Bertschinger et al. 2017). Thus node (farmer) vulnerability to infection could also be modeled in terms of specific diseases and scenarios, and could account for varietal differences in resistance.

A key point to consider for potato seed systems is transmission mechanisms. As a case in point, *Potato virus X* (PVX) and *Andean potato mottle comovirus* (APMoV) are transmitted by contact while others such as *Potato virus Y* (PVY) and *Potato leafroll virus* (PLRV), *Potato yellow vein virus* (PYVV) are vectored by aphids (Fankhauser 2000). Networks could include both spread through seed transactions, and spread based on the spatial proximity of farm pairs (as a proxy for the probability of vector movement between a pair). In this study, farms were widely dispersed with both potato and other crops being grown in the intervening areas. Inoculum sources could come from non-CONPAPA potato farmers, or non-potato host species. To realistically model seed infection by vectors would require detailed disease specific data sets that support accurate estimation of dispersal kernels, including the effects of infected volunteers and tuber waste from potato harvesting.

Implementation of fully formal seed systems in many developing countries is beyond the available resources of the agencies and farmers involved. Reaching the quality levels enshrined in statutes may not be feasible. This means that most potato farmers in developing countries operate wholly within informal seed systems. The CONPAPA seed system has been described as a mixed formal and informal system (Kromann et al. 2017). CONPAPA defines seed quality explicitly in three levels with real quality control measures in place. This means farmers can buy improved seed of known quality with achievable quality levels for the stakeholders involved. The adoption of this alternative seed quality assessment scheme has been incorporated into formal Ecuadorian seed regulation (Kromann et al. 2017), thus formalizing the standards CONPAPA developed. This has been described as “providing flexibility” (FAO 2006) and is recommended as a means of achieving greater confidence by stakeholder and adoption of improved seed. Therefore, the CONPAPA seed system could be characterized as predominantly formal with the quality declared seed sources accounting for 47% of the seed in this study. In practice, the mean time between seed replenishment was reported to be approximately 3-4 seasons, though we also found that improved seed are often planted together with reused seed in any given year. This is a much higher rate of improved seed use than the 2-3% formal seed sources reported for Ecuador and Bolivia (Almekinders et al. 2007; Devaux et al. 2010).

CONPAPA's cooperative model, combined with the seed quality assessment system could help to overcome issues of access and household economic insecurity that determined participation in formal seed systems elsewhere (Okello et al. 2016). This could have important consequences since potato is becoming increasingly important as a staple crop in areas where informal seed systems prevail (Devaux et al. 2014).

We evaluated the CONPAPA structure as a first step to support improved sampling, IPM, risk assessment for pathogen and pest movement, and farmer decision-making. Identification of key control points that influence the success of seed systems (e.g., farmers, farms, information sources) supports enhancement of the system (e.g., maximizing the distribution of new seed varieties using fewer distribution channels, managing disease outbreaks, and targeting improvement of communication and infrastructure). Resources can be invested in particular nodes to improve practices to control pest and disease outbreaks, leading to improvements in the seed system. We present results for the CONPAPA system as part of an ongoing project to develop general recommendations for improving seed system structure. While we illustrate here how a seed system could potentially be resilient to removal of a key node (Fig. 5), the temporal and structural dynamics of seed systems such as CONPAPA need to be better understood to anticipate how they will react to important stressors, and to develop strategies for reducing disease risk while increasing availability of improved varieties.

Seed system and network analyses provide one window into global change phenomena encompassing environmental and societal concerns. The adoption of formal seed systems is inherently a risk avoidance measure that aims to increase productivity and improve economic outcomes for farmers, but the implications are wide reaching. Global change in land use, land cover and biodiversity is often mediated through agricultural practices, development and trade.

Links are easily made between seed systems and land use change, agrochemical use, biodiversity, climate change, and invasive species more broadly, in addition to disease impacts. Local seed systems such as the one in this study are linked internationally via plant breeding networks, through which resistance genes may be distributed, with the associated need to manage connectivity for movement of pathogens (Garrett et al. 2017). Network analysis and a systems approach can be used to expand our understanding of interacting biophysical, socioeconomic and informational elements, and to put management interventions into their proper context at local and regional scales.

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Tables

TABLE 1. The number of transactions and number of farmers using each cultivar for the current season, as reported in November 2015 (with percentages).

Cultivar	Total transactions	Seed potato		Table potato		No. Farmers using the cultivar	
Superchola	90	40	32%	50	36%	31	33%
Fripapa	56	28	22%	28	20%	16	17%
Puca-shungo	27	13	10%	14	10%	12	13%
Yana-shungo	17	9	7%	8	6%	8	8%
Unica	16	7	6%	9	7%	6	6%
Carolina	13	6	5%	7	5%	4	4%
Victoria	10	4	3%	6	4%	4	4%
Gabriela	8	3	2%	5	4%	3	3%
Chaucha	7	4	3%	3	2%	3	3%
Carrizo	6	3	2%	3	2%	2	2%
Suprema	4	2	2%	2	1%	2	2%
Americana	2	1	1%	1	1%	1	1%
Natividad	2	2	2%	0	0%	1	1%
Norteña	2	2	2%	0	0%	1	1%
Tulca	2	1	1%	1	1%	1	1%

TABLE 2. Volume of seed (quintals) and product exchanged (with percentages).

Variety	Total volume				Volume per transaction	
	product		Seed		Product	Seed
Superchola	4580	40%	425	35%	143	11
Fripapa	2405	21%	323	26%	172	15
Puca-shungo	999	9%	80	7%	111	7
Carrizo	960	8%	66	5%	480	22
Victoria	760	7%	48	4%	190	12
Unica	600	5%	116	9%	200	19
Carolina	470	4%	79	6%	118	13
Yana-shungo	350	3%	43	3%	58	5
Gabriela	90	1%	6	0%	45	3
Chaucha	80	1%	16	1%	27	5
Suprema	15	0%	21	2%	15	11
Americana	0	0%	1	0%	.	1
Tulca	0	0%	0	0%	.	.
Natividad		0%	90	7%		45
Norteña		0%	0	0%		.

TABLE 3. Pests and diseases reported by farmers in Tungurahua, Ecuador, in order by the frequency of reports. Pests and diseases known to cause seed degeneration are indicated.

Pathogen/disease or pest	Causing degeneration	Women reporting	Men reporting	% farmers
Phytophthora infestans (Late blight)	Yes	15	30	94
Premnotrypes spp. (Andean potato weevil)	Yes	10	26	75
Rhizoctonia solani (Potato black leg)	Yes	7	16	48
Puccinia pittieriana (Common rust)	No	6	12	38
Epitrix spp. (Potato flea beetles)	Yes	3	9	25
Phtorimaea operculella, *Symmestrichema tangolias*, *Tecia solanivora* (Potato moths)	Yes	4	4	17
Fusarium spp. (Fusarium rot)	Yes	1	6	15
*Liriomyza spp.** (Leaf miner)	Yes	5	2	15
Slugs*	No	4	0	8
Frankliniella tuberosi (Thrips)	Yes	2	1	6
Nematodes	Yes	1	1	4
Spongospora subterranean (Powdery scab)	Yes	1	1	4
Septoria lycopersici (Annular leaf spot)	No	0	1	2
Viruses	Yes	1	0	2
White fly	Yes	1	0	2

Gender differences (*) are significant in a Chi square test (a=0.05, df=1)

Figures

Fig. 1. Potato production by farmers in the CONPAPA seed system in Tungurahua Province, Ecuador (photos: J. F. Hernandez Nopsa).

Fig. 2. A seed system transaction network in which nodes represent 48 farmers associated with CONPAPA in Tungurahua, Ecuador, along with other institutions and individuals linked with them. Links indicate potato movement, and are weighted by the volume (proportional to line thickness) of seed potato and table potato bought, sold, used or traded by farmers. Data are from the most recent season reported in November 2015. Black lines indicate seed, and gray lines represent potato for food consumption. Self-loops represent seed produced on-farm. Dotted lines represent transactions where volumes were not reported.

Fig. 3. A network depicting farmer-reported information sources for integrated pest and disease management (IPM). Link thickness is proportional to the reported level of trust that the farmer has in that source of information.

Fig. 4. Disease invasion is simulated with initial infection starting at a random node and proceeding through the network defined by farmer transactions for seed (black) lines and table potato (grey). Link widths are scaled to volume of transaction. This network represents the last two seasons as well as the current season reported in November 2015. The risk at each node is evaluated in terms of the number of nodes that would become infected before the disease was detected at that node, if it were the node being used for monitoring. Monitoring a low risk node (blue) would mean that only a small number of nodes become infected before disease is detected at that node. Three scenarios were evaluated, where the probability/risk of the disease starting at a given farmer node is weighted differently for **A,** all farmers are equally likely to be an initial source of spread; for **B,** risk of being an initial source decreases as the maximum quality of

information increases (per the IPM information network in Fig. 3); and for **C,** risk of being an initial source decreases based on the number of information sources (node in-degree, not including self-loops) as depicted in the IPM information network in Fig. 3.

Fig. 5. A scenario analysis evaluating potential compensation in the system if the CONPAPA leadership group no longer played its central role. The figure compares the current scenario, where it provides the majority of seed (**A),** versus a hypothetical scenario where farmers get their seed from the nearest seed multiplier **(B),** and CONPAPA no longer plays a role. **A,** Seed transactions weighted by the volume based on reports from the last three plantings, including CONPAPA. **B,** Seed transactions weighted by volume in a scenario where seed normally going from CONPAPA to multipliers was replaced with seed from the government agency (INIAP). Seed that went from the CONPAPA leadership group to farmers is now provided by the nearest multiplier. Active multipliers are farmers 7, 27, 34 and 46.

Fig. 1.

Fig. 2.

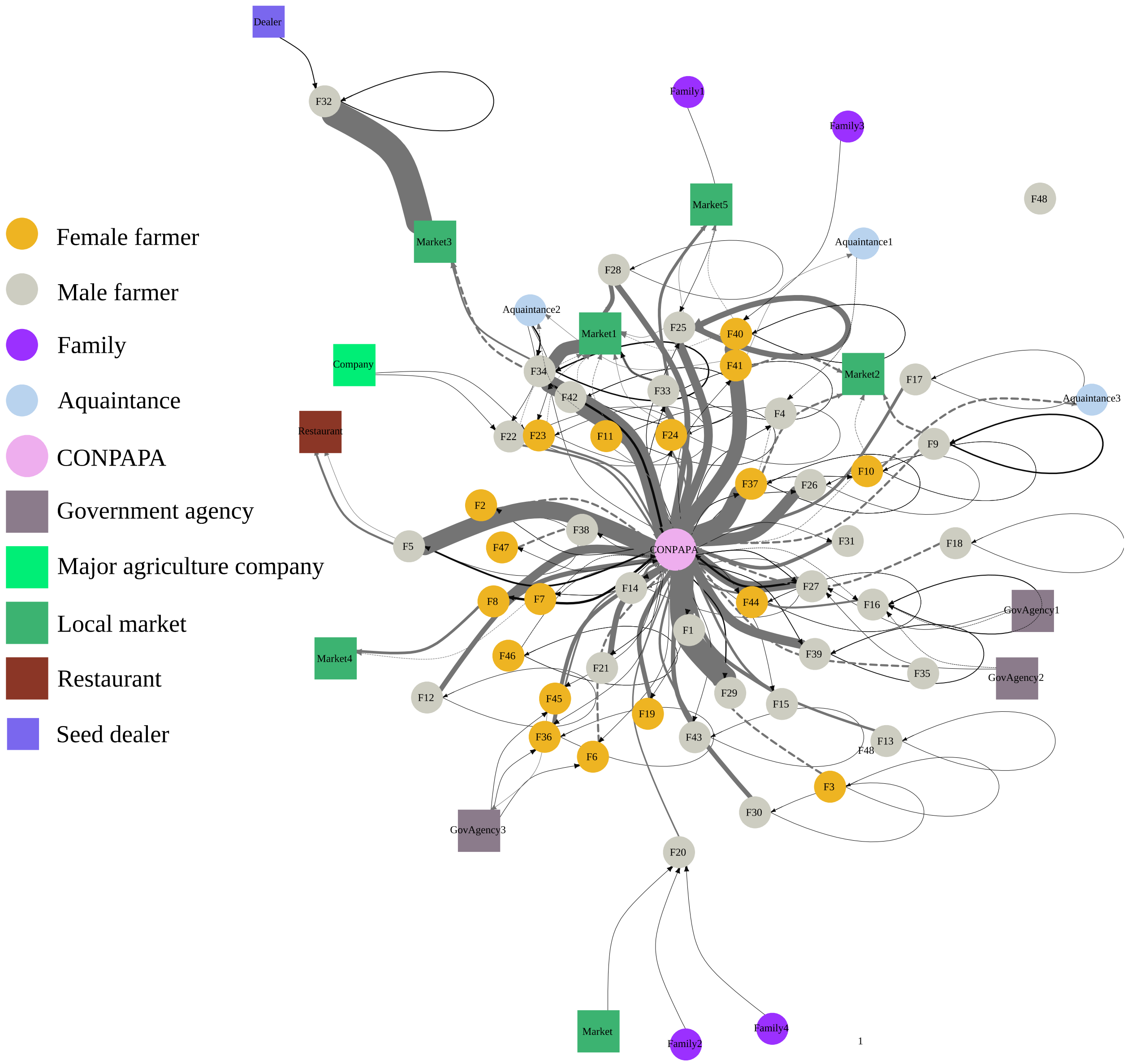
Female farmer
Male farmer
Family
Aquaintance
CONPAPA
Government agency
Major agriculture company
Local market
Restaurant
Seed dealer
Dealer
F32
Market3
Family1
Family3
Market5
F48
Aquaintance1
F28
Aquaintance2
Market1
F25
F40
F41
Market2
F17
Aquaintance3
Company
F34
F42
F33
F4
Restaurant
F22
F23
F11
F24
F9
F10
F37
F26
F2
F38
F5
F47
CONPAPA
F31
F18
F8
F7
F14
F27
F44
F16
GovAgency1
F1
Market4
F46
F39
F21
F35
GovAgency2
F12
F45
F29
F15
F19
F36
F43
F13
F6
F3
F30
GovAgency3
F20
Market
Family2
Family4

Fig. 3.

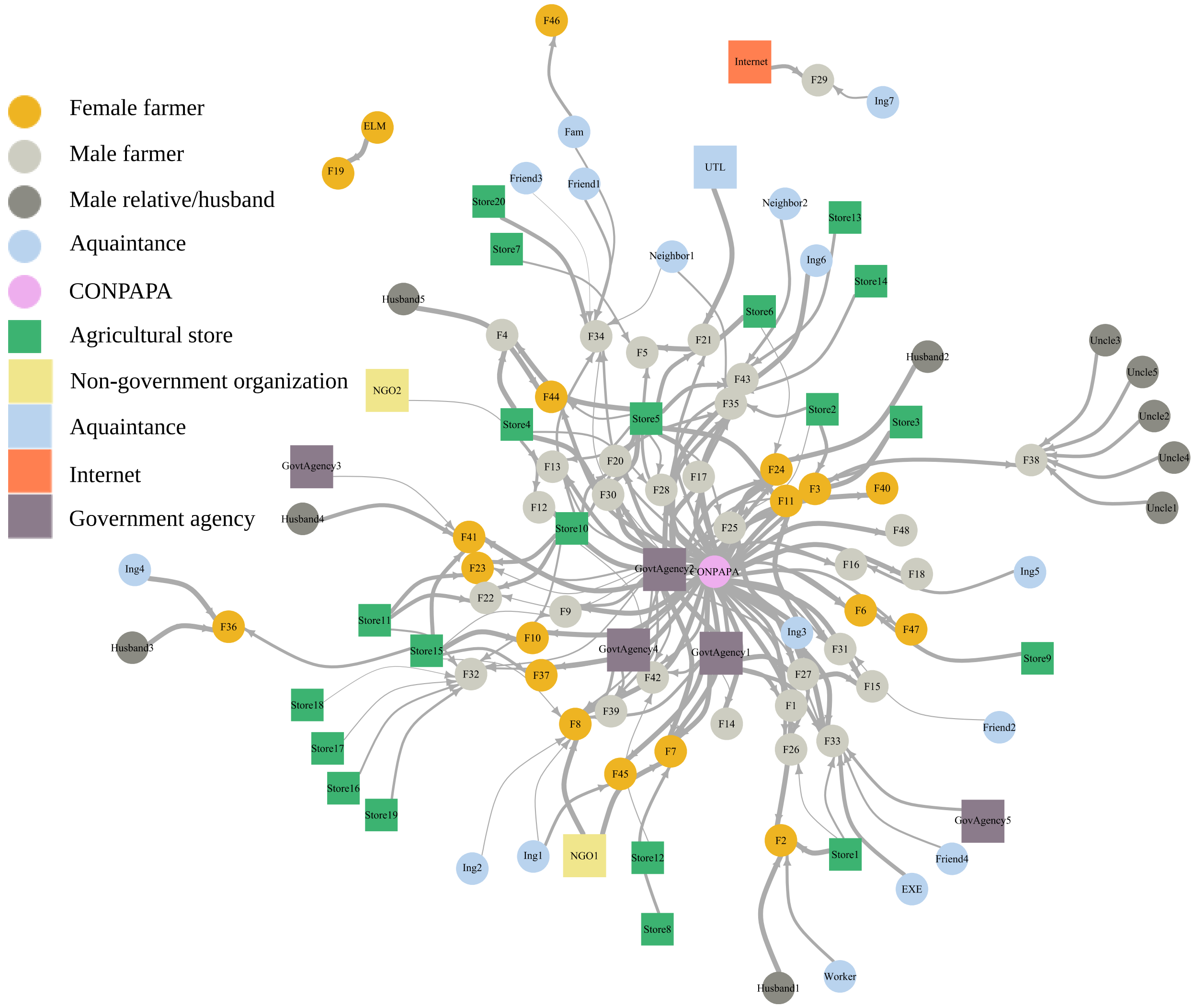
Female farmer
Male farmer
Male relative/husband
Aquaintance
CONPAPA
Agricultural store
Non-government organization
Aquaintance
Internet
Government agency
F46
Internet
F29
Ing7
ELM
F19
Fam
Friend3
Friend1
UTL
Store20
Neighbor2
Store13
Store7
Neighbor1
Ing6
Store14
Husband5
Store6
F4
F34
F5
F21
Husband2
Uncle3
Uncle5
F43
NGO2
F44
F35
Store2
Store3
Uncle2
Store4
Store5
F38
Uncle4
GovtAgency3
F13
F20
F17
F24
F3
F40
Uncle1
F30
F28
F11
F12
Husband4
Store10
F25
F48
F41
GovtAgency2
CONPAPA
F16
F18
Ing5
Ing4
F23
F22
F9
F6
F47
F36
Store11
Ing3
Husband3
F10
GovtAgency4
GovtAgency1
F31
Store15
Store9
F32
F37
F42
F27
F15
Store18
F39
F1
Friend2
F8
F14
Store17
F33
F26
F7
F45
Store16
GovAgency5
Store19
F2
Store1
Friend4
Ing1
NGO1
Store12
Ing2
EXE
Store8
Worker
Husband1

Fig 4. (A)

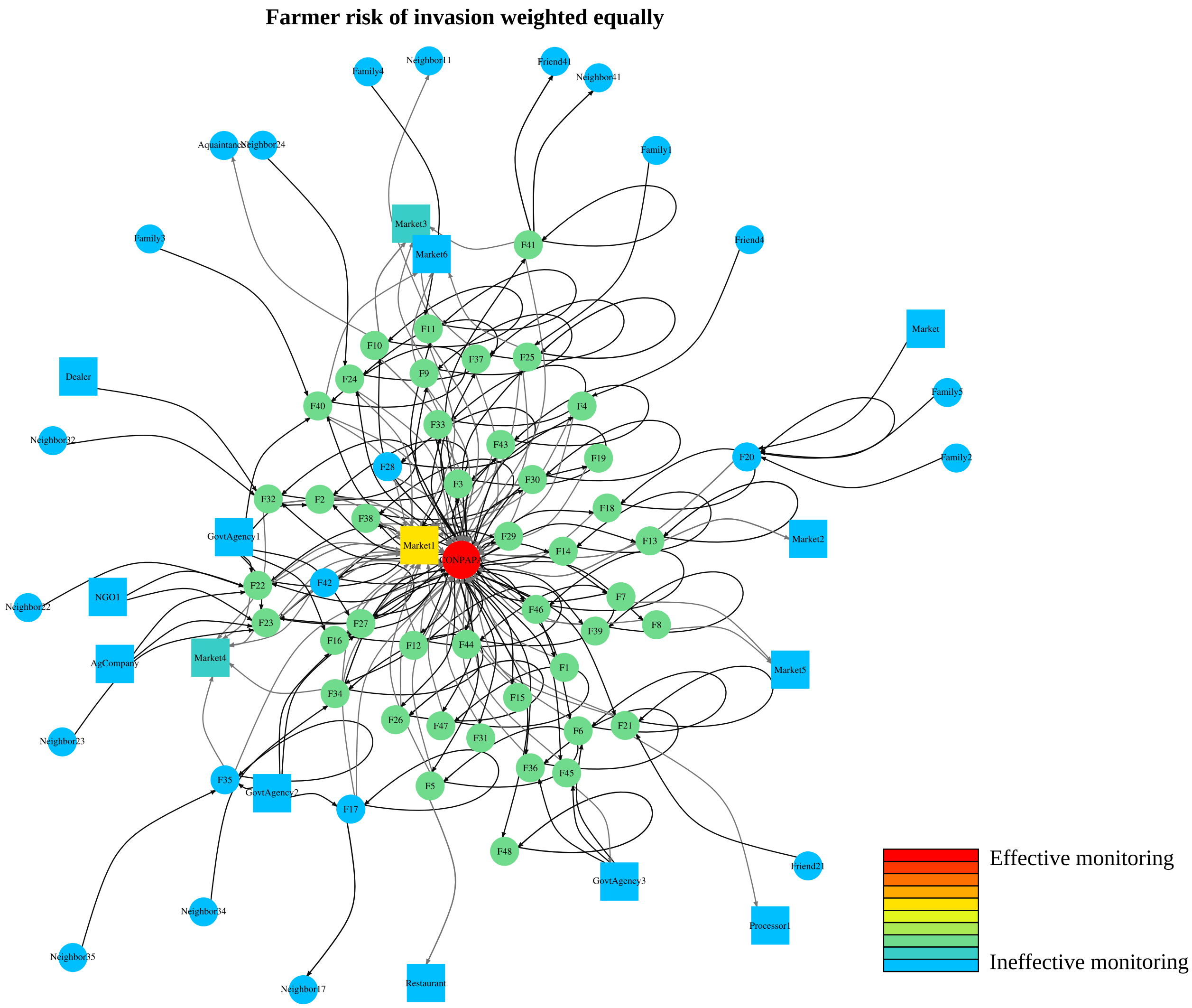
Farmer risk of invasion weighted equally
Effective monitoring
Ineffective monitoring
CONPAPA
Market1
Market
Market2
Market3
Market4
Market5
Market6
GovtAgency1
GovtAgency2
GovtAgency3
NGO1
AgCompany
Dealer
Processor1
Restaurant
Family1
Family2
Family3
Family4
Family5
Friend4
Friend21
Friend41
Neighbor11
Neighbor17
Neighbor22
Neighbor23
Neighbor24
Neighbor32
Neighbor34
Neighbor35
Neighbor41
Aquaintance
F1
F2
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Fig 4. (B)

Farmer risk weighted by quality of information

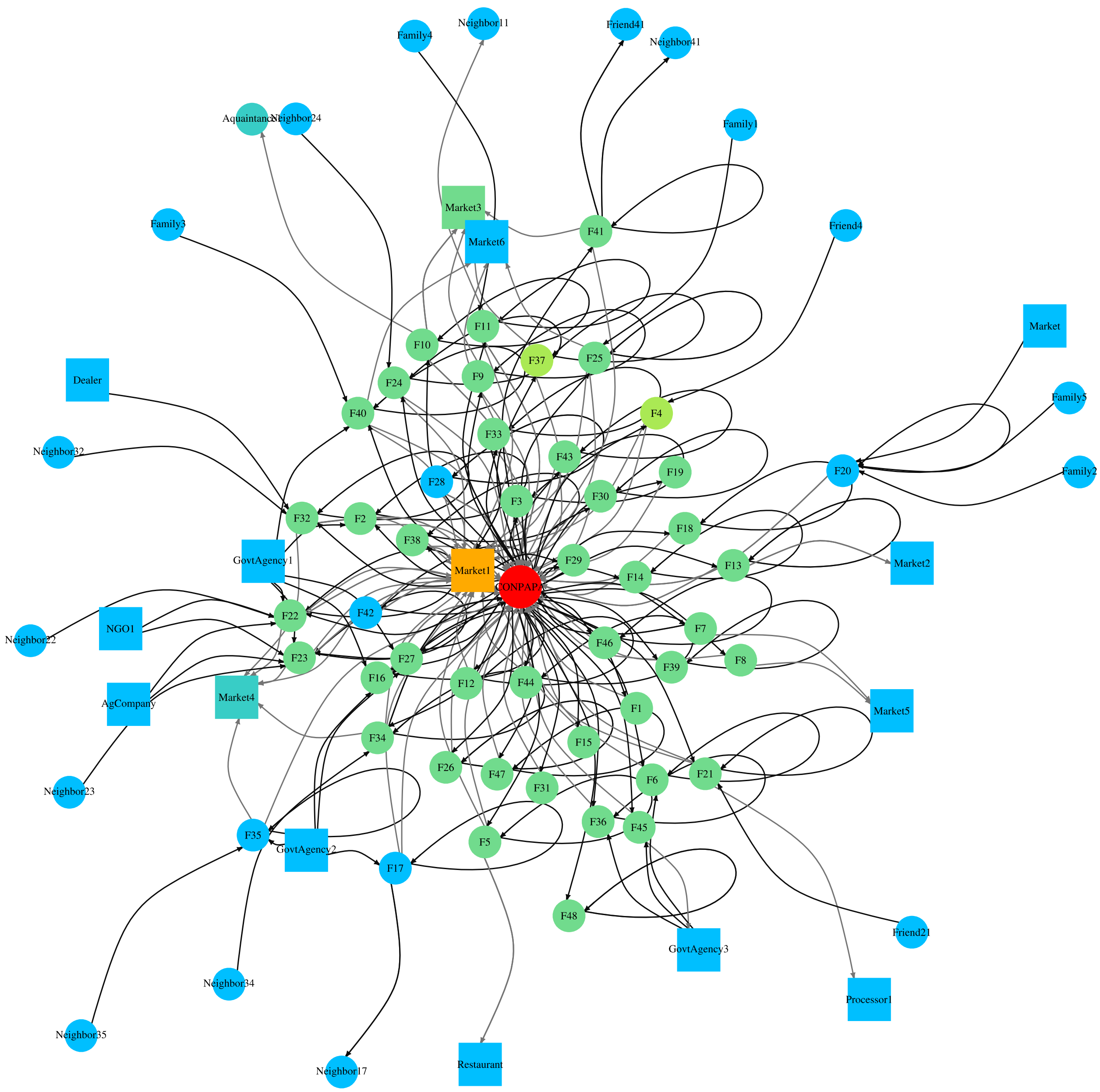


Fig. 4. (C)

Farmer risk weighted by number of information sources

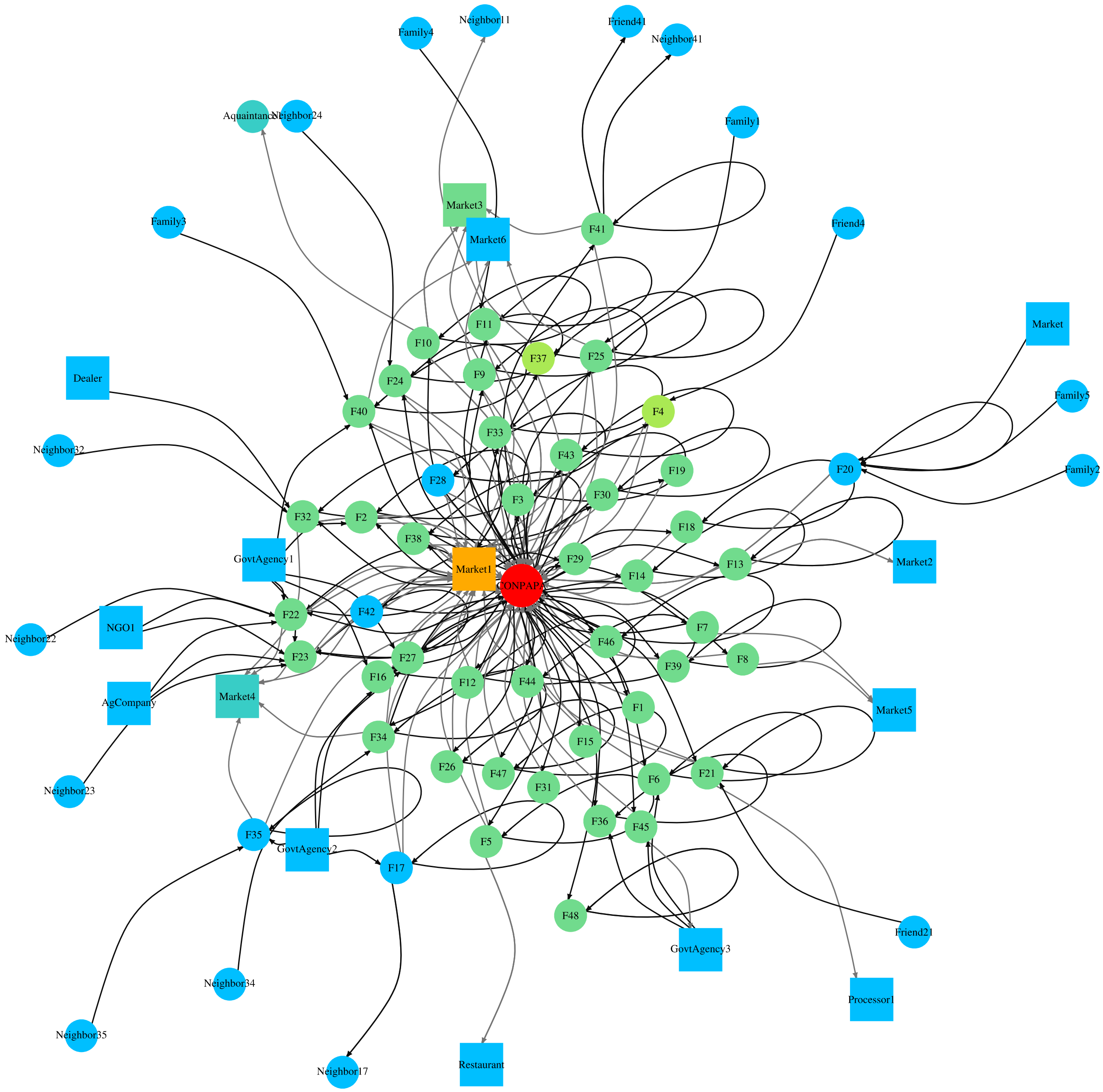


Fig. 5. (A)

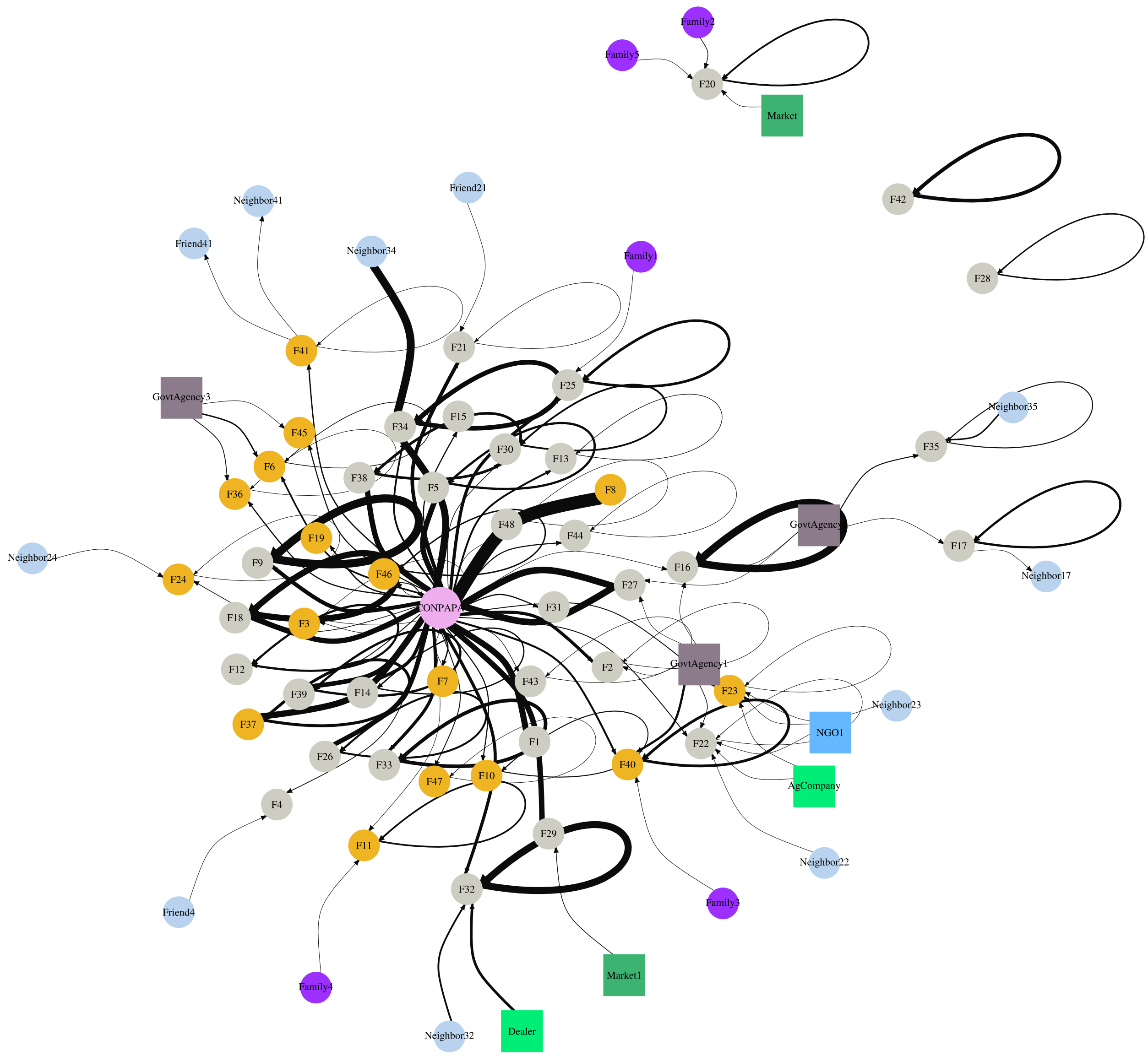
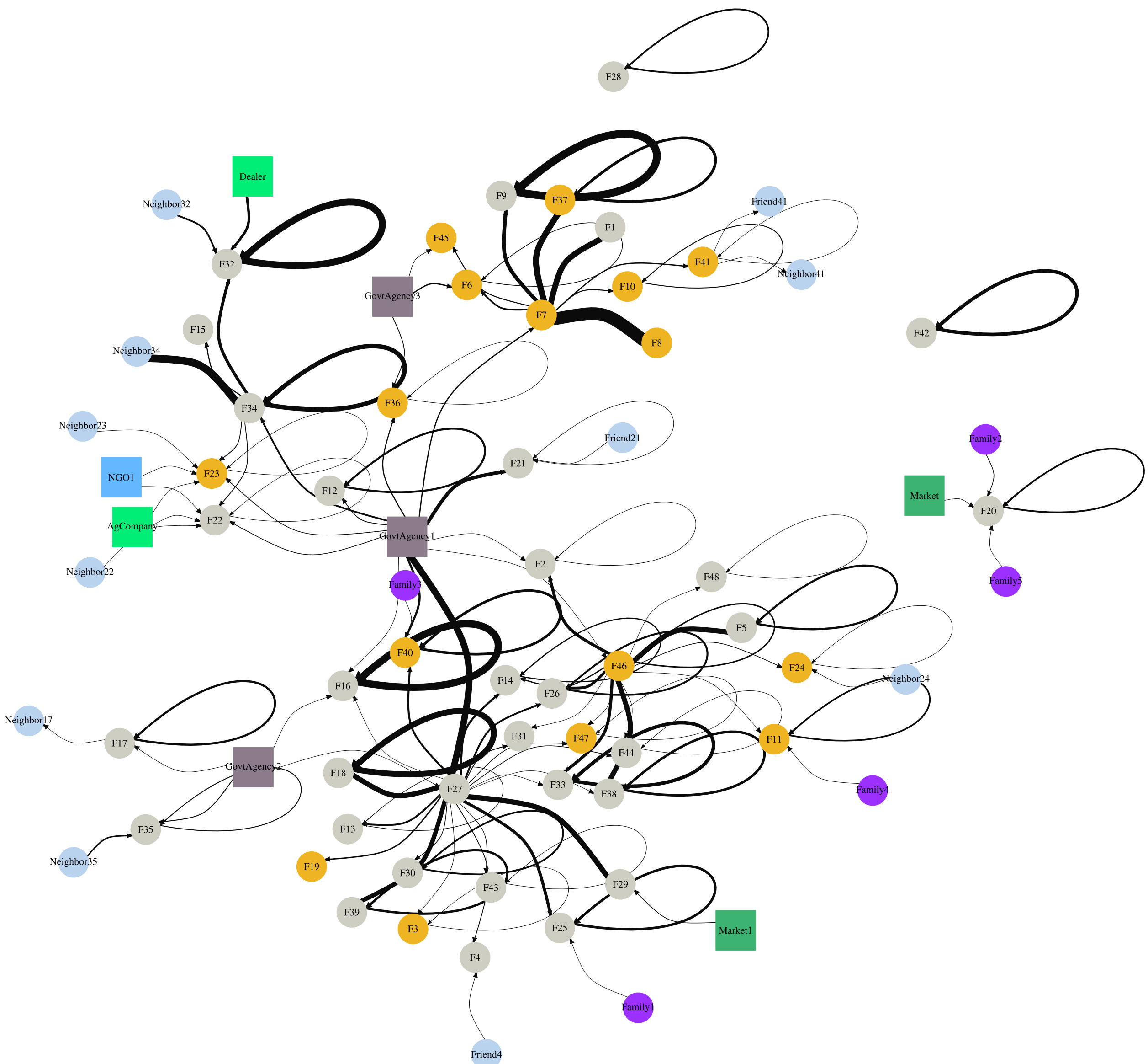

Family2
Family5
F20
Market
F42
Friend21
Neighbor41
Friend41
Neighbor34
Family1
F28
F41
F21
F25
GovtAgency3
F15
Neighbor35
F45
F34
F35
F30
F13
F6
F38
F5
F36
F8
F48
GovtAgency
F44
F19
F17
Neighbor24
F9
F16
F46
Neighbor17
F24
F27
CONPAPA
F31
F18
F3
F12
F2
GovtAgency1
F43
F7
F23
F39
F14
Neighbor23
F37
NGO1
F1
F26
F22
F33
F40
F47
F10
AgCompany
F4
F29
F11
Neighbor22
F32
Family3
Friend4
Market1
Family4
Neighbor32
Dealer

Fig. 5. (B)


F28
Dealer
Neighbor32
F32
F9
F37
F1
Friend41
F45
F41
Neighbor41
GovtAgency3
F6
F10
F7
F8
F42
F15
Neighbor34
F36
F34
Neighbor23
Friend21
F21
Family2
NGO1
F23
F12
Market
F20
AgCompany
F22
GovtAgency1
F2
Neighbor22
Family3
F48
Family5
F5
F40
F46
F24
F14
Neighbor24
F16
F26
Neighbor17
F17
F31
F47
F11
F44
GovtAgency2
F18
F33
F38
F27
Family4
F13
F35
F19
F30
F29
Neighbor35
F43
F39
Market1
F3
F25
F4
Family1
Friend4