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RESEARCH ARTICLE

Network simulations to study seed exchange for agrobiodiversity conservation

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Abstract Crop diversity is essential for sustainable development because diverse crops cope better with disease and climate change. A way to maintain crop diversity is to sustain seed exchange among farmers. Network simulations help in establishing which network properties promote crop diversity conservation. Here, we modelled the likelihood that an introduced crop variety will spread in a seed exchange network. The network model is based on published data on a directed network of barley seed flows in seven villages of Northern Ethiopia. Results show that the number of households that can be reached when introducing a new variety depends on the number of outgoing links of the household that first received the new variety. The distribution of the number of both incoming and outgoing links shows a departure from a normal distribution. This trend is explained by the presence of a minority of highly connected households and of a majority of weakly connected households. For the whole network, there is no significant correlation between the number of incoming and outgoing links of households. The findings explain the common observation that individual farmers do not cultivate all varieties present in a seed system. Absence of reciprocal exchange makes such networks less vulnerable to wholesale displacement of farmer varieties by improved ones.

Keywords Biodiversity · Complex networks · Degree distribution · Methods in ecology and evolution · Seeds · Simulation models · Small-world networks

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1 Introduction

The conservation of agricultural biodiversity (agrobiodiversity) is important for many reasons (Jarvis et al. 2011). Agrobiodiversity is (i) part of humanity's cultural heritage, (ii) essential to avoid yield losses due to pests and diseases, and (iii) important to enable adaptation to climate change (Bellon et al. 2011). Seed exchange networks preserve the in situ dynamics needed to maintain agrobiodiversity (Louwaars and de Boef 2012), but it is still unclear which network features are conducive to agrobiodiversity preservation.

Network approaches are becoming fruitful across the life and social sciences, thus providing a way to bridge the gap between natural and social scientists (Labeyrie et al. 2014). However, real-world networks of seed exchange are still poorly known. There have only been few analyses of seed systems using tools from network theory (Thomas et al. 2011; Calvet-Mir et al. 2012; Pautasso et al. 2013). Seed exchange is a process that is particularly well suited to be studied from a network perspective. This is because the nodes (farmers, households, communities) and links (exchange of seeds and information) of the network can be intuitively recognized (de Boef et al. 2010) (Table 1).

In many developing countries, seed systems tend to be local. Farmers normally obtain seeds from one's own field or from neighbouring farmers and relatives (Hodgkin et al. 2007; Gildemacher et al. 2009). Long-distance transport is difficult, information about seeds is locally available, and local seeds are normally adapted to their environment (Stromberg et al. 2010; Ruiz et al. 2014). Nevertheless, occasional exchange has been shown to take place also with distant villages and regional markets (Delaunay et al. 2009; Jensen et al. 2013). The combination of local connectivity with long-distance connections suggests that seed exchange takes place in small-world networks (Watts and Strogatz 1998).

Table 1 Explanation of some key network terminology used in the article

Concept	Explanation
Adjacency matrix	The table summarizing the presence or absence of links between the individuals of a network
Degree	Number of links of an individual
Directed network	A network where the presence of a link from individual *a* to individual *b* does not imply that there is a link from *b* to *a*
Incoming link	Link directed into an individual. In the case of seed exchange, an incoming link implies that seed was received by the individual
Invasion threshold	The boundary between extinction and persistence of an introduced item (e.g. a crop variety) in a network
Link	A connection between two individuals in a network. In the case of seed exchange, links are materialized by the movement of seed between individuals
Outgoing link	Link directed out of an individual. In the case of seed exchange, an outgoing link implies that seed was given by the individual
Network	A set of connected individuals
Node	The individual element of a network. In the context of seed exchange, nodes can be farmers, households, firms, communities, villages or regions
Small-world network	A network not only with neighbouring connectivity but also with some long-distance connections

We have less knowledge in the context of seed exchange about a key network feature, i.e. the degree distribution (the frequency distribution of the number of links per individual). Local and small-world networks can be expected to follow a normal distribution in the number of links per individual, with most individuals having the average value in the number of links. However, many real-world networks (both in social and natural systems) have been shown to have a skewed degree distribution (most individuals with a few links, whilst a few individuals have a high number of links; Moslonka-Lefebvre et al. 2011). Such heterogeneity in the structure of networks can have a profound influence on their dynamic properties. For example, heterogeneity in the number of links among individuals can reduce the invasion threshold of introduced pathogens, ideas, or seeds (Pautasso et al. 2010b).

Seed exchange is a directed process: if farmer *x* gives seed to farmer *y*, the reverse link from farmer *y* to farmer *x* may or may not be present. It is thus important to study the degree distribution both for incoming and outgoing links. The correlation between incoming and outgoing links of each individual of a seed exchange network is also a key issue. This correlation has been shown to modify the effect of a skewed degree distribution on network dynamics (Moslonka-Lefebvre et al. 2009). There is little information available in the literature on this correlation for seed exchange networks.

The directedness of seed exchange also makes it important to study whether seed systems that appear at first sight to be completely connected are indeed forming a giant component matching the whole network. A giant component is the largest set of individuals of a network that can be reached from any individual. Alternatively, only a fraction of individuals might be reached when introducing a new variety into the system starting from each of the individuals of the network (Pautasso et al. 2010a).

Using published data about a network of barley seed flows in Northern Ethiopia, in this study, we investigate these three network features: (i) the frequency distribution of incoming and outgoing links, (ii) the correlation between incoming and outgoing links, (iii) and the number of reachable households when introducing a new variety into the system from the various households. These properties provide key information about the structure and functioning of networks in general, not just seed exchange networks, and have the potential to better inform efforts to preserve crop biodiversity in a changing world.

Barley is one of the major crops in Ethiopia, which is thought to be a secondary centre of diversification of this crop (Bjørnstad and Abay 2010). The Ethiopian diversity of local barley varieties reflects the range of environmental conditions under which barley can be grown and depends on local seed systems for its preservation (van Leur and Gebre 2003; Fig. 1). The area under barley cultivation in Ethiopia has been recently declining because of replacement with wheat and rye, thus relegating barley cultivation to marginal areas, with potential loss of genetic diversity and cultural knowledge (Abebe et al. 2010).

2 Methods

Data on barley seed flows in a network of seven villages of Northern Ethiopia were obtained from Abay et al. (2011). The survey was carried out in 2008 at the household level, with interviews in the local language of a constant number of farmer households per village chosen randomly (Abay et al. 2011). Households were considered as nodes (the elements of the network), and provision of seed from household *x* to household *y* was considered as a directional link from node *x* to node *y*.

The frequency distribution of the number of incoming and outgoing links was calculated by counting how many links originated from and arrived into each household. The correlation of the number of incoming and outgoing links was studied by plotting these two variables against each other in a scatter plot.

The number of reachable households when introducing a new variety into the system was investigated using the epidemiological model along a continuum described by Pautasso and Jeger (2008). Most network models have treated individuals as either having a certain property or not, whereas there are many situations (including seed exchange) where a

Fig. 1 Barley fields in Ethiopia, photo courtesy of Christopher McLeod

continuum between two states would be more realistic (Moslonka-Lefebvre et al. 2012). Seed exchange does not just result in the presence or absence of a certain landrace in a given household but in a proportion of farmers' seed belonging to that landrace.

The model was deterministic, with fixed adjacency matrix (based on the contact structure depicted in Abay et al. 2011) and discrete time steps. Two parameters governed the epidemic development: the probabilities of variety transmission between nodes (P_t) and of variety persistence in a node (P_p). The transmission probability $P_{t(x,\ y)}$ from node x to node y was either zero (unconnected nodes) or a constant value P_t, equal for all links. For simplicity, also P_p was set equal for all nodes, but the result that the number of households reachable when introducing a new variety partly depends on the number of outgoing links of the starting household is robust to varying P_p among households.

For each iteration, the variety status $P_{i(x)}$ of a given node x at time step i was governed by the following dynamics:

$$P_{i+1}(x) = \sum P_{t(x,y)} P_{i(y)}$$

where the sum is over all nodes y.

At the beginning of the simulation, $P_{i(x)}$ was set to zero for all nodes x except for the starting node s of the introduction, with $P_{0(s)}=1$. The development of the variety introduction (at the threshold conditions, i.e. the combination of P_p and P_t for which equilibrium is reached; Chakrabarti et al. 2008) was assessed on the basis of the sum of $P_{i(x)}$ across all nodes and on the basis of the number of nodes with $P_{i(x)}$ higher than an arbitrary value (0.01). One percent of a farmer's household seed is not negligible, because a single household can cultivate a high number of varieties; some of which will make up a small proportion of the overall seed conserved from season to season. By choosing a higher threshold for considering the variety present, rare varieties would be likely to be overlooked.

3 Results and discussion

3.1 Frequency distribution of the number of incoming and outgoing links

The frequency distributions of both the incoming and outgoing links of the households were skewed. Most households had one link only, and only a few households had more than two links (Fig. 2). This result is in line with previous research documenting the special role of some farmers in preserving

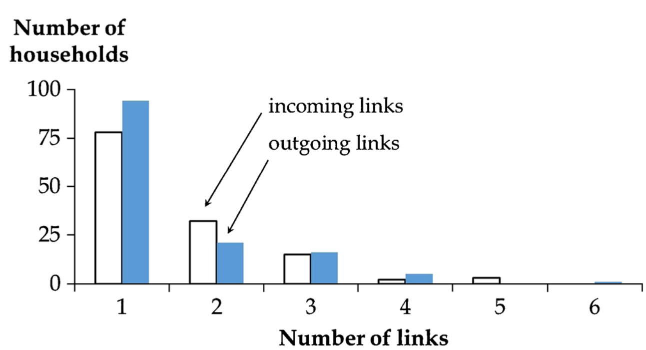

Fig. 2 Frequency distribution of the number of incoming and outgoing seed exchange connections of the households of the studied barley seed system. Most surveyed households reported few seed exchange connections, both in the incoming and outgoing directions. Some households were more connected than the majority of surveyed households

crop diversity (Subedi et al. 2003; Rana et al. 2007; Fuentes et al. 2012). This observation is also in agreement with the analysis of Abay et al. (2011), who identified households with a special role based on other network features such as centrality and betweeness. This particular role was confirmed by the skewed frequency distribution of incoming and outgoing links also observed for some villages when analyzing data within villages.

The observed heterogeneity in the network structure mimics the patterns observed in many other networks in natural, social and technical settings (May 2006; Jeger et al. 2007; Johnson et al. 2010). Inequality in the number of links among individuals can be a consequence of preferential attachment. This mechanism operates when new individuals entering a network tend to become connected to individuals that are already more connected than others. On its own, the presence of households with more links than others tends to facilitate the spread of new varieties in a system.

3.2 Correlation between incoming and outgoing links

There was no correlation between incoming and outgoing links for the studied seed exchange network (Fig. 3). Heterogeneity in the contact structure of networks tends to result in lower percolation thresholds (in our case, in higher likelihood of diffusion of a variety; Chadès et al. 2011), but for directed networks, this is only the case if there is a positive correlation between the number of incoming and outgoing links of individuals (Woolhouse et al. 2005; Moslonka-Lefebvre et al. 2009). The finding of a skewed degree distribution is thus counterbalanced by the absence of a positive correlation between incoming and outgoing links, which makes it difficult for a new variety to spread in the seed exchange network.

The absence of correlation between incoming and outgoing links was confirmed within four villages, but in the other villages, there were marginally significant positive and negative correlations. The imperfect consistency of findings at the whole network and the village level calls for caution in the upscaling and downscaling in network analyses of seed flows and other processes (Stumpf et al. 2005; Lindström et al. 2013; Pautasso and Jeger 2014). There is the need for more comparative analysis of seed exchange network features for various crops and regions (Aw-Hassan et al. 2008; Bajracharya et al. 2012; Samberg et al. 2013). It is important to recognize that seed exchange network features may depend on the scale of observation, the degree of aggregation and the level of sampling effort.

3.3 Simulation of the introduction of a new variety

The number of households reached by an introduced variety was variable depending on the household from which the introduction was started. Some (~20 %) of this variation was explained by the number of outgoing links of the starting household (Fig. 4). The maximum number of reached households was about 30, i.e. 15 % of the total number of households in the system. The Ethiopian barley seed flow network analyzed here shows that it is difficult to reach the majority of households in a system, even if they are all connected in one single network, because of the directedness of the network, which results in the fragmentation of the system.

Most research on networks has focused on the presence of undirected links, i.e. reciprocity. However, seed exchange networks are not necessarily reciprocal. The network simulation suggests that directedness, together with the absence of correlation between incoming and outgoing links, can contribute to local differentiation of landraces, because seed flows tend to remain confined within small groups of farmers. At the same time, such fragmentation can make seed systems more resilient against replacement of local varieties with improved ones (Marfo et al. 2008; Cavatassi et al. 2011; Döring et al. 2014). Further application of network modelling approaches is needed with comparable data about seed systems from other regions.

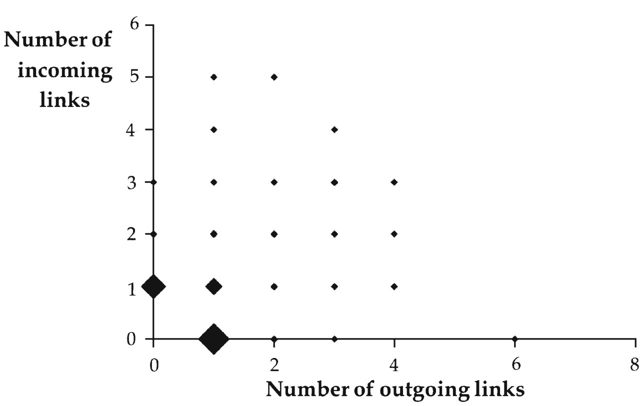

Fig. 3 Correlation between incoming and outgoing links of households for the analyzed barley seed exchange network. Most households have one incoming connection and/or one outgoing connection. On the whole, there is no correlation between incoming and outgoing seed exchange links

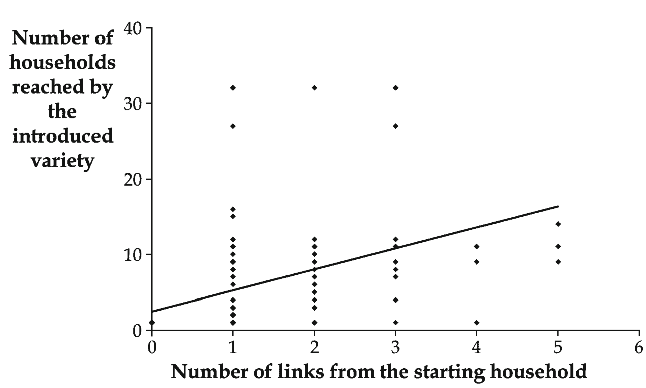

Fig. 4 Number of households reached by an introduced variety (using the simulation model described in the article) as a function of the number of outgoing connections of the household to whom the variety was first given or that first created it (n=197, r^2=0.18, y=2.48+2.77x, p<0.001)

4 Conclusions

The conservation of agrobiodiversity depends on the interplay between local differentiation of landraces and their (limited) diffusion so as to counteract local extinction (Abay et al. 2011; Dyer et al. 2011; Abebe et al. 2013). If diffusion (due to exchange, gift, trade, barter, inheritance, or other social processes; Leclerc and Coppens d'Eeckenbrugge 2012) is too effective, homogenization of genetic resources might follow. Seed systems can maintain agrobiodiversity, but they can also replace it with new improved varieties (as has often happened in industrialized countries over the last decades) (Almekinders et al. 1994; Portis et al. 2012; Kawa et al. 2013).

This study used a seed exchange data set with information about both incoming and outgoing links to assess three key network features that have been overlooked in the literature on seed exchange, despite their importance, because most available data sets on seed exchange have only information about either incoming or outgoing links. The results (skewed frequency distribution of the number of incoming and outgoing links, absence of correlation between the number of incoming and outgoing links, limited number of households that can be reached when introducing a new variety) can explain why individual farmers do not normally cultivate all varieties present in a region or village. The general absence of reciprocity in the studied seed exchange network makes it less vulnerable to the replacement of farmer varieties by the so-called improved ones. Further research is needed to test whether the network patterns observed in this case study are found more generally in seed systems throughout the world. Together with network analysis, simulation models provide a new approach in the study and management of the diversity of crop landraces in seed systems and deserve wider application.

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