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Seed exchange networks as important processes for maize diversity conservation and seed access in a highland region of Mexico

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Abstract

Seed exchanges that smallholder households perform form networks that are central to *in situ* agrobiodiversity conservation. Sociodemographic factors such as market accessibility and household assets could be shaping the structure of these networks and impacting diversity, however, formal evidence is scarce. Through surveys in nine rural communities of the Cofre de Perote highland region in Mexico, we modeled seed exchange networks for native maize and conducted a social network analysis followed by statistical modeling. Results show that access to urban centers is negatively related to the robustness of community networks. Within communities, households with bigger plots, more time producing, sufficient maize for self-consumption, and fewer members, were able to save seeds for the next cropping season and were more likely to donate seeds. Additionally, households that exchanged more, produced more maize morphotypes. We conclude that the maize seed networks under study are serving as seed reservoirs for families in case of scarcity, thus contributing to food security. They are also important for *in situ* agrobiodiversity conservation of six maize morphotypes. However, it is necessary to promote seed exchanges between households of communities with more access to urban centers, to strengthen networks, and preserve their maize diversity and seed scarcity-dampening function.

Keywords Seed exchange networks; Agrobiodiversity conservation; Seed access; Highland native maize

Introduction

Smallholder households represent around 85% of production units worldwide (Lowder et al., 2016), enabling continuous crop evolution and domestication, as well as food supply for rural and urban populations (Bellon et al., 2018, 2021). Smallholders that produce annual crops commonly select the best grains from their harvest and save these as seeds for the next cropping season, however, it is frequent that they exchange, donate or borrow seeds among households, thus building up local Seed Exchange Networks (SEN) (Coomes et al., 2015; Pautasso et al., 2012). SEN are believed to be linked to agrobiodiversity conservation (Pautasso et al., 2012), but changing economic and sociodemographic conditions around the world, are driving rural communities to increasingly integrate into urban centers and their markets, weakening food production for self-consumption (Eakin et al., 2018; Rivera-Núñez et al., 2022). In Mexico, for example, many smallholder households that cultivate maize mostly for self-consumption (Bellon et al., 2021), are struggling to meet grain self-sufficiency for the entire cropping season (Novotny et al., 2021; Rivera-Núñez et al., 2022). These circumstances could be having an impact on the probability of households saving, giving, or receiving seeds from other households, thus shaping the structure of SEN.

Mexico, considered the center of origin of maize (Piperno, 2018), has been domesticating this plant in *milpas* (maize-based traditional polyculture) for approximately 9,000 years (Piperno et al., 2009). *Milpas* are a central part of the life and nutrition of thousands of peasant households (Novotny et al., 2021) and maize is the most important food crop for the rural and urban populations in Mexico (Fernández et al., 2013). Around 88.6% of maize producers are smallholders with plots smaller than 5 hectares that hold the potential of feeding 54.7 million people in Mexico with their work (Bellon et al., 2018). In this small-holder context of Mexico, SEN are important for *in situ* maize conservation (Badstue et al., 2007; Bellon et al., 2011; Gómez et al., 2004; Llamas-Guzmán et al., 2022; Louette et al., 1997; Sotelo, 2017) as they are an important source of seeds when extreme climatic events take place and crops are lost (Fenzi et al., 2022). Maize SEN vary across regions of Mexico, as the ways people manage their seeds reflect the country's vast biocultural diversity (Bellon et al., 2011). However, some common patterns have emerged across communities where SEN have been studied. In these communities, most seeds are obtained from self-supply, as just around one third of the seeds are obtained from outside sources (Badstue et al., 2007; Louette et al., 1997). Moreover, commercial seeds are rarely used, especially in highland regions (Brush & Perales, 2007). The main reported reasons for obtaining seeds outside the household are experimentation and seed scarcity; in contrast, the most frequent reason to give the seed are the social responsibility that households have with another member of the community (Badstue et al., 2007; Louette et al., 1997). When there is a seed transaction between households, seeds are usually exchanged through pre-existing social relations, for example, in Oaxaca, households exchange with their family, acquaintances, friend or neighbors (Badstue et al., 2007). Patrilineal inheritance is frequent; in Chiapas, for example, when a new household is formed, seeds are given from the father to the son (Sotelo, 2017). Moreover, when seeds are exchanged, they commonly come from the same community (Louette et al., 1997), as the SEN are sustained by pre-existing social relations (Llamas-Guzmán et al., 2022) and maize varieties are adapted to specific altitudinal conditions, especially on highlands (Mercer et al., 2008).

Smallholders of highlands predominantly produce native varieties (Perales et al., 2003). In the face of climate change, highland native varieties are the most threatened because they are adapted to very specific local climates and, probably, will not perform well in changing conditions (Mercer & Perales, 2010). This is why, highland SEN are assumed to be very important for sustaining a diverse and well adapted germplasm for future conditions (Bellon et al., 2011). SEN are thought to be key for agrobiodiversity conservation (Pautasso et al., 2012) since it has been reported that households that exchange more seeds produce a greater crop diversity (Calvet-Mir et al., 2012; Llamas-Guzmán et al., 2022; Song et al., 2019). However, this is not the case in some contexts (Abizaid et al., 2016; Kawa et al., 2013; Thomas & Caillon, 2016). Therefore, it is necessary to evaluate if SEN contribute to maize diversity conservation in the highlands of the center of origin of maize where evolution under domestication is ongoing.

Multiple factors could drive the level of dependence of a community on its local SEN, and as a consequence, determine its structure. Network structure in this context is defined by the way households of a community exchange seeds among them (frequency and identity of participants). Rural communities are increasingly accessing different types of markets and integrating their livelihoods into urban pole economies (Eakin et al., 2018). The access to markets includes both local markets, in which there is an exchange of agrobiodiversity produced in different eco-regions (Lotero-Velásquez et al., 2022), and formal seed markets, referring to the system of production and distribution of commercial seeds by companies (Almekinders et al., 1994; Berlan & Lewontin, 1986). Formal seed markets have a greater presence in communities whose livelihoods are more integrated into urban centers, having better physical and economic access to markets (Brush & Perales, 2007). In these contexts, the adoption of commercial varieties could be having a negative impact on landrace diversity (McLean-Rodríguez et al., 2019; Zimmerer et al., 2019), and on SEN structures. If households join formal seed markets and stop producing and exchanging local varieties, eventually local networks would have fewer members and get fragmented. It is known that the formal and local seed systems coexist (Almekinders et al., 1994), even though formal markets tend to displace local agrobiodiversity (Kloppenburg, 2004). But it is unclear to what extent the presence of formal markets alter the structure of SEN. Furthermore, in Mexico, the growth of cities is changing smallholder´s livelihoods (Lerner & Appendini, 2011), because they are diversifying labor into non-farm activities due to market integration, and agriculture is ceasing to be the principal activity (Eakin et al., 2018). This fact could drive further households to exchange less or even stop exchanging seeds. Moreover, kinship relations are known to be more distant in communities that are closer to urban areas (Colleran, 2020) and as SEN are often supported by kinship relations (Labeyrie et al., 2016), accessibility to urban centers could be a driver of network fragmentation. However, to our knowledge, there are no quantitative studies of the extent to which access to urban poles relate to the structure of maize local SEN.

Farmer households function as production units, as they rely on their labor to make a living from land, even though sometimes they engage into non-agricultural labor (Chayanov, 1966). According to Boserup's classical theory (Boserup, 1965), the decrease in land access by farmer households (driven by population growth) results in land-use change and agricultural intensification at the community level. In Latin America, there is a known decreasing trend in the plot size of newly founded households (Lowder et al., 2016; Negrete-Yankelevich et al., 2013). As a consequence, younger households have a smaller production (Pacheco-Cobos et al., 2015) and find it harder to produce enough food to meet their annual grain needs (Rivera-Núñez et al., 2022). Moreover, if the number of household members exceeds production capacity, it could be harder for households to save a part of the harvest for seed. If households are not able to allocate part of the production for seed for the next cropping season, they are likely to acquire seeds through SEN, requesting them from households that have larger productions (Louette et al., 1997). In other rural contexts, SEN are useful to obtain seeds in case of harvest failure (van Niekerk & Wynberg, 2017). However, the extent to which household characteristics influence their probability to exchange, and, the capacity of SEN to function for seed replenishment in case of scarcity, remains underexplored.

Recently in Latin America, men are increasingly migrating and engaging in non-farm labor, which has led women to become in charge of agricultural tasks (Deere, 2009). Classical peasant theory postulates that households have a division of labor based on gender, in which men are engaged in productive tasks and women in domestic labor (Chayanov, 1966). Seed provisioning and exchanging is considered a productive task managed by men in some regions (Ricciardi, 2015) but currently, it is no longer clear if men or women are more frequently exchanging seeds in different contexts.

Social Network Analysis (SNA) addresses formally the study of the structure of a set of nodes and the interactions between them (Scott & Carrington, 2011) and has been a useful approach to estimating the relative influence of the multiple factors (e.g. gene and knowledge diffusion, climate change, social relations) that shape SEN functioning (Abizaid et al., 2016; Fenzi et al., 2022; Labeyrie et al., 2016; Thomas et al., 2012) and their contribution to agrobiodiversity conservation (Calvet-Mir et al., 2012; Llamas-Guzmán et al., 2022). In the SEN context, households constitute the nodes, and seed exchanges are the edges of the network (Labeyrie et al., 2021). Within SNA framework, one way to compare the vulnerability of a community SEN due to fragmentation, is by measuring their robustness. Robustness refers to the capacity of a network to keep connected even if each one of its nodes is removed one by one (Piraveenan et al., 2013). In the case of SEN, robustness indicates the extent to which households could keep on obtaining seeds in a scenario where certain households will no longer belong to the network. Moreover, Exponential Random Graph Models (ERGM), can be used to estimate the explanatory potential of household characteristics on the probability that there are exchange links between them (Lusher et al., 2013).

The highlands of the Cofre de Perote region in southeast Mexico, represent a useful case study to evaluate the factors that shape local SEN because, as in other tropical high-elevation regions, SEN are the main source of seeds outside household units (Bellon et al., 2011) as commercial varieties are only moderately present (Khoury et al., 2022; Perales et al., 2003). In this context in which smallholders depend on their seeds and SEN for their provisioning, we use SNA and ERGM to formally explore the sociodemographic characteristics that structure the networks and to identify the role of SEN in maize agrobiodiversity conservation. We hypothesize that (1) at the community level, SEN are less robust as communities have more access to urban centers, and (2) at the household level, men and women exchange with the same frequency and that, households that have bigger plots, more time producing maize, sufficient maize to feed the family, and fewer members, give seeds more often. Moreover, (3) households that give and receive more seeds are the ones that produce more maize diversity on their plots.

Method

Study site

The study was conducted in nine communities of the Cofre de Perote mountain, in east central Mexico, specifically at Acajete and Xico municipalities in Veracruz state. The study site is a mountainous highland region, and the studied communities range from 1739 to 2566 masl (INEGI, 2020; Table 1). The selected communities represent a gradient of accessibility (measured as self-reported transportation time) to urban areas, the cities of Coatepec, Xalapa, and Xico (Fig. 1). Direct distance was not used as an indicator of access because the quality of roads and the available transportation means (public bus, motorcycle or walking) vary considerably between communities. The most accessible community is located 25 minutes away from the nearest urban pole, while the least is 150 minutes away. The communities that have more access to urban centers are also the largest, Xico Viejo, the most accessible community, has 138 households, and Buena Vista, the farthest, is comprised of 14 households (INEGI, 2020). The formal seed market where households buy seeds is composed of agribusiness stores in urban centers where they can also buy other supplies, such as fertilizers and pesticides.

In these communities, smallholder families produce *milpas* destined most often exclusively for their subsistence. According to our data, just 4.3% of households sell a small part of their production. Even though their grain supply depends on the *milpa*, it is frequent that the resulting harvest is not enough to meet all year's feeding needs, so they have to buy maize grain in the market (Negrete-Yankelevich et al., 2018).

Surveys

We conducted surveys under a *snowball* sampling method (Lusher et al., 2013), which consisted of two waves. In both waves, before starting the survey, we informed respondents what the study implied by reading aloud a pre-established explanation and asked people for their participation consent. We used protection equipment against COVID-19 and offered masks and hand sanitizer to participants. The first wave was carried out during meetings between December 2020 and April 2021 and 165 surveys were conducted in the nine study communities. The meetings were organized in local community halls to invite farmers to participate in a larger project oriented to promote sustainable food security in rural areas. Each household of the first wave was asked to name every household with whom they had exchanged maize seeds during all the time they had been producing *milpa*. Afterwards, every household that was mentioned as a seed exchanger and that belonged to the study communities was surveyed. This was repeated until no new names emerged. With that, we obtained 140 new surveys in the second wave, which was carried out between August 2021 and April 2022. Taking into consideration both waves 50% of the households of the studied communities were surveyed (Table 1). Of all surveys, 54.7% were answered by women. Morphotypes were designated according to local names because that is how households recognize them and exchange seeds. In addition to seed exchange questions, in both waves, we asked households: (1) which maize morphotypes they cultivated, (2) how long they had been producing maize, (3) the size of their maize plot, (4) how many members the household had, (5) if the maize harvest of the last cropping season was sufficient to feed the family for the entire year, (6) if they had ever bought commercial maize seeds, and (7) the market in which they bought them. In addition, we went to the agribusiness stores (that interviewees mentioned as their suppliers) and asked which maize hybrid varieties they sold.

Data analysis

SEN were constructed under the SNA framework and were conceptualized at two scales, the regional level, in which all households of every community were considered, and the community level, in which only households of a particular community and the households of other communities that exchanged with them were considered.

During interviews, there were 114 reported exchanges with households that are not part of the studied communities, so we constructed open networks, in which all mentioned households were considered, and closed networks, in which exclusively households of the studied communities were included. In the surveys, 25 families mentioned they had exchanged but did not remember with whom they did so, therefore we excluded 38 exchanges of this kind. We measured in-degree and out-degree centrality, which represent the number of times that a household had received and given seeds (through-out its productive life) respectively, and total centrality, as the sum of both. Density (De) was measured as the ratio between the number of present exchanges (PE) and the number of possible exchanges (PoE) given the number of households on the network (De=PE/PoE) (Kolaczyk y Csárdi, 2014). Descriptive statistics and network visualization were performed in *statnet* (Handcock et al., 2016) and *ggraph* (Pedersen, 2021) packages on RStudio 1.4.1103 and Cytoscape 3.9.0 software (Shannon et al., 2003).

Community-scale

To estimate if the probability of buying seeds from the formal seed markets increases with the accessibility to urban centers, we adjusted a generalized linear mixed model with a binomial distribution, using maximum likelihood by the Laplace fitting method. The accessibility of the community to urban centers was used as the fixed explanatory variable. The random variable was the community to which households belonged. The response variable was the presence or absence of seed acquisition in the formal market by households.

Additionally, we conducted a robustness analysis of the open networks of each of the nine communities, which indicates the capability of the households to continue obtaining seeds from others even if other households progressively got out of the network. The robustness coefficient is a percentage that expresses the area under the curve of the number of households in the largest group of nodes that keep connected after households are progressively removed from the network, one by one (González González et al., 2021; Kasthurirathna et al., 2013). Robustness was measured as:

Ec. (1) $$R = \frac{A_O}{A_c} = \frac{200\sum_{k=0}^{R} T_k - 100T_0}{R^2}$$

where A_O is the area under the curve of the observed network and A_c is the area under the curve of a complete network in which every node is connected to all nodes. T_k is the size of the largest component after *k* nodes have been removed. T_0 is the size of the largest component of the observed network before any node has been removed and *R* is the network size (number of nodes; (for more details see Piraveenan et al., 2013). A network of any size in which all nodes are connected will have 100% robustness (Kasthurirathna et al., 2013). Node removal was done in two ways, randomly, and by degree. For the random node removal, 200 randomly ordered lists of the nodes were generated. In the case of by degree removal, the nodes that had the greatest degree centrality were removed first, allowing us to explore if SEN robustness depended on the key households that exchanged more. Robustness computation was carried out using NetworkX 2.5 package (Hagberg et al., 2008) on Python 3.9.6, following González-González et al. (2021). As the robustness coefficient is a percentage, a beta regression was used to model if the accessibility of the community to urban centers influences SEN robustness (Cribari-Neto & Zeileis, 2010; Douma & Weedon, 2019), using the betareg package (Cribari-Neto & Zeileis, 2010).

Household scale

To test if the probability of exchanging seeds depends on household characteristics, an ERGM of social selection was used. This model estimates if the characteristics of the nodes affect tie formation (Lusher et al., 2013). As we did not interview the households outside our study site, and we do not know their characteristics, we used the regional closed network to adjust the model (Labeyrie et al., 2016; Thomas & Caillon, 2016). ERGM has the form:

Ec. (2) $$P(X = x) = \frac{1}{k} exp\big(\theta z(x) + \theta_a z_a(x, y)\big)$$

Where X is the population of all possible networks and x denotes the observed network. The statistic $z(x)$ is a count of the number of times that a certain configuration appears on the graph x, θ is the estimated parameter to evaluate the probability of its occurrence (configurations 1 and 2 of Fig. 2), and k is a normalizing constant. The parameter θ_a is estimated through z_a statistic to estimate the interaction between network configurations (x) and household characteristics (y) (configurations 2 and 3 of Fig. 2) (Lusher et al., 2013).

The following is a description of the eight parameters estimated from the ERGM. Two parameters of the form $\theta z(x)$ were estimated, the first one measures the probability of a seed exchange to occur, independently of the household's particular characteristics (configuration 1, Fig. 2), and the second one the probability of exchanges to be reciprocal (configuration 2, Fig. 2). Six parameters of the form $\theta_a z_a(x, y)$ were estimated. Configuration 3 of Fig. 2 was used to estimate the probability that two households of the same community exchange between them and the probability that there are exchanges between household members of the same gender. The other four parameters correspond to configuration 4 of Fig. 2., these parameters show the probability that a household gives seeds to others given the value for each of the four characteristics the household has. The characteristics that we considered were 1) plot size, 2) the number of years of maize production, 3) self-reported maize sufficiency, and 4) the number of household members. Model parameters were estimated using Markov Chain Monte Carlo (MCMC) method and the convergence of the model was verified through multiple runs (Krivitsky et al., 2021). The goodness of fit of the model was tested to corroborate the reliability of the parameters, following the method of Koskinen & Snijders (2013). The package statnet was used to adjust the model (Handcock et al., 2016).

It is expected that households produce more maize morphotypes if they exchange seeds with many households. To test this, we used a generalized linear model with a Poisson error distribution, and, the maximum likelihood by the Laplace method. The degree centrality of each household was used as the explanatory variable (number of links in the network per household) and, the number of grown morphotypes was the response variable. To measure the degree centrality, the closed regional network was used. Statistical model simplification was performed using Akaike's Information Criteria (AIC). Only models with a minimum decrease of two AIC units with respect to the null model were considered plausible (Burnham & Anderson, 2002).

Results

Maize morphotypes and seed management

We found that households produced nine native morphotypes (Table 1) of the *Cónico* maize race (as previously reported by Leyva-Madrigal et al., 2020) and two hybrid varieties (elotero A-7573 and H-318 Bajío), which are designed to produce *elotes* (corn-on-the-cob), and are both called *elotero* by farmers. Only six out of the nine native morphotypes were reported to be exchanged (*blanco, blanco angosto, negro, amarillo, pinto,* and *rojo*).

General characteristics of seed exchange networks

Of the 165 surveyed households on the first wave of interviews, 22 had not exchanged seeds, so they were not part of the network. Considering both waves, a total of 283 households constituted the closed regional network. The regional open network, in which all exchanging households of every community were included, was composed of 380 nodes and 726 exchanges. Of these, 316 households had received and 277 had given seeds. In total, there were exchanges between households belonging to 38 communities in seven municipalities (Fig. 3). The network was composed principally of *blanco* morphotype exchanges (52.7%), even though *amarillo* (20.2%) and *negro* (18.2%) were commonly exchanged too. *Pinto, rojo,* and *blanco angosto* were the least exchanged morphotypes (7.6%, 1.0%, 0.3%). Furthermore, almost all exchanges were made within the community, and only 23.69% occurred between households of different communities. There were some households in every community that exchanged notably more than others (Fig. 4). Exchanges took place mainly between households with some pre-existing relation, 64.9% were family members, 17.8% acquaintances, and 15.4% friends. Only 1.8% of the exchanges were carried out among households that did not report a pre-existing relationship. Households tended to provide and receive seeds free of charge, through gifts (49.5%) or right-away reciprocated exchanges (47.1%), and only 3.4% of seed transactions were through monetary trade. The main reason to exchange was the lack of seeds (63.8%), but it was also common that households exchanged to test another morphotype (20.3%) or because they wanted to have bigger ears (19.8%) and/or healthier plants without plagues (8.6%). In all community networks, the average degree is between two and three exchanges per household, but densities differ, the least dense networks corresponded to communities with greater access to urban centers. In addition, these networks included a smaller proportion of the existing households (Table 2).

Seed exchange network structure in relation to the accessibility of communities to urban centers

The accessibility of communities to urban centers were related to a significant increase in the probability of households purchasing hybrid seeds ($X^2_{(302, 299)}$=5.33, p=0.02; Fig. 5). A total of 48 households bought commercial seeds, but most of them did it just once (64.6%) or twice (12.5%), and only a few households had bought seeds three times (6.2%). A minority of households bought seeds every year (16.6%), and they were all from communities that where between 25 and 30 minutes away from urban centers.

We found that, in general, networks were more robust to random removal of households than to degree removal (Fig. 6) due to the centralization of networks (Fig. 4). However, the difference between random and degree robustness were relatively small. The robustness of networks is due to network density, in other words, no matter the size of the network or the number of households in the community, the number of exchanges per household is between two and three (Table 2), so in smaller communities, the network is denser. The accessibility to urban centers affected network robustness, both for random and degree removal (Fig. 6). This pattern could be related to the fact that communities with greater access are growing but their seed networks are not, so it would be worth it to know if households that are not exchanging keep on sowing native maize.

The position of households in the network explained by their characteristics

According to ERGM, the probability of any two households of the regional network exchanging between them is very low (<0.001; Table 3). This is caused by the null connection between the municipal networks of Xico and Acajete (Fig. 4), and by the fact that households exchange more probably with other households of their own community with whom they have some pre-existing relationship. Reciprocal exchanges between households of the same community have 17.6% of occurrence. Exchanges become 8.08% more likely if they occur within gender, for which male exchanges were more frequent. The probability of a seed transactions to occur between household members of the same gender and community, and were the household that provides the seeds is the one that has maize sufficiency for the year, more years of production, a bigger plot, and fewer household members, is 18.69% (Table 3).

Agrobiodiversity conservation through seed exchange networks

The number of produced morphotypes by the households increased with the number of exchanges made by the household (Fig. 7). Therefore, households with a greater degree centrality were more likely to produce a higher number of morphotypes on their plot.

Discussion

The robustness of the networks and their relation to accessibility to urban centers

This study evaluated, under a quantitative approach, the factors that shape the structure of maize SEN in a highland region. At the community level, SEN structure was thought to be influenced by the accessibility of rural communities to urban centers, an aspect that had not been tested quantitatively. As hypothesized in this study, SEN become less robust as communities' accessibility to urban centers increases. While networks of the three communities with the least access to cities were composed of almost all existing households, networks of communities with more access to urban centers consisted of around half of the existing households. In the latter communities, it could be that, with time, some households have had left the network, and/or that newer households might have never joined it. In this region, SEN are not extremely centralized, therefore when the households that exchange more frequently are removed first, the decrease in robustness is similar to that observed when households are removed randomly. Consequently, network robustness depends on the number of exchanges in the community, not necessarily the distribution of those exchanges.

Both, access to markets and influence of urban centers on rural livelihoods, could be causing the observed decrease in network robustness in relation to accessibility to urban centers. In this highland region, as in others, the use of commercial maize varieties is moderate (Brush & Perales, 2007; Dyer & López-Feldman, 2013), presumably because high genetic variability is needed to meet all environmental conditions, and commercial varieties sold in the available markets do not meet this requirement (Perales et al., 2003). Also, available commercial seeds are not attractive for rural families because they do not adjust to households production purposes. Hybrid seeds sold in the region are efficient for *elote* production, destined mainly to snack sales in urban centers. Rural households produce maize to obtain mature grain as staple food (mainly for self-consumption as tortillas and tamales). For these reasons, even though households have bought commercial seeds, most of them did it just once, and it was mentioned that when they realized that commercial seeds did not show good productivity results, they stopped buying them. Nevertheless, in the communities with more accessibility to cities, households have more access to *elote* selling markets, so it is more feasible to buy this type of seed and make a profit from its production. In this sense, the accessibility to cities is related to the transition to market-oriented production, and the replacement of native for hybrid varieties could be related to this transition, as has been shown previously (McLean-Rodríguez et al., 2019). So, although formal and local seed systems coexist, as previously reported (Almekinders et al., 1994), the fact that there are fewer households on networks of communities with more access to urban centers could be related to the adoption of commercial varieties for selling purposes. Considering these results, access to selling markets could have a greater influence on the robustness of networks in midlands and lowlands, where commercial seeds are more common (Brush & Perales, 2007; Reyes-García et al., 2013). Furthermore, in this region, the dissemination of hybrid or native varieties through NGO and government agencies is unusual, in contrast to other regions in which the dissemination of commercial varieties through them has been an effective strategy for the adoption of this kind of seeds, especially in communities that are more integrated into selling markets (Leyte et al., 2022).

Kinship relations become more distant in rural communities that are not integrated into markets (Colleran, 2020), and, as in previous studies (Labeyrie et al., 2016), we found that SEN are mostly based on them, therefore, the decrease in kinship relations could be one of the reasons for the decrease in robustness in the networks of communities with more access to urban centers. Furthermore, in Mexico, smallholders are not necessarily abandoning subsistence maize because of market integration (Eakin et al., 2018), but engagement in non-farm activities in urban centers leads to a decrement in nutritional self-sufficiency (Novotny et al., 2021). Consequently, if fewer households in communities near urban centers produce subsistence maize as their main activity, and seed exchange practices become less frequent, SEN get fragmented, losing their robustness. Therefore, the decrease in kinship relations and increase in engagement in off-farm labor are both likely correlated with accessibility to urban centers and could be having a simultaneous impact on network robustness. It would be important for further research to explore formally the interactive role of these factors.

Household characteristics and their position on the network

In Latin America, newly formed households tend to have smaller plots (Lowder et al., 2016), thus, it is common that the harvest is not enough to meet the cropping season feeding necessities and seed supply for the following planting season (Rivera-Núñez et al., 2022). In this context, SEN could be fundamental to get seeds in case of scarcity. Moreover, male migration may be promoting women to be increasingly involved in seed exchanges. It is unclear to what extent household sociodemographic characteristics could be shaping maize SEN. Here it was hypothesized that men and women would exchange seeds with the same frequency and that households that had bigger plots, maize self-sufficiency, more time producing maize, and fewer members, would give seeds more often. We found that in all communities, a greater proportion of exchanges were made by men and that there was a tendency for exchanges to be made between household members of the same gender. Contrary to our hypothesis, men keep on exchanging more frequently than women, even in the face of male migration (Deere, 2009). At least until this study was made, SEN in this region followed the classical peasant theory in which men are mostly in charge of productive tasks, although women participate as well to some extent (Chayanov, 1966). Furthermore, we found that households with the hypothesized characteristics are the ones that are more likely to give seeds to others. These characteristics point to having a surplus as the main precondition for households supplying seeds. The main reason for exchanging was the lack of seeds, thus, in this region, as in others (van Niekerk & Wynberg, 2017), SEN work as seed banks that enable households to keep on sowing maize even if they did not have a good harvest the previous year. In other words, SEN could be one of the factors that help households achieve food security over time. Through SEN, households in a vulnerable situation (having small plots, being young, having a higher number of household members, and not having sufficient maize for the cropping season), can get quality seeds adapted to the local conditions, and keep on producing maize. Current sociodemographic conditions in which newly formed households have smaller plots (Lowder et al., 2016), and find it hard to meet grain self-sufficiency because of off-farm labor (Novotny et al., 2021; Rivera-Núñez et al., 2022) are shaping the way that maize SEN are functioning. These networks could be a mechanism that helps households face vulnerability, letting them replenish seed supplies in case of shortage. However, this mechanism depends entirely on the persistence of households with seed surpluses.

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Nonetheless, contrary to what has been reported for SEN of the Peruvian Amazon (Abizaid et al., 2016), networks in this study tended to be reciprocal. This was because we considered lifetime exchanges, therefore some years households received, and others gave seeds to the same households. Although it is more likely that households with sociodemographic characteristics that enable them to have surpluses give seeds to others, networks are not extremely centralized on particular households, indicating that most households in the SEN receive seeds at times of scarcity and most households give seeds at times of surplus. This, in turn, is related to the robustness of the network. Furthermore, reciprocity through time indicates that when a household gives seeds to another that has lost that variety, the first household has the opportunity to get back seeds in the future in the case that variety gets lost (Violon et al., 2016). This reciprocity through time helps achieve diversity conservation. Also, we registered that there was an additional form of reciprocity that was excluded from our analysis, as it is not directly relevant to the conservation of local germplasm. We observed that it is common for a household that asks another for seeds, to give in return grain bought on local stores that is used as food supply (to make *tortillas*), but is not suitable as seed. This form of reciprocity has been reported before (Badstue et al., 2006) and could become increasingly important to sustain SEN as households engage in off-farm labor and do not have enough local seeds but have access to grain bought at local stores, but its role in sustaining SEN has not been explored.

As previously reported (Bellon et al., 2011; Llamas-Guzmán et al., 2022), it was more likely that exchanges occurred between households from the same community. In addition to the pre-existing social relations (Labeyrie et al., 2016) and the obvious practicality, the higher frequency of intra-community exchanges could be related to the great diversity of environmental conditions within short distances that prevail in highland regions. Households cannot get seeds from a place that differs too much from the place where they cultivate, because maize is extremely adapted to specific environmental conditions (Perales et al., 2003). Consequently, maintaining maize genetic diversity in these conditions requires seeds to move slowly and continuously through networks, for seeds to get adapted as they move through the landscape (Dyer & Taylor, 2008).

Agrobiodiversity conservation through seed exchange networks

Highland maize native varieties are the most vulnerable to future conditions under climate change (K. L. Mercer & Perales, 2010). This is why the adequate functioning of SEN and the diffusion of diverse varieties through them is especially important in these regions (Bellon et al., 2011). In other crops (Calvet-Mir et al., 2012; Llamas-Guzmán et al., 2022; Pautasso et al., 2012; Song et al., 2019), SEN have been demonstrated to be important in diversity conservation. In Cofre de Perote, we demonstrated that households that had a greater centrality in the networks sowed more maize morphotypes. Households that exchange seeds more frequently can access and produce more diversity, playing a key role as maize diversity guardians. There are some regions of the world where this pattern does not occur because there, the families with more knowledge or prestige are the ones that exchange more frequently (Abizaid et al., 2016; Kawa et al., 2013; Thomas & Caillon, 2016). In Cofre de Perote, as in other regions, if farmers with a great diversity got out of the networks, there would be varieties that would be lost (Llamas-Guzmán et al., 2022) and it would be harder for households that are lacking seeds to obtain them (van Niekerk & Wynberg, 2017). These households are particularly important for rare morphotypes to keep on existing, as they are the ones who can diffuse them. However, in all communities, there are three morphotypes that households did not exchange, and only a few households produce them (eight out of the 305 households plant one of those three non-exchanged morphotypes). Furthermore, it is worth noticing that the number of morphotypes in the community was not necessarily related to the accessibility to urban centers, because, in the community with most, as well as the one with least access, there are five morphotypes and, in all communities, each household produces on average two morphotypes, which could be an indicator that in this highland region, as in others (Perales et al., 2003), accessibility to urban centers is not having a negative impact on maize diversity.

SEN are endogenous processes to communities, enabling *in situ* maize diversity conservation, and, based on the findings of this study, it would be necessary to strengthen networks of communities that have more access to urban centers. There are some methods in which this could be achieved, one of them is promoting exchanges between households even though they do not have a kinship relation, by rising awareness of the importance of seed-exchanging practices. Another way of strengthening SEN is by providing key information on seed diffusion and maize participative improvement to the households that were identified as central (Abay et al., 2011). In addition, it would be important for future research to study the underlying reason for the rarity three morphotypes that are not being exchanged, and to evaluate the possibility of diffusing those seeds to preserve them, as has been done before by Aw-Hassan et al. (2008) with barley seeds in Syria.

Limitations

The networks represented in this study are a model of the exchanges that households have done throughout their lifetime based on self-reports. Our analysis may be an underestimation as there might have been some exchanges that were not recalled. Moreover, networks are dynamic processes, and since we collapsed exchanges over time, there is more representativity of exchanges made by older households. As a result, we cannot assure that older households give seeds with more probability. Nevertheless, it is probable that the reported exchanges are mostly recent ones, because those are the easiest to remember. We recommend for future studies, to ask interviewees for the exchanges made on a defined lapse of time. Another limitation is that, as we defined maize morphotypes based on a local classification, we could be over or underestimating maize diversity. However, the formalization conducted in this study enabled us to shed light on some sociodemographic patterns that can currently explain SEN structures.

Conclusion

At the community level, SEN robustness decreased with accessibility to urban centers. Accessibility to selling markets and changes in livelihood strategies in communities with easier access to urban life could be causing this pattern. Consequently, it would be necessary to concentrate efforts to strengthen networks in communities with more access to urban centers by promoting exchanges between households that are not already connected. Within communities, households that give seeds more frequently are under sociodemographic conditions that enable them to save seeds for the next cropping season. Therefore, maize SEN in this highland region are functioning as sources of seeds in case of scarcity, thus contributing to food security. Additionally, SEN are working as seed banks to which any household can access, because networks are not extremely centralized on particular households and there is a tendency of reciprocity through time. In addition, seed exchange frequency is related to maize morphotype diversity, and, in this sense, SEN are promoting *in situ* crop diversity conservation. Knowledge and diffusion of the morphotypes that are rarely or never exchanged would be necessary for them to persist. Due to the heterogeneity of conditions of the highlands, the diffusion of the seeds through networks becomes especially important for them to keep on adapting to different conditions. This diffusion has to be slow to allow for adaptation.

SNA proved to be a powerful tool, as we were able to shed light on the factors that shape SEN and their role on the persistence of rural livelihoods and native maize diversity. This formal approach could be used in different contexts worldwide to promote programs and politics that assure SEN persistence. It is necessary to develop informed strategies to promote crop diversity conservation in the face of changing climatic conditions. The importance of SEN for the continuity of crop diversity has been proven in multiple contexts. In this study, we provide a novel approach to move in the direction of formally assessing SEN, the factors that structure them, and their effects on seed diversity conservation.

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Disclosure statement

The authors report that there are no competing interests to declare. Ethics clearance obtained from: Comité de Ética en Investigación de la Facultad de Psicología-Xalapa Universidad Veracruzana (CONBIOETICA30CEI00820150409).

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Table 1. Characteristics of the households in the study communities of the Cofre de Perote.

Community	Accessibility to urban centers (min)	Number of households [a]	Altitude [a]	Surveys	Male exchanges (%)	Households with enough maize (%)	Number of household members [b]	Plot size (ha) [b]	Number of plots [b]	Age of production (median years)	Number of morphotypes [b]	Morphotypes per community [c]
Xico Viejo	25	138	1740	44	0.7	0.28	5.5±2.7	1.1±1.1	1.1±0.5	20 – 50	2.2±0.8	R; B; N; A; P
Matlalapa	30	122	2086	56	0.7	0.33	6.5±3.8	1.2±0.9	1.4±0.6	20 – 50	1.9±0.8	BA; BAN; B; N; A; P
Micoxtla	30	91	1739	42	0.5	0.57	5.1±2.3	1.3±0.8	1.3±0.5	20 – 50	2.1±0.7	BA; B; N; A; P
Coatitilán	30	73	2029	37	0.5	0.37	5.3±3.4	1.3±1.6	1.3±0.5	10 – 20	1.9±0.8	BG; BAN; B; N; A; P
Pocitos	60	41	2130	25	0.7	0.54	6.2±3.1	1.1±0.8	1.4±0.6	20 – 50	1.9±0.9	BG; B; N; A; P
Zapotal	60	77	2441	50	0.7	0.68	4.1±1.8	1.8±1.9	1.3±0.4	20 – 50	2.3±1.1	R, BA, NA; B; N; A; P
Encinal II	90	29	2428	20	0.6	0.52	5.7±3.3	1.8±1.3	1.4±0.6	20 – 50	2.5±1.0	R, BA; B; N; A; P
Saucal	90	20	2566	20	0.7	0.50	5.4±1.7	1.8±1.6	1.3±0.7	10 – 20	2.3±0.6	BG, BA; B; N; A; P
Buena Vista	150	14	2160	10	0.7	0.20	6.3±2.6	1.1±0.6	1.4±0.5	10 – 20	2.4±0.6	BG; B; N; A; P

[a] National Institute of Statistics and Geography (INEGI, 2020)
[b] (Mean±SD; n=305)
[c] B: *blanco,* N: *negro,* A: *amarillo,* and P: *pinto* morphotypes that are present in all communities. BA: *Blanco angosto*; BAN: *Blanco ancho*; BG: *Blanco grande*; R: *Rojo*; NA: *Negro angosto*

Table 2. Characteristics of community SEN. The Network size is equal to the number of households in the network, all exchanges are included, therefore households of other communities are included as a node in each community network if there is an existing tie (exchange event). Number of households belonging to that particular community (excluding the households of other communities connected to that community). Proportion of SEN households is the percentage of households in the community that participates in the SEN (Households on the network/Households on the community). Density is the division of present exchanges (PE) between the number of possible exchanges (PoE) given the number of households on the network (De=PE/PoE).

Community	Network size (No. households)	Number of households of the community	Proportion of SEN households	Average degree centrality (links per household)	Density (PE/PoE)
Regional	380	283	46%	3.86	0.005
Xico Viejo	70	52	37%	3	0.021
Matlalapa	86	58	47%	2.23	0.013
Micoxtla	52	45	49%	3.23	0.031
Coatitilán	57	38	52%	2.56	0.022
Pocitos	69	52	67%	3.10	0.022
Zapotal	39	27	65%	2.71	0.035
Encinal	39	23	79%	2.30	0.030
Saucal	26	20	100%	3.38	0.067
Buena Vista	13	11	84%	2.15	0.089

Table 3. Results of Exponential Random Graph Models (ERGM). Parameter estimates are expressed in log odds with standard deviation in parentheses (**p≤0.01, ***p≤0.001).

Terms	**Null model**	**Complete model**
Edges	-5.203(0.04)***	-8.351 (0.27)***
Households of the same community		3.906 (0.18)***
Reciprocal ties		2.907 (0.17)***
Gender reciprocity		0.480 (0.10)***
Probability of giving seeds		
Maize sufficiency for the cropping season		0.310 (0.10)**
Years of production		0.127 (0.04)**
Size of the plot		0.116 (0.03)***
Number of household members		-0.045 (0.01)**
AIC	5004	3471

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Figure 1. The nine study communities in the Cofre de Perote region and urban areas with seed markets. The route from each community to the more accessible urban center is colored according to self-reported transportation time. The location of the formal seed market is shown by the yellow triangles.

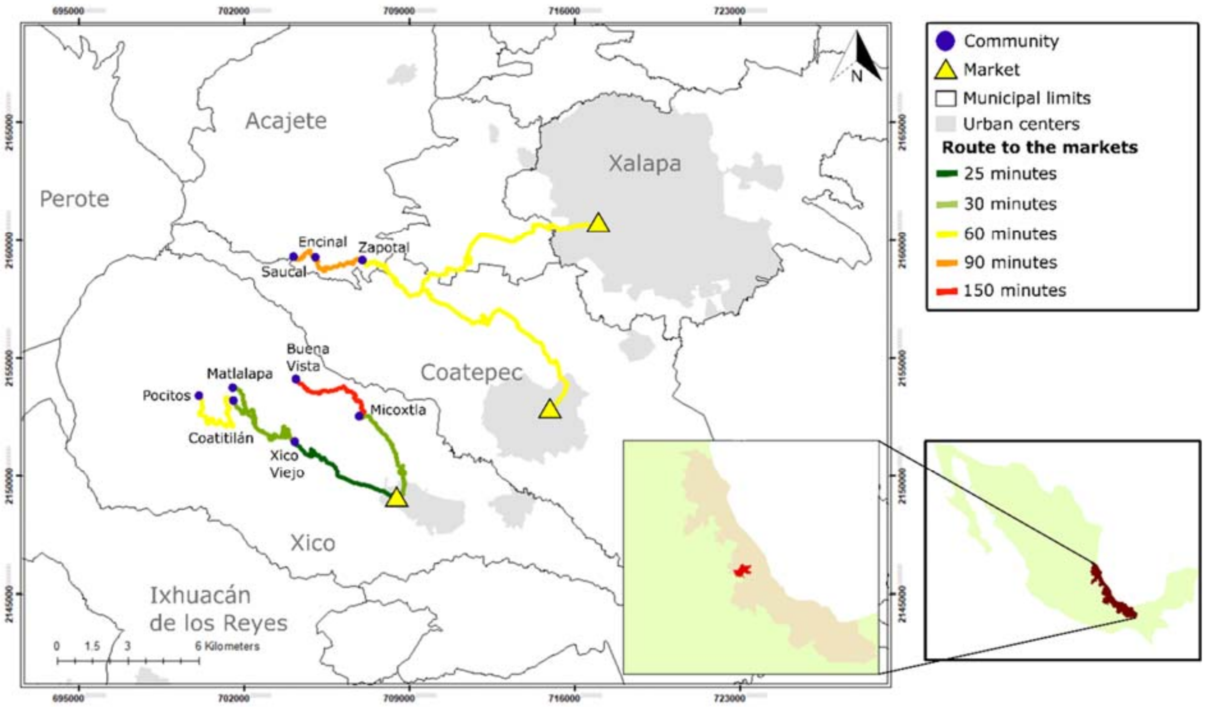

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Figure 2. Configurations used to estimate the parameters of the ERGM. Each configuration indicates the probability that 1) there is an exchange between any two households; 2) the exchanges are reciprocal; 3) an exchange occurs between two households with the same characteristic; 4) a household with a certain characteristic gives seeds to other households, no matter the characteristics of the others.

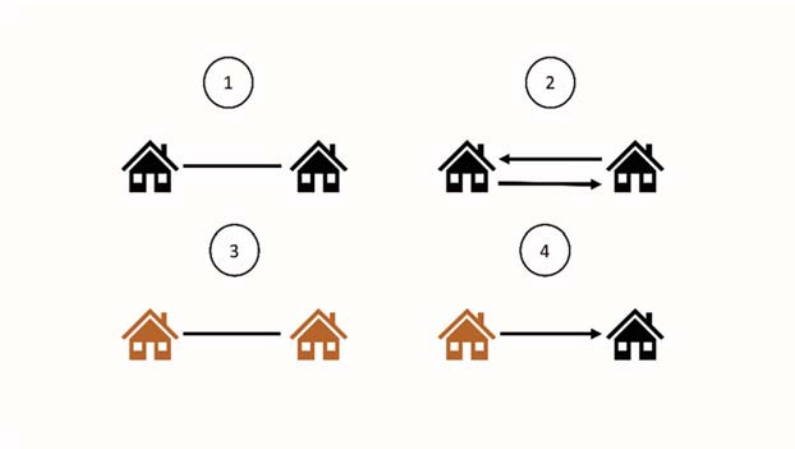

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Figure 3. Regional SEN. In this mountainous region, seed exchanges are given among communities that are close to each other, because maize morphotypes are extremely adapted to local conditions. Seeds are purchased in the three available markets regardless of distance.

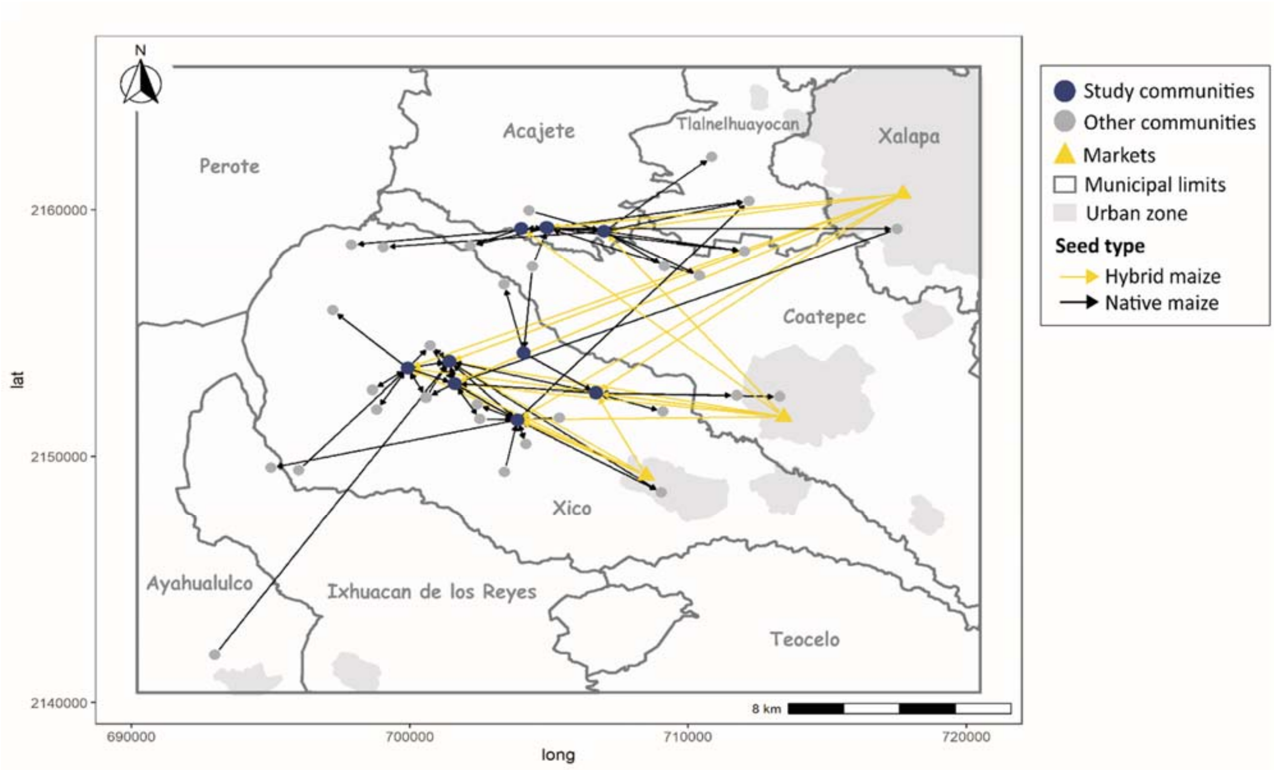

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Figure 4. SEN of native maize. Each group of households represents a community.

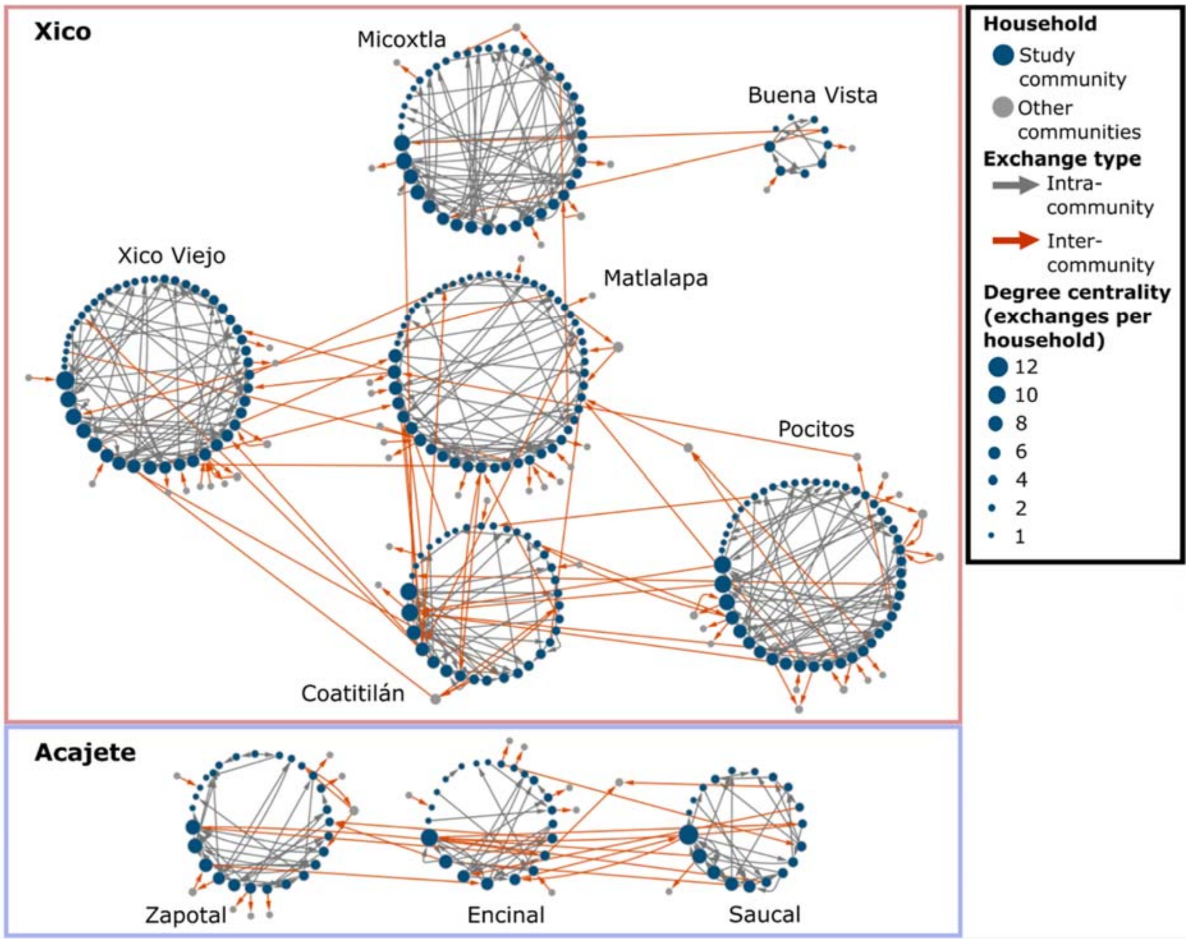

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Figure 5. . The proportion of households that purchased commercial seeds in each community. Bars are ordered according to the accessibility of the community to urban centers. In communities that have more access, more interviewed households had bought commercial seeds.

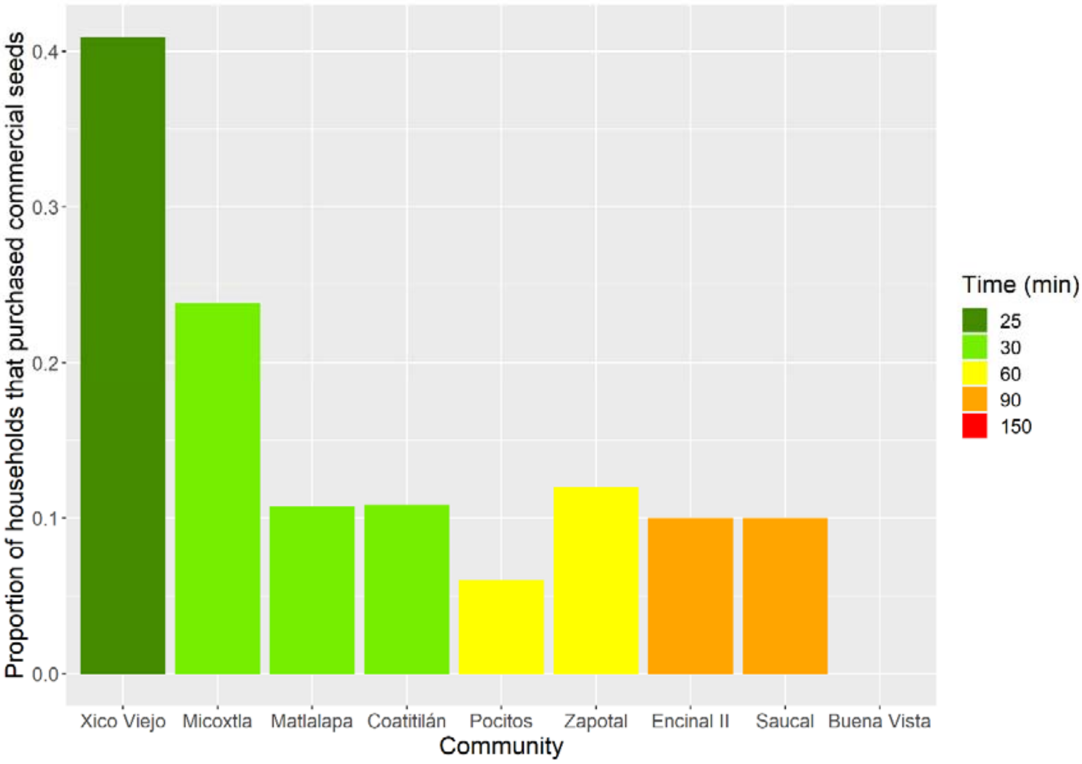

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Figure 6. . Robustness of the SEN. By (a) degree removal and (b) random removal. The lines represent the estimated beta regression model (Degree removal: $X^2_{(9, 3)}$=16.00, p<0.001; Random removal: $X^2_{(9, 3)}$=11.23, p<0.001).

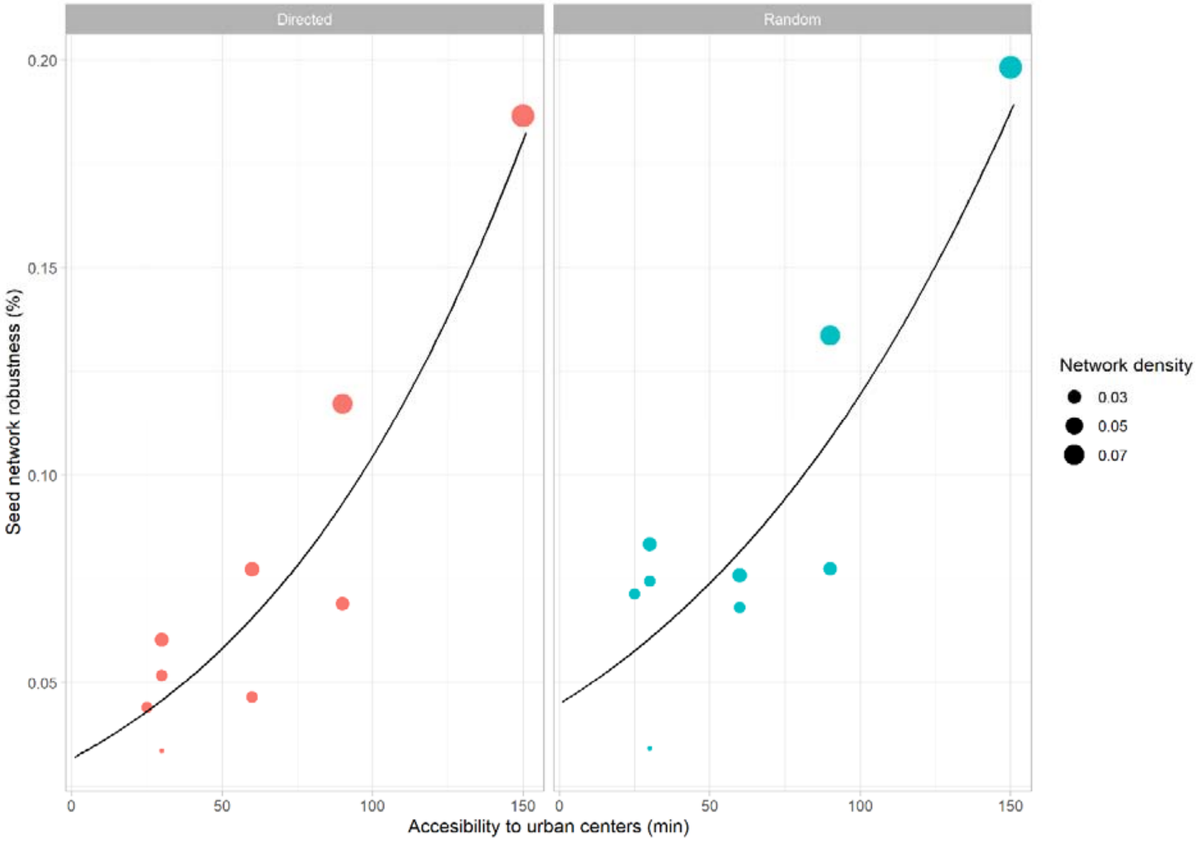

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Figure 7. The number of morphotypes on the plot explained by the degree centrality of the households. Bars represent the mean number of maize morphotypes that each household produces, given its degree centrality (±se). The red line represents the estimated model with the confidence interval ($X^2_{(288,286)}$=5.99, p<0.001).