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Seed Exchange Networks of Native Maize, Beans, and Squash in San Juan Ixtenco and San Luis Huamantla, Tlaxcala, Mexico

Luz P. Llamas-Guzmán [1,*], Elena Lazos Chavero [1], Hugo R. Perales Rivera [2] and Alejandro Casas [3]

[1] Instituto de Investigaciones Sociales, Universidad Nacional Autónoma de México, Mexico City 04510, Mexico; lazos@unam.mx
[2] Departamento de Agricultura, Sociedad y Ambiente, El Colegio de la Frontera Sur, Unidad San Cristóbal de las Casas, Carretera Panamericana y Periferico Sur s/n, María Auxiliadora, San Cristóbal de las Casas 29290, Mexico; hperales@ecosur.mx
[3] Instituto de Investigaciones en Ecosistemas y Sustentabilidad, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro 8701, Col. San José de la Huerta, Morelia 58190, Mexico; acasas@cieco.unam.mx
* Correspondence: luzllamasg@gmail.com

Abstract: Seed exchange networks among farmers favor circulation of crop varieties and have been discussed as an effective means of crop diversity conservation. This study aims to document the processes and structure of seed exchange networks of native maize, beans, and squash among farmers and other participating sectors (local market or seed banks), analyzing their influence on agrobiodiversity conservation in the municipalities of Ixtenco and Huamantla, in the Mexican state of Tlaxcala. Through interviews, questionnaires, and social network analysis, nodal farmers were identified. In the maize network, five nodal farmers were detected, the *blanco* maize being the most commonly exchanged seed. In the bean network, three nodal farmers were identified, with *amarillo* beans as the most exchanged seed. In the squash network, no nodal farmer was identified. For maize and beans, the greater the number of exchanges, the greater the varieties exchanged. The local market of Huamantla and the Vicente Guerrero seed bank are relevant seed sources. The nodal farmers propitiate circulation of a large number of seed varieties in the exchange networks and contribute to maintenance and conservation of agrobiodiversity.

Keywords: native seeds; nodal farmers; seed networks; agrobiodiversity; social network analysis

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1. Introduction

Farmers worldwide continually select native seed varieties for planting, adapting the attributes of the plants they cultivate to particular socio-environmental contexts and local management practices [1–3]. Seed varieties conserved by farmers form part of agrobiodiversity, and represent important reservoirs of genetic diversity [4–7]. Mexico is considered to be one of the nations with the greatest agrobiodiversity, and center of origin and diversification of maize, a variety of species of beans, and some species of squash [2,8,9], which are crucial to the diet of—and a source of income for—rural families [10]. Maintaining native varieties and free exchange of seeds among farmers is key to preserving agrobiodiversity and achieving sustainable agriculture in peasant communities [7,11–13].

Seed exchange involves a variety of strategies carried out by farmers to acquire or renew seeds [6,14] and is undertaken through social relations among family members, friends, and acquaintances [15,16]. Social networks are defined as sets of relationships among social actors which possess a structure through which information, behaviors, attitudes, and values are transmitted [17,18]. Studying the structure of a social network allows for understanding of the influence and significance of the actors in these networks, as well as the manner in which they are connected and form groups with other actors. Social Network Analysis (SNA) is a methodological tool that allows visualizing the structure

of social relations (edges) among social actors (nodes), and measuring and analyzing interactions among members of the networks [17].

In recent years, SNA has been employed to evaluate management of agrobiodiversity [19,20]. These studies have allowed analyzing, visualizing, and measuring each node that forms part of a seed network [21–25], as well as identifying nodal farmers, those who are involved in a large number of exchanges of seed varieties [20,22,23,25–27].

Subedi et al. [20,26] and Poudel et al. [28] identified nodal farmers as those who maintain a relatively high seed diversity and are perceived in their communities as having extensive knowledge of plant varieties. They supply other farmers with seeds and maintain links which allow them to acquire new varieties. Authors such as Calvet-Mir et al. [24], Devkota et al. [25], Poudel et al. [22], Rodier and Struik [23] and Song et al. [27] have used SNA to identify nodal farmers, as those with the greatest level of centrality (number of connections a node contains) in a network. Rodier and Struik [23] defined nodal farmers as those with four or more direct connections in a network, while connector farmers are those who have high values of betweenness centrality (measure which indicates that a node may act as a bridge within the network). Nodal and connectors farmers are key actors in seed exchange networks. Nodal farmers have a high crop diversity as well as the capacity to exchange seed varieties with other farmers, thus promoting circulation of seeds [22,25]. Connector farmers may spread certain seed varieties toward other subgroups of the network, facilitating seeds reaching other farmers of distant areas or those who are less connected to the network [22]. In this manner, nodal and connector farmers contribute to the maintenance and conservation of agrobiodiversity [21,25,27]. However, seed networks are dynamic, a nodal or connector farmer may abandon this role after a certain period of time and other farmers may take on these roles. These changes may occur even from one agricultural cycle to another or after a few years [29].

One of the sustainable development goals is the eradication of hunger [30]. It is estimated that by 2050, the global population will reach 9.7 billion, and 10.8 billion by 2080. Therefore, there will be an increase in the demand for food production [31]. The family farming activities produces ~80% of the food worldwide [32,33]. Active participation by small-scale farmers in the conservation of local varieties is essential to achieving food security, as they tend to carry out environmentally sustainable agricultural practices, conserving agricultural land, as well as bearing knowledge and germplasm of native seeds—thereby also enhancing cultural diversity. These practices, together with seed exchanges, favor conservation of agrobiodiversity, which is crucial to achieving food security and sustainable development [12,13]. The seed exchange networks are central to agrobiodiversity conservation since farmers can access local seeds [16]. The farmers of Mexico select and save their seeds year after year to plant [2,9]; however, those who lose seeds, due to environmental factors such as droughts, frosts, floods, or pathogens, or those who seek to renew and acquire new varieties, frequently approach family members and friends within their community [6]. If networks of family members and friends are not able to provide them with seeds, nodal farmers can be an option to achieve the variety [20]. Aside from seed exchange networks, other options for farmers to obtain seeds include community seed banks, seed fairs, and local markets [34].

In order to analyze the functioning of the maize, beans, and squash seeds networks, this study examined the cases of the municipalities of San Juan Ixtenco (Ixtenco) and San Luis Huamantla (Huamantla) in the Mexican state of Tlaxcala. Farmers of these municipalities have maintained and preserved different races of maize (*Zea mays* L.) that belong to the conical racial group, which include the races *Chalqueño*, *Cónico*, *Elotes cónicos*, and *Cacahuacintle* [35]. This racial group is found from 2000 to 2800 m, and they are characterized by the production of conical cobs, with large numbers of grain rows (14–20), 4–8 mm grains and the presence of anthocyanins in the grains. To this racial group belong different native varieties of maize such as *azul*, *amarillo*, *blanco*, *negro*, etc. [35]. Moreover, the farmers of these municipalities maintained beans (*Phaseolus vulgaris* L.) [36], and squash (*Cucurbita pepo* L.) [37,38]. All these varieties of maize, beans and squash have been maintained due to

traditions, diet, and economic criteria [39,40]. The municipality of Ixtenco represents a bastion in the conservation of different native varieties. In this municipality, there are maize varieties such as *negro*, *xocoyul* and *ajo* or *tunicado* (*Zea mays* var. tunicata A. St. Hil.) that are only preserved in this region. In the case of Huamantla (and despite being close to Ixtenco), commercial native varieties, such as *blanco* maize, and those used for animals, such as *amarillo* maize, hold greater importance among farmers. This study aims to analyze the structure and processes of interaction among farmers that conform seed exchange networks of native maize, beans, and squash and understand their influence on agrobiodiversity conservation in the municipalities referred to. To reach this goal, the seed exchange network was analyzed to identify the nodal farmers and to characterize the interactions related to seed exchange among farmers. Our main hypothesis was that maize, beans, and squash seed exchange networks can play an important role in maintaining diversity due to favoring of the movement of different seeds among farmers. We expected to find that the maize seed network contains a greater number of seed exchanges of different varieties of seeds and a greater number of nodal farmers than the bean and squash networks, since maize holds a greater dietary and commercial importance for the region's farmers. Finally, we expected to find a greater exchange of varieties that are widely used for subsistence and commerce due to the fact that farmers seek these types of seeds for cultivation.

2. Materials and Methods

2.1. Study Zone

The state of Tlaxcala has a sub-humid temperate climate with an average annual mean temperature of 14 °C and an annual precipitation averaging 800 mm with summer rains [41] (Figure 1). Seasonal agricultural systems are mainly cultivated to provide crops for family consumption. Problems associated with agricultural production include droughts and frosts [42].

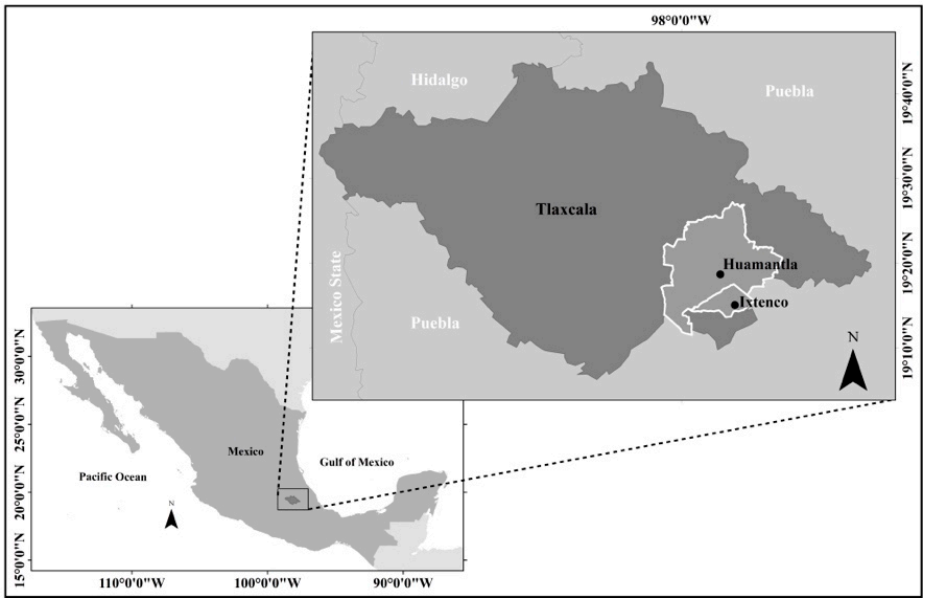

Figure 1. State of Tlaxcala, Mexico and location of the municipalities of Ixtenco and Huamantla.

2.2. Description of Study Sites

The municipalities of Ixtenco and Huamantla, in the western part of the state of Tlaxcala close to La Malinche volcano, are located 9.5 km from each other (Figure 1). In the municipality of Ixtenco, 6791 inhabitants live in 1689 homes, in a single *ejido* with a total area of 5917 hectares and 1777 *ejido* members [41,43]. The annual seed fair called "Fiesta del maíz" has been carried out for the past nine years [44]; in this event farmers of the municipality sell maize, beans, and squash as well their seeds. During the 2019 agricultural

cycle, 10,251 tons of maize was reported to have been produced in seasonal crop systems, with an average yield of 3 ton/ha. Total bean production was 1.6 tons, with an average yield of 0.8 ton/ha [45].

The municipality of Huamantla has 84,979 inhabitants who live in 20,870 homes in 24 *ejidos* [41]. In this municipality, two *ejidos* were selected for fieldwork: San Luis Huamantla, with an area of 4826 hectares and 1946 *ejido* members, and Zaragoza, with a surface area of 1022 hectares and 322 *ejido* members [41,43]. During the 2019 agricultural cycle, a production of 19,500 tons of maize was reported in seasonal agricultural systems, with an average yield of 2.6 ton/ha. Total bean production was 39 tons, with an average yield of 0.7 ton/ha [45].

2.3. Interviews with Farmers

During 2018, 40 semi-structured interviews and 100 surveys were carried out in the study sites. A total of 20 interviews were carried out with farmers of Ixtenco (6 women and 14 men) and 20 with farmers of Huamantla (only men were interviewed) (Appendix A). Average age of farmers interviewed was 57.8 (age range 24–89 years). To select farmers, the snowball sampling technique was used. This technique allows for the obtainment of a series of contacts starting with a single informant. The researcher asks this informant for a contact with another person with certain characteristics depending on the research topic, who in turn is asked to name another person [46,47]. The first contact was initiated with key actors, including the coordinator of the seed fair "Fiesta del maíz" and participating farmers. These farmers in turn provided data about other farmers who had at least one variety of maize, beans, or squash. Later, interviews were carried out with farmers who participated in at least one seed exchange. The interview addressed the following topics: (a) conservation of and information regarding seed varieties, (b) seed exchanges, (c) soil preparation for planting, (d) seed sale, (e) knowledge of seed laws, and (f) festivities related to seeds. For the first topic, we recorded the number of varieties of maize, bean, and squash whose seeds were planted by each farmer. The second addressed with whom they exchanged seeds (family members, friends, neighbors, and other acquaintances) and dates of exchanges. The third covered plot description: surface area, location, soil type, and cultivation problems. The fourth addressed seed sale: place, quantity, and varieties sold. The fifth consisted of documenting the farmer's understanding of seed laws at the state and national levels. The final topic addressed farmer's participation in seed-related celebrations. All interviews were transcribed and codified by assigning key words (for example "maize exchange", "beans exchange", "squash exchange") for later analysis.

2.4. Questionnaires Applied to Farmers

Based on information from the interviews, in 2019 a survey was carried out with 100 farmers (50 per municipality): 13 women and 37 men from Ixtenco and 6 women and 44 men from Huamantla (Appendix A). In order to select farmers from the municipality of Ixtenco, for most streets of the village one of every five consecutive houses was selected. Given the difficulty of carrying out this methodology in Huamantla, as it is a city, which makes it complicated to contact the farmers, the local authorities were asked to invite men and women farmers. In the municipality of Ixtenco, approximately 1000 *ejido* members plant and conserve their seeds [48]. In the case of the *ejido* of San Luis Huamantla (the largest of the region) approximately 600 *ejido* members maintain their seeds and the total production of the *ejido* [49]. Based on this information, to expand the sample, 80 farmers of each municipality were invited to be surveyed. Selection of this sample size considered a 93% confidence level with a sampling error of 7%; however, a response was obtained from only 50 farmers per municipality.

2.5. Analysis of the Seed Networks

A graphic representation of the seed exchange network was constructed based on data from the surveys. Variables analyzed were number of maize, beans, and squash varieties

that each farmer conserved, whether any of these varieties had been exchanged during the past five years, and if so with whom. These data served to determine the exchange network of each crop and to quantify the crop diversity that each farmer conserved (number of maize, bean, and squash varieties). We maintained in this research the local names of the native maize, beans and squash varieties. The majority of farmers of the two municipalities saved their own seeds every year to plant the following season, and therefore carried out few exchanges. For this reason, and due to the low frequency of exchanges each year mentioned by people interviewed, the decision was made to record the number of exchanges carried out by each farmer within the past five years (2015–2019). In order to provide a visual representation of the network, the open access program Cytoscape 3.7.1 was used [50,51]. The following data were employed for the SNA: farmer's municipality, gender, varieties of maize, beans, and squash exchanged, social relationship with whom the exchange was carried out (family member, friend, neighbor, or acquaintance), and place of origin of the person with whom the exchange was carried out, and place of origin of the seed (e.g., local market, seed bank).

The networks were analyzed as directed networks. Nodes represent farmers, local markets, stores, seed banks and other places, such as different states of Mexico and municipalities, where seeds were exchanged (Puebla, Querétaro, Terrenate, Altzayanca, El Carmen Tepexquitla, and Vicente Guerrero). Edges indicate the direction of a seed exchange between farmers. Outdegree is the number of times that a farmer gave seeds to another, and indegree is the number of times a farmer received seeds from another. Closeness centrality was interpreted as the speed with which a farmer could spread a seed variety. Finally, betweenness centrality was defined as the capacity to spread a variety to other sub-groups in the network, by which the variety may reach farmers of different sites. Nodal farmers were identified as those who carried out four or more seed exchanges (farmers with high outdegree within the network) involving three or more different seed varieties. In the case of squash, nodal farmers were defined as those who carried out four or more seed exchanges, although involving only one variety, due to the fact that in the study region only one local squash variety was cultivated. Connector farmers were identified as those with the highest values of betweenness centrality in the network ($\geq$0.5). In order to detect the nodal and connector farmers of each crop, and due to the fact that some farmers planted only one crop and/or variety, the maize, bean, and squash networks were analyzed separately. To carry out statistical analyses, the R program (R v.1.2.5.033 R Development Core Team) was employed, using the lm () and ggplot2 () functions.

3. Results

3.1. Agricultural Crops Registered in Ixtenco and Huamantla

On average, farmers cultivate 7 ha (range 0.004–60 ha). In Ixtenco, the farmers mainly conserve *blanco* (84%), *azul* (64%), *negro* (44%), *amarillo* (34%), *xocoyul* (28%) and *crema* (26%) maize, and in Huamantla *blanco* (80%), *amarillo* (52%) and *azul* (50%). These maize varieties are important for the market demand, owing to their color, appearance of cobs, their specific use for making traditional food and the quality of their kernels, which are used for handcrafts (Table 1 and Appendix B). In the case of bean crops, the farmers of the two municipalities, mainly conserve *negro*, *amarillo* and *bayo*, varieties used for family consumption and market (Table 1). In Ixtenco, a greater number of farmers conserve the squash crop (82%) than in Huamantla (72%), this crop is used for family consumption and for market (Table 1). In Ixtenco and Huamantla, 21 (42%) of the farmers maintain other crops such as *Vicia faba* (broad bean), *Lathyrus sativus* (pea) and *Avena sativa* (oat) (Table 1).

Table 1. Number of farmers who conserve maize, beans, squash and other crops in the municipalities of Ixtenco and Huamantla, Tlaxcala, Mexico.

Variety	Number of Farmers Who Conserve the Variety in Ixtenco (n = 50)	Number of Farmers Who Conserve the Variety in Huamantla (n = 50)	Benefits and Importance of the Variety to Farmers
Maize varieties			
Blanco	42 (84%)	40 (80%)	The grain has a high market demand. Used for *tortillas* and flour. Appreciated for the weight, size, and color of cobs.
Amarillo	17 (34%)	26 (52%)	Principally for animal consumption. Appreciated for color and weight of cobs.
Azul	32 (64%)	25 (50%)	Appreciated for color and appearance of cobs. Due to increased demand in recent years, it is sold at a higher price than other varieties.
Crema	13 (26%)	4 (8%)	Appreciated for the weight of cobs.
Negro	22 (44%)	7 (14%)	Highly appreciated by farmers of Ixtenco. Used to make the traditional cooked fermented corn drink "*atole agrio*".
Cacahuacintle	23 (46%)	3 (6%)	Used for making traditional Mexican food such as *pozole*, and maize flour.
Ocho carreras	-	3 (6%)	Appreciated for size and weight of cobs.
Xocoyul	14 (28%)	2 (4%)	Its flour is used for preparing the beverage *atole*, appreciated for its pink color.
Campeón	1 (2%)	2 (4%)	Appreciated for the large size and weight of cobs.
Ajo o tunicado	5 (10%)	-	High cultural value in Ixtenco due to cob characteristics.
Chalqueño	-	3 (6%)	Appreciated for color and size of kernel.
Rojo	18 (36%)	1 (2%)	Used to make maize flour.
Cruza blanco-campeón	-	1 (2%)	Appreciated for color and the cobs.
Sangre de cristo	10 (20%)	-	Its flour is used for *atole* and the kernels for handcrafts.
Arrocillo-palomero	2 (4%)	1 (2%)	Marketed and used for family consumption.
Ancho	-	1 (2%)	Appreciated for short agricultural cycle.
Bean varieties			
Amarillo	23 (46%)	22 (44%)	It is marketed and used for family consumption.
Negro	25 (50%)	11 (22%)	It cooks rapidly and is marketed and used for family consumption.
Bayo	14 (28%)	18 (36%)	It is marketed and used for family consumption.
Mantequilla	3 (6%)	2 (4%)	It is marketed and used for family consumption.

Table 1. *Cont.*

Variety	Number of Farmers Who Conserve the Variety in Ixtenco (n = 50)	Number of Farmers Who Conserve the Variety in Huamantla (n = 50)	Benefits and Importance of the Variety to Farmers
Parraleño	3 (6%)	-	It is marketed and used for family consumption.
Pinto	3 (6%)	3 (6%)	It is marketed and used for family consumption.
Ojo de liebre	1 (2%)	2 (4%)	It is marketed and used for family consumption.
Vaquita	-	3 (6%)	It is marketed and used for family consumption.
Morado	-	1 (2%)	It is marketed and used for family consumption.
Flor de mayo	-	1 (2%)	It is marketed and used for family consumption.
		Squash variety	
Squash	41 (82%)	36 (72%)	It is appreciated by farmers for the size of the seeds, its color, and its productivity.
		Other crops	
*	21 (42%)	21 (42%)	These crops are for market and used for family consumption.

* *Vicia faba* (broad bean), *Lathyrus sativus* (pea), *Avena sativa* (oat), *Opuntia* spp. (prickly pear), *Amaranthus* spp. (amaranth), *Triticum aestivum* L. (wheat), *Secale cereal* L. (rye), *Lens* spp. (lentil), *Physalis ixocarpa* (green tomato), *Helianthus* L. (sunflower), *Prunus persica* (peach), *Medicago sativa* (lucerne), *Agave* (maguey) and *Brassica oleracea* var. itálica (broccoli).

3.2. Maize Exchange Network

A total of 18 different maize varieties were exchanged and on average, each farmer carried out 1.93 ± 1.47 exchanges of 1.62 ± 0.94 maize varieties in the past five years (Table 2). As shown in Table 2, *blanco* maize had the greatest number of exchanges (52), followed by *amarillo* (26) and *azul* (22) maize. These varieties were the three most exchanged among farmers. Exchanges were carried out among acquaintances from the same locality (73), family members (26) and to a lesser extent friends (20), neighbors (12) and people who the farmers did not know, yet approached to obtain seeds (13). The number of exchanges carried out varies according to the variety of maize (Table 2).

Table 2. Number and percentage of exchanges carried out by variety of maize among farmers of Ixtenco (I) and Huamantla (H), Tlaxcala, Mexico from 2015 to 2019.

Maize Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers Who Exchanged the Variety	Number of Exchanges among Actors in the Maize Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintan (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Blanco	52	36	I	19	14	2 (10.53%)	4 (21.05%)	2 (10.53%)	10 (52.63%)	1 (5.26%)	3
			H	33	22	5 (15.15%)	-	5 (15.15%)	21 (63.64%)	2 (6.06%)	2
Amarillo	26	18	I	11	9	5 (45.45%)	2 (18.18%)	-	3 (27.27%)	1 (9.09%)	-
			H	15	9	2 (13.33%)	1 (6.67%)	1 (6.67%)	10 (66.67%)	1 (6.67%)	1
Azul	22	17	I	10	8	1 (10%)	3 (30%)	-	5 (50%)	1 (10%)	-
			H	12	9	3 (25%)	1 (8.33%)	1 (8.33%)	5 (41.67%)	2 (16.67%)	1
Crema	7	7	I	5	3	1 (20%)	1 (20%)	-	3 (60%)	-	1
			H	2	2	-	-	-	1 (50%)	1 (50%)	1
Negro	7	5	I	3	3	1 (33.33%)	1 (33.33%)	-	-	1 (33.33%)	-
			H	4	2	-	1 (25%)	-	3 (75%)	-	-
Cacahuacintle	5	3	I	3	2	2 (66.67%)	1 (33.33%)	-	-	-	-
			H	2	1	-	1 (50%)	-	1 (50%)	-	-
Ocho carreras	4	2	I	-	-	-	-	-	-	-	-
			H	4	2	-	-	2 (50%)	2 (50%)	-	-

Table 2. *Cont.*

Maize Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers Who Exchanged the Variety	Number of Exchanges among Actors in the Maize Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintan (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Xocoyul	3	3	I	2	2	-	1 (50%)	-	1 (50%)	-	-
			H	1	1	-	-	-	1 (100%)	-	-
Campeón	3	3	I	1	1	1 (100%)	-	-	-	-	1
			H	2	2	1 (50%)	-	-	1 (50%)	-	1
Ajo o tunicado	3	2	I	3	2	2 (66.67%)	-	-	1 (33.33%)	-	1
			H	-	-	-	-	-	-	-	-
Chalqueño	2	2	I	-	-	-	-	-	-	-	-
			H	2	2	-	-	-	1 (50%)	1 (50%)	-
Rojo	2	2	I	1	1	-	-	-	1 (100%)	-	-
			H	1	1	-	1 (100%)	-	-	-	-
Cruza crema-blanco	2	2	I	2	2	-	1 (50%)	-	-	1 (50%)	1
			H	-	-	-	-	-	-	-	-
Cruza blanco-campeón	2	1	I	-	-	-	-	-	-	-	-
			H	2	1	-	-	1 (50%)	1 (50%)	-	-
Sangre de cristo	1	1	I	1	1	-	-	-	1 (100%)	-	-
			H	-	-	-	-	-	-	-	-

Table 2. *Cont.*

Maize Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers Who Exchanged the Variety	Number of Exchanges among Actors in the Maize Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintan (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Arrocillo-palomero	1	1	I	1	1	-	1 (100%)	-	-	-	-
			H	-	-	-	-	-	-	-	-
Amealco	1	1	I	1	1	-	-	-	-	1 (100%)	1
			H	-	-	-	-	-	-	-	-
Ancho	1	1	I	1	1	-	-	-	1 (100%)	-	-
			H	-	-	-	-	-	-	-	-
		Total Ixtenco	I	64	51	15	15	2	26	6	8
		Total Huamantla	H	80	54	11	5	10	47	7	6
		Total	I-H	144	105	26	20	12	73	13	14

The directed network of the maize crop consists of 134 nodes with a total of 144 exchanges from 2015 to 2019 (Table 2 and Figure 2).

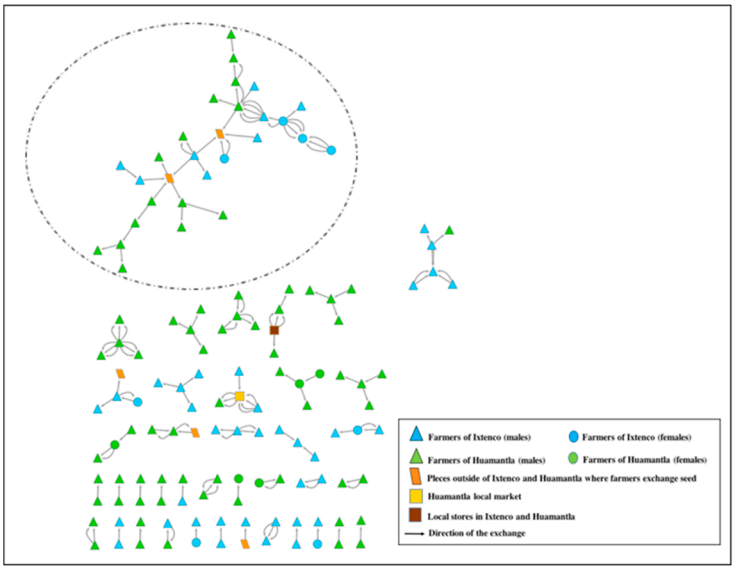

Figure 2. Maize seed network consisting of 134 nodes among farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seed (orange), local markets (yellow) and local stores (brown). The arrow indicates the direction of the exchange. Note: The dotted circle indicates the principal module of the network.

In Figure 2, the maize network shows a principal module and sub-networks separated from the principal module. Some 22 dyads are observed, in which 31 exchanges were carried out. The *blanco* maize variety was involved in 15 exchanges, the *azul* variety in 5, *amarillo* in 6, and the *chalqueño*, *rojo*, *amealco*, *crema*, and *xocoyul* varieties in only one exchange each. These dyads involved seventeen farmers from Ixtenco (15 men and 2 women) and 26 (24 men and 2 women) from Huamantla. One farmer from Ixtenco exchanged maize seed with a farmer from the state of Queretaro. The greatest number of exchanges (12) were between people who knew each other and lived in the same location. A total of 10 exchanges (one third) took place between family members living in the same location. The exchanges among family members occurred from fathers to sons or sons to fathers, between brothers, or among political family. Exchanges between neighbors (4) and friends (4) occurred between people of the same location, and only one exchange took place between a farmer and a person unknown to them.

A total of 5 triads were identified, involving 16 exchanges. Each variety was involved in the following number of exchanges among triads: *azul* (6), *blanco* (4), *amarillo* (3), *ocho carreras* (2), and *crema* (1). Twelve of these exchanges were among acquaintances of the same location, three among neighbors, and only one among family members. Ten tetrads and one hexad were identified. In the tetrads, 47 exchanges were conducted, many of which involved the local market node of Huamantla, where farmers from Ixtenco and Huamantla buy and sell *blanco*, *azul*, and *amarillo* maize seed. The exchanges in the tetrads were among acquaintances (24), people who did not know each other (12), family members (4), neighbors, (4) and friends (3). In the hexads, eight exchanges were carried out, involving *blanco* maize (5 exchanges) and *crema* maize (3) and these exchanges were among acquaintances (7) and friends (1).

Five nodal farmers were identified in this network (four men and one woman; Table 3). Four of these nodal farmers are from the municipality of Ixtenco and one from Huamantla. Three connector farmers were identified: one from Ixtenco and two from Huamantla.

Table 3. Measures of centrality of the nodes conforming the maize seed exchange network of Ixtenco and Huamantla, Tlaxcala, Mexico.

Node	Location of Farmer/Site Where the Seed Is from	Nodal (N) or Connector Farmer (C)	Outdegree	Indegree	Number of Different Varieties Exchanged	Betweenness Centrality	Closeness Centrality
F84	Huamantla	N	9	0	3	0	1
F121	Ixtenco	N	7	0	5	0	0.444
F33	Ixtenco	N	5	0	3	0	0.571
F44	Ixtenco	N	5	2	5	0.006	0.5
F11	Ixtenco		4	0	2	0	1
F21	Ixtenco		4	0	2	0	1
F34	Ixtenco	N	4	0	4	0	0.666
Agrochemical store	Agrochemical store		4	0	4	0	0.75
F5	Ixtenco		3	1	3	0.333	1
F132	Ixtenco		3	0	3	0	1
F32	Ixtenco		3	0	3	0	1
Huamantla local market	Huamantla local market		3	5	3	0.333	1
F41	Ixtenco		3	0	3	0	1
F71	Huamantla		3	1	2	0.005	0.666
F100	Huamantla		3	7	3	0.0185	0.8
F85	Huamantla		3	0	2	0	1
F1	Ixtenco		2	0	2	0	1
F30	Ixtenco	C	2	1	1	0.5	1
F35	Ixtenco		2	0	2	0	1
F62	Huamantla		2	1	2	0.333	1
F64	Huamantla		2	1	1	0.333	1
F88	Huamantla		2	4	2	0.333	1
F79	Huamantla	C	2	1	2	0.5	1
F96	Huamantla	C	2	2	2	1	1
F98	Huamantla		2	1	1	0.333	1

Nodal (N) and connector farmers (C) are identified. Outdegree indicates the number of times a farmer gave maize seeds to another farmer and indegree the number of times a farmer received seeds from another farmer.

The greater the number of exchanges that a farmer carried out with other farmers, the greater the number of maize varieties exchanged; that is, farmers who carried out more seed exchanges with other farmers also exchanged a greater number of different maize seed varieties (Figure 3).

Figure 4 provides a close-up view of the principal module of the network, which includes 20.1% of the nodes, of which 12 are farmers from Ixtenco and 15 from Huamantla. In this principal module, farmers from Ixtenco and Huamantla had carried out seed exchanges with people from the municipality of Terrenate and the state of Puebla.

The principal module involves a greater number of seed exchanges between farmers of the same municipality. Four women farmers stand out, all of them from Ixtenco. Of these, F121 is considered a woman nodal farmer due to the high outdegree carrying out a large number of exchanges: seven exchanges of a total of five different varieties (*azul*, *cacahuacintle*, *amarillo*, *negro*, and *ajo* maize; Table 3). This nodal farmer has given *cacahuacintle*, *amarillo*, *negro*, and *ajo* maize seeds to a woman farmer from Ixtenco (F29), and *negro* and *azul* maize seeds to another farmer, also from Ixtenco (F44), the latter in turn has shared seeds of these two varieties with a farmer of Huamantla (F100). Another nodal farmer (F33 from Ixtenco) carried out five exchanges of three maize varieties (*amarillo*, *azul*, and *blanco*) with people from Ixtenco, as well with people from the municipalities of Huamantla and Terrenate, and other areas of the state of Puebla (Table 3).

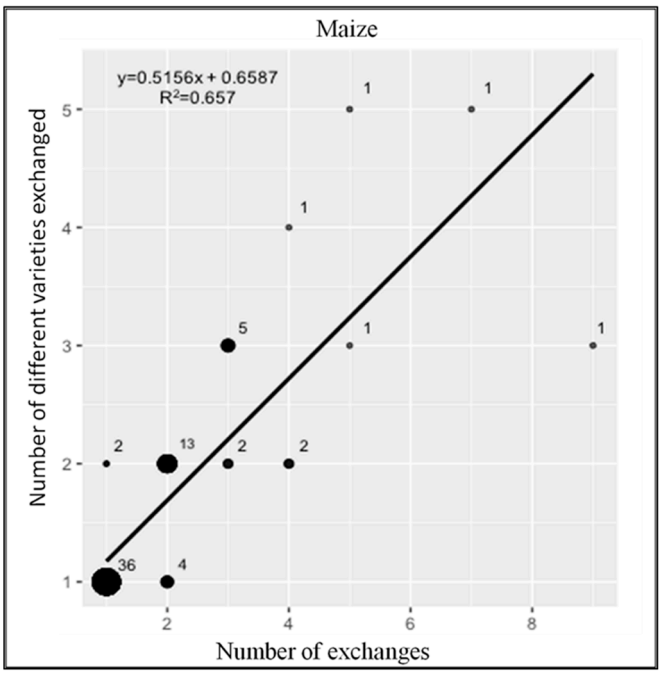

Figure 3. Relationship between number of exchanges and number of maize varieties exchanged by each farmer of Ixtenco and Huamantla participating in the maize seed exchange network (n = 69). Note: This graph employed outdegree of each node of the network, without considering local markets and stores.

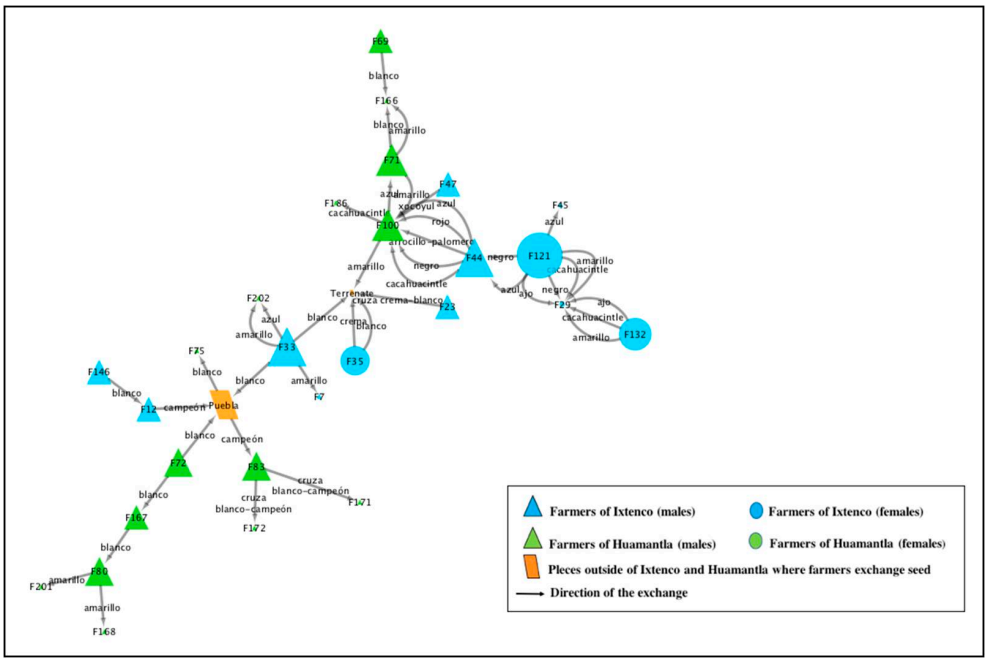

Figure 4. Principal module of the maize network with respect to outdegree. The greater the node size, the greater the number of exchanges carried out. Farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seeds (orange), local markets (yellow) and local stores (brown). The arrow indicates the direction of the exchange.

3.3. Bean Exchange Network

A total of nine different bean varieties were exchanged in the two municipalities (Table 4). On average, each farmer carried out 2.3 ± 1.84 exchanges of 1.93 ± 1.08 varieties of beans from 2015 to 2019. As shown in Table 4, *amarillo* and *negro* beans were involved

in the greatest number of exchanges (28), followed by *bayo* (19). The bean exchanges were principally carried out between acquaintances from the same location (43), followed by people who did not know each other but approached these farmers to obtain seeds (22), and to a lesser extent between family members (17) and friends (10).

The directed network for exchange of bean seeds consists of 79 nodes, with a total of 92 exchanges from 2015 to 2019 (Figure 5).

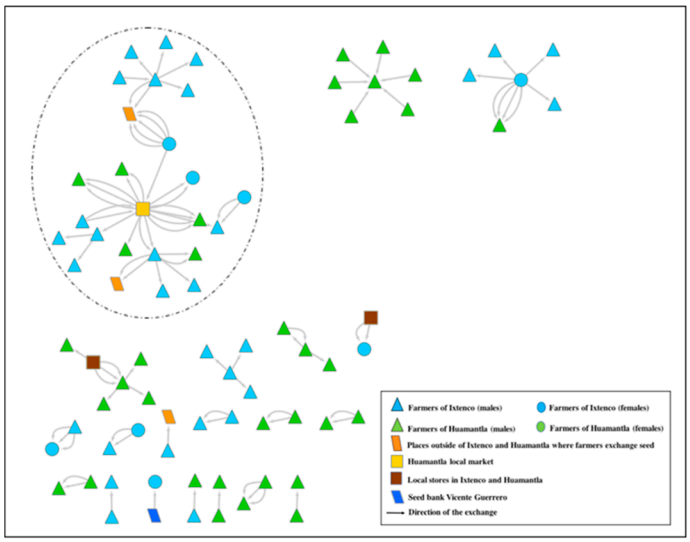

Figure 5. Bean seed network consisting of 79 nodes among farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seeds (orange), local markets (yellow), local stores (brown) and local seed bank (dark blue). The arrow indicates the direction of the exchange. Note: The dotted circle indicates the principal module of the network.

In Figure 5, the network shows a principal module which includes different municipalities of Tlaxcala to which farmers have spread seeds, including Terrenate and El Carmen Tequexquitla. This network includes 14 dyads, in which 24 exchanges were carried out, involving 12 nodes of Ixtenco and 13 nodes of Huamantla. In these dyads, farmers from Ixtenco obtained seeds through a local store, and one farmer gave seeds to a person from Puebla. The majority of the dyads involved family members and acquaintances of the same location exchanging *amarillo* bean seeds. *Amarillo* beans were involved in eight exchanges, the *bayo* variety in seven, *negro* beans in six, and *parraleño*, *morado*, and *pinto* beans in one exchange each. Twelve farmers from Ixtenco (eight men and four women) were involved in these dyads, and 13 (all men) from Huamantla. One farmer from Ixtenco exchanged *parraleño* beans with a farmer from the state of Puebla, and a woman farmer from Ixtenco acquired *amarillo* bean seed in a local store. Most exchanges (15) were carried out between people who knew each other and lived in the same location. Six exchanges were recorded between family members and three between friends. In one triad, *amarillo* and *mantequilla* bean seeds were exchanged between farmers from Huamantla. One woman farmer from Ixtenco received *morado* bean seeds from the Vicente Guerrero seed bank. This fragmented part of the network is composed of a tetrad, two hexads and a heptad.

In this network, three nodal farmers (two women and one man) were detected, all from the municipality of Ixtenco (Table 5). Only one connector farmer was detected in the municipality of Huamantla.

Table 4. Number and percentage of exchanges carried out by variety of bean among farmers of Ixtenco (I) and Huamantla (H), Tlaxcala, Mexico from 2015 to 2019.

Bean Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers who Exchanged the Variety	Number of Exchanges among Actors in the Bean Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintances (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Amarillo	28	21	I	18	11	2 (11.11%)	4 (22.22%)	-	8 (44.44%)	4 (22.22%)	3
			H	10	10	1 (10%)	-	-	6 (60%)	3 (30%)	-
Negro	28	28	I	19	13	3 (15.79%)	5 (26.32%)	-	8 (42.11%)	3 (15.79%)	3
			H	9	8	2 (22.22%)	-	-	3 (33.33%)	4 (44.44%)	-
Bayo	19	19	I	7	6	3 (42.86%)	1 (14.29%)	-	3 (42.86%)		1
			H	12	11	1 (8.33%)	-	-	6 (50%)	5 (41.67%)	-
Mantequilla	6	6	I	4	3	2 (50%)	-	-	1 (25%)	1 (25%)	1
			H	2	2	1 (50%)	-	-	1 (50%)	-	-
Parraleño	3	3	I	3	2	1 (33.33%)	-	-	2 (66.67%)	-	1
			H	-	-	-	-	-	-	-	-
Pinto	3	3	I	1	1	1 (100%)	-	-	-	-	1
			H	2	2	-	-	-	1 (50%)	1 (50%)	-
Ojo de liebre	2	2	I	1	1	-	-	-	1 (100%)	-	-
			H	1	1	-	-	-	1 (100%)	-	-

Table 4. *Cont.*

Bean Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers who Exchanged the Variety	Number of Exchanges among Actors in the Bean Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintances (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Location
Vaquita	2	2	I	1	1	-	-	-		1 (100%)	-
			H	1	1	-	-	-	1 (100%)	-	-
Morado	1	1	I	1	1	-	-	-	1 (100%)	-	-
			H	-	-	-	-	-	-	-	-
		Total Ixtenco	I	55	39	12	10	-	24	9	20
		Total Huamantla	H	37	35	5	-	-	19	13	-
		Total	I-H	92	74	17	10	-	43	22	20

Table 5. Measures of centrality of the nodes conforming the bean seed exchange network of Ixtenco and Huamantla, Tlaxcala, Mexico.

Node	Locality of Farmer/Site Where the Seed Is from	Nodal (N) or Connector Farmer (C)	Outdegree	Indegree	Number of Different Varieties Exchanged	Betweenness Centrality	Closeness Centrality
Huamantla local market	Huamantla local market		16	3	7	0.050	0.7
F14	Ixtenco	N	8	0	4	0	1
F32	Ixtenco		6	2	2	0.021	1
F33	Ixtenco	N	6	1	4	0.009	1
F35	Ixtenco	N	6	0	5	0	0.444
Huamantla local store	Huamantla local store		4	0	3	0	0.625
F22	Ixtenco		3	0	3	0	1
F70	Huamantla		3	3	3	0.15	1
F15	Ixtenco		2	0	2	0	1
F25	Ixtenco		2	1	2	0.010	1
Ixtenco local store	Ixtenco local store		2	0	1	0	1
F34	Ixtenco		2	0	2	0	0.428
F121	Ixtenco		2	0	2	0	1
F48	Ixtenco		2	0	2	0	1
F61	Huamantla		2	0	2	0	1
F84	Huamantla	C	2	1	2	0.5	1
F1	Ixtenco		1	0	1	0	1
Vicente Guerrero seed bank	Vicente Guerrero seed bank		1	0	1	0	1
F12	Ixtenco		1	0	1	0	1
F2	Ixtenco		0	1	1	0	0
F40	Ixtenco		0	3	2	0	0
F27	Ixtenco		0	2	2	0	0
F29	Ixtenco		0	2	1	0	0
F43	Ixtenco		0	3	3	0	0
F45	Ixtenco		0	2	2	0	0

Nodal (N) and connector farmers (C) are identified. Outdegree indicates the number of times a farmer gave bean seeds to another farmer, and indegree the number of times a farmer received seeds from another farmer.

As with maize, the greater the number of bean seed exchanges carried out among farmers, the greater the number of varieties exchanged (Figure 6).

The principal module of the network included 31.6% of nodes, of which 17 were farmers from Ixtenco and five from Huamantla (Figure 7). This module includes the node of the Huamantla local market, in which farmers of the municipalities studied obtain and sell seeds. In this local market, *amarillo*, *bayo*, *mantequilla*, *negro*, *pinto*, and *vaquita* bean seeds may be acquired. Two farmers of the module gave seeds to people of Terrenate and El Carmen Tequexquitla, municipalities close to Huamantla.

The principal module included two nodal farmers (F33 and F35); F33 gave seeds of four varieties (*amarillo* bean, *bayo*, *negro*, and *ojo de liebre*) to six people, two of whom were from Terrenate. Meanwhile, F35 carries *amarillo* bean seeds to sell in the Huamantla local market and provides *amarillo*, *negro*, *bayo*, *pinto*, and *mantequilla* bean seeds to people of Terrenate.

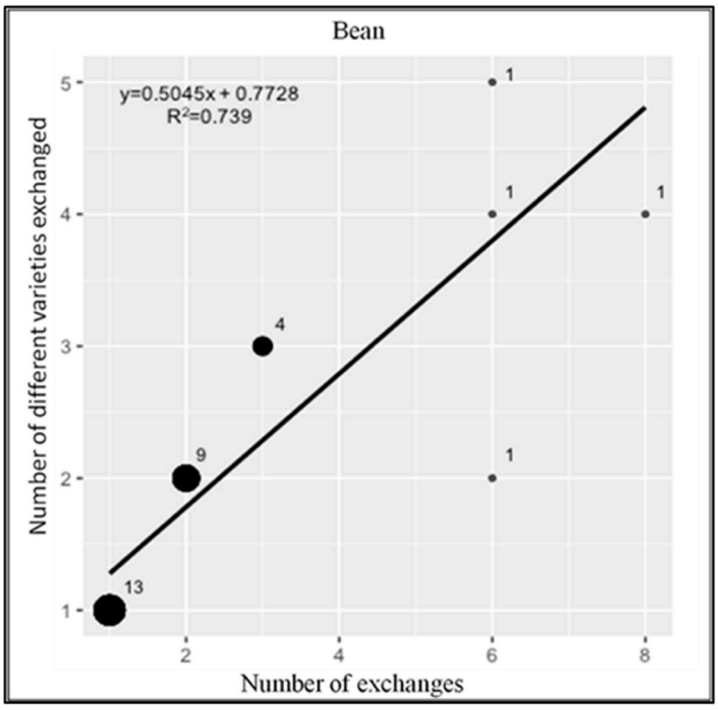

Figure 6. Relationship between number of exchanges and number of bean varieties exchanged by each farmer of Ixtenco and Huamantla participating in the bean seed exchange network (n = 30). Note: This graph employed outdegree of each node of the network, without considering local markets and stores.

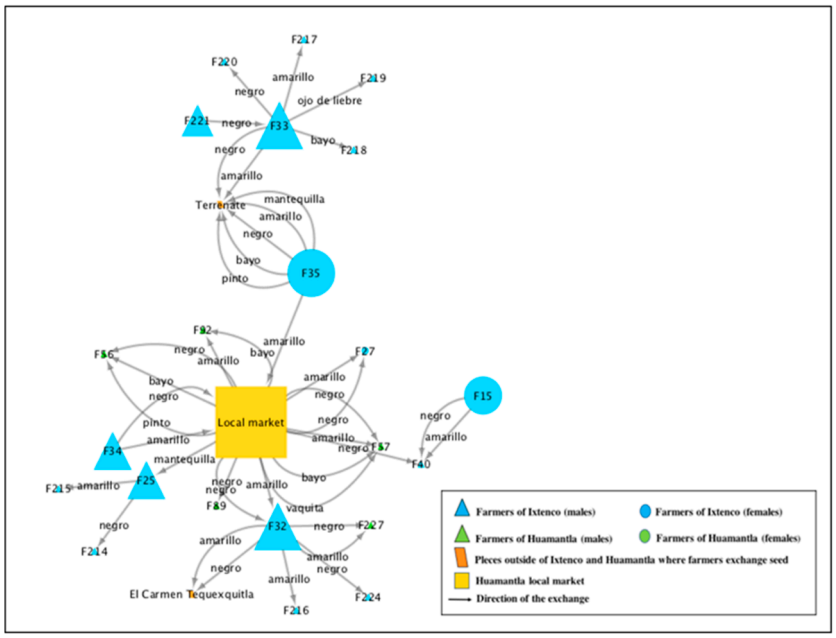

Figure 7. Principal module of the bean network with respect to outdegree. The greater the node size, the greater the number of exchanges carried out. Farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seed (orange), local markets (yellow) and local stores (brown). The arrow indicates the direction of the exchange.

3.4. Squash Exchange Network

Only one native variety of squash is cultivated in the study area. Farmers call it "creole squash". The farmers involved in this network carried out 1.17 ± 0.51 exchanges of this

variety. Squash was involved in a total of 41 exchanges, approximately half of which were between acquaintances of the same locality (20). The others were with people who the farmers did not know, but approached to obtain seeds (8), others were friends (6), family members (5), and neighbors (2) (Table 6).

The directed network of this crop consists of 64 nodes, with a total of 41 exchanges from 2015 to 2019 (Figure 8). This network involves a series of segmented subnetworks.

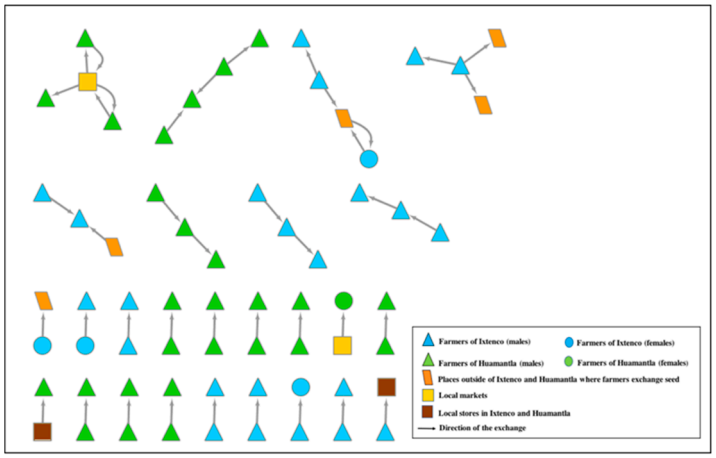

Figure 8. Squash seed network consisting of 64 nodes among farmers of Ixtenco (blue) and Huamantla (green), other places where they exchange seed (orange), local markets (yellow) and local stores (brown). The arrow indicates the direction of the exchange.

The squash network consists of 18 dyads in which 18 exchanges were carried out (Figure 8). The exchanges in these dyads were between farmers of the same locality—principally acquaintances, and three farmers obtained squash seeds through local stores and local markets. A total of 14 farmers of Ixtenco (11 men and three women) and 18 from Huamantla (17 men and one woman) were involved in these dyads. One female farmer from Ixtenco carried out an exchange with a male farmer from the nearby municipality of Terrenate. In these dyads, seeds were also acquired at the Ixtenco local market and local stores in Ixtenco and Huamantla. Nine exchanges between acquaintances of the same locality were recorded, including, four exchanges between family members—from parents to sons and among political family. Three exchanges were carried out between people who did not know each other, one between friends, and one between neighbors. Four triads were identified, involving a total of eight exchanges between farmers of the same location and one with a person from Querétaro. Four tetrads were identified, with a total of 15 exchanges, one of which involved the Huamantla local market, where three farmers from Huamantla went to obtain or sell squash seeds. Some farmers had given squash seeds to people of sites close to the study municipalities, including Vicente Guerrero, Apizaco, and Terrenate, and some farmers had given seeds to people of other states such as Puebla.

In this network, no nodal farmer and only three connector farmers were found (two from Ixtenco and one from Huamantla) (Table 7).

Table 6. Number and percentages of exchanges carried out of squash seeds among farmers of Ixtenco (I) and Huamantla (H), Tlaxcala, Mexico from 2015 to 2019.

Squash Variety	Total Exchanges per Variety (Fa + Fr + N + A + Nk)	Number of Farmers Who Exchanged the Variety	Locality	Number of Exchanges per Variety	Number of Farmers Who Exchanged the Variety	Number of Exchanges among Actors in the Squash Network					
						Family Members (Fa)	Friends (Fr)	Neighbors (N)	Acquaintan (A)	Does Not Know the Person (Nk)	Total Exchanges Outside the Locality
Squash	41	41	I	21	15	4 (19.05%)	4 (19.05%)	2 (9.52%)	10 (47.62%)	1 (4.76%)	5
			H	20	16	1 (5%)	2 (10%)	-	10 (50%)	7 (35%)	-
		Total Ixtenco	I	21	15	4	4	2	10	1	10
		Total Huamantla	H	20	16	1	2	-	10	7	-
		Total	I-H	41	31	5	6	2	20	8	10

Table 7. Measurements of centrality of the nodes conforming the squash seed exchange network of Ixtenco and Huamantla, Tlaxcala, Mexico.

Node	Location of the Farmer/Site Where the Seed Is from	Nodal (N) or Connector Farmer (C)	Outdegree	Indegree	Number of Different Varieties Exchanged	Betweenness Centrality	Closeness Centrality
F32	Ixtenco		3	0	1	0	1
Huamantla local market	Huamantla local market		3	2	1	0.666	1
F5	Ixtenco		2	0	1	0	0.75
F63	Huamantla		2	0	1	0	1
F1	Ixtenco		1	0	1	0	1
F2	Ixtenco		1	1	1	0	1
Vicente Guerrero	Vicente Guerrero		1	2	1	0.166	1
F4	Ixtenco		1	0	1	0	1
F6	Ixtenco		1	0	1	0	1
F16	Ixtenco	C	1	1	1	0.5	1
F17	Ixtenco		1	0	1	0	1
F26	Ixtenco	C	1	1	1	0.5	1
F28	Ixtenco		1	0	1	0	0.666
FI2	Ixtenco		1	0	1	0	1
F35	Ixtenco		1	0	1	0	1
F49	Ixtenco		1	0	1	0	1
F61	Huamantla		1	0	1	0	1
F60	Huamantla		1	1	1	0	0.6
Ixtenco local market	Ixtenco local market		1	0	1	0	1
F82	Huamantla		1	0	1	0	1
Huamantla local store	Huamantla local store		1	0	1	0	1
F53	Huamantla		1	1	1	0	0.6
F77	Huamantla		1	0	1	0	1
F70	Huamantla		1	0	1	0	1
F58	Huamantla	C	1	1	1	0.5	1

Nodal (N) and connector farmers (C) are indicated. Outdegree indicates the number of times a farmer gave squash seeds to another farmer, and indegree the number of times farmer received seeds of another farmer.

3.5. Seed Exchange among Farmers from Ixtenco and Huamantla

Of all farmers interviewed (n = 40), in the past five years, 42.5% of those from Ixtenco and 22.5% of those from Huamantla carried out at least one seed exchange. Farmers named several reasons for exchanging seeds: recovering seeds, increasing varieties, making handcrafts, replacement, lending seeds, planting the crop for the first time, and experimenting (Table 8). Twenty percent of farmers interviewed actively participate in the "Fiesta del maíz", all of whom live in the municipality of Ixtenco.

One of the principal reasons farmers interviewed seek seeds is to recover from loss due to frost:

> *"We've been very careful about caring for[seeds], although on some occasions the weather hasn't favored us. For example, in 2011, due to frost, seed was lost out in the entire region. In 2012 we had planted, but also it came to frost when we'd reestablished [the crops of] 90% of the entire region of Huamantla and its 39 communities. So we were in need of going to bring creole seeds from near [the volcano] the Malinche and on the other side of Puebla, and we again recovered creole seeds"*. Farmer from Huamantla, 26 April 2019

For some farmers who are also artisans, it is important to obtain new varieties of different colors:

> *"[Seeds] of colors we plant practically for mosaic made seed grains to exchange among each other, because some dedicate themselves to making figures, well more than figures, necklaces, earrings, some things with cornhusk, so for this, [we need] colored maize"*. Farmer from Ixtenco, 12 November 2018

Table 8. Reasons farmers exchange maize, bean, and squash seeds (n = 40).

	Reasons Farmers Exchange Seed	Percentage of Farmers Who Carry out Each Reason
Recover seed	To recover seeds they lost due to frost, pests during storage, or low crop yield	42.5%
Increase varieties	To obtain seeds with a variety of colors to plant, and conserve	12.5%
Make handcrafts from seeds	To obtain different colored seeds to plant and harvest for use in handcrafts, such as mosaic made of seed grains and jewelry	12.5%
Seed replacement	To replace "old" seeds or that with low productivity	7.5%
Lend seed	To lend seed of the same or different varieties, of the same quantity or different quantities	2.5%
Plant the crop	To plant the crop for the first time	2.5%
Experiment	To experiment with new varieties in their plots	2.5%

3.6. Maize, Bean, and Squash Exchange Networks and Conservation of Crop Diversity

On average, each farmer conserves 3.17 ± 2.22 varieties of maize and 1.34 ± 1.46 varieties of beans. However, not all the maize, bean, and squash varieties a farmer conserves are exchanged; in other words, farmers are conserving more varieties than those they are exchanging for the maize, bean, and squash crops (Figure 9 and Table 9).

Farmers who exchange seeds do so on average with 1.93 ± 1.47 varieties of maize and 2.3 ± 1.84 varieties of beans. In the case of squash, each farmer exchanges on average 1.17 ± 0.51 of the only native variety present in the region.

Of the 99 farmers who plant maize, 58 carried out at least one exchange during the past five years. In the case of beans, 33 farmers carried out at least one exchange, and 31 farmers carried out one exchange of squash seeds (Table 9).

The five nodal farmers for maize conserve on average 6.4 ± 2.70 varieties of maize, and the three nodal farmers for beans conserve on average 4.33 ± 0.57 bean varieties (Tables 3 and 5).

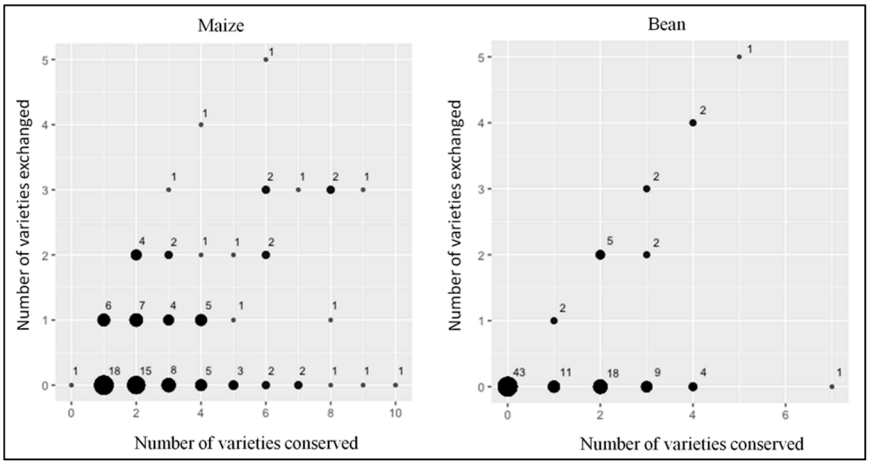

Figure 9. Relationship between the number of varieties of maize and beans conserved per farmer to the number of varieties exchanged in the municipalities of Ixtenco and Huamantla (n = 100).

Table 9. Number of farmers who plant and exchange maize, beans, and squash seeds in the municipalities of Ixtenco and Huamantla, Tlaxcala, Mexico (n = 100).

Number of Farmers Who Plant and Exchange Maize, Beans, and Squash			
Number of farmers who plant the crop			
Locality	Maize	Beans	Squash
Ixtenco	49	28	41
Huamantla	50	29	36
Total	99	57	77
Number of farmers who exchange the seed			
Locality	Maize	Beans	Squash
Ixtenco	27	17	15
Huamantla	31	16	16
Total	58	33	31

4. Discussion

4.1. Structure of Seed Exchange Networks

In the seed exchange networks of maize, beans, and squash, nodal farmers identified exhibited a high outdegree that is, they carried out the greatest number of exchanges and shared a greater number of seed varieties. Connector farmers exchanged seeds with people from sites close to the municipalities studied. Nodal farmers as well as connectors are key to the seed exchange network due to their role in conservation and circulation of seeds.

Previous studies regarding exchange networks have detected a different number of nodal farmers, depending on the seeds exchanged [21,23,25,27]. In this study, from 2015 to 2019 which corresponds to the past five years of seed exchanges analyzed, a total of eight nodal farmers were identified: five for the maize network, three for the bean network, and none for the squash network. These nodal farmers conserve 6.4 $\pm$ 2.70 varieties of maize and 4.33 $\pm$ 0.57 of bean varieties, and carried out six exchanges, which directly contribute to the maintenance of local genetic flow and diversity. On average, farmers cultivate 7 ha (range 0.004–60 ha), while nodal farmers cultivate 5.9 ha (range 1.5–20 ha), and two of them participate in the seed fair of Ixtenco.

Nodal farmers play a central role in seed exchanges as they maintain a connection to a network of farmers over several years. They conserve a diversity of seeds with agricultural and commercial interest for the farmers, seeds which contribute to farmers' income as well as their family's consumption. These nodal farmers hold knowledge and represent a source of knowledge regarding seed maintenance, and obtain new varieties through gradual selection over the years or by acquiring new seeds [20,26]. Farmers of the maize and bean seed exchange network (e.g., F121 and F33; Figure 4), directly promote movement of seed varieties (upon giving seeds to other farmers) as well as indirectly (upon giving seeds to farmers who in turn pass it on to other actors of the network). In the absence of these nodal farmers who interconnect several farmers, several varieties could be lost, and the structures of the seed exchange network would be modified.

Nearly 63% of the nodal farmers identified in this study are men, although women also participate in a variety of farm-related activities, such as planting, harvesting, fertilization, weeding, and seed selection. Previous studies, such as those by Devkota et al. [25], Rodier and Struik [23], and Song et al. [27], identified women nodal farmers who conserve a large diversity of seeds. In this study, a female nodal farmer from Ixtenco carried out seven maize exchanges, involving five varieties. Through this farmer, *negro* maize seeds reached farmers of the municipality of Huamantla.

Previous studies have reported nodal farmers to be of an advanced age [25]. In this study, the average age of nodal farmers was 46 years and that of all participating farmers was 58. Therefore, it is important to involve the nodal farmers in strategies focused on

maintaining agrobiodiversity [20], and to invite more farmers to participate [52], principally youth from their communities. Furthermore, through the nodal and connector farmers, they could distribute seeds that are being lost or important crops for the region that have disappeared, such as lentils.

In each agricultural cycle, farmers save their own seeds to plant [27]. They select their own seeds based on size and color for replanting, and only given the situations listed in Table 8, do they carry out exchanges. One of the principal reasons for exchanging seeds is its loss due to frost and drought that affect the study area year after year, with crops planted at lower altitudes being the most affected by these phenomena (Table 8).

Comparing the networks of the three types of crops, the maize network contains the greatest number of nodes (134), while the bean network has 79 nodes, and the squash network 64 nodes. Maize is the principal crop of the region and year after year farmers plant for family consumption and for sale as grain, above all white varieties, which have a greater market demand. Furthermore, maize crops cover a greater surface area than beans or squash, which are principally planted for family consumption. In the past years, many farmers have stopped planting these two crops due to use of agrochemicals to cultivate maize. In the case of squash, upon planting only one local variety and as the crop is principally used for family consumption, the frequency of exchange is less than that of maize and beans.

In the municipalities of Ixtenco and Huamantla, a great diversity of varieties is exchanged (18). Nevertheless, the *blanco* maize is the most exchanged among farmers given its high commercial value in the region in comparison to other varieties. The price of maize grain in the region varies due to the supply and demand price that intermediaries offer, which ranges from USD 0.15 to USD 0.25 per kilogram, while the price of seeds range from USD 0.30 to USD 0.69 per kilogram. Furthermore, this maize is used to produce a variety of foods such as tortillas and *atole* (a thick hot drink made of boiled ground corn). To obtain it, farmers of sites near the state of Tlaxcala travel to Ixtenco and Huamantla in search of the *blanco* maize. Nevertheless, in recent years, other varieties, such as the *azul* maize, have increased in commercial value, and therefore farmers seek it for planting.

4.2. Fragmented Exchange Networks

Most exchanges of maize, beans, and squash seeds occurred in the dyads of the networks, and these exchanges were principally between people of the same community who knew each other, and between family members (parents, siblings, aunts and uncles, and political family). In this manner, the seeds are maintained and remain among farmers of each community and are preserved in the family. Furthermore, farmers who seek a specific variety know which of their family members or close contacts could provide it. Of all maize varieties, white maize was involved in the greatest number of exchanges between acquaintances (Table 2). As this variety bears a high commercial value, farmers seek it most often to renew it and obtain higher crop yields.

Differences were observed in the structuring of the networks of Huamantla and Ixtenco; as Huamantla is a city, seed exchanges are facilitated between acquaintances, not only between family members or friends. As beans and squash represent crops that are being lost in the region, it is difficult to acquire seeds, including through nearby networks and, therefore, farmers may need to approach their networks of acquaintances or even local markets to acquire the variety desired. Carrying out exchanges among relatives reduces the probability of losing different seed varieties; if a close family member conserves the seeds in question, a farmer may be able to quickly obtain them; the search time of the variety is reduced, the quality of the seeds are guaranteed, and there is certainty that the seeds are adapted to local conditions. Furthermore, a farmer who does not have the seeds they desire may know who, in their community or among other acquaintances, may have them. Acquiring seeds from family members and acquaintances may reduce the cost of obtaining them. In some cases, seeds exchanged among family members are lent or given away [25]. Among friends and acquaintances, seeds may be lent or sold at a price lower than the

market price. Furthermore, exchanges among family members and acquaintances reinforce trust [53]. When a seed is acquired, a farmer trusts the information provided to maintain and conserve the variety. Upon acquiring new seeds with family members or others of the same location, the seeds tend to remain in the region, and they are already adapted to local conditions [27,54]. In the study municipalities, networks among friends, family members, and acquaintances were a source for acquiring seeds. As previously mentioned, within these networks, the *blanco* maize is mainly exchanged, and to a lesser extent the other varieties recorded in Table 2. In the case of bean seeds, the most frequently exchanged varieties are the *amarillo*, *bayo*, and *negro* beans (Table 4).

4.3. Local Market and Seed Bank in the Exchange Networks

Farmers who have lost seeds to frost or pests attend the Huamantla local market to acquire bean seeds, and to a lesser extent maize and squash seeds. Some rotate maize with beans in their plot after some years with the aim of increasing the yield. Since few farmers still plant beans, it is difficult to obtain the seeds from people of the locality; however, the Huamantla local market presents an option for obtaining bean seeds. As those who sell seeds in the Huamantla market are from Ixtenco, Huamantla, and other nearby areas, the seeds they sell are adapted to the environmental conditions of the region, which improves the chance of a good harvest.

Aside from the local markets, community seed banks are an important source of seed varieties [55,56]. One such source involved in the bean seed exchange network is the seed bank of the municipality of Vicente Guerrero. This seed bank provided *morado* bean seeds to a farmer of Ixtenco, who currently maintains the variety. Farmers from Ixtenco and Vicente Guerrero maintain contact through seed fairs carried out in both municipalities. The Ixtenco seed fair has allowed farmers of this municipality to display and sell grains for consumption, as well as seeds [44,57]. Two nodal farmers actively participate in this fair, which provides them with the opportunity to access and exchange new seed varieties. Previous studies show that seed fairs play an important role in the flow of seeds, and may contribute to conservation of native varieties [58,59]. Leyte et al. [60] found that in the Philippines and Vietnam livestock exchanges networks, the government agencies were a primary source of high quality seeds, with Philippines dairy case being dominated by actors in active cooperatives, while in the Vietnamese beef networks, farmer to farmer exchanges were more important, indicating that formal and informal seed systems play essential roles in access to forage seeds. By contrast, government agencies are not an important source of seeds for farmers of the municipalities of Ixtenco and Huamantla; rather, they save their own seeds. Nonetheless, the dynamics of the network could change and the seed fairs, local markets, seed banks or government agencies could become more relevant in the seed supply.

Limitations of this study include (a) sample size. Our small sample size (n = 100) did not allow us to detect more nodal farmers nor carry out statistical analyzes to detect differences between nodal and non-nodal farmers, (b) limited study area. Carrying out fieldwork in a greater number of municipalities would allow for determination of the distance of movement of the seeds, (c) lack of monitoring exchanges in good and bad cycles. Violon et al. [61] emphasize the need to carry out studies throughout several agricultural cycles to identify changes in farmers' strategies for acquiring seeds. As frosts and droughts affect the study area, it would be important to document how farmers acquire seeds under contrasting climatic conditions, (d) lack of genetic studies. As we did not carry out genetic analyses of native varieties, it is possible that we over or underestimated the number of native maize and bean varieties, (e) multiple factors operate in conservation. It would be convenient to measure additional factors that come into play in conservation of agrobiodiversity, such as the commercial networks that encourage farmers to plant native varieties. Furthermore, the importance of understanding the cultural impact on seed exchange has been pointed out [27]. In Ixtenco, farmers maintain and exchange varieties that are of biocultural importance to the community, such as *negro*, *xocoyul*, and *ajo* maize,

and it would be important to have a better understanding of why they select these varieties, and (f) it is necessary to identify in greater detail the role of nodal women in the seed exchange networks [62].

5. Conclusions

Social network analysis allows for identification of the structure and processes of interaction within the seed exchange network of maize, beans, and squash among farmers from the municipalities of Ixtenco and Huamantla, Tlaxcala, Mexico. This analysis allowed for the detection of nodal farmers for seeds of these crops—those involved in the greatest number of exchanges of different varieties. It was found that the nodal farmers of the maize and bean seed networks, upon carrying out more exchanges, also exchanged a greater number of varieties. Thus, these farmers promote circulation of a large number of seeds within the network, thereby contributing to the maintenance and conservation of agrobiodiversity. Farmers involved in the maize and bean seed exchange networks of the two study municipalities attend the Huamantla market to obtain seeds, and it is important to further identify the seed varieties sold in this market. Given the large number of exchanges undertaken by the nodal farmers, as well as their capacity to conserve, acquire new varieties and their knowledge regarding maintenance of seed varieties, these farmers are important for the conservation of local agrobiodiversity and key actors in the seed exchange networks.

There is a need for future studies to address the dynamics of seed exchange networks over time. For example, it would be important to determine whether nodal farmers maintain their role over many years or for a limited time and to understand how their presence or absence affects the number of seed exchanges conducted. Furthermore, there is a need to determine the relative importance of other actors of the network, such as markets, government agencies, and seed banks, in seed provisioning over time. The exchange between farmers represents the possibility of recovering lost seeds immediately and therefore of recovering crops. Understanding the functioning of exchange networks offers the opportunity to change the weaknesses of the system and to carry out actions which guarantee exchanges between farmers. Studying seed exchange networks in broader spatial, ecological and cultural contexts is particularly important in countries such as Mexico with high biocultural diversity. The regional and case studies such as this one provides methodological tools and experiences useful for conducting studies at larger scales. Understanding the dynamics of the networks allows for appreciation of the restrictions and the ability to take action in improving the network's efficiency, thereby promoting conservation of agrobiodiversity.

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Appendix A

Guide to interview of farmers of the communities of Ixtenco and Huamantla
State:
Municipality: Date:
Interviewer name:
Interviewee name:
Gender: M F Age:

Native seed networks

1. How many plots do you have and what do you grow in each of them?
2. What is the total surface area of your plots?
3. Describe each plot (surface area, location, soil type, climate).
4. Why do you cultivate these plots?
5. Are the plots you cultivate your own or do you rent them?
6. [If rented:] How much do you pay for rent?

Maize

7. Where do you obtain the seed for each variety of maize you plant (friend, neighbor, family member, market, save own seeds, etc.)?
8. Do you always obtain seed from this source/these sources? Why?
9. How long have you been conserving these seeds?
10. Why do you like cultivate each variety?
11. Why do you prefer to plant these varieties and not others?
12. What do you use each variety for?
13. Would you try planting other varieties? Why?

Beans and Squash

14. Do you plant squash and beans?
15. Where do you obtain squash and bean seeds?
16. Since when do you have the seeds?
17. What varieties of squash and beans do you have? Name of the squash and beans varieties
18. Do you plant beans and squash the same time as maize?
19. Is the maize, bean, and squash seed you produce for self-consumption, sale, or both?
20. How many months does the maize you harvest for your family last?
21. How many months do the beans and squash last your family?
22. Can you tell us the names of all the people you have ever given maize, bean, and squash seed?
23. Can you name the people that have given you maize, bean, and squash seed?
24. Last season, did anyone give you seeds to plant? Why?

Preparing the land for planting

25. How do you prepare the land for planting?
26. When does maize planting begin (for each variety)?
27. How long does it take for the cob to fully form (for each variety)?
28. When do you begin to plant beans (each variety)?
29. When do you begin to plant squash (each variety)?

30. How many harvests of maize do you have per year?
31. In the first, how much do you harvest? In the second?
32. How do you control weeds?
33. Do you use fertilizer/herbicide?
34. How much does the herbicide cost?
35. How much does the fertilizer cost?
36. Which family members plant?
37. Do women participate in agriculture? What do they help with? When you are not there, do they help with agriculture?
38. Do women select seeds? Do they exchange seeds?
39. When women marry, do they inherit seed?
40. Within the community, are there people who leave seed as inheritance? Have you received seed as inheritance?
41. What crops do you plant besides maize, beans, and squash?
42. Do you have animals? How many cattle? What do you give them to eat?
43. Do you carry out any income generating activities aside from agriculture?

Seed loss, storage, and pests

44. Have you ever lost your maize, bean, or squash seed? If so, how (frost, poor harvest, etc.)? What variety?
45. How do you recover lost seed? Who do you ask for seed? Do you purchase it? Does someone lend it to you? Who?
46. Do you return borrowed seed? The same seed and the same quantity? Or do you return the favor by giving another variety of seed that they lent to you?
47. Do you or have you had problems with any maize, bean, or squash pest? Which pests? How do you control them?

Seed sale

48. Do you sell seed?
49. If so, to whom? What price?
50. Do you know the destination of this seed?

Organization and seed laws

51. Do you belong to any farmers' organization?
52. Do you know of the Law to foment and protect maize as original heritage, in constant food diversification for the State of Tlaxcala?
53. Do you know of the Law of Production, Certification, and Commerce of Seeds or the Law of Plant Varieties?

Festivities related to seeds

54. What do maize, beans, and squash mean to you?
55. Do you participate in any festivity of maize, beans, and squash?
56. In this municipality, the people carry out maize, beans, and squash fairs? When?

Hybrid seed

57. Do you plant any hybrid seeds? Why?
58. Which hybrid seeds do you purchase?
59. Where do you purchase them?
60. What amount of hybrid seed do you purchase? By kilo, bag, or sack?
61. Are the seeds certified?
62. How much do you pay for hybrid seed?
63. Do you receive any subsidy for seed purchase? If so, how much?
64. What characteristics do these seeds have? What do you consider their advantages to be?
65. Do you use fertilizer to cultivate these seeds?

66. Do you sell the crops cultivated with these seeds? Do you conserve some seed for the following planting?
67. If you sell seed, to whom? At what price?
68. Do you know the destination of these seeds?
69. Do you replant these seeds for harvest?
70. In what cases do you replant these seeds for harvest?

Questionnaire on seed networks

Date: State: Municipality:
Farmer name:
Gender: Male Female Age:
Notes:
How many plots do you have?
For each plot:
Surface area:
Type (irrigated/seasonal):
Elevation (high, medium, low):
What quantity of seed do you need to plant the plot?

MAIZE

How many varieties of maize do you have? Which varieties?
For each variety
How long have you had it?
Who gave it to you (family member, friend, neighbor, acquaintance? Other:
What do you like about this variety?
Have you ever lost it? YES/NO How? Frost Drought Hail Pests Other:
How did you recover it and when? By purchase or gift? If gift, who gave it to you? Was it lent to you? If borrowed, from whom?
Which of these varieties is the most important to you and why?
During the past 5 years
Have you exchanged/sold/gifted/lent any of your maize varieties during the past 5 years? YES/NO
Which ones?
With whom have you exchanged/sold/gifted/lent it/them? Friend ( ) Neighbor ( ) Family member ( ) Other:
What amount of seed did you exchange/sell/gift/lend?
Since when have you exchanged/sold/gifted/lent this seed?

BEAN

How many bean varieties do you have? Which varieties?
For each variety:
How long have you had it?
Who gave it to you (family member, friend, neighbor, acquaintance? Other:
What do you like about this variety?
Have you ever lost it? YES/NO How? Frost Drought Hail Pest Other:
How did you recover it and when? By purchase or gift? If gift, who gave it to you? Was it lent to you? If borrowed, from whom?
Which of these varieties is the most important to you and why?
During the past 5 years
Have you exchanged/sold/gifted/lent any of your maize varieties during the past 5 years? YES/NO
Which ones?
With whom did you exchange/sold/gifted/lent it/them? Friend ( ) Neighbor ( ) Family member ( ) Other:
What amount of seed did you exchange/sell/gift/lend?
Since when have you exchanged/sold/gifted/lent this seed?

SQUASH
How many varieties of squash do you have? Which varieties? **For each variety:** How long have you had it? Who gave it to you (family member, friend, neighbor, acquaintance? Other: What do you like about this variety? Have you ever lost it? YES/NO How? Frost Drought Hail Pest Other: How did you recover it and when? By purchase or gift? If gift, who gave it to you? Was it lent to you? If borrowed, from whom? Which of these varieties is the most important to you and why? **During the past 5 years** Have you exchanged/sold/gifted/lent any of your squash varieties during the past 5 years? YES/NO Which ones? With whom did you exchange/sold/gifted/lent it/them? Friend ( ) Neighbor ( ) Family member ( ) Other: What amount of seed did you exchange/sell/gift/lend? Since when have you exchanged/sold/gifted/lent this seed?
SEED SELECTION
What characteristics do you focus on upon selecting maize seed? What characteristics do you focus on upon selecting bean seed? What characteristics do you focus on upon selecting squash seed? Would you try planting another variety of maize? YES/NO Why? Would you try planting another variety of beans? YES/NO Why? Would you try planting another variety of squash? YES/NO Why?
OTHER CROPS
Do you plant anything aside from maize, beans, and squash? YES/NO What?
GRAIN
Do you plant anything aside from maize, beans, and squash? YES/NO What? Sale of grain Is the grain you produce for: Family -consumption ( ) Sale ( ) Both ( )? Do you know the destination of your grain? YES/NO Do you always sell in the same place/to the same person? YES/NO How much do you sell? What is the destination of your grain? How much do you sell your grain for?
PARTICIPATION OF WOMEN IN SEED SELECTION/SEED FAIRS
Do women participate in agricultural activities? YES/NO In what activities do they participate? Do women select seed? YES/NO The women, where does seed selection begin? At home/In plot Other: Do they exchange seed? YES/NO Do you living only from agriculture? YES/NO Do you participate in the seed fairl of Ixtenco? YES/NO Why do you participate? Why don't you participate? Farmer from other municipality: Do you know or have you heard of the seed fair in Ixtenco? YES/NO

HYBRID SEEDS
Have you planted any hybrid maize seed? YES/NO
Which varieties? of which brand?
Where do you purchase or obtain it?
How much do you purchase?
Do you replant, sell, or exchange this seed?
Why do you like hybrid seed? Or Why do you not like hybrid seed?
Have you ever planted hybrid varieties? YES/NO
Why or why not?
Would you be interested in trying hybrid seed? YES/NO Why?
If you already plant some hybrid maize, would you be interested in trying other hybrid maize varieties? YES/NO Why?
Do you receive any subsidy for seed purchase? YES/NO
How much?
Do you receive any subsidy to purchase fertilizer or herbicide? YES/NO How much?
Have any government programs given away/exchanged seeds? YES/NO
Which programs? When?
Have you participated? YES/NO Why or why not?
Do you belong to any farmers' organization? YES/NO Which one?
What are the advantages of belonging to this organization?

Appendix B

Varieties of Maize, Beans, and Squash of Ixtenco and Huamantla, Tlaxcala, Mexico

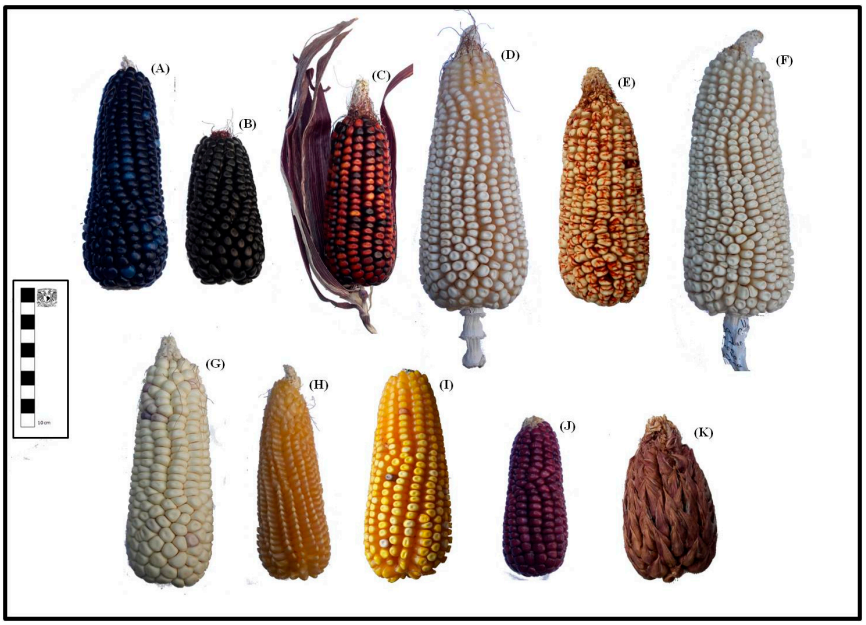

Figure A1. Different varieties of maize of Ixtenco and Huamantla, Tlaxcala, Mexico. *Azul* (**A**), *negro* (**B**), *rojo* (**C**), *blanco* (**D**), *sangre de cristo* (**E**), *crema* (**F**), *cacahuacintle* (**G**), *arrocillo-palomero* (**H**), *amarillo* (**I**), *xocoyul* (**J**) and *ajo/tunicado* (**K**).

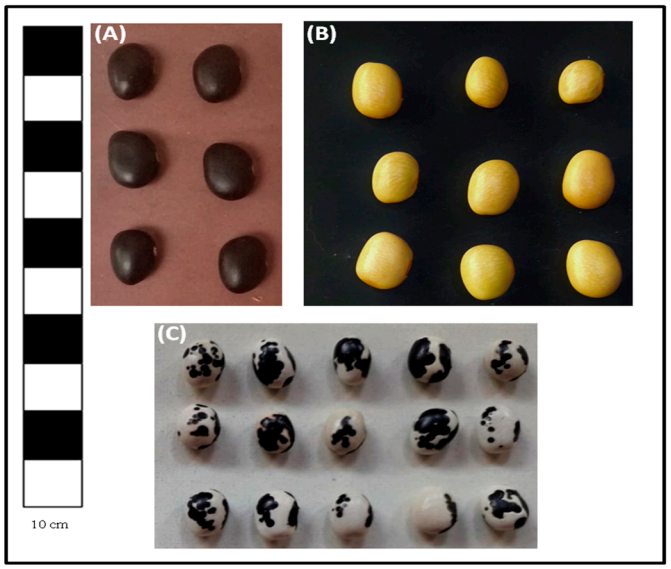

Figure A2. Bean varieties of Ixtenco and Huamantla, Tlaxcala, Mexico. *Negro* (**A**), *mantequilla* (**B**) and *vaquita* (**C**).

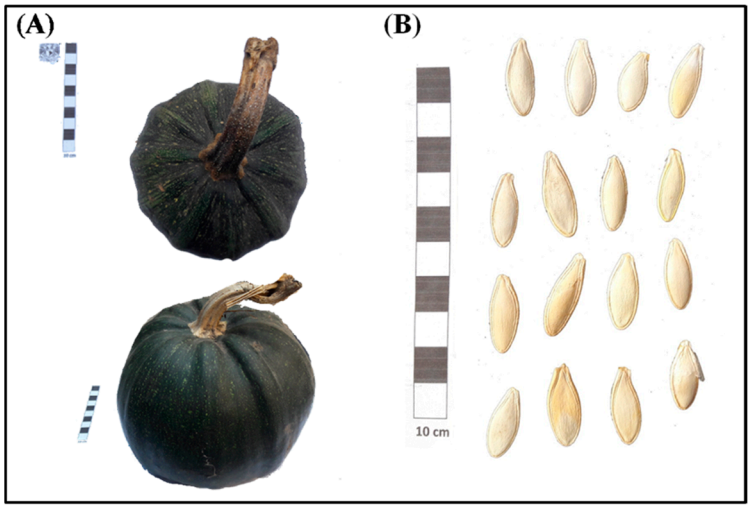

Figure A3. Squash variety of Ixtenco and Huamantla, Tlaxcala, Mexico. Squash fruit (**A**) and squash seeds (**B**).

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