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The contribution of strong and weak ties to resilience: The case of small-scale maize farming systems in Mexico

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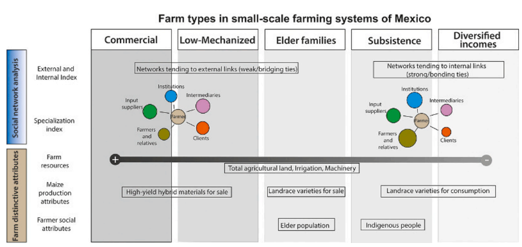
HIGHLIGHTS

- Comparing the contribution of strong and weak ties for different farm types brings variety in resilience strategies.
- Farm types' particularities influence the differential contribution of strong *versus* weak ties in their innovation networks.
- The major contribution of weak ties in innovation networks occurs in farm units with more access to farm resources.
- Strong ties dominate innovation networks from farm units that cultivate maize as part of their persistence strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The relevance of social interactions (social ties) to farming systems' resilience is widely recognized. However, controversies exist around the contribution that farmers interacting with external actors (weak/bridging ties) *versus* with other farmers (strong/bonding ties) have in their resilience strategies through innovation. Farmers use different strategies to respond to their farming systems and contexts' particularities. Comparing the contribution of both strong and weak ties in different farming systems brings variety in resilience strategies.
OBJECTIVE: To generate evidence of the complementary contribution of social ties to resilience by comparing indexes associated with strong and weak ties from innovation networks of different farm types.
METHODS: This paper applies an ego-centric social network analysis to farm units characterized by a farm typology to compare their strong/bonding and weak/binding ties contribution to innovation networks. It uses data from 29,796 farm units of maize smallholders in different regions from Central and Southern Mexico covering the gradient from commercial to subsistence farming. The analysis estimates two indexes based on actors' similarity/dissimilarity, that are External and Internal and Specialization Indexes.
RESULTS AND CONCLUSIONS: Our findings quantify differential contributions of strong *versus* weak ties to resilience strategies associated with innovation networks among different types of small-scale maize farmers.

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They demonstrate how differences among five farm types regarding farm resources access, maize production systems and farmers' social attributes influence their innovation networks. A gradient exists between farm types in their innovation network indexes regarding the contribution of strong *versus* weak ties. Commercial farmers, as the winners of the modernization process, have better access to resources and establish a wider variety of relationships with weak ties. However, interactions with other farmers are essential for technology adoption. In contrast, weak ties represented by institutions have a minor participation in innovation networks of diversified income and subsistence farm units. Strong ties dominate these farm types producing maize for consumption as part of their persistence strategies. Low-mechanized and elder family farm types, affected by geographic remoteness and population ageing processes, represent intermediate points in the gradient of farm resources and network indexes.

SIGNIFICANCE: Jointly farm typology and social network approaches open new avenues to enhance farming system resilience. These approaches show how farmers establish their social interactions for innovation, creating specific combinations of strong and weak ties that are farm type specific. Diverse resilience strategies appear from these combinations involving not only adaptation but also persistence strategies that require further exploration.

1. Introduction

Covid-19 has become just the latest of the challenges that farming systems face. It has joined a long list of agricultural challenges, including food availability, natural resource sustainability, climate change resilience, poverty and inequality, and resilience to protracted crises for citing some challenges (FAO, 2017). Resilience plays a critical role in these challenges and is essential for agricultural systems. Nevertheless, how resilience takes place is an open question when considering farming systems' diversity. Farming systems represent how humans interact with their environments, shaping global and local land management landscapes (Václavík et al., 2013). Diversity is at the centre of agricultural resilience. Farmers use various strategies to guarantee their farms' flexibility and adaptability as part of their ability to cope with change and maintain functions, commonly understood as resilience (Bruce et al., 2021). Farms' resilience strategies are resource and context-dependent (van der Lee et al., 2022) including buffer capabilities (the ability to persist or "bounce back) as well as adaptive and transformative capabilities (the ability to change or "bounce forward") (Darnhofer, 2014). Several activities contribute to farming systems' resilience such as increasing productive and economic efficiency, farm diversification, and technological innovation (Bruce et al., 2021).

Innovation and resilience tend to be used interchangeably, assuming that innovation leads to resilience and resilience leads to innovation (Díaz-José et al., 2018). However, in scientific literature, resilience is usually used to discuss processes, while innovation represents a pathway for achieving resilience (Zupancic, 2022). The literature on climate-smart agriculture exemplifies this as it typically focuses on technological innovations to increase resilience against climate change (FAO, 2013; Douxchamps et al., 2016). However, technology is not the only angle of innovation. Agricultural innovation systems approaches define innovation as the successful combination of technological innovation (hardware), social innovation (orgware) and knowledge systems (software) (Hermans et al., 2017). In innovation studies, knowledge has received particular attention regarding how knowledge is exchanged and by/from whom.

Social network analysis (SNA) has been applied to understand the role of knowledge exchange in innovation processes. Granovetter's (1983) proposal of a systematic analysis of social networks has found fertile ground in research on the diffusion of technological innovation (Rogers, 2003), mainly associated with learning processes and information exchange as strategies for resilience through adaptation and transformation. The tie strength between actors who participate in the information flows for innovation (innovation network) plays a central role in terms of strong/bonding ties (from local actors like relations with relatives, friends, and peers) *versus* weak/bonding ties (links with external actors and institutions) (Rockenbauch and Sakdapolrak, 2017). It is commonly accepted that resilient farms benefit from combining formal and informal sources of knowledge and having access to a wide range of information (Bruce et al., 2021). However, disagreements exist on what type of ties configuration (weak, strong or both) promotes innovation and how they contribute to resilience. Comparing the contribution of weak and strong ties in different farm units is key to understanding how various resilience strategies take place (Meuwissen et al., 2019).

This paper applies an ego-centric social network analysis to farm units previously characterized by a farm typology to compare social network indexes associated with strong and weak ties. It looks to make the case for the importance of diversity in farming systems to define resilience strategies associated with innovations. The paper compares the innovation networks of 29,796 farm units of maize smallholders from Central and Southern Mexico that have been formerly characterized by their differential access to resources, and their distinctive productive as well as social attributes. Findings allow the discussion of how strong and weak ties have a differential contribution to resilience strategies associated with innovation when comparing different types of maize farming systems. Furthermore, they generate quantitative evidence of the joint contribution of strong and weak ties in innovation networks and the importance of considering farm units differences to enhance distinctive resilience strategies.

2. The contribution of strong and weak ties for innovation and resilience

Strong and weak ties have been incorporated into social network analysis. Granovetter (1983) proposed these terms to distinguish the strength of an interpersonal tie concerning "the amount of time, the emotional intensity, the intimacy and the reciprocal services which characterize the tie". With time, these concepts have been associated to Putnam (2000) work on social capital; thus, strong ties are generally linked with bonding capital and weak ties with bridging capital. Although Granovetter's original definition of tie strength considers these four attributes, these concepts are commonly used to distinguish between "people like you or similar" (strong/bonding ties) *versus* "people not like you or dissimilar" (weak/bridging ties) (Newman and Dale, 2005; Rockenbauch and Sakdapolrak, 2017).

As strong ties are shared with similar people, they are considered homophilius and normally characterized by trust and solidarity (Rockenbauch and Sakdapolrak, 2017). These ties are recognized by their bonding function to create solidary and social cohesion (Newman and Dale, 2005). Networks with strong ties promote information sharing and learning and provide mutual help during a crisis (Prell et al., 2016; Fath et al., 2021). In contrast, weak ties involve less frequent interaction with dissimilar actors who creates bridges that foster connections and create heterogenous social networks (Rockenbauch and Sakdapolrak, 2017). These networks offer new ideas as actors have different pools of information (Dapilah et al., 2020).

There has been an evolution in the discussion about the contribution of weak and strong ties to innovation and resilience in farming systems. A dominant narrative that started with Granovetter's seminal work exists in innovation studies that promote weak ties from external actors and heterophilic communication networks to facilitate access to new information, opportunities, and resources conducive to innovation (Van Rijn et al., 2012; Hermans et al., 2017). These attributes are also identified when studying the contribution of weak ties to achieve resilience through the sustainable governance of natural resources, as they are essential to promote vertical and horizontal relationships (Marín and Gelcich, 2012). Furthermore, the values of trust, as well as the easiness of communication and learning from strong ties, are recognized by resilience work (Rico García-Amado et al., 2012). These attributes have been essential to contest the dominant innovation narrative and highlight the value of strong ties to promote social learning (Van den Broeck and Dercon, 2011). This contestation in recent years has brought a joint narrative indicating that farmers use both weak and strong ties in their innovation process and resilience strategies but in context-specific configurations (Cofré-Bravo et al., 2019; Bruce et al., 2021). This paper looks to contribute to the complementary narrative by generating quantitative evidence comparing different strong and weak ties configurations based on actors' similarity/dissimilarity in diverse farm types innovation networks.

The use of social network analysis indexes to understand the role of social ties (both strong and weak) has been considered in resilience (Rockenbauch and Sakdapolrak, 2017) and innovation literature (Rost, 2011; Fritsch and Kauffeld-Monz, 2008). Network structure indicators such as density, centrality and homophily, usually are applied (Borgatti et al., 1998). However, when exploring social ties, indicators elaborated from an ego-centric approach facilitate the measurement of weak/bridging ties and heterogenous networks *versus* strong/bonding ties and homogenous networks. Some examples of these indicators and indexes are external and internal index, heterogeneity, similar/dissimilar actors ratio, and bridging social capital index (Krackhardt and Stern, 1988; Borgatti et al., 1998; Newig et al., 2010; Rost, 2011; Borck et al., 2015; Isaac et al., 2014; Marín and Gelcich, 2012). This paper focuses on indicators quantifying differences in strong and weak ties contributions between the innovation network of maize smallholder farms in Mexico.

Maize-based farming systems in Mexico are widely recognized for their diversity due to agroecological and socio-cultural conditions (Sweeney et al., 2013; Aguilar et al., 2003). Diversity is manifested in farm structures and production orientations (Eakin et al., 2014a), as well as the multiple roles of maize (Appendini, 2009; Appendini and Quijada, 2016). A wide range of farming systems, from small-scale subsistence to large-scale commercial farming systems co-exist (Zepeda et al., 2020). Smallholder maize farm households have raised particular interest concerning their resilience with adaptive strategies such as the: use of maize genetic diversity (Bellon et al., 2011); the diversification of crop, land, and farm management practices (Alayon-Gamboa and Ku-Vera, 2011); and the use of technological and social innovations (McCune et al., 2012; Díaz-José et al., 2018). Innovations have received particular attention in social network studies which tend to highlight the importance of heterogenous networks and weak ties for adopting technological innovations (Zarazúa et al., 2012; Sánchez Gómez et al., 2016; Roldán-Suárez et al., 2019). This paper quantifies the differential contribution of strong/bonding and weak/bridging to resilience through innovation networks of maize small-scale farm units in Mexico characterized by differential access to resources.

3. Data collection and analysis

3.1. Data collection

Data were collected by researchers at the International Maize and Wheat Improvement Center (CIMMYT) and the Research Center for Economics, Social and Technological Agroindustry and World Agriculture (CIESTAAM) from small-scale farmers[1] who cultivated maize in Central and Southern Mexico during 2017–2018. It was a part of the more extensive subsidy programme ProAgro Productivity implemented by Mexican Government *Secretaria de Agricultura, Ganaderia, Desarrollo Rural, Pesca y Alimentacion* (SAGARPA, currently known as SADER) and CIMMYT that provided technical advisory support to farmers in 1346 localities from 273 municipalities of 16 states from the Central and South part of Mexico (Campeche, Chiapas, Guanajuato, Guerrero, Hidalgo, Jalisco, Mexico, Michoacan, Oaxaca, Puebla, Queretaro, Quintana Roo, Tabasco, Tlaxcala, Veracruz y Yucatan) (see details of locations in Annex 1). As farmers were beneficiaries of ProAgro, the sample is not random and does not intend to represent the 1.99 million farm units that cultivate maize in the country (Bellon et al., 2018).

All the data were consolidated into two databases:

a) The *farm typology database* contains information on the structural, functional, and social dimensions of 3811 farms. A semi-structured questionnaire was used to gather information using 47 variables to classify farm types based on structural (mainly resource access), functional (focused on resources management) and social (family demographics) dimensions (Zepeda et al., 2020) (see questionnaire in annex 2). Although this database represents a subgroup of the social network database, its data generates a robust case for a farm typology characterization.
b) The *social network database* contains information to analyze the social network developed around the adoption of agricultural practices by 29,796 farm units. Information was gathered using a structured questionnaire that integrates a catalogue of agricultural practices (innovations) and the following questions "Which agricultural practices are you performing? If so, from whom did you learn to implement each of these practices?" Agricultural practices were predefined at the state level by farm technical advisors who identified the state's most relevant technological innovation for maize. Responses were categorized and grouped in a list of stakeholders

Table 1
Stakeholders define in the social network database.

Category	Type	Main function
Farmers	Farmers and relatives	Agriculture in a leading or supportive role
Institutions	Research and education institutes, Governmental institutions, Agricultural advisers, financial institutions	Support by research, education, policies, training, and funding
Input suppliers	Providers of seeds, fertilizers, pesticides, and equipment	Provide production inputs
Clients	Retailers, agroindustry buyers and intermediary buyers	Buy, collect, and process agriculture outputs
Intermediaries	Farmers' organizations, actors with multiple functions and NGOs	Promote collective benefits concerning access to projects, knowledge, or markets

Source: Roldán-Suárez (2022).

[1] This group appeared as subsistence farmers, and the requirement was having not >5 ha per farm in rainfed conditions and 0.2 g = ha with irrigation. https://www.agricultura.gob.mx/sites/default/files/sagarpa/document/2018/07/11/1088/manual-especificaciones-marzo2017.pdf

described in Table 1. The questionnaire also gathered general information about farm resources, farmers' social attributes, and the maize production system (see questionnaire in annex 3).

3.2. Data analysis

Data analyses consisted of two steps: (i) extrapolation and description of farm types to the social network database and (ii) network analysis to estimate indexes referring to the configuration of social ties. For this study, we used the open-source program R (V 4.0.4), embedded in R-Studio (V 1.4.1106).

3.2.1. Farm typologies

This study relies upon a previous farm typology analysis using the *farm typology database* published by Zepeda et al. (2020). The analysis made a classification based on a Principal Components Analysis on farm resources (land area, livestock, water access, machinery and equipment, labor, *etc.*), crop management and livelihood strategies (crop distribution, the proportion of on/off/non-farm activities, *etc.*), farm family social attributes (ethnicity, family age and composition, and education level) and maize production characteristics (yield, genetic material type and production purpose). Five farm types were characterized and named as follows: 1) Commercial and mechanized farm households (*commercial*), 2) Low mechanized farm households (*low-mechanized*), 3) Semi-commercial farm households of Elder Families (*elder families*), 4) Farm households with diversified income, (*diversified incomes*), and 5) Subsistence farm households with women participation (*subsistence*). Information of this analysis can be found in annex 4.

This group's classification was extrapolated to the *social network database* by using a random forest prediction, through the variables related directly or indirectly. It consisted of the application of the average prediction trees in an aleatoric vector with n-regressions model to draw an average trend (Breiman, 2001). This kind of model has proved reliable for successfully classifying new events in a trained network (Ho, 1998; Breiman, 2001). Means, standard deviation, and the significance for mean comparisons were performed following the Kruskall-Wallis test at the 5% alpha level for information gathered in the *social network database*. This information covers farmer social characteristics, farm production resources, and maize production orientation, which helped to identify differences between farm types. A most detailed description based on Zepeda et al. (2020) farm types' characterization complemented this characterization.

3.2.2. Social network analysis

The study used a two-mode ego-centric network approach in which a farm unit represents the first type of actor or mode or ego and alters are represented by actors in other stakeholder's categories who contribute to the adoption of agricultural practices (Ovalle-Perandones et al., 2010; Rost, 2011). The analysis consisted of estimating two indexes to quantify the contribution and configuration of strong *versus* weak ties for different farm types. The first analysis (a) estimated the *External and Internal Index* (*E*-I index) as an index that quantifies the ego-alter similarity that defines the network configuration. The second analysis (b) calculated the value of a *Specialization Index* that estimated the contribution of strong and weak ties in the innovation network.

3.2.2.1. External and Internal Index (E-I index). The EI index proposed by Krackhardt and Stern (1988) has been extensively used in social network analysis to quantify the relational structure within and between groups (Everett and Borgatti, 2012).

For the analysis, all the links that ego has with an alter in the category "farmers" were considered internal (I). The links between ego and alters in the remaining categories (institutions, input suppliers, clients and intermediaries) were labelled as external. We applied a modified version of the *E*-I index proposed by Borck et al. (2015), considering the differences between the number of nodes among different farm types. In the formula for calculating this index *EL* is defined as the total weighted of external connections (sum of the weights of all external ties) and *IL* is defined as the total weighted of all internal connections for each individual or farmer as follows:

$$E - I\ index = \frac{EL - IL}{EL + IL}$$

Where.

EL = the normalized number of external connections for individual *i*.

EL = the normalized number of internal connections for individual *i*.

Since we have weighted data instead of binary data, we normalized the EL number dividing E by the maximum observed value for each farmer or individual as follows:

$$EL = \frac{E_x - E_{min}}{E_{max} + E_{min}}$$

And the same procedure to normalize the internal links (IL):

$$IL = \frac{IL_x - IL_{min}}{IL_{max} + IL_{min}}$$

The possible scores for this index encompass from −1.0 to +1.0. As the E-I index approaches to +1.0, all the links would be external to the subunits. A score of −1.0 would indicate that all the links are internal. If the links are divided equally, the index will equal to zero. The significant differences between the means of E-I indexes of all farming types were performed following the Kruskall-Wallis test at the 5% alpha level.

3.2.2.2. Specialization index (d'). The specialization analysis index (d') was proposed by Blüthgen et al. (2006) and performed in Dormann (2022) in ecology studies. This index explores the diversity of relationships between individual farmers and other stakeholders involved in the maize production network. This diversity was used to compare the contribution of stakeholders in different farm-type networks (Table 2).

The analysis consisted of building a weighted two mode-network using a *W-weighted* adjacency matrix (Table 3), with given f farmers and s stakeholders in a matrix *X* of dimension *f* x *s* elements, in which aij = 0 when there is no edge between nodes or smallholder farmers i and stakeholder j, and aij = w when and edge exist (w is a real number) (Amano et al., 2018; Chessa et al., 2014). A contingency table can represent the interaction with f rows and s columns, each cell containing the frequency aij of interaction between a farmer i and a stakeholder j (see Blüthgen et al., 2006).

Each interaction was then assigned as a proportion of the total (m) as follows:

pij = aij/m, where $\sum_{i=1}^{f}\sum_{j=1}^{s}p_{ij} = 1$.

P'ij is the proportion of the number of interactions concerning the row total (Aij) and q' the proportion of all interactions by partner j concerning the total number of interactions (m).

p'ij = aij/Ai, $\sum_{j=1}^{s}p'_{ij} = 1$, qj = Aj/m, and $\sum_{j=1}^{s}q_j = 1$

The specialization of a farmer *i* the index d' compared the

Table 2
A farmer and stakeholder interaction matrix.

	Stakeholder 1	S 2	…	S s	Total*
Farmer 1	a11	a12	…	a1s	Ai = 1=$\sum_{j=1}^{s}a_{1j}$
F2	a21	a22	…	a2s	Ai = 2=$\sum_{j=1}^{s}a_{2j}$
F3	a31	a32		a3s	Ai = 3=$\sum_{j=1}^{s}a_{3j}$
…	…	…	…	…	…
F f	af1	af2	…	afs	Ai = f=$\sum_{j=1}^{s}a_{fj}$
Total	Aj = 1=$\sum_{j=1}^{f}a_{i1}$	Aj = 2=$\sum_{j=1}^{f}a_{i2}$	…	Aj = s=$\sum_{j=1}^{f}a_{is}$	m=$\sum_{i=1}^{f}\sum_{j=1}^{s}a_{ij}$

* Interaction frequencies (aij) between farmers (c) and stakeholders (s). Total rows Ai, columns Aj and total elements m.

Table 3
Average values of farm resources, maize production (resources and orientation) and farmers' social attributes from the social network database. Superscripletters indicate if two values are significant similar or different in a gradient value from the highest (a) to lowest value (d/e) based on the Kruskall-Wallis test at the 5% alpha level.

Attributes	Variables	Measures	Farm types				
			Commercial 2% (692)	Low mechanized 19% (5650)	Elder families 17% (5148)	Diversified income 39% (11,519)	Subsistence 23% (6787)
Farm resources	Total agricultural land	Ha	5.77^{a} (4.79)	2.46^{b} (1.16)	2.25^{c} (1.22)	1.86^{e} (1.61)	1.98^{d} (2.18)
	Irrigation	Rainfed 0 Both 0.5 Irrigated 1	0.42^{a} (0.48)	0.09^{b} (0.27)	0.05^{c} (0.21)	0.04^{d} (0.19)	0.02^{e} (0.15)
	Machinery	Percentage	67^{a} (27)	38^{c} (30)	44^{b} (26)	37^{d} (29)	25^{e} (0.31)
Maize production	Maize genetic type	Landrace 0 Improved 0.5 Hybrid 1	0.86^{b} (0.35)	1.00^{a} (0.00)	0.01^{d} (0.06)	0.16^{c} (0.36)	0.10^{c} (0.24)
	Maize yield	Mg/ha	6.99^{a} (3.95)	3.06^{b} (1.66)	1.88^{c} (1.73)	1.15^{e} (1.13)	1.77^{d} (1.64)
	Maize sale	Percentage	87^{e} (25)	81^{d} (22)	75^{c} (19)	2^{a} (6)	25^{b} (37)
	Maize sale price	Mexican pesos	3393^{c} (971)	3399^{b} (850)	3650^{a} (1256)	1003^{e} (1109)	1223^{d} (1943)
Farmer social attributes	Sex	Female 0 Male 1	0.87^{a} (0.34)	0.81^{b} (0.40)	0.81^{b} (0.39)	0.76^{d} (0.43)	0.78^{c} (0.41)
	Ethnicity	Non- Indigenous 0 Indigenous 1	0.00^{b} (0.00)	0.00^{b} (0.00)	0.00^{b} (0.00)	0.00^{b} (0.00)	1.00^{a} (0.00)
	Education	years	5.3^{a} (3.63)	4.67^{a} (3.66)	4.56^{a} (3.36)	4.10^{b} (3.31)	3.65^{c} (3.45)
	Farmer age	years	61.27^{b} (14.12)	60.73^{b} (14.68)	62.90^{a} (13.85)	62.74^{a} (14.31)	60.69^{b} (13.42)

distribution of the interactions with each partner (p'j) related to the overall partner availability (qj).

$$d_i = \sum_{j=1}^{s}\left(p'_{ij}.ln\frac{p'_{ij}}{q_j}\right)$$

This index was normalized ranging from 0 (most generalized ties) to 1 (most diversified ties or wider specialization). Here, values near 0 referred highlight the dominance of strong ties and homogenous networks, while a near 1 value reflects more heterogenous networks, including both strong and weak ties.

$$d' = \frac{d_i - d_{min}}{d_{max} - d_{min}}$$

The Kruskall-Wallis test was performed to find statistical differences in the specialization index among the different groups. Finally, a normalized degree index (Martín González et al., 2010) was calculated to identify the centralization patterns by the actors with whom farmers are linked and how these patterns differ among the distinct networks.

4. Results

4.1. Farm typologies

According to the prediction tree model (Fig. 1), the most relevant characteristics of farm classification (shared in both datasets) were: ethnicity (indigenous or not indigenous), maize genetic material (landrace or improved or hybrid genetic materials), production purpose (self-consumption *versus* market) and total agricultural land (total). The prediction evaluates one farmer at the time and defines the probability of being grouped in one of the original groups.

The results from the descriptive statistics analysis confirm differences between farm types that have been widely discussed (Barkin, 2002; Appendini, 2009; Eakin et al., 2014a, 2014b). Table 3 presents the values for each farmer type on variables that refer to farm resources and maize production characteristics. The table also presents social variables about the main person farming within the family farm units. There is a clear trend of decremental values in access to resources from commercial (who represent a distinctive group) to subsistence and diversified farm types concerning land, irrigation and machinery, and irrigation. Low mechanized and elder families farm types appear as intermediate groups concerning these farm assets.

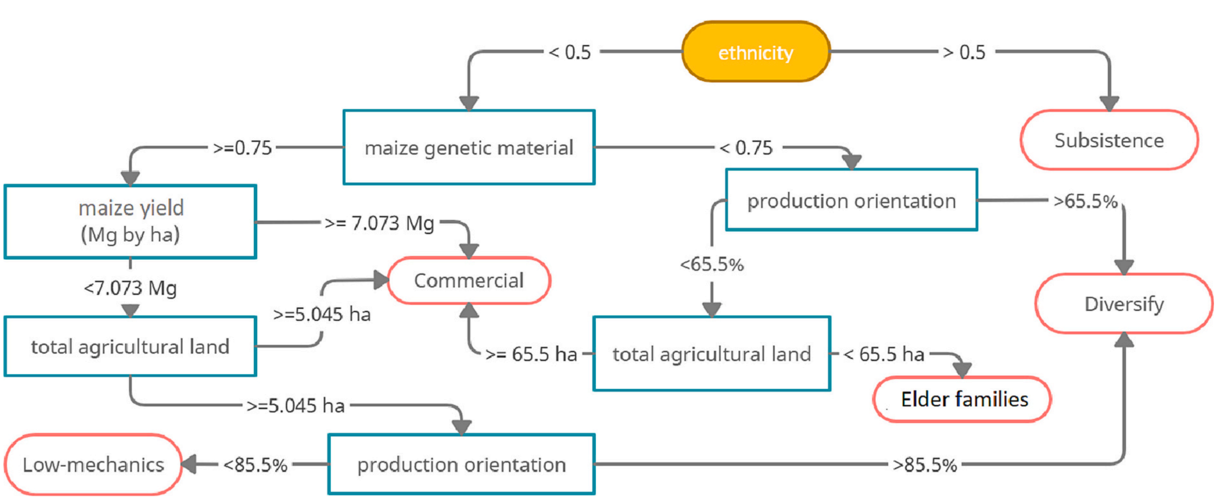

Fig. 1. Prediction tree for the extrapolation of farm typologies.

Differences are also evident in maize production attributes as previously reported by Sweeney et al., 2013 and Zepeda et al., 2020). Commercial farm types using mostly hybrid genetic materials and commercializing most of their production are the ones who obtain the highest maize yield. There is a yield gap of more than three Mg (ton/ha) between commercial and the next closest farm type, low-mechanized farmers, who use only hybrids. Landraces are cultivated by elder families, subsistence and diversified income farm units with yields that does not surpass the 2 Mg/ha. Maize sale prices present high values for the farm types selling most of their production (commercial, low-mechanized farm, and elder families) as they have been able to negotiate "high commodity prices" (Eakin et al., 2014b). The low sale prices received by subsistence and diversified farm types have been explained in terms of cash losses when landrace maize production is valued at the price of commercially available maize in local markets (Arslan and Taylor, 2009).

Social attributes become distinctive attributes of original farm types. The presence of women characterized diversified income and, in some extent subsistence farm types. Ethnicity becomes the primary trait to identify subsistence farmers with the lowest education value. The highest values on farmer age reflect the condition that characterized elder families farm types. However, the predicted new farmer's characteristics approximate to the Zepeda et al. (2020) typology as they are based on the individual farmer instead of the farm household description.

A brief description from information reported in Zepeda et al. (2020) for the farm typology characterization (see details in Annex 4) is used to complement and contextualize the previous description. The information is helpful to understand distinctive attributes of each farm type as this characterization contemplates other farm resources (such as livestock and labor), farm management and family livelihood strategies (crop distribution, proportion of on/off/non-farm activities, *etc.*), and farm family social attributes (such as family age and composition).

4.1.1. Commercial farms (commercial)

This farm type presents the major land extension in irrigated and flat conditions. Their farms are near urban areas. They present the most considerable quantities of livestock, and most of their cultivation activities are mechanized. Most of their income comes from agricultural activities on their farms, and they are the ones who hire more labour. The gap between this group and the others concerning their total income and their maize yield is significant, representing more than double from the near farm type (low mechanized farms).

4.1.2. Low Mechanized farms (low-mechanized)

Their farms are in the lowest altitude regions, far from urban areas with low access to irrigation infrastructure and machinery. Their maize production is manual as they cultivate in hilly and rainfed conditions. However, they are the ones who use more hybrid seeds and reach higher yields. Their primary income comes from agriculture representing 70% of their total income. Like subsistence farmers, their income is one of the more unstable throughout the year.

4.1.3. Elder families' farms (elder families)

The most distinctive attribute of this farm type is that they present the highest family age rate with an average age of 65 years old and a smaller family size (number of members). Their farms are near urban areas. Their farming activities are semi-mechanized or undertaken by animal traction. Their production is semi-commercial. They commercialize their maize production but cultivate landraces because self-provision is crucial for their livelihood. More than half of their income comes from agriculture that is complemented by cash transfers of social protection programs.

4.1.4. Diversified income farms (diversified income)

The location of their farms is near urban areas and in some cases peri-urban areas. Although their land area is the smallest, some of agricultural activities are manual and others mechanized as they have access to machinery. Some of their fields are irrigated. Livestock represents a critical income. Their maize production is used for human and animal consumption on their farms. Their income is diversified, and non-farm (temporal migration to cities) activities contribute more than crop and livestock incomes.

4.1.5. Subsistence farms (subsistence

This farm type presents one of the small land areas, and they are located the farthest from urban areas. Maize is cultivated in mountainous areas or stony soils and that is why most of the activities are manual. These farm type concentrates the major percentage of indigenous people, and they present the lowest years of education. Their agricultural income is the lowest and the most unstable during the year. Their cash transfers from social protection are the highest. They also receive income from selling their labor in off-farm activities. They are the group that buys more maize to satisfy the annual household consumption needs.

4.2. Network analysis

The network analysis results also show differences between farm types that, in most cases, are significant. This is because they are based on the information flows around maize technological innovations adopted by farmers and the primary source of information. We call them innovation networks because they map the information/knowledge flow for promoting the adoption of agricultural practices for maize production to improve productivity.

4.2.1. External and Internal Index (EI index)

Differences in the External and Internal Index values between the innovation networks of the five farm types are evident, as illustrated in Fig. 2. The *E*-I index values for all farm types tend to converge around zero, suggesting an equitable distribution of strong and weak ties within their respective innovation networks. However, it is worth noting that the commercial and elder families' farm types markedly deviate from the remaining farm units, displaying a pronounced inclination towards association with external links, which indicates weaker ties. Conversely, the low-mechanized units occupy an intermediate stance concerning their network connections. Finally, the subsistence and diversified farms have relatively higher level of internal linkages or strong ties.

4.2.2. Specialization index and normalized degree

The variation in the specialization index provides important information related to the differential contribution of strong and weak ties. Although most of the values tend to more generalized ties, the commercial network (Fig. 3 C) has the highest d' index, with the weighted mean degree of specialization d' > than the rest of the networks ($p \leq 0.05$). Commercial farmers use both strong and weak in their innovation networks. First, input suppliers and, in second place, institutions play an important role in adopting agriculture practices. In contrast, the subsistence and diversified networks are dominated by generalized (low and similar d') centered in strong rather than in weak ties (Fig. 3 A and B). The minor contribution of weak ties in adopting new agricultural practices is first played by institutions and later by input suppliers. Elder and Low-mechanized farmer' networks were located in between generalized to specialized, differing among the two extremes but following commercial farmers in the pattern of external contribution. Although in all the cases, strong ties (links to other farmers and relatives) are the most frequent by the farmers, the normalized degree shows how the commercial networks establish a wider variety of relationships, including weak and strong ties, while the rest of the networks are centered mostly in strong with different magnitude.

A clear trend appears when combining the social network index values and the farm typology characteristics. As Fig. 4 shows, the

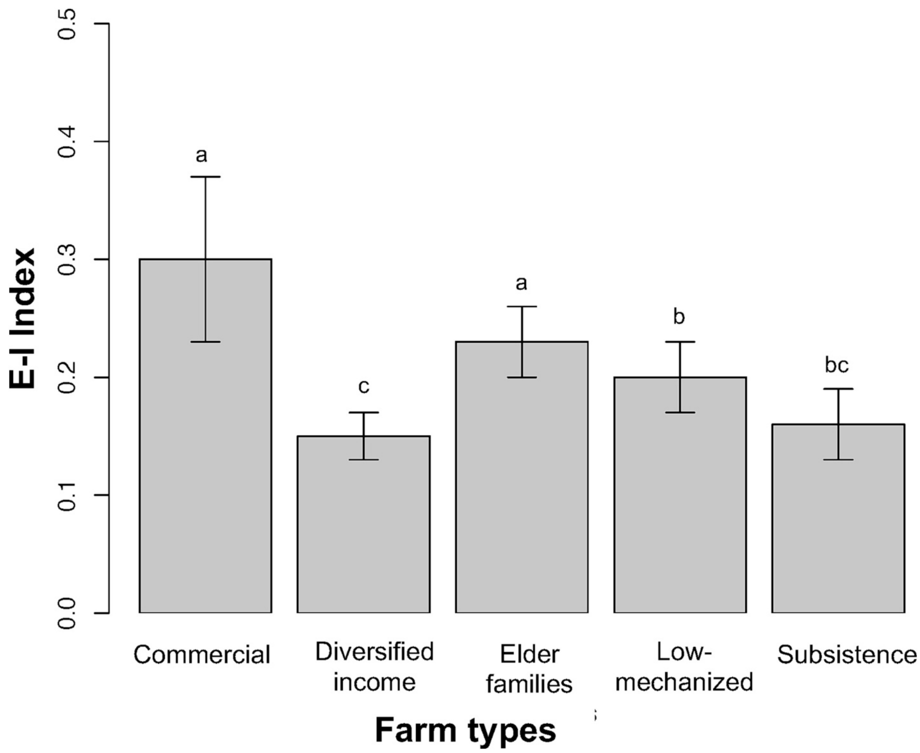

Fig. 2. Results of the E-I calculated across the five farm types*.
* Bars show the average E-I index values for each farm type. The pair-wise comparison using the Kruskal Wallis test is represented by a, b and c showing that they are significantly different ($p < 0.05$).

commercial farm type presents the highest values on the social network indexes with significant ties for innovation from peer farmers and input suppliers. Commercial farm types are also characterized by the highest values on farm resources (like farmland area, irrigation, and machinery) and a maize production system using high yielded hybrids varieties for commercial purposes, attributes that characterized this farm type as Fig. 1 and Table 3 illustrate and Eakin et al. (2014b) reported. On the other extreme of the spectrum, the lowest values of *E*-I and Specialization Indexes are from diversified income units, followed by subsistence farm types who receive support from institutions and later supply inputs. Diversified and subsistence farm types also present the lowest values for farm resources, cultivate landraces for self-consumption purposes, characteristics that distinguish these types in Table 3 that have been documented by Eakin et al. (2014a) and other authors. Finally, low-mechanized and elder families farm types present intermediate values for both social network analysis and farm resources.

5. Discussion

Findings from E-I and Specialization indexes show that strong and weak ties contribute to innovation networks of different maize smallholder farm types in Mexico. This result is in line with the narrative that values the complementary contribution of weak and strong ties for innovation processes that lead to resilience (Rost, 2011; Cofré-Bravo et al., 2019; Bruce et al., 2021). Results also demonstrate differences between innovation networks that can be explained by farm-type attributes highlighting the context specific-nature of their innovation-resilience strategies (Darnhofer, 2014; Rockenbauch and Sakdapolrak, 2017). Each farm type presents characteristics described in literature discussing maize farming systems in Mexico. Nevertheless, for the case of the contribution of strong and weak ties to their innovation networks, findings distinguish three groups. We will elaborate on this discussion focusing on these three groups.

The first group is represented by commercial farm units presenting a more comprehensive network and more variety of relationships. Their social ties configuration towards weak ties facilitates the adoption of innovations (Van Rijn et al., 2012). Social networks of commercial farm types are exposed to dynamic processes driven by markets, technology, and competition that increase the dependency on external resources and the need to establish a wider variety of linkages that create social and information proximity (Fritsch and Kauffeld-Monz, 2008). However, the contribution of strong ties (represented by other farmers and relatives) should not be underestimated for the adoption of agricultural practices. Commercial farmers have more access to farm resources to practice highly productive farming systems using external inputs and receiving external support, attributes that have been proven to facilitate innovation (Cofré-Bravo et al., 2019). They form part of what Eakin et al. (2014b) call the agrarian winners of the maize boom in Mexico who have received and negotiated governmental investment and support to modernize their maize farming systems. They not only count on the resources for high productive and commercial production but also on an extensive network that facilitates knowledge flows between them and research centers, transnational enterprises, agroindustry, and farmers associations (Casas et al., 2000).

Low-mechanized and elder families farm types represent intermediate points in the gradient of commercial to diversified income farming systems. The contribution of weak ties is similar between these two farm units in terms of input suppliers and institutions playing essential roles in their innovation networks. Nevertheless, low-mechanized farm units have higher values on agricultural land area and maize yields using hybrid materials for commercial purposes, evidencing the importance of resource endowment for social interactions (Cofré-Bravo et al., 2019). They reflect the partial modernization process in some tropical regions of Mexico with limited mechanization and irrigation facilities (Hellin et al., 2013). The location of low mechanized farm units far away from urban areas explains the challenges of interacting with other stakeholders different from farmers (McCune et al., 2012; Díaz-José et al., 2018). However, spatial distance cannot be used to explain the limited

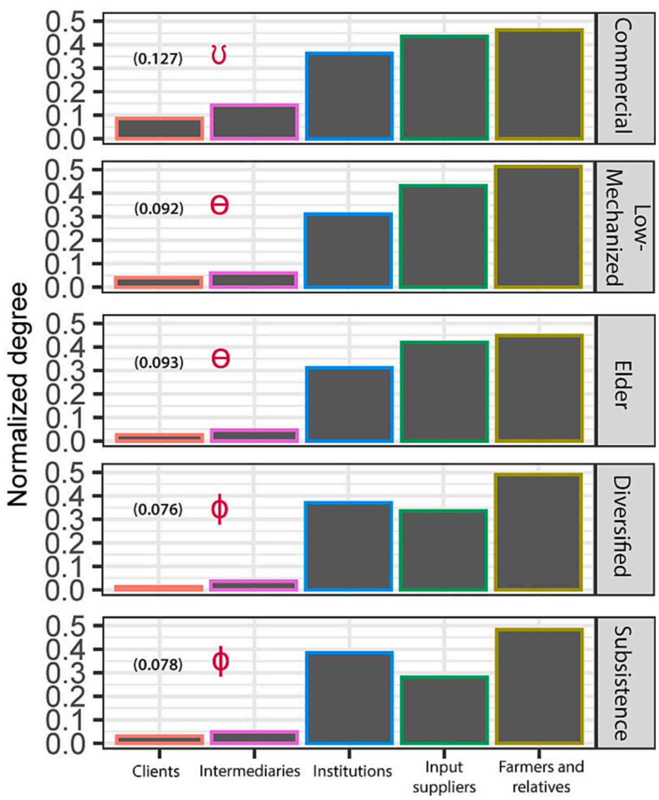

Fig. 3. Patterns of specialization and normalized degree index within smallholder farmer' networks*.
* Bars show the normalized degree (Martín González et al., 2010) as the normalized number of links of each type of actors with whom the smallholder farmers are linked. The number in parentheses indicates the specialization index (d') for the different networks. The pair-wise comparison using the Kruskal Wallis test, shows that indices (d') containing different symbols (in red) are significantly different ($p < 0.05$).

contribution of weak ties to elder families' farm units as they are located near urban areas. Elder families farm types commercialize their maize production but cultivate landraces because self-provision is crucial for their livelihood. These farm types illustrate the ageing process occurring in Mexico (SAGARPA and FAO, 2014) and worldwide (FAO, 2017). This distinctive social attribute highlights the relevance of family dynamics for resilience strategies (Darnhofer, 2014). Both farm types illustrate how factors such as rural isolation or stage of life shape the possibilities of social interactions.

Finally, diversified income and subsistence farm types are the third group centered on strong/bonding ties. Weak ties from institutions are also present in their innovation networks as they are beneficiaries from social protection programs. These two farm types have less access to farm resources and cultivate maize landraces for consumption. Diversified income but especially subsistence farmers, are the ones that literature commonly identifies as small-scale farmers. These farm types have received particular attention concerning their persistence to survive political and climatic challenging conditions (Appendini and Liverman, 1994; Eakin et al., 2014a; Bada and Fox, 2022). Diversified income farm types receive the lowest values on both social network indexes showing that they rely more on strong ties. This result highlights that more than distance to urban areas, as some of these farm types are in peri-urban areas, is their persistence to grow maize for tradition and consumption the one defining their innovation network (Lerner et al., 2014). Persistence becomes vital due to the socio-cultural significance of producing and consuming maize as part of their culture and traditions (Lerner and Appendini, 2011; Eakin et al., 2014a). The redundancy and self-exclusion of networks as strong rather than weak ties could then be explained to preserve maize culture through time (Wood et al., 2014; Gosnell et al., 2019).

Results in this study show visible trends between social network indexes and farm types, illustrating the differential contribution of social ties between farm types. They call to explore further how different configurations of strong/bonding and weak/bridging ties can lead to greater resilience (Newman and Dale, 2005). Farm, farming systems and farmers' attributes, and their contextual circumstances become crucial to find what mixes of strong and weak ties will be strong enough to "engage in joint problem-solving in the face of adversity but loose enough to give them room to pursue new opportunities" (Fath et al., 2021). Adaptation is only half the advantage gained by such social networks; further exploration is required to identify persistence's contribution to enhancing the farming system's collective capacity to use innovations as a pathway to resilience.

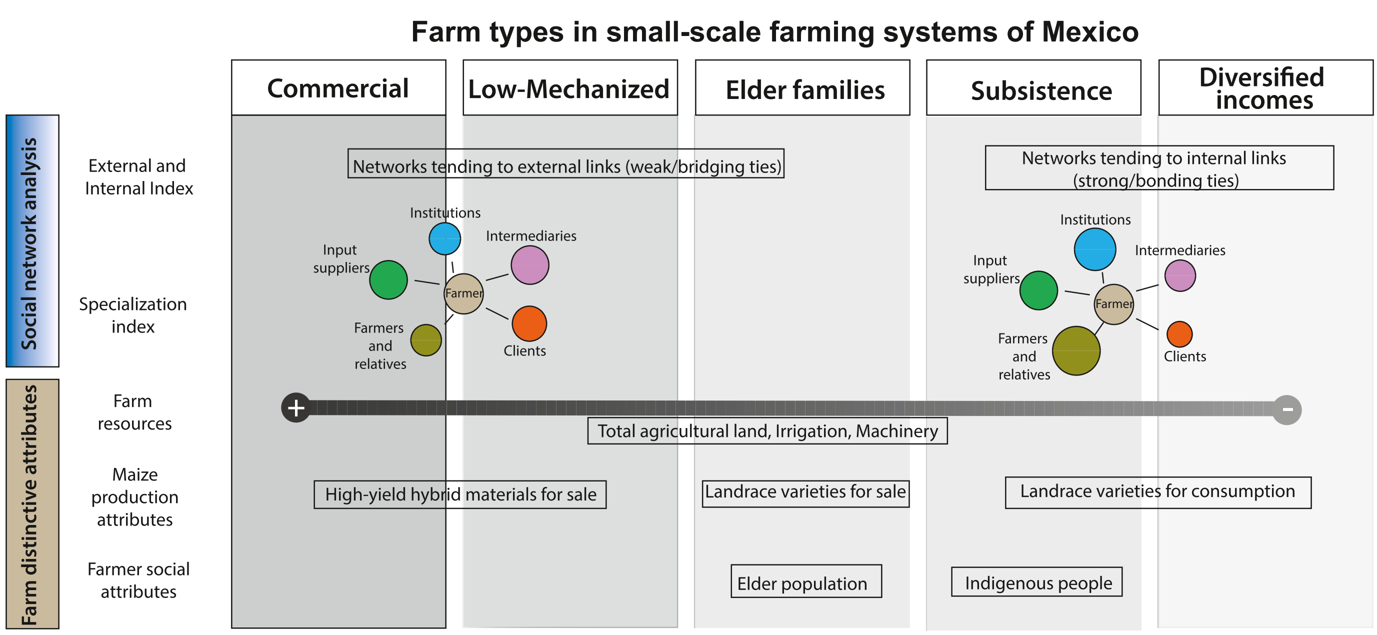

Fig. 4. Graphic summary of the analysis's main findings.

6. Conclusion

At a time when agriculture faces increasing and diverse challenges, various combinations of strong and weak ties are needed to enhance the resilience strategies used by different types of farmers. Each farm type had developed a functional combination (or adapted to it) based on their access to resources and productive attributes concerning their innovation process. Despite the heterogeneity and diversity of relationships, the balance tends to tilt towards either internal or external links, as farm types seek to position themselves on one side or the other based on their capacity to respond and available resources. Commercial farm units rely on weak relationships to evolve towards new models that enable them to maintain or transform the productive system. In contrast, subsistence farming systems have endured for centuries and find strategies within their environment and their strong ties to resist and maintain the system. They illustrate how diverse possibilities appear when particular attributes and contexts are considered for strengthening strong and weak ties highlighting the need to promote not only weak but also strong ties to increase resilience through innovation. The contribution of weak and strong ties to heterogenous innovation networks has proved crucial for increasing resilience through adaptation. However, it implies different results in the same innovative scale of adoption and production enhancement, and then, food or economic security. Further research is required to explore how weak and strong ties interact and contribute to resilience through persistence in innovation networks.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103716.

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