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Humans, Plants, and Networks

A Critical Review

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Abstract: In recent years, Social Network Analysis (SNA) has increasingly been applied to the study of complex human-plant relations. This quantitative approach has enabled a better understanding of (1) how social networks help explain agrobiodiversity management, and (2) how social relations influence the transmission of local ecological knowledge (LEK) related to plants. In this paper, we critically review the most recent works pertaining to these two lines of research. First, our results show that this fast-developing literature proposes new insights on local agrobiodiversity management mechanisms, as well as on the ways seed exchange systems are articulated around other social relationships, such as kinship. Second, current works show that inter-individual connections affect LEK transmission, the position of individuals in networks being related to the LEK they hold. We conclude by stressing the importance of combining this method with comprehensive approaches and longitudinal data collection to develop deeper insights into human-plant relations.

Keywords: agrobiodiversity, human-plant relations, knowledge transmission, local ecological knowledge, quantitative methods, seed exchange networks, social network analysis

Introduction

The social network approach is characterized by a specific focus on inter-individual relations and by a conceptual apparatus grounded in structuralist assumptions, in which systems are analyzed in terms of the structural relations among their elements. It has a long-standing history in the social sciences, starting back in the 1930s with Jacob Moreno and Helen Jennings's analysis of the impact of inter-individual relationships on runaways among the alumni of an all-girls high school in New York State (Moreno 1934; described in Borgatti et al. 2009). Because of its specific emphasis on social interactions and connections, it echoed a number of conceptual questions tackled by the social sciences while at the same time offering a new perspective and new tools to answer these questions (Mitchell 1974). For instance, in the 1940s, the Manchester school, at that time strongly influenced by the structural-functionalist paradigm, developed a number of studies based on a social network approach to understand how interpersonal ties helped explain conflicting situations in Rhodesia, at that time under British colonial rule (McCarty and Molina 2014). Following these precursors, social scientists examined topical questions such as the distribution of power within social groups (Burt 2004), the influence of social structures on individuals' behaviors (Granovetter 1985), and many others, that produced major works that ground contemporary research in social sciences. This rapid theoretical integration was parallel to the development of computer sciences and of mathematics that provided increasingly elaborated analysis tools, such as the graph theory, that strongly enhanced the ability of researchers to formalize and analyze social interactions. It was, for instance, applied in anthropology to the study of kinship systems through the development of p-graph models (White and Johansen 2005). Thus, the social network approach has constantly grown over these years; it is now fully settled in academia and offers a rich and highly dynamic body of research.

Interestingly, if we now look at a historical sketch of the studies dealing with human-plant relations, we see that only recently has a social network approach been applied to this research topic. In the first half of the twentieth century, while social scientists were tuning their methodologies to social networks, the precursors of ethnobiology and environmental anthropology were equally laying the groundwork of these fields. Ethnobiology developed toward the systematic study of folk nomenclature and classification (for example, Berlin et al. 1974; Conklin 1955). Ethnoecology, by means of integrating the concept of ecosystem, enabled systematic studies and quantification of human-plant interactions (Ford 2011; see also Hunn 2007), as applied for instance by Roy Rappaport (1967), but without a social network perspective. Historical ecology, on another line, emphasized the importance of taking into account a diachronical perspective while studying these phenomena (for example, Balée 1994; Posey 1985). These precursory works gave birth to a wealth of studies, that today range from agronomic research focusing on local management practices (see Alexiades 2009) to new lines of research dealing with the psychology of connectedness to nature (Cervinka et al. 2011; Luck et al. 2011) or proposing decentered approaches to human-plant relations through "multi-species ethnography" (Kirksey and Helmreich 2010; Tsing 2012).

Within this very rich and diverse body of research, the social network approach started to be used in two main fields: the study of agrobiodiversity management and the study of the transmission of Local Ecological Knowledge (LEK). In these two fields, the understanding of inter-individual patterns of exchange and communication was a key research objective. In agrobiodiversity studies, researchers aimed at understanding how people manage cultivated crops, how they select varieties and landraces and breed species (for example, Wilson and Dufour 2002), and how this local management affects agrobiodiversity, from the genetic and species up to the landscape level (Pautasso et al. 2013). With breeding practices at the center of most of these inquiries, the ways in which farmers acquire and exchange seeds quickly received increasing attention. Researchers then started to analyze local seed exchange and seed supply systems (for example, Crissman and Uquillas 1989), stressing the importance of such systems for food security (Almekinders et al. 1994). This research domain grew very fast, looking at cash and subsistence crops cultivated in fields or home gardens in a variety of geographical contexts, and brought some key findings to the field, as we will see below.

The social network approach was also recently integrated in a body of research focusing on cultural transmission of LEK. In this line of research, the main theoretical models were inspired by cognitive anthropology (for example, Romney et al. 1986) or evolutionary theory (for example, Cavalli-Sforza and Feldman 1981), which pointed toward the intrinsically individual nature of cultural practices and knowledge; following these theories, culture is enacted, reproduced, and transmitted at the individual level, between individuals. An important set of studies were conducted following this line (for example, Atran et al. 1999; Boster 1986), aiming at analyzing the intra-cultural variations of LEK and cultural practices, that is, understanding how LEK and cultural practices were distributed and transmitted between individuals belonging to a common cultural background. Social networks started to receive attention in this context, first as a metaphor to refer to the web of social relations structuring local exchanges, such as kinship (for example, Boster 1986) and only very recently under a quantitative approach (for example, Hopkins 2011). The widespread use of such an approach in studies on organizations (for example, Nohria and Eccles 1992) or in communication studies (for example, Rogers and Kincaid 1981) apparently did not influence research in ethnoecology at an earlier stage.

The overall aim of this article is to do a comprehensive review of the works that are making use of a social network approach to study human-plant relations. Given that a wide diversity of concepts and analysis methods is observed among the works referring to social networks, we refer here to Örjan Bodin et al. (2011, see also Alexander and Armitage 2015), who propose a useful distinction between three main approaches to social networks. First, the "binary metaphorical approaches", that limit the analysis to observing the absence or presence of a social network. Second, the "descriptive approaches", that propose a description of a network's features, its structure and components, but lack clarity and depth in analyzing its structure and the outcomes related to the network's structure. And last, the "structurally explicit approaches", that aim at analyzing the structure of networks and explicitly integrate networks' component properties. In this review, we focus on publications that are making use of quantitative analyses applied to social networks that belong to the descriptive or structurally explicit categories, hereafter Social Network Analysis (SNA). Specifically, we will (1) show how SNA is used to study the relations between humans and plants; (2) assess what SNA adds to the understanding of these relations; and finally (3) highlight the caveats and current research gaps that pave this emerging research avenue.

Methods

We used a systematic quantitative literature review (Petticrew and Roberts 2008) in order to select all articles that were using quantitative SNA to describe and assess the relations between humans and plants. The use of systematic methods to search and categorize the literature avoids potential biases and provides reproducible and reliable assessments of the current status of the research field (Guitart et al. 2012). We compiled a database of peer-reviewed scientific journals published in English indexed by Scopus during January and February 2015. Key words used for the searches were “social network analysis” or “social networks” and “plants,” “seed exchange,” “germplasm,” “germplasm exchange,” “propagule,” “propagule exchange,” “seed,” “ethnobotany,” “ethnobotanical,” “traditional ecological knowledge,” “local ecological knowledge,” “ecological knowledge,” “indigenous knowledge," and "plants knowledge" anywhere in the title, abstract, or keywords. The selection of keywords was based on the authors' experience in the fields of social network analysis, agrobiodiversity conservation, natural resource management, and traditional/local ecological knowledge. Some of the searches did not give any result (for example, "social network analysis," or "social networks" and "propagule," or "propagule exchange"). We also included in our database some recent peer-reviewed articles (2015 and 2016) that were not yet available in Scopus and were suggested by the editors and reviewers of the present article. We targeted journal contributions that (1) use social network analysis as a research method, (2) use human beings (that is, individuals, farms, households) as actors within the networks, and (3) explicitly deal with plant materials (that is, the entire plant, seeds, or any other type of propagule) or with LEK related to plants. We excluded articles taking into account social links or social exchanges but not mapping or collecting systematic data on these links (Bellon et al. 2011; Ceuterick et al. 2011; Dzomeku et al. 2010; Márquez and Schwartz 2008; Marshall et al. 2011; McGuire 2008; Sorice et al. 2011). In these papers, "social network" is used following the binary metaphorical approach, as an umbrella term equivalent to "inter-individual relationships" or to "social relations" in general, without any analysis of the structure of the web of relations under focus. We also excluded articles focusing on networks of plant diseases, plant trade, or plant genetic markers since they did not explicitly deal with the use of plants by human beings (Moslonka-Lefebvre et al. 2011; Thomas et al. 2012; Wu and Guclu 2013). We did not include in our corpus a recent review on seed exchange networks for agrobiodiversity conservation (Pautasso et al. 2013), since SNA is only one of the several methodologies the authors examine, although we use it to discuss our results. Finally, we did not incorporate the extensive and growing literature on SNA and natural resource management, because it did not focus explicitly on plant material and knowledge (for example, Beilin et al. 2013; Bodin and Crona 2009; Calvet-Mir et al. 2015; Turner et al.

2014) and several reviews and collective publications are already available on the topic (Alexander and Armitage 2015; Bodin and Prell 2011; Crona and Hubacek 2010).

Our final dataset included 18 articles. From each of these contributions, we extracted the following information: article's author(s), year of publication, journal, location of the study, theme of the article, author(s)' analytical objective(s), type of network analyzed, SNA measures used, and outcomes reported. To offer a more nuanced analysis, we also recorded categorical information on the author(s)' own judgment about using SNA as a method to analyze human-plant interaction (strengths and weaknesses). The database of articles was analyzed to detect patterns in the literature, the geographical spread of case studies, the types of SNA measures used, and the types of results obtained. This analysis highlights reliable conclusions that can be drawn from the literature, and biases in past studies that may produce weaknesses (for example, recall bias), which may help to improve future research agendas (that is, to fill knowledge gaps).

By only using peer-reviewed research, we guarantee that each included article has already been assessed by experts in the field and has a suitable standard for publication in academic literature. We did not explicitly assess/weigh different studies as more or less reliable based on the chosen network measures or reported outcomes.

Results

Characteristics of the Corpus

Our final database includes 18 articles, 16 of them published after 2010. The diversity of journals where these articles have been published reflects the broad and cross-disciplinary interest in using SNA to elucidate the interaction between humans and plants. Our corpus includes journals that range in their main field from anthropology (for example, *Current Anthropology*) through to biology (for example, *Journal of Theoretical Biology*), and from interdisciplinary studies (for example, *Ecology and Society, Experimental Agriculture*) to research methodologies (for example, *Field Methods*). The geographical scope of the research is wide and includes studies in Europe (4), North America (2), South America (4), Asia (3), Africa (5), and Oceania (2). The majority of the articles (14 out of 18 articles) focus on germplasm exchange (that is, exchange of seeds, seedlings, and other type of propagules), while two focused on both germplasm and knowledge exchange (Díaz-Reviriego et al. 2015; Kawa et al. 2013). From the 14 that deal with germplasm exchange, two (Calvet-Mir et al. 2012; Reyes-García et al. 2013) link the position of individuals within the seed exchange network with their LEK about agrobiodiversity and agroecological practices, but without studying exchanges of knowledge. Two articles focus solely on knowledge exchange, one of them dealing with ethnomedicinal and food-related knowledge (Haselmair et al. 2014) and the other one focused on ethnomedicinal knowledge (Hopkins 2011). Finally, Diana Lope-Alzina (2014) looks at the exchange of food products coming from home gardens, including plant materials. Across all these case studies, seven focus on agricultural crops (wheat, barley, rice, sorghum, and manioc), three deal with plants grown in home gardens, one analyzes agricultural and home garden crops and three assess cultivated plants generally. The last four articles deal either with house potted plants (Ellen and Komáromi 2013) or medicinal plants (Díaz-Reviriego et al. 2015; Hopkins 2011), in one case in association with food (Haselmair et al. 2014).

<INSERT TABLE 1 ABOUT HERE>

Table 1: Characteristics of the reviewed corpus

SNA as a Tool to Grasp the Circulation of Plant Material and Knowledge

Across all the articles, the social network approach is implemented to study flows of plant material and/or of plant-related knowledge. However, the analysis of these flows is used to tackle quite different research objectives. Most of the studies are interested in understanding how the circulation of plant material affects agrobiodiversity in different settings: home gardens or intensive/extensive agriculture. In these cases, the diversity is studied at the intra-specific level within one species (that is, landraces) (Abay et al. 2011; Aw-Hassan et al. 2008; Kawa et al. 2013; Labeyrie et al. 2016; Poudel et al. 2015; Subedi et al. 2003), or at the inter- and intra-specific levels (Calvet-Mir et al. 2012; Reyes-García et al. 2013; Ricciardi 2015; Thomas and Caillon 2016; Violon et al. 2016; Wencélius et al. 2016). A quite distinct study in the context of agroecosystems (Díaz-Reviriego et al. 2016) focuses on the medicinal plant material and medicinal plant knowledge exchange in home gardens. The other papers address very different questions: two articles aim at studying the dynamics of knowledge transmission, one through the identification of sources of knowledge cited by informants in different locations (Haselmair et al. 2014), the other one by mapping the herbal remedy enquiry network across one single community (Hopkins 2011). An original study by Roy Ellen and Réka Komáromi (2013) traces how biological and social factors interact to shape exchanges of potted houseplants in UK, and one study aims at analyzing how food exchanges are shaped by pre-existing social relations within a rural community (Lope-Alzina 2014). Standing a bit aside of this corpus is the study by Pierre Barbillon and colleagues (2015) that applies a modeling approach to assess the best structure of seed exchange networks.

All the studies gathered in our corpus focus on exchange networks. Most of them (16) analyze exchange networks using a socio-centric approach, one of the two possible approaches to networks as highlighted by the literature on SNA; while only two of them use the egocentric networks approach. Socio-centric networks, also known as whole or complete networks, refer to networks where a set of actors and the entire set of ties linking these actors together are studied within chosen boundaries (Prell 2011). Egocentric networks, also known as personal networks, reflect the relationships that are centered on unique individuals, somehow similar to their "personal communities." Ego networks consist of a focal actor (that is, ego), the actors to whom ego is directly connected (the alters) and the relations among this set of individuals (both ego to alters and inter-alter relations) (Prell 2011).

Each approach provides a different perspective on social interactions, and allows different types of analyses. Here we describe the main types of network analyses used under these two perspectives and the main insights they provided regarding the research objectives of the different articles.

Socio-centric Networks

Among the articles that analyze socio-centric networks, two only assess the general network structure (Aw-Hassan et al. 2008; Subedi et al. 2003) and eight evaluate some network-level measures, among which four deeply analyze them (Calvet-Mir et al. 2012; Díaz-Reviriego et al. 2015; Reyes-García et al. 2013; Wencélius et al. 2016). Most of the articles focus on individual-level centrality measures, while two (Díaz-Reviriego et al. 2015; Thomas and Caillon 2016) also analyze intermediate level measures that link network characteristics to individual ones. One stands aside and applies a modeling approach to asses seed exchange networks (Barbillon et al. 2015). In line with this modeling approach, Vanesse Labeyrie et al. (2016) use ERGM (exponential random graph models) to test for homophily, that is, a situation in which similar actors are attracted to one another and thus choose to interact with each other.

The network-level measures include size, number of components, density and network centrality. Based on Stephen Borgatti et al. (2002) these measures can be defined as the number of actors (or nodes) in the network (size); the number of connected subgraphs in which all actors are directly or indirectly in contact with each other (number of components); the number of links in the network, expressed as a proportion (from 0 to 1) of the maximum possible number of links (density); and the tendency (expressed in percentage) for a few actors in the network to have many links or nominations (network centrality).

The use of network-level measures provides an overview of the structure of the network, which can be analyzed concerning chosen outcomes, such as the variety of landraces that can be observed in a given area or community. For instance, Laura Calvet-Mir et al. (2012), by using these measures in their study, showed that, although fragmented and with a low density, the informal network of seed exchange was still active and represented a more important mechanism of seed exchange than the local seed bank.

At the node-level, the most used measures are centrality measures (that is, measures assessing the position of nodes in the network), and specifically degree (indegree and outdegree), betweenness, and harmonic closeness (Borgatti et al. 2002; Freeman 1979). Degree is the number of immediate contacts an actor has in a network, simply counting how many actors are directly tied to a focal actor, ignoring both the direction and value of the tie. Indegree refers to the number of nominations that a person receives on other people's lists and it is used to represent more popular/well-connected stakeholders in the network. Outdegree refers to the number of outgoing ties a focal actor has and is an indicator for involvement or dependence. Betweenness indicates how many times an actor rests on the shortest path between any other two nodes in a network. This measure is indicative of brokering across the network. Harmonic closeness identifies nodes that are connected to the highest proportion of other nodes via multiple steps, calculating the central actors' ability to reach peripheral (not very connected) network members.

These individual-level measures are useful for identifying the relationship between an individual's network position and selected outcomes. For instance, a common approach among the selected articles analyzing the role of seed exchange networks is to measure centrality for each individual in a seed exchange network, and to look for a correlation between the centrality value and the variety of seeds cultivated by network members. Using such approach, Nicholas Kawa et al. (2013) showed that more central individuals (using indegree, outdegree, and betweenness) in manioc exchange networks do not hold the highest diversity of manioc, a result that suggests that such networks can constrain varietal distribution and contribute to low crop diversity in this context. Focusing on ethnomedicinal knowledge, Allison Hopkins (2011) highlighted that individuals with higher indegree in a network of enquiries about herbal remedies tend to hold more knowledge about these remedies, a result that highlights the potential importance of such networks in knowledge diffusion.

The most used intermediate measure is dyadic reciprocity, which is the extent of reciprocated ties within the network. The calculation of the mutual nominations among actors indicates the level of interaction between two pair of nodes. For example, Isabel Díaz-Reviriego et al. 2015 found that connections in the network of medicinal plant material and knowledge exchange were not reciprocal, implying asymmetry and hierarchy. Knowledgeable women were the ones in charge of distributing plant material and knowledge with their kin relatives.

It is important to highlight that recently, some authors (Barbillon et al. 2015; Labeyrie et al. 2016) started to adopt a SNA analytical approach rather than a descriptive one. This approach goes beyond the network and node level measures described above and considers the set of all possible alternative networks weighted on their similarity to an observed network, disambiguating the influence of confounding processes. For example, Labeyrie et al. (2016) use ERGM, a method increasingly used in SNA that specifies the probability of observing the network as a function of various mechanisms, resulting from attributes of nodes and edges and endogenous characteristics of the network.

Egocentric Networks

The articles studying ego networks focus on the individual actor's level and are primarily concerned with seeing how the social environment of chosen informants varies across selected features. By selecting informants (referred to as ego) and documenting the individuals (or things) with which these informants relate (referred to as alters), researchers are able to compare ego-networks across various characteristics. These include the size (that is, the number of alters each informant is personally related to), the density (that is, the extent to which the cited alters share ties with each other), the composition of such networks according to selected alters' characteristics (that is, wealth, age categories, kinship relation with ego), and the intensity of exchange/relation between ego and the alters and between alters (for example, the strength of the relationships, the number of direct ties or one-way exchanges, the number of reciprocal ties, and so on).

Within this approach, the focus is not on the position of individuals in a given structure, but on comparing a sample of informants according to the characteristics of their close social environment. Ruth Haselmair et al. (2014) use such an approach to compare the sources of knowledge related to traditional Tyrolean dishes and to herbal remedies across a sample of Austrian migrants living in Australia, Brazil, and Peru. In their study, they collect information on personal networks related to the transmission of knowledge in these two domains, including both human alters and non-human sources of knowledge (such as books or the internet). By comparing the size and composition of the personal networks of sources of knowledge, they show for instance that in the two domains, individual alters are the most important sources of knowledge compared to other knowledge sources (books, internet).

Thus, we see through these various examples that the social network approach can provide insights on different aspects of material and information flows across human groups. By focusing either on bounded communities or on personal networks, researchers can focus on different types of social interactions.

A Social Network Perspective for What Results?

These works have drawn a large set of outcomes. First, they enabled significant advances in the understanding of the linkages between social connectivity and agrobiodiversity management. The articles included in our sample have indeed furthered the understanding of how plant material exchange networks function, as well as the social and spatial extent of such networks. This may appear as a trivial observation but these insights have been key in revealing and assessing the role that such, frequently informal, exchange systems played in agroecosystems in general. In this regard, the provision of quantitative and systematic data through SNA helped researchers demonstrate the importance of informal seed supply networks (1) in relation with in situ conservation of crop diversity; (2) as a counterpart to commercial, market-driven seed circulation systems; and (3) in relation with contemporary food security and food sovereignty challenges (Demeulenaere 2014; see Pautasso et al. 2013 and Thomas et al. 2015 for a detailed discussion about the importance of farmer seed networks in agriculture).

Studies on networks of plant material exchanges have taken advantage of the high scalability of SNA to explore the intensity and patterns of inter-individual transactions at the micro level (for example, intra-household seed circulation, compare Wencélius et al. 2016), at the village or community level (for example, Kawa et al. 2013; Violon et al. 2016), and up to the landscape level (for example, a Pyrenean valley, compare Calvet-Mir et al. 2012). Their results have fed a rich debate about the role and the impact of such networks and their structure on agrobiodiversity conservation mechanisms. Overall, most of the studies acknowledge the importance of seed exchange networks for in situ agrobiodiversity conservation, since use and conservation are interdependent (for example, Abay et al. 201; Calvet-Mir et al. 2012; Reyes-García et al. 2013). However, the network structure and the position of individuals within these networks have also been shown to negatively influence plant material circulation and accessibility. For instance, as mentioned above, Calvet-Mir et al.'s research (2012) showed that individuals more central in the plant propagule exchange network tended to hold more diverse home gardens. Yet, on the contrary, Kawa et al. (2013) showed that in their case study on manioc cuttings, the structure of the network fostered the reliance of network members on households that were maintaining relatively few varieties as source materials. In this case the network is shown to constrain varietal distribution, and thus to contribute negatively to agrobiodiversity conservation. Partially building on these results, three articles explicitly explore the effect of network structure and topology on plant material circulation through mathematical modeling (Barbillon et al. 2015) or based on empirical data (Labeyrie et al. 2016; Ricciardi et al. 2015; see table 2 for more details).

A second line of research underlying most of these articles explores the linkages between the structure of plant material exchange networks and the social systems in which they are embedded. The aim here is to understand how seed and plant material exchanges are articulated within the complex web of social relations that organize the collective life of any human community and thus how social norms and structures affect the circulation of plant material. For instance, Aden Aw-Hassan et al. (2008) showed that trust is a key factor explaining why individuals exchange barley seeds in their study context, and as such, it needs to draw specific attention from researchers; while Lope-Alzina (2014) shows that exchanges of home garden products occur mainly between kin-related individuals. The importance of considering the sociocultural context, while studying exchange network patterns, is also highlighted by Jean Wencélius et al. (2016), who argue that, in their case study, data collected from a single household member is not satisfactory, since it fails to account for intra-household dynamics of seed transactions, which are directly related to the polygamous marriage system dominant in their study area. Along the same lines, Vincent Ricciardi (2015) discusses the need to understand the extent to which a household acts as a collective entity in seed exchange. These authors maintain that community-based agrobiodiversity management projects could lead to unintended and/or inequitable outcomes if the network measures on which they are based are not crossed with other variables (for example, gender, geographic position, produce trade channels). Other studies already consider the sociocultural context from the very beginning of their research (Ellen and Komáromi 2013; Thomas and Caillon 2016). Mathieu Thomas and Sophie Caillon (2016) base their work on a rich ethnographic background to build three categories of plants according to their biocultural properties (for example, as prestige-related goods), and then separately analyze the exchange networks related to these three categories. Ellen and Komáromi (2013) also base their research on a detailed ethnographic account of home plant exchanges, to show that prevailing social relations seem to play a key role in framing these exchanges, besides other factors such as the reproductive properties of plant species. Standing apart from these works is the study of Labeyrie et al. (2016) that models the probability of tie formation (that is, seed exchange) as a function of the social ascription of the individuals (for example, residence, dialect, demographic characteristics).

The key results of the studies focusing on LEK transmission and circulation gathered in our sample relate globally to the same points. On one hand, some studies explore how the network structure and the individual position within the network have an effect on the knowledge held at the individual level. In these cases, the exchange networks that ground the analysis are either plant material exchange networks (Calvet-Mir et al. 2012; Reyes-García et al. 2013), or herbal remedy inquiry networks (Hopkins 2011). Calvet-Mir et al. (2012) and Reyes-García et al. (2013) focus on exchanges of plant material from home gardens and show that individuals having a central position in these networks tend to hold more agroecological knowledge, as well as crop diversity, than peripheral individuals do. Hopkins (2011), by analyzing the relation between individuals' ethnomedicinal knowledge and their centrality in the network of inquiry about medicinal plants, shows also that more central individuals tend to hold more knowledge, although the correlation remains quite low in this case.

Some very different insights on knowledge transmission are provided by Haselmair et al. (2014), as explained above. In their case study, no structural properties of the networks are explored. Egocentric networks are rather used as a support to trigger the discourse of informants about the various sources (individuals, books, internet) from which they have learned during their entire life, and thus provide a precise overview of the learning process across different life stages.

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Table 2: Overview of the research design and main outcomes of the reviewed articles

Discussion

Our review indicates a growing scholarly use of quantitative SNA as a new method to deal with human-plant relations, based on the increasing popularity of the subject since 2010 and the variety of journals engaging with this theme. The size of our database did not allow any relevant statistical inference to test likely relationships between the types of networks analyzed, SNA measures used, and outcomes reported. However, researchers report positive impressions on the adequacy of using a quantitative SNA approach to study human-plant relations, 14 out of the 18 reviewed articles highlighted strengths associated to the use of

SNA. These findings are in line with the Bodin et al. (2011) and Pautasso et al. (2013) reviews, which point out that SNA is a new and promising tool to study seed exchange networks and natural resource governance and offers considerable potential to bridge the divide between natural and social sciences. However, across this heterogeneous corpus, some important questions are raised related to the use of the social network approach, and are not always explicitly addressed by the authors. These issues relate to two main aspects: the methodology of SNA in itself, and the understanding of networks' dynamics.

Implementing the SNA Methodology

As we saw in this review, all of the research dealing with case studies relies on small samples, which is due to the methodology in itself. Indeed, the right implementation of SNA depends on the collection of well-defined data sets that will be suitable for statistical analyses. The most common data collection methods in SNA are time and resource consumption and this characteristic limits the size and the number of networks that can practically be studied within common fieldwork settings. For instance, to conduct analyses on the structure of the network—which is the case for most of the articles in our sample—researchers need data pertaining to a whole network, that is, a complete set of individuals within chosen boundaries. Studies exploring the structure of large-scale exchange systems are almost impossible to undertake in study contexts where the primary data needs to be collected in the field. Consequently, the only available research dealing with the dynamics of local exchange networks is a collection of case studies relying on small-scale data sets. The ways these case studies are compared and the possible application of observed results in different settings is a sensitive point that requires further reflection.

A related issue is the question of the scale to which SNA can be implemented. A key advantage of the SNA method is its scalability. Theoretically, the statistical analysis of network graphs is not limited by the sample size, and SNA of very large networks (for example, the global Facebook network) are quite common nowadays. However, when SNA is applied to the study of complex social phenomena such as the exchanges of plant material or the transmission of LEK, the network data in itself is not sufficient. To provide a deep understanding of the socio-cultural context in which these networks are embedded, one needs some good ethnographic background data that cannot be collected on a large scale. Thus SNA, when applied to the study of human-plant relations, appears better suited for small-scale, local research. As the articles in our sample show, within this local scale a large range of applications are still possible, from the intra-household level (Wencélius et al. 2016) to the landscape unit level (Calvet-Mir et al. 2012). Acknowledging which scale is the best for analysis is an important aspect to consider when researching these topics, as highlighted by Ricciardi et al. (2015).

Another key point in the implementation of quantitative SNA methods relates to the selection of the type of interactions/exchanges that will be at the center of the analysis. In the case of plant material circulation, this methodological choice is obvious. Researchers normally rely on a name generator procedure, that is, asking to cite all the people with whom they had exchanged (given or received) seeds in their life. However, when SNA is applied to flows of intangible elements, such as information or knowledge, the choice of a reliable name generator that will allow the record of the selected interactions may raise quite difficult problems. It may be neither possible nor relevant to directly ask to the informants about with whom they exchange knowledge on a specific topic. Thus, a solution in these cases is to use a different type of indicator (for example, home garden plant material, as in Reyes-García et al. 2013) as the basis for interaction, which will be related to the knowledge domain under examination (in this case agroecological knowledge). However, this kind of approach relies on specific assumptions (for example, that plant material circulation is related to agroecological knowledge circulation), which must be explicitly stated and taken into account during research.

A last key methodological aspect of quantitative SNA is its potential to fit into interdisciplinary approaches. As it provides a way to formalize the interactions between individuals through quantitative tools, this method appears as a good bridge to link data sets related to individuals (for example, crop diversity in individual farmers' fields, ethnobotanical uses or knowledge) and data sets related to social interactions (that is, social networks) within a single analytical frame. This characteristic partly explains why this method is receiving growing attention in many research fields dealing with human-environment relations in general, such as natural resource management or seed exchange systems.

Understanding Network Structure and Dynamics

A second set of observations relate to a key aspect of social network research, the analysis and the integration into the network structure and dynamics' research frame.

First, the applications of SNA to the study of human-plant relations relate to larger theoretical debates, recurrent in social network research and in social sciences in general, about the interplay between structure and agency (Bourdieu 2000; Emirbayer and Goodwin 1994; Giddens 1987; Granovetter 1985; Ratner 2000). The social network approach relies on the structuralist assumption that the structure of the relations affects and constrains individual actions. In this regard, some key issues are to understand to what extent the structure of the network actually influences individuals' behaviors; and vice versa, to what extent individuals influence the network's structure, by choosing with whom they interact, given the local constraints that frame exchanges (Knoke 1990; Stevenson and Greenberg 2000). Complex relations exist between the context, the actors, their knowledge and perceptions, the network structure and dynamics. From our review, we can notice that this aspect is largely overlooked. Despite the fact that all of the studies rely on ethnographic data (to contextualize the study, understand the patterns of exchange and the types of plant material, and/or knowledge that flows through networks), the social processes that may be involved in shaping the exchange networks are partly overlooked (see exceptions in Ellen and Komáromi 2013; Labeyrie et al. 2016; Thomas and Caillon 2016). We suggest that this is due to the research objectives of most of the studies we reviewed. In these, the exchange networks are given a causal explanatory role in relation with selected outcomes (that is, agrobiodiversity, knowledge), so the main focus is on how the networks affect these outcomes, and not on the background processes that potentially explain network formation and the observed exchange patterns. As several authors in our review highlight (for example, Hopkins 2011; Ricciardi 2015), further research is needed to better include social relationships and interactions (such as kinship and acquaintanceship, mutual obligations, preferential exchanges, and power relations) in the analyses, and to understand the interplay between network structure and social processes. Notwithstanding, recent articles (Barbillon et al. 2015; Labeyrie et al. 2016) already take into account the mutual relation between network structure and social processes through mathematical modeling, transcending this shortcoming and opening a field that should be further investigated.

Another relevant question relates to the ability of the social network approach to capture the dynamic dimension (that is, network change over time) of the systems of relations under study. Although throughout the corpus, researchers acknowledge the dynamic dimension of exchanges and interactions, most of them do not take into account this dimension in depth. Hence, there is a paradox within many studies making use of SNA: while aiming at studying the dynamics of exchanges and transmission, they are limited by the highly detailed data sets that are required to conduct these analyses. Thus, most of the studies focus on a one-time step or a short time-span, providing a "snapshot" of interactions in a rather static way, and do not provide a diachronical/longitudinal perspective that would allow a real understanding of the dynamics of the system. Some articles, however, overcome this limit, by either collecting data pertaining to the whole life cycle of informants or by repeating their survey over time. Haselmair et al. (2014) asked their informants to name all the sources of knowledge that they have been dealing with during their entire lives, and Ellen and Komáromi (2013) asked about the origin of all potted plants present in the house at the time of the interviews. Despite being faced with the recall bias limit (Bernard et al. 1984), these approaches provide a good understanding of the interactions' evolution during a given time period. Poudel et al. (2015), by repeating their survey on exchanges of rice varieties over three different years, are able to produce an original and very detailed understanding of the dynamics of varieties exchange, showing for instance that some key individuals keep a central position in these networks across the years. Along the same lines, Violon et al. (2016), by repeating their survey over two consecutive years, provide some key findings on the temporal evolution of local seed supply networks in changing climatic conditions. Thus, these research designs show that the limits imposed by the social network approach can be overcome, and we call for future research to integrate a diachronical perspective on these complex interaction patterns.

Conclusion

We conclude by highlighting some theoretical and policy implications of our review. At a theoretical level, our study emphasizes the necessity to go beyond descriptive approaches of SNA and incorporate analytical ones. Future research should take into account the social reality and spatial dimension of social networks and try to overcome the main methodological caveats identified (that is, the importance of associating social network data with extended qualitative data enabling a good understanding of the processes underlying network structure and dynamics, and the importance of extending the longitudinal perspective on social networks through time). In order to do so, it is of paramount importance to build interdisciplinary teams that combine methods from different fields (for example, anthropology, ecology, mathematics), as already pointed out by Pautasso et al. 2013. Our study also has policy implications; SNA has been proven to be a useful tool in providing data in interdisciplinary and applied contexts assessing and planning resource management. For example, the insights provided by the works using the social network approach to study plant material circulation in agricultural contexts are of great interest to agrobiodiversity management and conservation and thus to the crucial challenges of food security and food sovereignty (Almekinders et al. 1994; Pautasso et al. 2013; Thomas et al. 2012; 2015). Policies that aim at sustaining agrobiodiversity conservation, enhancing food security and sovereignty, and maintaining LEK should be aware of the social and biological processes weaving human-plant relations disentangled by SNA.

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Authors	Year	Journal	Location	Research theme
Abay et al.	2011	*Plant Genetic Resources*	Ethiopia	Germplasm exchange—agricultural crop (barley varieties)
Aw-Hassan et al.	2008	*Experimental Agriculture*	Syria	Germplasm exchange—agricultural crop (barley varieties)
Barbillon et al.	2015	*Journal of Theoretical Biology*	France	Germplasm exchange—agricultural crop (modeling, wheat varieties)
Calvet-Mir et al.	2012	*Ecology and Society*	Spain	Germplasm exchange and agroecological knowledge—home gardens crops
Díaz-Reviriego et al.	2015	*Ecology and Society*	Bolivia	Germplasm exchange and medicinal knowledge—medicinal plants
Ellen and Komáromi	2013	*Anthropology Today*	United Kingdom	Germplasm exchange—house potted plants
Haselmair and Pirker et al.	2014	*Journal of Ethnobiology and Ethnomedicine*	Australia, Brazil, Peru	Knowledge transmission—traditional Tyrolean dishes and medicinal plants
Hopkins	2011	*Field Methods*	Mexico	Knowledge transmission—medicinal plants
Kawa et al.	2013	*Current Anthropology*	Brazil	Germplasm exchange and knowledge transmission—agricultural crop

				(manioc varieties)
Labeyrie et al.	2016	*PNAS*	Kenya	Germplasm exchange—agricultural crop (sorghum varieties)
Lope-Alzina	2014	*Gaia Scientia*	Mexico	Food products exchange—home garden crops
Poudel et al.	2015	*International Journal of Biodiversity*	Nepal	Germplasm exchange—agricultural crop (rice varieties)
Reyes-García et al.	2013	*Journal of Ethnobiology and Ethnomedicine*	Spain	Germplasm exchange and agroecological knowledge—home garden crops
Ricciardi	2015	*Agricultural Systems*	Ghana	Germplasm exchange—agricultural and home garden crops
Subedi et al.	2003	*Culture and Agriculture*	Nepal	Germplasm exchange—agricultural crop (rice varieties)
Thomas and Caillon	2016	*Ecology and Society*	Vanuatu	Germplasm exchange—cultivated plants
Violon et al.	2016	*Ecology and Society*	Cameroon	Germplasm exchange—cultivated plants (species and landraces)
Wencélius et al.	2016	*Ecology and Society*	Cameroon	Germplasm exchange—cultivated plants (species and landraces)

Article	Objectives	Type of network	SNA measures	Outcomes
Abay et al. 2011	Characterize the barley seed exchange networks	Socio-centric	Node level: degree, betweenness, harmonic closeness	Identification of the farmers' role in seed exchange, that will help develop more effective conservation, breeding, or seed interventions
Aw-Hassan et al. 2008	Determine the extent of diffusion of new barley varieties through farmer-to-farmer seed exchange	Socio-centric	Network level: general structure	Existence of an active local seed system functioning through informal networks and built on trust and reputation for access to knowledge and new seeds. Effectiveness of the informal seed system in the dissemination of new varieties
Barbillon et al. 2015	Investigate the role of the network topology in a dynamic extinction-colonization model comparing different scenarios of social organization and attesting their effects on the persistence of one crop variety, based on different studies of the Réseau Semences Paysannes (RSP), a French farmers' organization	Socio-centric	Simulation of five network models with fixed (size of the network and number of edges) and changing (topology) parameters	The number of edges was the most important feature of the network. The topology (distribution of the edges) impact was less important but not negligible and its impact depended on the other parameters (extinction rate e, colonization rate c, and number of edges). If the relevant parameters led to a probable extinction, networks with high degree nodes (PA) were more resistant than networks with balanced degrees (LAT, ER, or COM). Conversely, if persistence was quite certain, more patches were occupied in balanced networks than in the PA networks
Calvet-Mir et al. 2012	Assess the structure of seed exchange network and estimate the association between an individual's centrality and (1) landrace in situ conservation and (2) landrace knowledge	Socio-centric	Network level: size, number of components, density, centrality Node level: indegree, ego betweenness	Seed exchange network is active but fragmented, decentralized, and has a low density of exchanges. Individual centrality in the network of seed exchange is positively associated with local landrace conservation and knowledge
Díaz-Reviriego et al. 2015	Assess the influence that knowledge and plant material exchange through social networks has on medicinal plant diversity in Tsimane' home gardens	Socio-centric	Network level: size, density, centrality Node level: degree, betweenness, ego betweenness Intermediate level: reciprocity	Tsimane' social organization, specifically kinship and gender relations influence exchange patterns significantly. People who are more central in the network maintained greater medicinal plant knowledge and total plant richness in their home gardens
Ellen and Komáromi 2013	Analyze how houseplant circulation is related to social exchanges and to reproductive features of particular species, and how these affect the dissemination	Egocentric	Ego-net level: size, number and types of edges (directed or reciprocal)	Prevailing social relations seem to affect plant exchanges. The reproductive characteristics of plants seem to affect their circulation. The patterns of potted houseplants

	and selection of culturally useful biological material			circulation are different from home garden plants
Haselmair et al. 2014	Explore the transmission and the sources of knowledge about food and medicinal plants among Tyroleans who immigrated to Australia, Brazil, and Peru	Egocentric	Ego-net level: size, density and composition	Knowledge of both food and medicinal plants is mainly transmitted during childhood by human alters, however specific patterns are found depending on the country
Hopkins 2011	Explore the potential association between the position of people in herbal remedy inquiry network, and herbal remedies knowledge	Socio-centric	Node level: indegree, outdegree, betweenness	Weak but positive association between competence scores in herbal remedies and network centrality scores. But this association disappears when age is introduced in the model, showing that older people tend to hold more knowledge and be more central in the networks
Kawa et al. 2013	Assess if the position of a household in the manioc exchange network is positively correlated with the number of manioc varieties managed and the manioc agricultural knowledge	Socio-centric	Node level: indegree, outdegree, betweenness	The centrality of households in the exchange networks had no significant correlation with the number of manioc varieties maintained by households. However, household centrality did show a significant correlation with households' perceived knowledge of manioc cultivation as well as the total area of manioc cultivated
Labeyrie et al. 2016	Use ERGM (exponential random graph models) to test whether homophily among members of same residence, dialect, and ethnolinguistic groups have shaped sorghum seed exchange networks	Socio-centric	Network level: size, density Use of ERGM to assess the influence of homophily on the structure of the networks by modeling the probability of tie formation as a function of the social membership of the individuals	The results of ERGM confirmed that residential homophily and ethnolinguistic homophily have shaped sorghum seed exchange networks. It means that geographic proximity among farmers and farmers who pertain to the same ethnolinguistic group have a higher propensity for seed exchanges
Lope-Alzina 2014	Analyze the food products exchange network	Socio-centric	Network level: clustering coefficient Node level: indegree, outdegree, betweenness	The most exchanged products were generated in home gardens (52.4 percent of all transactions). People tend to give and receive gifts within a kinship network
Poudel et al. 2015	Investigate whether the social seed networks and key members are stable over the years and examine the role of the social networks and the farmers in provision of seeds across the members of the community	Socio-centric	Node level: degree, betweenness, flow betweenness	Network members were more stable than the individual nodal farmers suggesting the importance of a large network with many subnetworks for on-farm conservation

Reyes-García et al. 2013	Assess the structure of plant propagation material exchange networks and assess the association between a gardeners centrality in such networks and their agroecological knowledge	Socio-centric	Network level: size, number of components, density, centrality Node level: weighted degree, brokerage	Networks with low densities, highly fragmented and low centralization. Gardeners who connect more pairs of otherwise unconnected gardeners (that is, brokers) have higher agroecological knowledge
Ricciardi 2015	Examine if improved seed distribution will lead to more equitable farmer access by identifying central farmers with high diffusive capabilities	Socio-centric	Node level: harmonic closeness	Harmonic closeness centrality can best be estimated per study community, but results were not constant after combining communities. Harmonic closeness centrality offers a method to explain which types of farmers have the most efficient seed distribution position in a given network. The results offer warning on using network parameters for equitable (re)introduction of open-pollinated varieties
Subedi et al. 2003	Explore and examine the informal flow of genetic materials, identify nodal farmers, and understand the dynamic processes of an informal system of crop diversity management	Socio-centric	Network level: structure (network mapping done manually)	Farmer's seed system influenced by the informal flow of genetic materials, which largely contribute to creating diversity on-farm. Community members have networks of affiliations that influence the management of crop diversity. Certain members of the community (nodal farmers) play a key role in the maintenance of crop diversity
Thomas and Caillon 2016	To assess if plant circulation is driven in part by farmers' quest to accumulate social prestige, and to assess if plants with different biocultural properties do not follow the same patterns of circulation	Socio-centric	Network level: size, density Node level: indegree, outdegree Intermediate level: dyadic reciprocity, triadic transitivity, triadic cycling	Social prestige seems to play a role in structuring plant circulation networks, conferring prestige to the biggest givers (high outdegree) and reinforces hierarchy. Influence of the farmer's social status is important for plants to which high cultural value is ascribed, and negligible for plants of low cultural value.
Violon et al. 2016	To understand to what extent climatic variability influences the transaction patterns within the same seed system	Socio-centric	Network level: size, density	The climatic shocks the Tupuri farmers had to face in 2011 (that is, late beginning of rains) did not lead to a dramatic change of their strategies in terms of crop choice and seed acquisitions. A significant geographic expansion of the network beyond the villages was observed during the climatically bad year. Women were responsible for dealing with emergency situations requesting seeds from kinship and uterine relationships

Wencélius et al. 2016	To explore the biases that would have been induced if households were chosen as the network nodes alone or if household heads were interviewed alone. To analyze the effects of farmers' attributes on characteristics of the network.	Socio-centric	Network level: size, number of components, density Node level: indegree, weighted indegree	Inferring household-level behaviors with data collected from a single household member is not satisfactory. Wealth is a structuring factor of the local seed circulation network, wealthy households benefit from a more diverse set of seed sources due to greater number of co-residents and intra-household dynamics of seed transactions