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# Chapitre 4. Etudes des interactions entre les sociétés et l'environnement : l'analyse des réseaux comme méthode pour faire le lien entre sciences biologiques et sociales

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# Network Analysis: Linking Social and Ecological Dynamics

## 4.1 Introduction

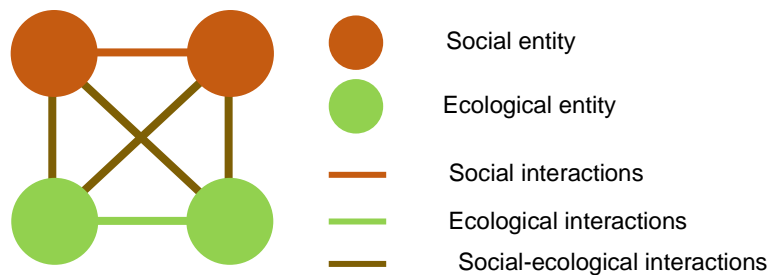
This chapter is intended for researchers and students involved in interdisciplinary research on interactions between societies and the environment. Network analysis methods have been used for several decades by some disciplines (sociology and physics), and are undergoing rapid developments in others (geography, anthropology, and ecology). They are also raising a growing interest in interdisciplinary research, such as the study of socio-ecological systems. Indeed, these methods open new perspectives for understanding the processes involved in the structure and dynamics of these systems, as well as their emerging properties. They also constitute integrative tools that facilitate collaboration between the humanities and social and life sciences, since the same formalisms and theoretical frameworks apply to the analysis of interaction networks, whether to describe social, ecological or socio-ecological processes.

However, network analysis methods remain relatively complex to implement, both for field data collection and analysis, and results interpretation can be difficult. Thus the use of these quantitative methods, that allow the analysis of the structural characteristics of networks, implies reflecting beforehand on their articulation with qualitative approaches. Such reflection will ease the elaboration of clear hypotheses that the network analysis would test, as it will help to explain the results of quantitative analyses, in particular by specifying the nature of the interactions and by contextualizing them in the more global systems of interactions, between individuals within social groups, between individuals and their environment, or between components of the environment.

The objective of this chapter is to introduce the basic principles of network analysis and to provide an overview of the main types of questions that can be answered in the field of ecological and social systems studies. It aims at enabling the readers to identify whether these analyses are relevant in regard with their research questions, and to think about their complementarity with methods and tools from both the biological sciences and the human and social sciences. Case studies are mostly drawn from the work of the MIRES scientific network (*Méthodes interdisciplinaires sur les réseaux d'échange de semences - Interdisciplinary methods on seed exchange networks*).

### 4.1.1 Societies-environment interactions, what complex systems?

Given the complexity of environmental problems, the development of interdisciplinary approaches has become necessary, giving rise to a field of study focusing on socio-ecological systems (SES, Berkes and Folke 1998). These approaches conceptualize the interactions between societies and their environment by defining social and ecological systems as a set of actors whose living conditions depend on the functioning of ecosystems, which they influence through their practices. SES are therefore coupled systems of social and ecological interactions that can be represented as networks (Figure 4.1): (i) actors are embedded in networks of social, economic, or political relationships that influence their practices; (ii) they interact with the different entities that make up ecosystems *via* these practices; and (iii) the different entities that make up ecosystems interact with each other (Bodin and Tengö 2012). All interactions between actors, between actors and components of ecosystems, and between components of ecosystems, constitute a social-ecological system.



**Figure 4.1.** *Network of coupled social and ecological interactions*  
(according to (Bodin and Tengö, 2012))

These coupled networks of social and ecological interactions have the characteristics of complex systems. Indeed, the emergence and the dynamics of links within these networks result from self-organization processes, themselves resulting from the interactions at work between the components of the system under consideration. These socio-ecological networks have emerging properties related to the structure of interactions, which cannot be deduced from the individual properties of the concerned entities themselves because of the large number of interactions between them (“the whole is more than the sum of the parts”). As a result, the behavior of these systems is non-linear and their empirical study, by observation and experimentation or simulation, requires modelling tools that explicitly take into account the interactions between entities. It is in this perspective that analytical methods based on network models, derived from graph theory, have been applied to the study of socio-ecological systems (Janssen *et al.* 2006). These methods explicitly take into account the interactions between entities and are therefore suitable tools for analyzing complex systems. They reduce complexity by highlighting regularities, repeated patterns of connectivity between entities, which reflect the processes involved in the functioning of the SES and determine its properties (Bodin *et al.* 2006; Bodin and Crona 2009; Bodin and Tengö 2012). These approaches make it possible to address two main categories of questions related to the study of socio-ecological systems:

- what are the processes involved in the emergence and dynamics of the structure of coupled networks of social and ecological interactions?
- how, in turn, do the structure of these networks determine the functioning of socio-ecological systems?

#### **4.1.2 Introduction to network formalism**

Network formalism represents entities as nodes and interactions as links. A set of attributes (or descriptors) can be associated with nodes and links. In particular, links can be directed according to the direction of interaction between the two entities. The structure of the network constitutes a kind of footprint of the social and ecological processes involved in the system under study. By analyzing this structure, it is thus possible to highlight the processes involved and to quantify their effects. Various methods exist for this ; we will only describe some of them in the examples below. Before that, we will review the main categories of approaches according to the scale of analysis of the network structure.

Structural analysis makes it possible to infer the processes involved in network formation and their dynamics according to the theory of social network analysis, which distinguishes two main types of processes (Lusher and Robins 2012): i) endogenous, self-organizing processes, linked to so-called “dependent” factors, i.e. those that depend on the position of the node within the network; and ii) exogenous processes, determined by so-called independent factors, linked to the intrinsic characteristics or attributes of the nodes and links, and that do not depend on their position within the network. These two types of processes interact in the emergence and evolution of the network structure. For example, a link may be formed between two people because they have a common friend (endogenous process of transitivity), or because they speak the same language (exogenous process of homophily), or because of the combined effect of these two factors.

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#### 4.1.2.1. *Endogenous processes*

The analysis of structural patterns at different levels, from the node to the entire network, allows the detection of different types of endogenous processes potentially shaping the network structure. The level at which the structural patterns will be analyzed has to be defined in relation with the questions addressed.

A first category of questions concerns the so-called local structural patterns. At the node level (which is the basic component of a network), a common question that arises is to know whether some actors have more relationships than others. The metric to measure this is the degree, i.e. the number of links a node has (Figure 4.2). It is then possible to specify whether nodes with a high degree are more popular than others, i.e. whether a large number of nodes make connections with them (high incoming degree), or whether they are more active, i.e. they establish connections with a large number of nodes (high outgoing degree).

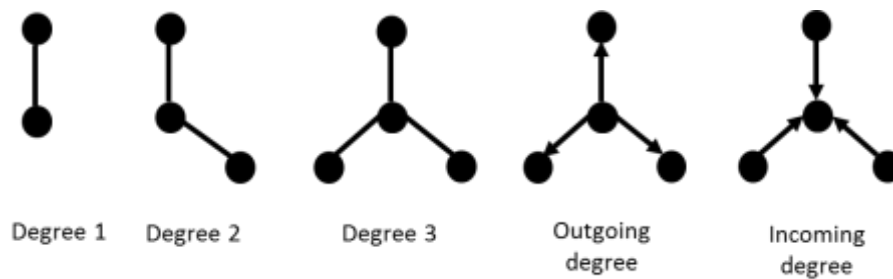


Figure 4.2. *Degree*

Other types of questions require examining the connectivity patterns between several nodes, particularly if we want to test whether the relationships between pairs of nodes (dyads) tend to be reciprocal, or whether indirect reciprocity mechanisms are at play, that would then be reflected by the patterns of cyclical triads (Figure 4.3). On the contrary, it is possible to test whether hierarchical mechanisms structure the networks, which translates into patterns of transitive triads. In this case, a node A linking to a node B will never receive a link directly established by node B, nor indirectly established by a node C to which node B has established a link. To test whether these processes have a significant effect on the network structure, statistical methods can be used to compare the observed frequency distribution for the different types of patterns with a random distribution, to test whether the links were established at random between the nodes.

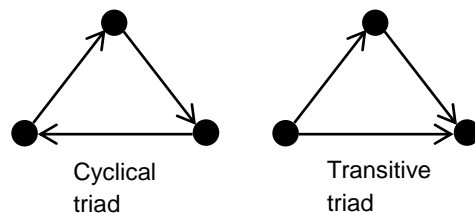
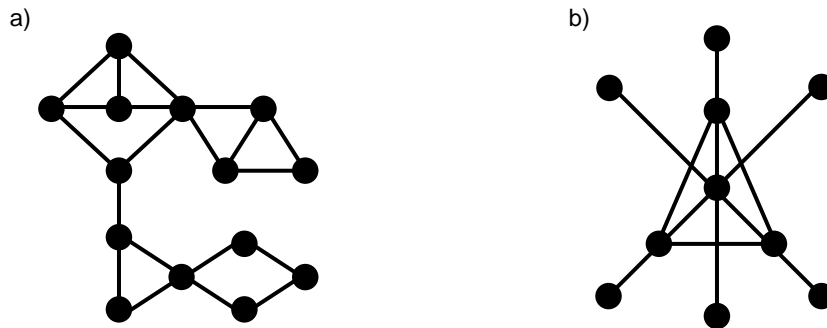


Figure 4.3. *Triads*

A second category of questions requires the analysis of macroscopic structures in networks. Connectivity patterns between nodes are then examined globally, seeking groups of nodes with similar connectivity patterns, connecting in a similar way to other nodes or to each other. This is the case, for example, when we

wish to identify communities, i.e. groups of nodes that have more interactions with each other than with other parts of the network. These communities are generally connected by “weak links” that act as bridges or brokers, resulting in macrostructures of the “structural holes” type (Figure 4.4a). It is also possible to highlight the existence of a central group of highly interconnected nodes to which poorly connected nodes are linked, resulting in core-periphery structures (Figure 4.4b).



**Figure 4.4.** a) *Communities and structural hole.* b) *Core-periphery structure*

Finally, the last category of questions requires the measurement of metrics at the scale of the network as a whole. Different metrics can be used to characterize network cohesion, the most commonly used being density, i.e. the ratio of the number of links in the studied network to the number of links that a complete graph with the same number of nodes would have.

#### 4.1.2.2. *Exogenous processes*

Exogenous processes are driven by nodes and links attributes, by opposition with the structure of the network in itself. In the case of node characteristics, for example, we can try to show the existence of homophily processes by testing whether individuals speaking the same language are more likely to interact with each other than with individuals speaking another language. We then examine the frequency distribution of the pairs of connected individuals (dyads) speaking the same language, compared to the one expected under the random (null) hypothesis. These may also be relationship characteristics, for example, testing whether relatives are more likely to interact with each other than those who do not.

The following sections present some illustrations of the methods that can be used to analyze the structure of networks and test the effect of endogenous and exogenous processes. These examples deal with networks of social interactions within socio-ecological systems, that determine the circulation of biological objects and ecological knowledge. They mobilize a range of in social networks analysis methods (Wasserman and Faust 1994; Degenne and Forsé 1999).

## 4.2 Examples of applications to the study of interactions between societies and the environment

Social interactions between actors affect ecosystem dynamics *via* their role in the circulation of biological resources and of the knowledge associated with their management. The application of network analysis methods to the study of these two main types of mechanisms will be illustrated by three case studies whose results have been published and analyzed in the articles by Thomas and Caillon (2016), Labeyrie *et al* (2016), and Salpeteur *et al* (2016). Our objective is to illustrate the type of research questions that network analysis can address in this area, and to synthesize the methods used to answer them.

The first two examples illustrate how social interactions guide the circulation of tangible objects that are associated with ecological flows: for example, the circulation of seeds of cultivated plants, domestic animals, and associated pathogens (Thomas and Caillon 2016; Labeyrie *et al.* 2016). The second example shows that

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these interactions are also decisive in the circulation of intangible objects, i.e. the knowledge and know-how associated with the use and management of the environment (Salpeteur *et al.* 2016).

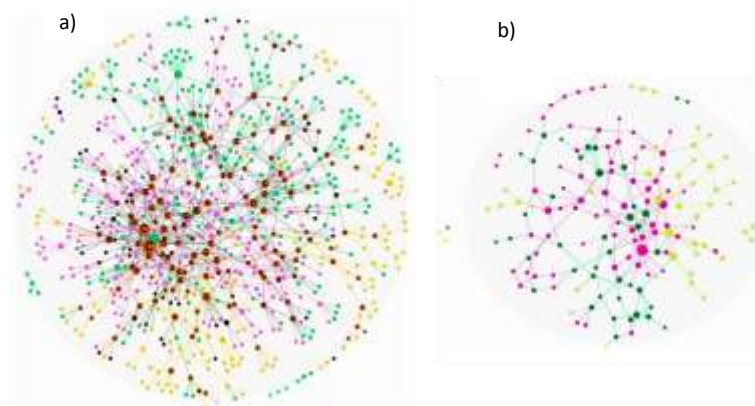
#### 4.2.1. Crop seed circulation and social networks

Seed circulation networks play a key role in the dynamics of crop diversity (Coomes *et al.* 2015). These networks, shaped by different social processes, are based on particular on various types of pre-existing relationships between individuals. The two case studies presented illustrate this relationship between the organization of societies and the circulation of cultivated plants in two geographical areas, Kenya and Vanuatu.

##### 4.2.1.1. Sorghum seed circulation and ethnolinguistic organization in Kenya

Population genetic studies at various spatial scales, ranging from the African continent to a village, have shown a relationship between the geographical structure of sorghum's genetic diversity and that of the ethnolinguistic diversity of farmer populations (Harlan and Stemler 1976; Labeyrie *et al.* 2014; Westengen *et al.* 2014). The hypothesis that seed circulation is more intense within ethnolinguistic groups than between groups has been proposed to explain this relationship, which would limit gene flows between the sorghum populations they grow and thus favor their differentiation. In this context, network analysis was mobilized to test whether ethnolinguistic homophily structures seed circulation networks connecting farmers in African rural societies, i.e. whether seed gifts and exchanges are more frequent between members of the same ethnolinguistic group than randomly (Labeyrie *et al.* 2016).

To test this hypothesis, we conducted our study in a village located in a contact zone between three language groups belonging to two ethnolinguistic units in the Mount Kenya region. Surveys were conducted among 197 households to document sorghum seed circulation events, representing about two thirds of the households in this area. This has allowed us to build the seed circulation network between individuals (Figure 4.5). The chosen network analysis methods require working on a closed network, thus excluding households that had no ties with other households surveyed. The analysis therefore focused on a subsample of 156 nodes and 235 non-oriented ties (“A and B exchanged seeds”), representing only 28% of the total ties reported in the surveys.



**Figure 4.5.** a) Global open seed circulation network (197 nodes, 1,067 links; nodes kept for the closed network in red). b) Closed sub-network (156 nodes, 235 links)

The statistical analyses were designed to test whether intra-group links – within (i) residential; (ii) language; and (iii) ethnolinguistics groups – were more likely than randomly expected. We also controlled the effect of geographical distance, by testing whether relationships were more likely between geographically close households. The effect of three endogenous processes was also tested: (i) popularity, i.e. the probability of a link between two nodes increases with the number of links they already have; (ii) transitivity, i.e. the probability of a link between two nodes increases when they are connected to the same node; (iii) the group's activity, i.e. the propensity of a node to establish links increases with the number of links established by the ethnolinguistic group to which it belongs. The non-parametric statistical methods used (Exponential Random Graph Models, Robins *et al.* 2007) test the effect of these different factors by comparing the value of the observed statistics, i.e. the frequency of the patterns, with expected under the null hypothesis, i.e. if relationships between individuals were established randomly.

The results obtained (Table 4.1) show that the effect of residential homophily is significant, and that linguistic homophily is observed only for one of the groups (the Mbeere), but not for the other two who belong to the same ethnolinguistic unit (the Chuka and the Tharaka). Farmers are therefore more likely to exchange with people belonging to the same residential and ethnolinguistic unit, but exchanges are not limited between language groups belonging to the same ethnolinguistic unit. There is also a significant effect of geographical distance, with the probability of a link being formed between two people being positively correlated with their geographical proximity. In addition, the Mbeere group has a lower activity than the other two language groups, i.e. a lower probability of making connections. And finally, the results show a significant effect of activity and transitivity, which are endogenous processes frequently observed in social networks (Lusher and Robins 2012).

Effect	Estimation
<b>Link</b>	– 4.71 (0.53)***
<b>Residential homophily</b>	0.81 (0.15)***
<b>Linguistic homophily (Mbeere)</b>	1.84 (0.43)***
<b>Linguistic homophily (Chuka)</b>	– 0.68 (0.42)
<b>Linguistic homophily (Tharaka)</b>	0.75 (0.42)
<i>Exogenous covariates:</i>	
<b>Geographical distance (km)</b>	– 0.99 (0.10)***
<b>Language group activity (Chuka)</b>	1.04 (0.35) **
<b>Language group activity (Tharaka)</b>	0.61 (0.25)*
<i>Endogenous covariates:</i>	
<b>Individual activity</b>	4.77 (1.82)**
<b>Transitivity</b>	0.72 (0.11)***
<b>Multiple connectivity</b>	– 0.01 (0.04)

**Table 4.1.** Results of the ERGM Model. The parameter estimate is expressed in log odds and the standard deviation is indicated in brackets: \* $P < 0.05$ ; \*\* $P < 0.01$ ; \*\*\* $P < 0.001$

The interpretation of these results required the use of ethnographic literature and further investigation to understand the social norms that regulate seed gifts between individuals and lead to the observed structure. Our surveys showed that the vast majority of seed gift events takes place between relatives (72%), particularly between women and their in-laws (45%). The ethnographic literature describing the rules of alliance and residence among these societies throw light on these results. These studies show that marriage alliances are concluded mainly between individuals from the same ethnolinguistic unit (ethnolinguistic endogamy), which was confirmed by our surveys (Table 4.2), and that women generally come from residential units far from their husbands' (residential exogamy) and settle in the latter's residential unit (virilocal residence), now



becoming full members of their in-laws kin groups. The social proximity of women to their in-laws therefore explains residential homophily, while the absence of matrimonial alliances between ethnolinguistic units explains homophily on this scale.

Language group	Chuka	Tharaka	Mbeere
Chuka	21 (20)	18 (26)	2 (15)
Tharaka		29 (34)	3 (20)
Mbeere			21 (12)

**Table 4.2.** Number of observed matrimonial alliances between language groups, and theoretical number expected under the null hypothesis, i.e. if the alliances were randomly established between individuals (in brackets).  $\chi^2$  test = 88.20, *ddl* = 4, *P*-value < 0.001.

This example therefore provides a good illustration of how network analysis can be used as a tool for interdisciplinary dialogue, making it possible, in this case, to decipher the social processes involved in the circulation of biological objects- seeds -, and thus to help explaining the distribution of sorghum genetic diversity in the studied area. Population genetics, by revealing a correspondence between the distribution of sorghum genetic diversity and the distribution of ethno-linguistic diversity of human populations in the studied area (Labeyrie *et al.* 2014) and on the African continent (Westengen *et al.* 2014), highlighted the interest of using network analysis to test the effect of ethnolinguistic organization on seed circulation. At a second stage, the interpretation of these results required a more detailed understanding of the social relationships underlying seed exchanges, and therefore to make use of extensive ethnographic information regarding matrimonial alliance and residency rules. Conversely, information about the effect of social norms on seed circulation has been used in further research to inform network models simulating the dynamics of cultivated diversity under different scenarios (Barbillon *et al.* 2015).

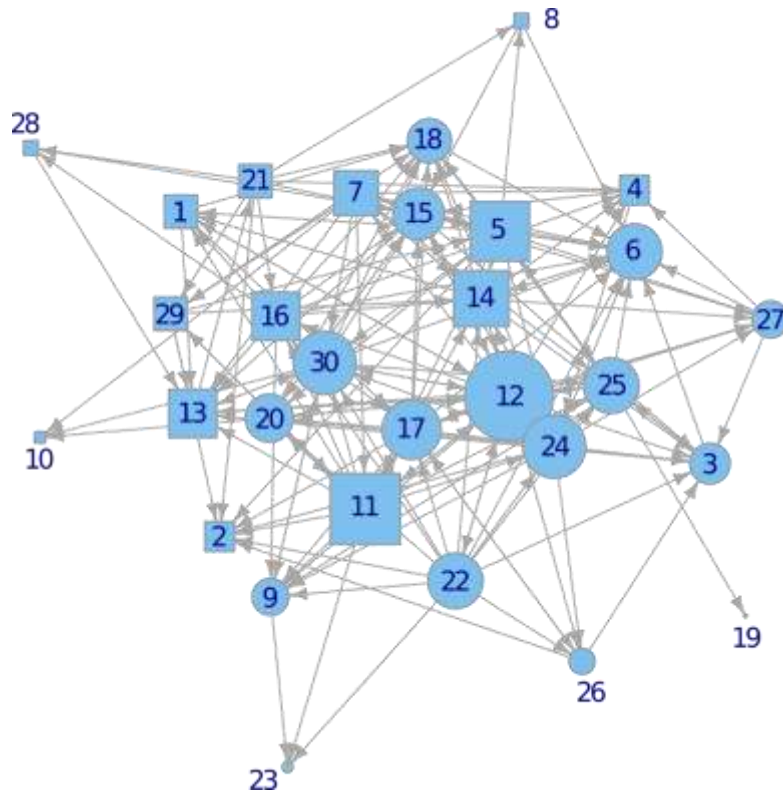
#### 4.2.1.2. Circulation of different categories of crops in Vanuatu

Ritualized exchanges of high-value objects have been widely studied by anthropologists in Oceania. They show, among other things, that the major ceremonies organized by individuals of high social status, the *Big Men*, were based on a multitude of exchanges of ritual objects and socially valued food plants. These *Big Men* won their title by virtue of the generosity with which they redistributed their wealth, especially during these final ceremonies. Although the *Big Men* no longer exist in Vanuatu today, our study aimed to test whether these hierarchical systems have left their mark on the circulation of the most commonly traded objects, i.e. food plants (Thomas and Caillon 2016). Network analysis was used in this case to characterize food plant circulation networks, and in particular to test the existence of individuals more active than the average in exchanges.

These plants do not have the same socio-cultural value, being classified locally into three categories: (1) subsistence species - mainly starchy tubers ; (2) accompanying species consumed with the previous ones at mealtimes; and (3) species that are usually snacked outside meals such as fruits and nuts. These three categories hold different statuses, subsistence species being culturally more valued than others. A secondary objective of this study was therefore to compare the circulation networks of these plant categories, in order to compare their structure.

To test these hypotheses, a field study was carried out in a 10-km zone along the coast on the island of Vanua Lava in the Banks region, north of the Vanuatu archipelago. Surveys to identify events in the circulation

of plant material of all cultivated plants – 31 species divided into 254 varieties – were conducted among 16 households, on a total of 30 adults who migrated from the neighboring island of Mota Lava. In the case of plants and of people, the investigators opted for an exhaustive approach: the interviews aimed to understand how these 30 first-generation migrants found each of the food plant varieties on this coast for the first time: who received the plant in the household and who gave them the plant. The circulation network of all the cultivated plants reconstituted this way included 2,049 oriented links (“A gave plants to B”), but only 577 of these links were retained for the ERGM analysis, which required the removal of links established outside the study area (Figure 4.6).



**Figure 4.6.** Closed seed circulation network (30 nodes and 577 links). Round knots represent women and squares represent men

The statistical analyses were designed to test: (i) whether some individuals give more or receive more than expected under the random assumption, measured by the frequency distribution of outgoing and incoming degrees, and (ii) whether individuals who give more receive less, measured by the correlation between incoming and outgoing degrees. The effect of exogenous and endogenous processes was also monitored.

Regarding exogenous factors, we tested: i) whether relationships are more likely between people of the same gender (homophily), and ii) whether relationships are more likely between people with a similar number of connections outside the community (degree of incoming external links).

Regarding endogenous factors, we controlled the effect of direct (number of reciprocal dyads) and indirect (frequency of circular triads) reciprocity, and hierarchy (frequency of transitive triads). These analyses were carried out using ERGM (*Exponential Random Graph Models*) models, applied to the global network (aggregated) and to the three sub-networks corresponding to the three categories of cultivated plants.

The results obtained (Table 4.3) show that the *Big Men's* hierarchical exchange systems are still reflected in the way food plants circulate, even if the gifts are not ritualized. Indeed, they highlight the existence of

individuals giving more than the average (the frequency distribution of outgoing degrees differs significantly from that expected if interactions were random), and receiving few cultivated plants from other inhabitants (no correlation between incoming and outgoing degrees).

On the other hand, the effect of direct and indirect reciprocity is not significant, but the study of such processes would require analyzing how crop circulation networks fit into society's overall exchange system, and thus documenting the circulation networks of other types of material goods, services or knowledge.

In addition, the comparison of the circulation networks of the three categories of cultivated plants shows that the circulation of the most culturally valued plants, i.e. subsistence crop, is governed by stricter exchange rules than the other categories.

Circulation network					
	Effects	Aggregated	<i>Starchy foods</i>	<i>Accompaniment</i>	Snack bar
Endogenous factors	Arc	- 3.519(1.075)*	- 4.522(0.874)*	- 3.506(0.752)*	- 4.821(0.664)*
	Reciprocity	- 0.392(0.377)	- 0.146(0.41)	- 3.517(14.928)	- 0.703(1.084)
	Incoming degree	0.342(0.403)	0.613(0.343)	- 0.537(0.503)	0.624(0.335)
	Outgoing degree	0.774(0.323)*	0.999(0.301)*	1.076(0.311)*	0.507(0.361)
	Transitive Triads (ATT)	0.286(0.166)	0.237(0.173)	0.156(0.658)	0.057(0.356)
	Cyclic Triads (ATC)	0.113(0.084)	0.034(0.102)	- 1.841(7.48)	- 0.253(0.354)
	Alternative path with 2 links (A2P)	- 0.195(0.049)*	- 0.132(0.057)*	- 0.03(0.167)	- 0.004(0.104)
Exogenous factors	Degree of incoming external links from senders	0.01(0.003)*	0.013(0.003)*	0.096(0.042)*	0.079(0.026)*
	Degree of incoming external links from recipients	0.006(0.003)*	0.009(0.004)*	- 0.087(0.053)	0.027(0.022)
	Heterophily based on the incoming degree of external links	- 0.008(0.003)*	- 0.013(0.005)*	- 0.087(0.049)	- 0.009(0.024)

\*  $p < 0.05$

**Table 4.3.** Results of the ERGM

In this study, while the same statistical methods (ERGM) were applied, network analysis was used according to a different approach than in the example on sorghum circulation: it is an anthropological question that called for the use of network analysis. In addition, the research process followed a different

sequence than in the case of sorghum: a first field phase involving surveys and participant observation allowed (i) to identify the different species and varieties of cultivated plants and to highlight their biocultural status; (ii) to gather ethnographic information on the functioning of society and the characteristics of individuals. This information was used before implementing the network analysis to define the hypotheses to be tested, and *a posteriori* to interpret the results. Ethnographic knowledge showed that individuals giving more plants than others were mostly the oldest migrants who managed to secure their land rights better according to the criteria of the island's original inhabitants.

#### **4.2.2. Circulation of knowledge and structuring of know-how**

The analysis of social networks also makes it possible to study the circulation of knowledge and information within populations of natural resource users. It can be used on the one hand to analyze the information and knowledge exchange networks themselves (e. g. by mapping the exchange of advice on a theme), and on the other hand to analyze the structure of the social group(s) under focus, to see to what extent this structure explains the patterns of knowledge distribution within these groups. It has been shown, for example, that in some cases the central individuals in the advice exchange networks were also the most knowledgeable (case of medicinal plants, Tabi region in Mexico, Hopkins 2011). Similarly, it has been shown that local ecological knowledge may vary between groups of individuals structured according to their way of using natural resources (Crona and Bodin 2006).

The case study proposed here (Salpeteur *et al.* 2016) aimed to explore the role of informal relationships<sup>1</sup> in structuring knowledge and skills within a nomadic herding community in Gujarat, India. Two hypotheses guided the implementation of the research protocol, based on the distinction between theoretical and experience-based (practical) knowledge: (i) informal relationships, since they facilitate the verbal exchange of information or theoretical knowledge between connected individuals, may be associated with a greater homogeneity of knowledge between these individuals; and (ii) informal relationships reflect a structuring into social groups that share the same experience, and are therefore also potentially associated with a greater homogeneity of knowledge.

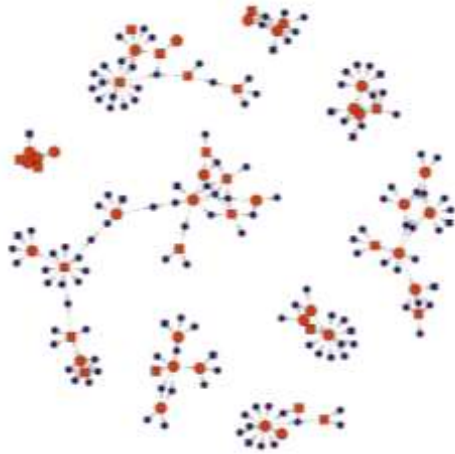
Two types of informal relationships were studied: migration relationships (linking individuals who have been on nomadization together), corresponding to a shared experience, and friendly relationships, which involve intense verbal exchanges, but not necessarily a common practice. Since relationships between men and women cannot be expressed in terms of friendship in this socio-cultural context, this type of relationship has been studied separately for each sex.

The survey was conducted in the village of Mindiyala (Kachchh district), including 135 individuals, representing 113 households, or about 25% of the village estimated at 450 households. The questionnaires included a section documenting social interactions (links) and a section with a set of questions to assess ecological knowledge in four areas: soil classification, ethnoveterinary techniques, local sheep breeds and ethnobotanical knowledge.

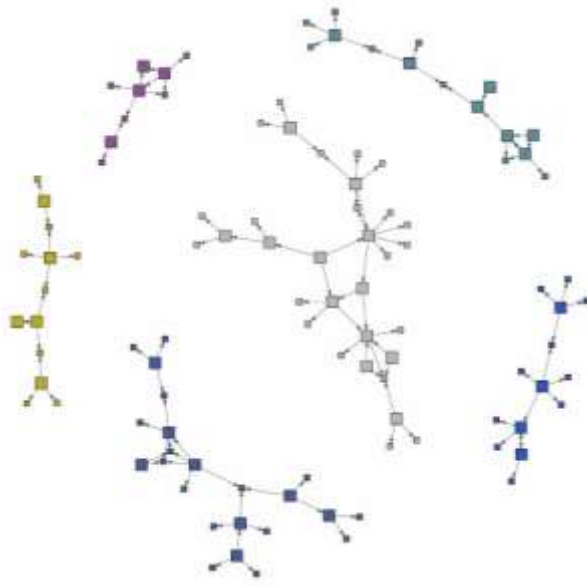
The data obtained was analyzed in two steps. First, the interaction networks were mapped, and groups of highly connected individuals were extracted from these networks. In two cases (migration network and female friendship network, Figures 4.7 and 4.8), independent sub-networks emerged directly. In the case of the male friendship network (Figure 4.9), the Girvan-Newman clustering method was used to extract these groups (Girvan and Newman 2002). These groups were then included in the analysis as individual attributes.

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1. Here, by informal relationship we mean an inter-individual relationship that is not subject to a strict normative framework. For example, an employment relationship will be considered formal, since it involves relatively well-defined standardized behavior from the protagonists.



**Figure 4.7.** *Migration groups. The nodes in red are the surveyed individuals (round: male, square: female); the blues are the individuals mentioned, but not surveyed (represented by default as round, when gender is unknown)*



**Figure 4.8.** *Friendship network, women. The marked segmentation of the network can be noticed.*



**Figure 4.9.** Friendship network, men. Each color corresponds to a cluster extracted using the Girvan-Newman method

Second, matrices of similarity between individuals were constructed from their responses in the four knowledge domains. A multivariate permutation variance analysis (perMANOVA) was then performed, with the similarity matrices being the dependent variable and membership in migration and friendship groups being included as independent (explanatory) variables. Other individual attributes were also tested (age, activity, kinship groups, education level). A separate analysis was conducted for migration groups and friendship groups to test their respective influence on variations in the four domains studied.

	LEK races	LEK soils	LEK tado	Botanical LEK
	<i>Value R<sup>2</sup></i>			
<b>Migration groups</b>	0.15472	0.16419**	0.19299**	0.19291*
<b>Segments</b>	0.09361	0.10410*	0.12342**	0.09044
<b>Gender</b>	0.02332	0.01845	0.02212	
<b>Age</b>	0.05835		0.05350	
<b>Schooling</b>				0.03479*
<b>Ceasing of activity</b>		0.05861		0.09290**

\*  $p < 0.05$ ; \*\*  $p < 0.01$

**Table 4.4.** Results of the perMANOVA analysis including migration groups. LEK: local ecological knowledge. Tado: tested veterinary technique. Segments: patrilineal lineage segments (kinship groups). Cessation of activity: time elapsed since the abandonment of the shepherd's activity.

Analyses carried out from migration groups (Table 4.4) show that several variables explain a significant part of the observed variability, in three areas of knowledge (soil, veterinary, and botanical). Migration groups, in particular, account for a significant part of the observed variability in these domains, between 16 and 19%. This means that responses tend to vary between individuals from different migration groups and to be similar within groups.

On the other hand, the analyses conducted on the basis of the friendship groups, both female and male, show almost no significant effect of the “friendship group” variable (Tables 4.5 and 4.6). In the case of the women's friendship network, no effect appears. In the case of male friendship networks, friendship groups significantly explain a part of the variability only in the case of soil knowledge (Table 4.6).

	TEK races	TEK soils	TEK tado	Botanical TEK
	<i>Value</i> <sup>R2</sup>			
<b>Friendship groups</b>	0.14698	0.14338	0.13857	0.17434
<b>Segments</b>	0.28307	0.34274	0.39054	0.35205
<b>Age</b>	0.05071	0.05647	0.06449	
<b>Schooling</b>				
<b>Ceasing of activity</b>				0.10358

\*  $p < 0.05$ ; \*\*  $p < 0.01$

**Table 4.5.** *permANOVA results for female friendship groups*

	TEK races	TEK soils	TEK tado	Botanical TEK
	<i>Value</i> <sup>R2</sup>			
<b>Friendship groups</b>	0.15284	0.17089**	0.16344	0.14917
<b>Segments</b>	0.20455	0.23666	0.20721	0.23250
<b>Age</b>	0.02769	0.06010	0.05131	0.05373
<b>Schooling</b>				
<b>Ceasing of activity</b>	0.05093	0.04537	0.07000	0.06028

\*  $p < 0.05$ ; \*\*  $p < 0.01$

**Table 4.6.** *permANOVA results for male friendship groups*

These results allow us to better understand the transmission of ecological knowledge in this specific case and to test our two hypotheses. It is clear that friendship networks, which involve the oral transmission of knowledge - mostly theoretical -, do not seem to participate in the transmission of this knowledge, since there is no specific homogenization of this knowledge within highly connected groups of individuals. On the contrary, migration networks seem to play a decisive role: individuals belonging to the same migration groups tend to have similar responses (and therefore similar knowledge) in three areas. This shows that informal relationships are not systematically accompanied by the transmission of ecological knowledge. Migration groups, which represent groups of individuals sharing the same experience, are a central place for the transmission and homogenization of knowledge within these nomadic herding communities.

Here, social network analysis was used to map two types of informal relationships and to study the role of these relationships in the transmission of local ecological knowledge. The approach does not integrate life sciences, but is based on an association between several disciplines in the human and social sciences: ethnoecology, social anthropology, and sociology (for its expertise in the method of analyzing social networks). Network formalism allows here to systematically map and analyze fluid social relations, whose role in

knowledge transmission is difficult to grasp by other means. The results of the social network analysis can then be used and combined with additional statistical analyses.

#### **4.3. Discussion: a necessary link between the quantitative and the qualitative**

The proposed examples illustrate the high interest of network analysis methods as a tool for interdisciplinary approaches, creating a space for discussion and establishing links between disciplines. A unique formalism allows to represent ecological interactions, for example the circulation of plant material and associated gene flows, and social interactions, for example friendship relations between individuals. This formalism sets a common ground for the involved disciplines, and is associated with similar methods of analysis to answer their respective questions.

The examples on the circulation of cultivated plants illustrate how one method can be used with different approaches, allowing to address questions arising in one case from population genetics and in the other from social anthropology. In the first case, the hypothesis to be tested had been well defined beforehand and aimed at understanding the patterns of geographical distribution of cultivated diversity. Network analysis then prompted the collection of more in-depth ethnographic information, to document the social processes at work in shaping seed circulation networks. In the second case, the anthropological approach, involving long field stays, generated a large number of hypotheses about the processes structuring plant circulation networks, which were addressed with network analysis. Several back-and-forth moves between ethnographical accounts and network analysis results were necessary to narrow the hypotheses and interpret the results, finally leading to a better understanding of social exchange processes.

These examples highlight the need to associate network analysis with qualitative approaches, which are essential to understand the social rules and norms regulating interactions between individuals, and are also necessary to understand how these interactions fit into the general system of interactions in the studied social systems.

However, disadvantages to network analysis approaches also need to be taken into account. In particular, it is necessary to underline the complexity and amount of time that are required for data collection and processing, when implementing network analysis methods. The questions addressed in the examples required the collection of all interactions between individuals, i.e. the description of the entire network. This required a large number of interviews that could be tedious and repetitive for both respondents and interviewers. A significant difficulty was also to identify unambiguously the individuals cited by the respondents, that required a large amount of information to be collected during the surveys.

Another disadvantage to note is the lack of appropriate statistical methods for the analysis of open networks (i.e. including links between respondents and other persons who were not interviewed). In these examples, a large part of the collected data could not be included in the analyses, because the available methods can only be applied to complete, closed networks, and therefore exclude relationships between individuals surveyed and those who were not. In the future, the analysis of socio-ecological networks requires the development of approaches adapted to the analysis of open networks and the development of lighter sampling strategies. Ongoing methodological developments for the analysis of the temporal dynamics of networks open up promising perspectives for understanding the functioning of socio-ecological systems and the mechanisms involved in their resilience. The development of methods for the analysis of multi-scale networks is also promising in this field of research.

#### **4.4. Bibliography**

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