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Emergence and Robustness of a Community Discussion Network on Mercury Contamination and Health in the Brazilian Amazon

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Information exchanges, debates, and negotiations through community social networks are essential to ensure the sustainability of the development process initiated in participatory research. The authors analyze the structural properties and robustness of a discussion network about mercury issues in a community in the Brazilian Amazon involved in a participatory research aimed at reducing exposure to the pollutant. Most of the villagers are connected in a large network and are separated from other individuals by few intermediaries. The structure of the discussion network displays resilience to the random elimination of villagers but shows vulnerability to the removal of one villager who has been a long-term collaborator of the project. Although the network exhibits a structure likely to favor an efficient flow of information, results show that specific actions should be taken to stimulate the emergence of a pool of opinion leaders and increase the redundancy of discussion channels.

Keywords: *social networks; community; preventive health innovation; diffusion of innovation; mercury; Brazil; Amazon; environmental health*

Participatory research has increasingly emerged as an important approach to promote development while taking into consideration the complex links between the health of the human population and the sustainability of the ecosystems on which human welfare depends (Forget & Lebel, 2001). This approach offers an opportunity for local people and researchers to share their knowledge, to create new understandings, and to work together to form and implement action plans (Cornwall & Jewkes, 1995). Participation of communities in the research process is essential to ensure local ownership

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of the research results and build solutions that are adapted to sociocultural contexts and meet population needs.

A successful participatory research program should allow the community to engage in a long-lasting process of development after the research program has ended and to adapt their actions to the evolution of the environmental and social contexts. Information exchanges, debates, and negotiations among the community members are key to promoting the sustainability of this process by allowing them to continuously interpret their situation through taking into account new information to promote adaptive development strategies. At the level of the entire community, the individuals involved in information sharing and discussion form a network that can be studied using the concepts and tools of social network analysis. In the present article, we analyze the structural properties and robustness of a discussion network in the context of changing socioenvironmental conditions to inquire into the process of communication among the members of a community that has been involved in a participatory research project.

INTRODUCTION

Background of the Caruso Project

Since 1994, the Caruso Project, participatory research based on the ecosystem approach to human health, has been exploring the links among the impact of human activities on the ecosystem, mercury environmental contamination, and the health effect of human exposure among riverside populations in the Tapajós region in the Brazilian Amazon. Biogeochemical studies have shown that deforestation resulting from “slash-and-burn” agricultural practices has caused intensive erosion of soils rich in naturally occurring mercury, significantly contributing to the contamination of waterways (Lucotte, Davidson, Mergler, Saint-Charles, & Guimarães, 2004), and that climatic conditions and aquatic vegetation in many of the Tapajós ecosystems are optimal for mercury methylation, speeding up the process of the incorporation of mercury into the aquatic food chain up to humans (Lucotte et al., 2004). Wide intra- and interspecies variations in mercury concentrations were observed in the aquatic fauna of the Tapajós region, the highest mercury levels being consistently found in piscivorous species and the lowest in herbivorous species (Lebel, Roulet, Mergler, Lucotte, & Larribe, 1997).

Because the nervous system is a prime target for methylmercury, the populations exposed to methyl mercury through fish consumption are placed at a disadvantage with respect to adequate development of intellectual and physical capacities because of nervous system deficits. Neurofunctional testing conducted with the inhabitants of Brasília Legal, a small village located on the banks of the Tapajós River, to determine the health impacts of mercury exposure through fish consumption showed significant declines in motor coordination, certain visual functions, and cytogenetic properties (Amorim et al., 2000; Lebel et al., 1998). In 1998, Caruso researchers invited the villagers to participate in a pilot project based on dietary changes that sought to reduce human mercury exposure while maintaining fish consumption. The consensus reached by the researchers and the community favored a recommendation where all fish can be eaten but where diet was directed toward more frequent consumption of less contaminated fish species. Comparison of diet and exposure of the same people in 1995 and in 2000 ($n = 47$) showed that they continued to eat the same quantity of fish but modified the relative proportions of piscivorous and herbivorous fish. Consequently, hair mercury levels among the tested population decreased by approximately 35% (Mergler et al., 2001).

Sustainable Solutions to Reduce Mercury Exposure in Changing Social and Environmental Conditions

The Tapajós region is a very active colonization frontier, with changing social and environmental conditions that may have a significant impact on mercury dynamics in the ecosystems as well as on human exposure to the contaminant (Lucotte et al., 2004). Changes in the villagers' fishing practices in response to the opening of new markets or to the reduction in the availability of the most-valued fish species as the result of overfishing by commercial fleets are likely to affect fish consumption and mercury exposure. Mercury contamination of the aquatic ecosystems of the Tapajós is also very likely to increase as the consequence of growing deforestation rates associated with the rapid expansion of the soybean agricultural frontier (Fearnside, 2001). Current land and fire use practices by the local farmers are also likely to create positive feedbacks in future fire susceptibility, fuel loading, and fire intensity, which may amplify the impacts of agriculture on deforestation and mercury mobilization into aquatic ecosystems (Cochrane et al., 1999). Furthermore, these rapid environmental changes are associated with intense migratory movements both locally and regionally (Perz, 2002).

Tangible results from the pilot project carried out in Brasília Legal highlight how the participatory approach has been successful in initiating a process of change in the community to reduce mercury exposure. However, it remains to be assessed whether the project has reached a sufficient level of autonomy to become independent from the outside project initiators. It is indeed essential for the community, in the longer term, to gain empowerment to respond to changing socioenvironmental conditions and to further develop and adapt their actions to sustain efficient solutions in regard to mercury contamination.

From 1994 to 2001, community meetings, face-to-face interviews, and informal discussion provided numerous opportunities for information sharing between researchers and many villagers. The interactions between researchers and community members were important to collectively discuss the research results and build strategies to reduce mercury sources and exposure. Equally important to the diffusion are the discussions and debates regarding mercury issues that may have emerged among the villagers themselves in the course of 7 years of participatory research in the community. Indeed, these discussions may extend the reach of the information about mercury issues beyond the individuals who were directly involved in the research and allow the diverse social groups to share their concern and to make sense of the available information as a basis for action.

To evaluate if continuous long-term information sharing among the villagers is likely to be efficient in allowing new information regarding mercury issues to reach most people of the community, we investigated the structural characteristics and robustness of the discussion network about mercury issues in the Brasília Legal community.

Social Network Analysis as a Tool to Investigate the Pattern of Information Exchanges About Mercury Issues

A network is a set of items, which are called nodes, with connections among them, called links. A social network is a collection of individuals, each of whom is connected with some subset of the others, through specific social ties (Wasserman & Faust, 1994). Social network analysis studies the relationships between the behavior of the individual at the micro level and the pattern of interactions among the individuals at the macro level (Wasserman & Faust, 1994). These relationships are explored by measuring composition

variables that are defined at the level of the individual, such as gender, age, economic activities, religious affiliations, and place of birth, and structural variables that are defined for pairs of individuals and describe ties of a specific kind (Wasserman & Faust, 1994). Structural variables are the cornerstone of social network data sets and are used to reveal the patterns of people's interactions. Friendships (Fararo & Sunshine, 1964), scientific collaborations (Newman, 2001), sexual relationships (Bearman, Moody, & Stovel, 2002; Liljeros, Edling, Amaral, Stanley, & Aberg, 2001), e-mail communications (Ebel, Mielsch, & Bornholdt, 2002), advice in organizations (Saint-Charles & Mongeau, 2005), and acquaintance relationships (Bernard, Kilworth, Evans, McCarty, & Selley, 1988; Csányi & Szendroi, 2003) are some of the wide variety of social interactions that have been studied from a social networks perspective.

Network Properties and Efficiency of the Communication Process

Three properties are especially relevant to assess the communication potential of a network, that is, the possibility that information can reach most individuals composing the network: the level of fragmentation of the network associated with the existence of distinct components, the degree distribution, and the average distance (Wasserman & Faust, 1994).

For an idea or information pertaining to an individual to reach another, the two have to be connected, either directly or through some other people. If there is a path between every pair of individuals in the information exchange network, the network is said to be connected, and messages can flow between all pairs of individuals. Alternatively, if the network is composed of several distinct subsets in which there is no path between the individuals of the different subsets, it is said to be disconnected. These subsets are called components, and information can circulate only between the individuals belonging to the same component but not between the individuals belonging to different components (Wasserman & Faust, 1994).

The degree of a node, k , is the number of links the node has to other nodes. The degree distribution, defined as the fraction of nodes in the network that have degree k , is obtained by counting the number of nodes with $k = 1, 2, 3 \dots$ links and dividing by the total number of nodes. Different classes of social networks can be distinguished according to their degree distribution (Albert & Barabási, 2002). Single-scale networks are characterized by a degree distribution exhibiting a fast decaying tail, such as exponential or Gaussian, with no highly connected nodes (Amaral, Scala, Barthélémy, & Stanley, 2000). By contrast, scale-free networks are characterized by a degree distribution with a tail that decays very slowly, such as a power law, which indicates that the huge majority of the nodes have a small degree, whereas a few nodes have a very high number of links and are responsible for the overall connectivity of the network (Amaral et al., 2000; Barabási & Albert, 1999). Single-scale degree distribution has been frequently found in social networks built on relationships that require face-to-face interaction because investment in time and energy necessarily imposes a severe limitation on the number of social ties an individual may possess (White & Houseman, 2003). Friendship and acquaintance networks (Amaral et al., 2000; Bernard et al., 1988; Fararo & Sunshine, 1964) as well as an adolescent romantic and sexual network in a high school in the United States (Bearman et al., 2002) are examples of single-scale social networks. The web of human sexual contact is a notable exception. Indeed, Liljeros et al. (2001) showed that the cumulative distribution of the number of different sexual partners in 1 year decays as a scale-free power law. In information-sharing networks,

the degree of a node is the number of discussion partners of the individual, and the analysis of the degree distribution provides information about involvement in the debates at the community level.

The ability of information to be transmitted from one individual to another is also dependent of the distance between them in the discussion network. The distance between two nodes is defined as the number of links in the shortest path between them (Wasserman & Faust, 1994). The average distance—the average of the distances between every pair of nodes in the network—is a global measure of separation and can be used to assess the efficiency of the communication process at the level of the entire network. Short average distance in social network is believed to promote efficient communication, allowing information to be transmitted between any two individuals with only a small number of intermediaries. Numerous authors have identified short average distances between individuals in a variety of social networks: film–actor collaborations (Watts & Strogatz, 1998), scientific collaborations (Newman, 2001), e-mail exchanges (Ebel et al., 2002), online acquaintance relationships (Csányi & Szendroi, 2003), and friendship on the Web (Adamic & Adar, 2003).

Network Robustness and Sustainability of the Communication Process

A key feature of networks is their topological robustness, which refers to their ability to respond to changes in the external conditions or internal organization while maintaining relatively normal behavior (Albert & Barabási, 2000). Robustness of networks to sustain efficient communication between all nodes of a given network has been evaluated, using computer simulations, by analyzing fragmentation of the network into small, isolated components and increasing the average distance, in response to the successive removal of selected nodes. Computer simulations used to evaluate network robustness can be compared with empirical longitudinal network data and are useful in developing models of network dynamics according to a variety of scenarios. Scale-free networks appear very sensitive to losing the rare highly connected nodes but relatively robust to randomly losing the more highly abundant less connected nodes (Albert & Barabási, 2000). In contrast, single-scale networks, in which nodes have similar numbers of connections, display similar responses to the loss of highly connected and random nodes (Albert & Barabási, 2000).

The main objectives of the present study are to analyze the structure of the mercury discussion network involving the villagers of the Brasília Legal community after 7 years of participatory research to identify individuals who may play a distinctive role in the information flow and to assess the robustness of the discussion network to sustain information exchanges even if a significant fraction of the community members cease to be involved in the discussion about mercury.

METHOD

The study was carried out in the village of Brasília Legal, situated on the banks of the Tapajós River, a major tributary of the Amazon River in Brazil. A map of the study region is available on the Caruso Project Web site (<http://www.unites.uqam.ca/gmf/caruso/caruso.htm>). In September 2001, a meeting was held in the Brasília Legal community to invite the villagers to participate in the network study. A complete mapping of the community, done in collaboration with the villagers, revealed that the

village had a total of 110 households. Data were collected using semistructured face-to-face interviews that were conducted by the principal investigator privately at the respective homes of the participants in October 2001. Because households are mostly represented by nuclear families, our strategy to maximize the size of our sample was to visit each household several times at different times of the day to invite the household heads (usually a couple) to participate in the interview. If the household heads were repeatedly absent after several visits, another person in the house was interviewed. This strategy allowed us to conduct the interview with a total of 158 persons, from a total of 96 households. People from the remaining 14 households could not be encountered because they were not permanent members of the community, had moved recently, or were temporarily absent for health or professional reasons.

Interpersonal communication on the mercury issue was assessed by asking the respondents to name the individuals with whom they usually discuss the subject, whether in the context of health, diet, or fishing. Our intention with the phrasing of the question was to preferentially select network partners with whom the respondent had substantial conversations about mercury and not merely casual talks. From a total of 363 nominations directed at individuals living in the village, including those living in the same household, 322 (89%) were directed at individuals who had been interviewed and 41 (11%) were directed at individuals who were not included in our sample. Network ties with individuals who could not be interviewed were dropped from the analysis because no information was available for these network partners. To obtain the most complete picture of the network possible, two individuals were considered as discussion partners if either person mentioned the other. Network data were stored as an actor-by-actor matrix using the UCINET software (Borgatti, Everett, & Freeman, 2002) and then exported to the Netdraw software (Borgatti, 2002) to visualize the structure of the discussion network as presented in Figure 1. The distance matrix among all pairs of nodes belonging to the main component was obtained using the UCINET software (Borgatti et al., 2002). Computer simulations were performed to test the robustness of the main component of the mercury discussion network by randomly removing 2%, 5%, 10%, and 20% of the nodes as well as all of the links attached to them. The networks obtained in 10 independent experiments for each percentage of randomly removed nodes were analyzed using the UCINET program to calculate the number of nodes and the average distance in the largest component.

RESULTS

Figure 1 presents the discussion network about mercury in the Brasília Legal village. The nodes are depicted as circles. Two nodes are connected by a line if one or both individuals reported discussing mercury issues with the other. The network analysis revealed one small component linking three individuals as well as 25 isolates who did not participate in the discussions about mercury. However, the most striking characteristic of the network is that the majority of the respondents belong to one main and relatively dense component comprising 130 members linked together by 281 discussion relationships. These villagers are probably not aware that they belong to a large discussion network, which emerges as a macro structure resulting from the integration of the individual interactions. However, this component defines both the boundaries and the preferential channels for potential circulation of the information about mercury and is examined in the next sections of the article.

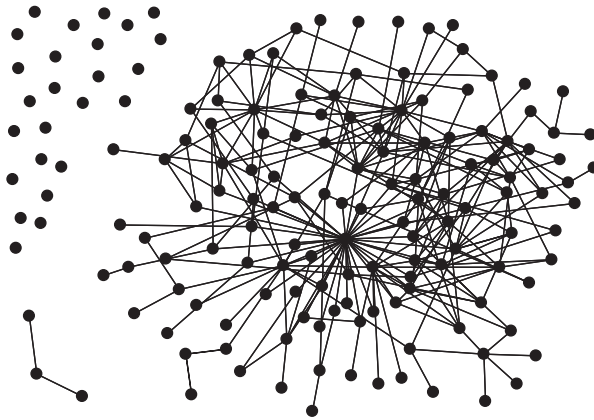


Figure 1. The discussion network about mercury issues among the villagers of Brasília Legal. NOTE: $N = 158$.

Figure 2 shows a linear log plot of the distribution of the number of discussion partners for the main component of the network. The degree distribution is well approximated by exponential decays, consistent with a single scale for the connectivities. However, one villager has a very high number of discussion partners and emerges as an outlier to the exponential distribution. This person has been—since the beginning of the Caruso Project—involved in many research activities and is hereafter referred to as the Caruso collaborator.

To further evaluate the role played by participation in the Caruso Project, villagers were divided into three groups according to the year of their first participation in the project. The average number of discussion partners of the villagers who participated for the first time in 1995 ($n = 36$), 2000 ($n = 31$), and 2001 ($n = 90$) decreases from 4.6 to 4.1 and 2.5, respectively (the Caruso collaborator has been removed from this analysis).

The average distance between villagers belonging to the main component of the mercury discussion network is 3.4, which means that, on average, people are separated by only 2.4 intermediaries. The distribution of distances is homogeneous, peaks around a value of 3, and exhibits a tail that decays even faster than would be expected for an exponential function (data not shown).

Each year, some individuals stop being involved in discussion about mercury, mainly as the result of migration out of the village. As a consequence, some paths that contribute to the system's interconnectedness are eliminated, affecting the circulation of information in the community. Two potentially negative effects are the fragmentation of the network in small noncommunicating components and the increase in the communication distance among villagers. The robustness of the main component of the mercury discussion network to sustain information exchanges between community members can be tested by randomly removing an increasing percentage of the nodes through computer simulations and by analyzing the impacts on network fragmentation and on the average distance.

Changes in the percentage of the individuals who remain connected in the largest component of the discussion network and in the average distance between individuals

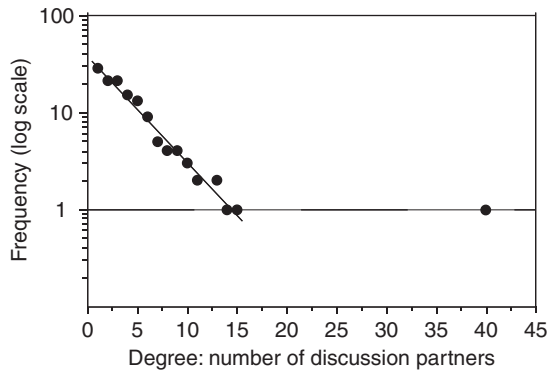


Figure 2. Linear log plot of the distribution of the numbers of discussion partners for the main component of the mercury discussion network.

NOTE: The full line is a guide for the eye of what an exponential decay would be.

in this component were calculated as the function of the random removal of 2%, 5%, 10%, and 20% of the nodes. The Caruso collaborator was excluded from the set of nodes that could be targeted for random removal from the network. However, to specifically evaluate the role of this person in the robustness of the network, two sets of simulations have been performed, either in the presence (filled circles) or alternatively in the absence (empty circles) of this individual from the network.

Data in Figure 3 show that, in the presence of the Caruso collaborator, most of the individuals (93%) remain connected in a large component, even if up to 20% of the nodes are randomly removed. The selective removal of the Caruso collaborator alone does not lead to a significant fragmentation of the network, and 98% of the individuals remain connected. However, in the absence of the Caruso collaborator, the discussion network becomes much more vulnerable to the random elimination of a fraction of the individuals, and we observe a synergistic effect on the fragmentation of the network as more individuals are randomly removed. Nevertheless, a large component, connecting 86% of the individuals on average, persists even if both the Caruso collaborator and 20% of the individuals are eliminated.

The average distance between the individuals who remain connected in the largest component of the discussion network increases significantly, from 3.4 to 4.1, as a consequence of the removal of the Caruso collaborator from the network (data not shown). However, average distance is little affected by the random removal of up to 20% of the nodes from the network, either in the presence (3.5) or the absence (4.3) of the Caruso collaborator.

DISCUSSION

The structural analysis of the discussion network about mercury in the Brasília Legal community revealed that most of the inhabitants of the village are connected in a large component, where they are on average separated from any other individuals by very few intermediaries. In a previous study, we showed that information exchanges about mercury among the members of the community are likely to influence the actions undertaken by

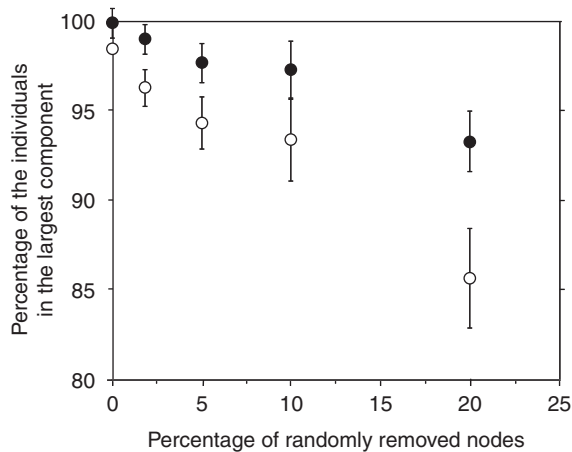


Figure 3. Percentage of individuals remaining connected in the largest component of the mercury discussion network as a function of the percentage of randomly removed nodes, in the presence (filled circles) or absence (empty circles) of the Caruso collaborator. NOTE: Error bars represent one standard deviation above or below the mean value of 10 simulations.

the villagers to reduce exposure (Mertens, Saint-Charles, Mergler, Passos, & Lucotte, 2005). Indeed, participation in the mercury discussion network was found to be associated with awareness of the critical information necessary to allow the individual to change dietary habits toward the preferential consumption of the less contaminated fish species. A short average distance in the discussion network is likely to favor an efficient flow of critical information regarding mercury issues in the village and to be important to create a common understanding of health problem associated with mercury contamination. This property of the discussion network may have contributed to the success of the pilot project in reducing mercury exposure while maintaining fish consumption.

Although the discussion network has been built using data from one unique time point (2001), the present study sheds some light on the possible dynamics of information exchanges about mercury in the village. On one side, the analysis of the structural properties of the discussion network provides insights about the past processes that allowed mercury to gradually become an issue on the agenda of the community. On the other side, the results from computer simulations allow us to test possible scenarios about the future evolution of the discussion network in response to a changing environment.

How Mercury Became an Issue on the Agenda of the Community

The discussion network on mercury illustrates how the problem of mercury contamination is now an important issue for the members of the Brasília Legal community. Because participation in discussions about mercury has probably been a progressive process, paralleling the gradual involvement of the community in the participatory research, it is likely that the discussion network we have described using data collected in 2001 is the result of a growing process. The degree distribution of the main component of the discussion network that decays exponentially is compatible with a random growing network model (Albert & Barabási, 2002). This model starts with a small number of nodes, adds a new node to the network at every time step, and assumes that

new nodes connect with equal probability to the nodes already present in the network. According to this model, older nodes in the network will, on average, have a higher number of links than new ones. Data showing that individuals who became involved earlier in the Caruso studies have, on average, a higher number of partners in the mercury discussion network provide further support for the random growing network model.

However, the very high degree of the Caruso collaborator suggests that a mechanism of targeted preferential attachment directed toward this person was also at play in the growing process. The central role of the Caruso collaborator in the discussion network may have emerged progressively both as a consequence of his distinctive role in the participatory research and because villagers have increasingly recognized this individual as a key resource person to turn to for reliable information about mercury issues.

The Evolution of the Discussion Network in a Changing Environment

The discussion network displays resilience to the random elimination of discussion partners, which suggests that the community will be able to sustain a communication process about mercury involving most of the villagers, even if a relatively high fraction of the individuals stop being involved in discussion about mercury. However, data show that the vulnerability of information exchanges at the community level is likely to increase significantly if the Caruso collaborator is no longer participating in the discussion network. This observation strongly suggests that circulation of information in the community is overly reliant on the Caruso collaborator and would be at risk in a situation where this person would either leave the village or lose interest in being intensely involved in mercury issues.

Study Limitations and Implications for Future Research

The focus of the analyses has been on the main component of the discussion network. However, any initiative to promote the diffusion of information in the community as well as equity in the involvement around mercury issues also needs to take into account the individuals who are disconnected from this component and can presumably not be reached by the main flow of information about mercury.

Furthermore, the individuals' position in the network and their number of discussion partners have revealed unequal involvement around mercury issues among the different social groups of the community as well as between men and women within households (Mertens et al., 2005; Mertens et al., 2006). A network intervention, aimed at promoting equitable participation of all villagers in the debates and actions to reduce both mercury sources and human exposure, is currently being carried out, integrating the information from the purely mathematical approach based on random deletion to evaluate the network robustness and the involvement of the villagers in the discussion according to their social characteristics (Mertens et al., 2005).

Our simulations are based on the random removal of individuals from the network. However, the dynamics of the discussion network are likely to involve both nonrandom elimination of discussion partners and the addition of new individuals and links. Indeed, several members of the same family may simultaneously leave the village, and the consequences of these group migrations out of the village remain to be addressed. Furthermore, each year new individuals arrive and settle in Brasília Legal. They are likely to progressively get involved in the discussion about mercury, contributing to new links in the network, which may offer alternative channels of communication and

compensate for the loss of connectivity resulting from migration out of the village. However, newcomers may also draw the villagers away from their involvement around mercury issues by diffusing opinions that bring discredit to them, or by establishing diverging agendas for the community. A longitudinal analysis is currently being carried out to inquire into the dynamics of the formation and dissolution of the links in the mercury discussion network and to investigate the role of potential underlying factors such as changes in the involvement and interest of the individuals and social groups in mercury issues and migrations in and out of the village.

The longitudinal study will also allow us to investigate possible changes in the structural configuration in the discussion network as the community engages in further stages in the diffusion process from the creation to the maintenance of a common understanding of mercury-related health problems. The mapping of the types (kinship, friendship, occupational) and strength (reciprocal and/or multiplex) of the social ties that are associated with information exchanges on mercury will also provide valuable information regarding the social processes taking place in the community associated with the different stages of the diffusion process. Using these data, we will refine our simulations and modeling approaches to be able to adapt our strategies to promote the appropriation of information about mercury to other communities of the Tapajós region.

Implications for Practice: A Two-Step Network Approach for Health Promotion Work

Participatory health promotion projects face two simultaneous challenges: achieve effective improvement in community health and guarantee a sufficient level of autonomy of the community in sustaining a better health status in a changing social and environmental context, independently from the work of the outside project initiators. Because it is usually not possible to carry out long-term longitudinal study to monitor the sustainability of health promotion work, there is a need to develop methods that provide the basis to design interventions that will maximize the conditions of long-lasting health improvement. We propose a two-step network approach that can be used as a method, first, to better understand the success and difficulties associated with health promotion work by analyzing how the relevant information circulates in the community and by identifying the key persons involved and, as a second step, to evaluate the potential for sustainability of the results of the health promotion work by analyzing the robustness of the information exchange network in the community. The first step of this approach has been applied in numerous studies (e.g., Bond, Valente, & Kendall, 1999; Stoebenau & Valente, 2003) and can be used to examine the extent to which health promotion agents have reached the community and to assess the degree to which communication with the agents has affected health. The second step of this approach is illustrated in the present article and in Mertens et al. (2006) and can be used to carry out interventions to increase the robustness of the network by designing and implementing specific participatory activities to stimulate either the emergence of a pool of opinion leaders able to reach the various social groups or a reorganization in the network to promote connectivity and increase redundancy of channels through which information can flow. This two-step methodology can be applied in a variety of health promotion contexts, and, as an example, it has been successfully used to evaluate the structural properties and robustness of the information exchange and collaboration networks between members of the civil society and health workers in a national occupational and environmental health program carried out by the Ministry of Health of Brazil (Mertens, Távora, Hoefel, & Guimarães, 2007).

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