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Insight, part of a Special Feature on Exploring Resilience in Social-Ecological Systems

Toward a Network Perspective of the Study of Resilience in Social-Ecological Systems

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ABSTRACT. Formal models used to study the resilience of social-ecological systems have not explicitly included important structural characteristics of this type of system. In this paper, we propose a network perspective for social-ecological systems that enables us to better focus on the structure of interactions between identifiable components of the system. This network perspective might be useful for developing formal models and comparing case studies of social-ecological systems. Based on an analysis of the case studies in this special issue, we identify three types of social-ecological networks: (1) ecosystems that are connected by people through flows of information or materials, (2) ecosystem networks that are disconnected and fragmented by the actions of people, and (3) artificial ecological networks created by people, such as irrigation systems. Each of these three archytypal social-ecological networks faces different problems that influence its resilience as it responds to the addition or removal of connections that affect its coordination or the diffusion of system attributes such as information or disease.

Key Words: *network topology; resilience; social-ecological systems; social-ecological networks*

INTRODUCTION

Comparative analyses of case studies on resilience assessment of regional social-ecological systems have been challenging. Major historical case studies involving subjects such as spruce budworm outbreaks (Ludwig et al. 1978), rangelands (Walker et al. 1981), and lakes (Scheffer 1990, Carpenter et al. 1992) focus on the dynamics of reasonably well defined ecosystems. These case studies have been formulated using simple mathematical models that allow a formal analysis of the long-run behavior of these systems, i.e., the characteristics of possible attractors and the thresholds between them. On the other hand, case studies in which social processes play a more important role and in which multiple types of resources are involved, as in Gunderson et al. (1995), Berkes and Folke (1998), and Berkes et al. (2003), are addressed in a qualitative way and lack a well defined quantitative approach. Although frameworks have been proposed to compare social-ecological systems in a more systematic way (Walker et al. 2002, Walker and Meyers 2004, Anderies et al. 2004), they have not yet accomplished this. Studies on the resilience of social-ecological systems lack the guidance of a clear framework. Obviously, there are a variety of frameworks for the study of social-ecological systems, but in our opinion they lack a clear formal description of structural changes, one of the key aspects of resilience theory and the propositions for research in this area (Walker et al. 2006).

We propose that tools and ideas developed for the study of networks may contribute to such a framework. A network perspective might be a useful complement to existing analyses because it focuses explicitly on the structure of the interactions between the components of social-ecological systems and the ways in which this structure affects the performance of the system. Another benefit of a network perspective is the availability of a uniform language with which to describe complex systems in terms of nodes and links.

Although quantitative studies of social networks have a history that stretches over about a century (Freeman 2004), during the last few years there has

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been tremendous growth in network analyses of many different networks. Network analysis is a method of research for understanding the structure of a system and is based on graph theory and statistics. We have analysis not only of small-scale networks from, e.g., sociology and social anthropology (Sampson 1969, Padgett and Ansell 1993) but also of large networks such as the Internet (Pastor-Satorras and Vespignani 2004) and authorship networks (Börner et al. 2003). From ecology we have food webs (Dunne et al. 2002), plant-pollinator networks (Olesen and Jordano 2002, Jordano et al. 2003, Olesen et al. 2002), landscape ecology networks (Keitt et al. 1997, Bunn et al. 2000, Urban and Keitt 2001), and networks of social insects (Fewell 2003). This highly diverse list of uses of the network approach illustrates its generality and makes it possible to compare structural differences between networks, even when the data are from different fields (e.g., Albert. et al. 2000, Girvan and Newman 2002, Dodds et al. 2003, Newman et al. 2004). In addition, recent studies on social phenomena have examined the contribution of the network structure to robustness (Albert et al. 2000, Dunne et al. 2004), collective action (Gould 1993, Hauert and Doebeli 2004), and diffusion processes (Pastor-Satorras and Vespignani 2001, Cowan and Jonard 2004). Furthermore, most network studies look at the dynamics of static networks (e.g. Cowan and Jonard 2004, Janssen and Jager 2003) or the dynamic development of particular network structures such as small-world or scale-free networks (Watts and Strogatz 1998, Barabasi and Albert 1999). However, there is even less emphasis on the more difficult question of how the nature of the nodes and links changes over time in a system in which they have functional diversity (e.g., Stark and Vedres 2005). From a resilience perspective, it is necessary to include dynamics in the structure of the network, and heterogeneity more explicitly.

Network analysis is also used in the context of social-ecological systems. However, it has previously concentrated on networks of human social agents such as individuals or organizations (Agarwal 2000, Tompkins et al. 2002, Schneider et al. 2003) or ecological networks such as food webs (Lassig et al. 2001, Sole and Montoya 2001, Dunne et al. 2002, Garlaschelli et al. 2003). Such studies mainly describe network structures. For social networks, the structure is discussed in relation to the ability of a community to solve problems that require selective action and to build up social capital. For food webs, comparative analysis is used to find the common features of these networks. Some studies find universal scale-independent regularities (Garlaschelli et al 2003), but others argue that regularities do not exist when a proper analysis is done (Camacho and Arenas 2005).

As far as we know, no systematic analysis has been performed on combined social, i.e., human-oriented, and ecological networks. Furthermore, most network studies on social or ecological systems focus on static networks with a low degree of heterogeneity among the nodes and links. From a resilience perspective, it is necessary to include dynamics and heterogeneity more explicitly.

A network approach may provide a way to compare case studies from a specific perspective relevant for the study of resilience. To perform this comparison, we need to define a typology of nodes, links, and network properties relevant for our empirical cases. This paper is an initial step in the development of a typology that makes network analysis useful for comparing social-ecological systems. For different typologies of social-ecological networks, we may, depending on the types of nodes, links, and network properties at hand, reveal different types of questions to be addressed for the further analysis of the resilience of social-ecological systems.

A clear advantage of the network approach is the structural properties that can be revealed. The interactive play between nodes is not just of interest at the individual level, at which the nodes interact purely on the basis of their individual qualities. Instead, the interest is also in the composition of the structure in which the interactions between nodes take place, i.e., the context that the nodes have created through their interactions. We see how interaction on the micro-scale creates and recreates structures on grander scales. Thus, a comparison of structures in different cases can reveal insights on how the functioning of the cases differs. Also, with the sampling of, for example, a social network by questionnaires and deep interviews, one can harvest qualitative data for the systems as well, e.g., local ecological knowledge and tacit knowledge. The network approach can therefore also be seen as a vehicle for gathering qualitative data.

We recognize the potential difficulties in analyzing social-ecological networks with the type of quantitative analysis that is commonly used, because the system under study, by definition, includes and mixes both social and ecological entities. Nodes may therefore represent not only individuals, communities, organizations, farmers, etc., but also ecological entities such as land properties, lakes, forests, paddies, etc. The links can symbolize flows of physical units such as water and organisms like seed dispersers or cattle as well as the exchange of management information between social actors.

In what follows, we first formalize social-ecological networks in more detail and examine the metrics used in network studies to describe some of the chosen characteristics of a network, all of which pose different types of challenges with regard to governing the resilience of social-ecological systems. The use of the network perspective is illustrated with four case studies from the set of case studies described in this special issue (Walker and Lawson 2006). We conclude by discussing potential future steps in the use of a network perspective for assessing the resilience of social-ecological systems.

DEFINING SOCIAL-ECOLOGICAL NETWORKS

Networks consist of nodes and links that can be used to represent a given system in terms of its localized components, i.e., nodes or vertices, and the relations between those components, i.e., links or edges. When we choose to represent a social-ecological system as a network, we must decide which attributes of the social-ecological system are of interest for the study, i.e., which attributes we want to translate into a network structure. This choice determines how the structural map of the system is constructed and therefore also influences the analysis, which is based on the structural map. Examples of different attributes include trust, power, management information, flows of water, movement of cattle, contamination, and seed dispersal. The nodes could therefore symbolize both social and ecological components. Note that we use the term “social nodes” for human-related nodes and the term “ecological nodes” for nodes that are not related to humans. This might initially be somewhat confusing, because there are many examples of nonhuman social nodes such as bees and ants. We decided to make this distinction because of the term “social-ecological systems,” which the research community is using to describe the type of systems we are interested in. Typical social components are individuals and/or organizations, as normally used in the social sciences. Typical ecological components are species, as in food webs, and/or individual patches of habitat in a landscape. Links can be directed or undirected, and they can depict relations of any chosen kind between the linked pair of nodes. The nature of the relations could be either entirely social, entirely ecological, or a mixture of both social and ecological components, e.g., a relation consisting of a farmer’s resource extraction from his/her farm. Human activities can create a social-ecological network by linking ecological nodes, i.e., independent ecological systems become connected by the activities of humans. For example, livestock can be moved around in a landscape, and previously unconnected areas of land then become connected. Another example is fishermen who fish in different lakes and transfer invasive species when transporting their boats between the lakes. Of course, those lakes could already be connected ecologically, but the human/social component has direct implications for ecosystem management for resilience. On the other hand, social connections can be created via ecological connections, e.g., rivers connect people from upstream and downstream, thereby creating a social-ecological network.

We acknowledge the difficulty in defining what should be included in the network representation of the social-ecological system under study. There is no such thing as the “right” way to represent the social-ecological network of a given system, just useful and not so useful ones. What qualifications must a particular component of a system possess to be included in the network? If we include it, should it be represented as a node by itself or lumped together with other similar components into a single node? Also, what determines if a relationship between components should be represented as a link? Components can have different relationships in different contexts, and the strength of the links may vary over time. Furthermore, because links can be of different sorts in the same network, e.g., human-human links and human-species links, we understand that we will face problems of link comparability in the structural analysis. These are important considerations that have to be addressed, and, if a quantitative structural network analysis is to carry any substantial meaning, these issues must be carefully examined. Because we focus on a more qualitative approach in this initial stage, we address these issues only briefly. First, in a real-world setting, because there is most likely some kind of linkage between basically every possible node in the system, it is essential to define what kind of relationships to look for. In this paper, where we review a number of case studies to illustrate the use of the proposed network approach, only the most important links and nodes are included, i.e., the links and the nodes that really characterize the systems. Of course, this approach is only possible a posteriori, i.e., when such knowledge is available. In other cases, one could start by looking for the major drivers of change, both social and/or ecological, and the major actors at work, both social and/or ecological as well, and from there define which components and which relationships seem to be the most influential and thus the ones to include in the network analysis.

Most network analyses examine static networks, but we will briefly discuss some important aspects of dynamic networks that are of relevance to resilience. Nodes and links are not always active. Some are sleeping nodes and links that are activated only in specific situations such as a crisis. Maintaining the capacity to reactivate these nodes and links in times of crisis is an important contribution to the system's resilience. When nodes or links disappear from a system, it seems that one characteristic of a resilient system is the ability to fill up that space in the network with new nodes and links (Walker et al. 1999). For example, if no such adaptation is possible in the food web, the extinction of a species can lead to several secondary extinctions and cascading changes in the web (e.g., see Ebenman et al. 2004).

NETWORK METRICS AND THE STUDY OF RESILIENCE OF SOCIAL-ECOLOGICAL SYSTEMS

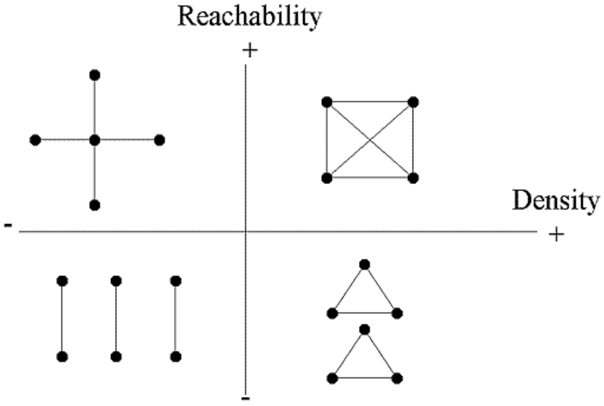
In our initial attempt to pursue the network approach when comparing cases studies in the context of resilience, we have chosen to focus mainly on two important and broad characteristics of network structures, namely, the level of connectivity and the level of centrality. These characteristics are described below and illustrated for the purpose of finding some archetypical networks in social-ecological systems. Although these characteristics are very general, they are still comprehensive, i.e., they do represent some of the very fundamental structural properties of importance in any kind of network and have been used to classify vulnerabilities of networks (Albert et al. 2000, Dunne et al. 2004). For example, scale-free networks, which have a high level of centrality, are vulnerable to targeted attacks on the nodes that function as hubs. On the other hand, scale-free networks are robust to the random removal of links. Naturally, there are other kinds of structural properties that could be of interest, e.g., the level of reciprocity or the degree to which ingoing links are reciprocated with outgoing links, but we believe that by using just connectivity and centrality we can capture the essential functional implications for the resilience of the structure of a given social-ecological network. We do not expect to find a simple relationship between network metrics and the resilience of social-ecological systems. The impact of structural relationships relates to the function of the flows within the network. Information flows and disease transmission have different consequences for the same system. A rapid transmission of SARS because of the system's high levels of connectivity is not desirable, but the faster information exchange on the treatment of the disease enabled by high levels of connectivity is.

We also present some metrics that can be used for each characteristic. These metrics can be measured in a quantitative way, although it might not always be straightforward when different kinds of links are considered simultaneously. Furthermore, we present some broad and general remarks about the possible implications of these characteristics on the functioning of social-ecological systems.

Level of connectivity

One characteristic represented by the level of connectivity is the density of the links within the network, i.e., the number of links divided by the maximum possible number of links. Another aspect of connectivity is reachability, or the extent to which all the nodes in the network are accessible to each other. These aspects are not independent, and one could say that high density normally implies high reachability. They are, however, not the same, and it is possible to have networks with both high density and low reachability if there is a high level of clustering, i.e., the links are distributed only within, and never between, isolated clusters (Fig. 1). Figure 1 shows the two dimensions of connectivity of relevance for resilience. The example of high reachability and low density is a simple network in which the minimum number of links is used to connect all the nodes, and they can all be reached within two steps. The example of low density and low reachability shows that none of the nodes can reach all of the other nodes. In the case of high density and high reachability, all possible links are included and each node is a neighbor of each other node. When we cut a high-density network in two, we get a low-reachability variation. These two characteristics of networks relate to resilience in the following way. If the subject of interest is the diffusion of a virus in a network, then networks whose nodes are harder to reach are less susceptible to the spread of disease. If the subject of interest is the resilience of a network to the disappearance of links, then higher-density networks include redundancy of links and are therefore more resilient to the removal of links.

Fig. 1. Different types of networks as a function of reachability and density.



In Tables 1 and 2 we present a number of the advantages and disadvantages of density and reachability with regard to the performance of the system. Although these tables should not be seen as exhaustive, we do try to capture some of the many effects these characteristics can have on network resilience. As is clear from the tables, sometimes density and reachability have a positive effect on the resilience of a system, and sometimes their impact is negative. A high level of density in the area of social relations may be beneficial to the spread of information, whereas a high level of density with regard to ecological links can lead to the rapid spread of undesirable ecological agents such as viruses and invasive species. Furthermore, in a particular social-ecological network, the spread of, e.g., viruses among ecological components could be enhanced if a far-reaching network of social agents brings together ecological components that are normally fairly isolated.

To exemplify the double-edged nature of connectivity when it comes to social networks, consider a number of interconnected resource managers of similar ecological systems that may or may not be interlinked themselves; it is obvious that these managers can improve knowledge and management by the exchange of experience and advice on how to manage their resources. However, a density of such social links that is too high may also hinder local experimentation, because management strategies can become locked-in (Bodin and Norberg 2005). The resilience feature in this type of network is the balance between learning from others and room for individual innovation. The same argument for balancing different structural aspects can be applied to ecological networks, e.g., a high density and/or high reachability of ecological links can facilitate rapid recolonization following local disturbances (Nystrom and Folke 2001) and prevent the fragmentation of species populations (e.g., Keitt et al. 1997), but it can also contribute to the rapid and far-reaching spread of viruses, as stated above.

There are several ways to measure these characteristics. The definition of density is straightforward, and to quantify reachablility we suggest using network diameter, i.e., the minimum path length connecting any pair of nodes in the network, and/or the size of the largest component, i.e., a set of nodes in which there exists a path between any two nodes; both these concepts are described by, e.g., Wasserman and Faust (1994). A short diameter implies that it is possible to move through the whole network in just a few steps. Similarly, if the largest component contains a large fraction of all the nodes in the network, there is, by definition, a high probability that any two nodes are interconnected.

Level of centrality

Level of centrality covers not only the distribution of links among the nodes in the network but also their structural importance. There are several formal metrics of centrality available, each with its own benefits (for an overview, see Wasserman and Faust 1994). Here we use the term centrality in a less

Table 1. Sensitivity of the performance of a system to differences in density.

Density	Advantages	Disdvantages
High	Good information exchange/learning gives better management (e.g., Pretty and Ward 2001) Enhanced diffusion of innovations (e.g., Abrahamson and Rosenkopf 1997)	Potential for systems to become superconnected and brittle (Redman and Kinzig 2003)
Low	Increased diversity in management practices, low risk for lock-ins, and global coherence (Bodin and Norberg 2005)	Limited spread of information

mathematically formalized way. With a high level of centrality we imply that there are some high-ranking nodes in the network that have a significantly higher-than-average number of links and/or have links stretching far beyond their local network neighborhoods. Well connected nodes, i. e., hubs, in the network, are most likely of higher importance than others that are not so well connected. In addition, nodes do not necessarily need a specific number of links to be of importance, because they can connect different clusters, i.e., brokerages.

Like connectivity, centrality has different effects on the resilience of social-ecological systems (Table 3). Centrality may facilitate coordination and control but reduce the diversity of the nodes when the network represents information exchange, because all the nodes are closely connected to the few central nodes and all of them receive similar information. Furthermore, the performance of a highly central network is strongly dependent on the existence of a few hubs, which could be key species or social leaders. If just a few of these hubs are removed, the network can dissolve into small and unconnected subnets. Albert et al. (2000) showed that scale-free networks are vulnerable to the disappearance of their hubs

Several formal metrics of centrality are available. Two of the most well known metrics are degree centrality (Freeman 1979) and betweenness centrality (Freeman 1979); the former simply measures the number of links a node possesses, whereas the latter aims at capturing how important a node is when it comes to decreasing the network distance, i.e., the path length, between any two nodes. Figure 2 illustrates two simple networks with different levels of centrality.

Archetypical social-ecological networks

We argue that the different archetypes of social-ecological networks experience different types of challenges with regard to resilience. Thus, by assessing the level of connectivity of social-ecological networks, these network can (1) be analyzed and categorized in terms of their performance when it comes to the various aspects of resilience outlined in Tables 1–3 and (2) considered comparable, i.e., the different cases can be compared with each other because they are categorized using the same common framework.

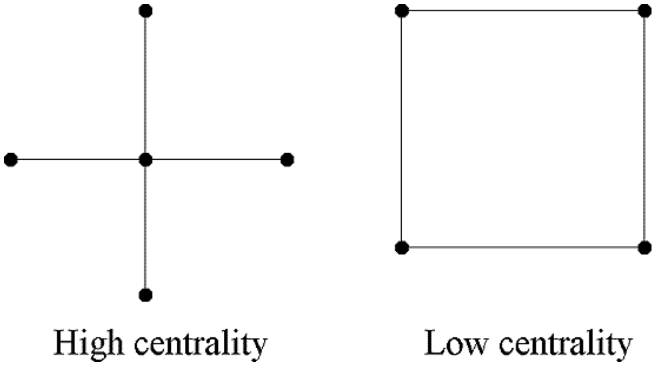
We distinguish three types of social-ecological networks:

1. ecosystem networks that are connected by people via information or physicial flows,
2. ecosystem networks that are disconnected and fragmented by people, and
3. ecosystem networks that connect people.

Table 2. Sensitivity of the performance of a system to differences in reachability.

Reachability	Advantages	Disdvantages
High	Access to distant information (Granovetter 1973)	
	Increased ability to respond to changes (see Aldrich 1999 and references therein)	Spread of contaminants over large distances
	Union of different social actors, e.g., government agencies and local users, to better match ecological and social boundaries (Schneider et al. 2003)	Increased spread of diseases such as HIV (Friedman et al. 1997)
	Enhanced possibilities of long-range interpatch dispersal (Urban and Keitt 2001)	
Low	Potential for the formation of coherent and efficient groups/clusters	Difficult recolonization (Keitt 1997, Nystrom and Folke 2001)
	Implications of disturbances such as, e.g., extinction of single species, do not extend beyond the local neighborhood in food webs (Krause et al. 2003)	Inaccessibility of distant information (Granovetter 1973)

Fig. 2. Two simple networks with different levels of centrality.



People can connect ecosystems in different ways. Knowledge about the governance of ecosystems might be exchanged to allow the experience derived from one location to be used to govern the ecosystems in another location. People can also connect ecosystems by physical flows, like fishermen introducing invasive species when putting their boats in different lakes or pastoralists who move cattle between different properties. A characteristic of this type of network is that links are added, which might increase the density, reachability, and centrality of the network as a whole. This makes the system more sensitive to the diffusion of information or physical flows.

Original ecosystem networks are frequently affected by human activities. Links are disconnected by, for example, overharvesting species in food webs, adding roads through ecosystems, and lowering the groundwater level. This reduction of reachability affects the resilience of any social-ecological system that depends on the redundancy of the links in its network, i.e., density. For the governance of ecological networks it is important to maintain the reachability of the system, for example, by conserving ecological nodes with high centrality.

The resilience of the first two types of networks is affected by the addition or removal of links. The third type of network is affected by the coordination of the flows in the network. Because of the physical interactions within ecosystems, the seemingly unrelated activities of resource users become dependent on one other. The actions of different

Table 3. Sensitivity of the performance of a system to differences in centrality.

Centrality	Advantages	Disadvantages
High	Efficient coordination when solving simple tasks (see Langan-Fox 2001 and references therein) Potential to be more accountable, i.e., the central actors can to some extent be held responsible for the group	Reduced distribution of information (e.g., Shaw 1981) Possible perception as undemocratic and unfair Greater vulnerability to targeted attacks (Albert et al. 2000)
Low	Possible perception as more fair and open to group participation Robustness to removal of nodes (e.g., social leader or species) High group efficiency when solving complex tasks (see Langan-Fox 2001 and references therein)	Possible lack of control and accountability Inefficiency when solving simple tasks

types of stakeholders affect different parts of the network, and, for the performance of the social-ecological system, it may be necessary to coordinate these activities. An example of this is irrigation, an artificial ecosystem in which the resilience of the system is highly dependent on the coordination of the use of water.

One of the questions for this type of system is how to organize the activities related to coordination. A long-lasting debate about irrigation is whether central bureaucratic organizations are necessary to coordinate the network (Wittfogel 1957) or whether self-organized local interactions can also lead to resilient irrigation systems (Lansing 1991).

In future research on social-ecological networks, we must also explore in more detail how the network metrics change over time, during the different phases of the adaptive cycle. In the *K* phase of the adaptive cycle, a network is likely to have high centrality and high reachability. Because maintaining connections costs resources, the network might have evolved into the *K* phase with a low density. A disturbance can affect the nodes or links. The expected reorganization phase probably consists of a high density of interactions between nodes, but low centrality and reachability. Vulnerability to a disturbance can be caused by (1) high connectivity, so that, e.g., disease spreads quickly; (2) high centrality, so that, e.g., there is a limited diversity of knowledge at the decision-making nodes; or (3) low density, so that, e.g., the loss of a link has a high impact on the entire system.

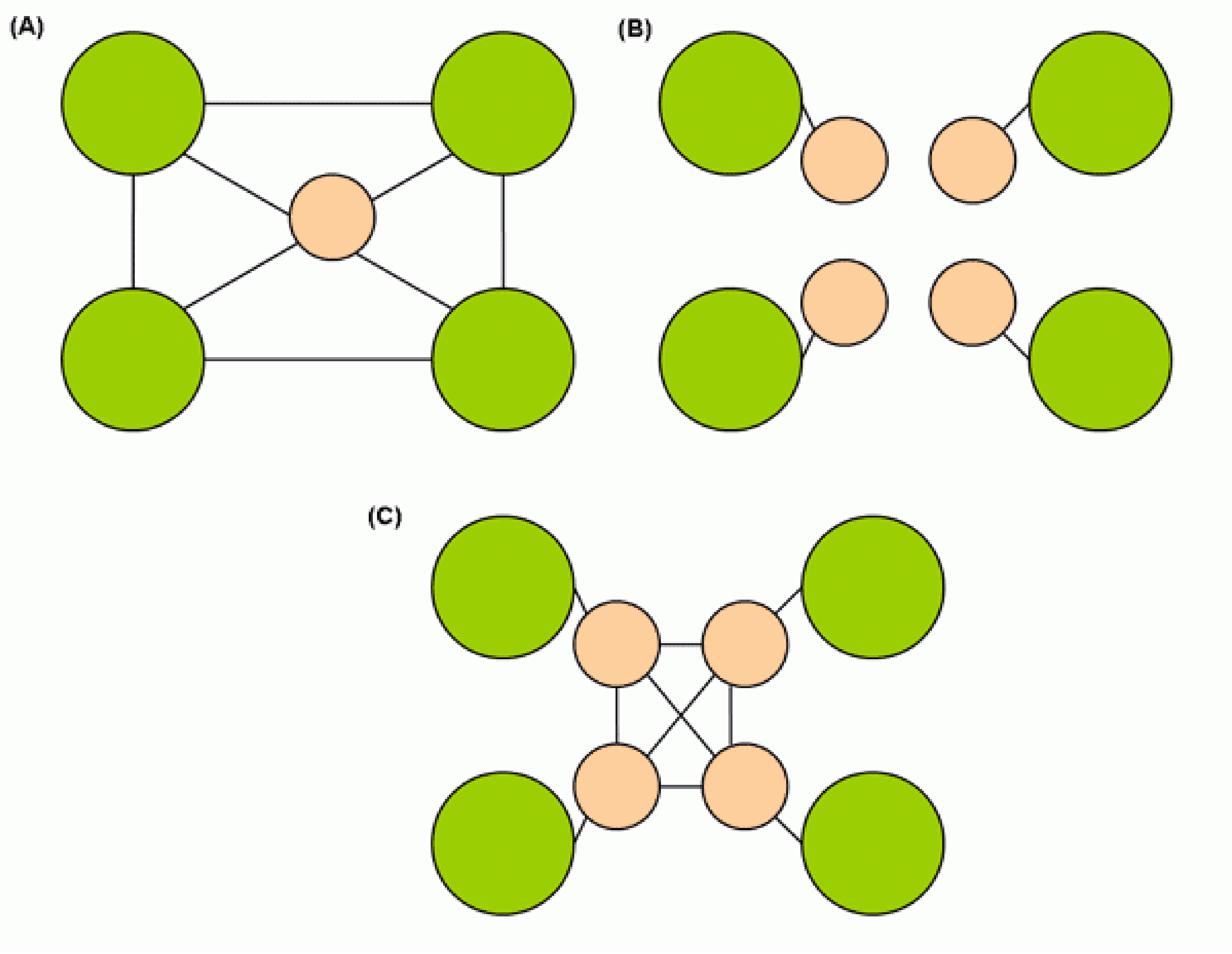
In the next section we will provide examples of the three types of networks, as discussed in more detail in the rest of this special issue.

ANALYZING CASE STUDIES AS SOCIAL-ECOLOGICAL NETWORKS

People connect ecosystems: agistment in Australian rangelands

In the rangelands of northern Australia, cattle-grazing enterprises dominate land use and have done so since Europeans first displaced indigenous populations in the late 1800s. The initial pastoral development phase of the Australian rangelands saw the establishment of large enterprises with few fences and highly connected subecological systems (Fig. 3A). The next phase of pastoral development saw governments breaking these properties into smaller spatial units in the hope of achieving a more

Fig. 3. Development of agistment networks in Australian rangelands. Large circles represent ecological subsystems; small circles, pastoral enterprises. (A) Open-range system with very large unfenced paddocks, uneven distribution of stock grazing pressure around watering points, and a high degree of natural drought-buffering capacity. (B) Fragmented system with more intense and evenly distributed grazing pressure and reduced natural drought-buffering capacity. (C) Fragmented system with agistment in which informal networks have developed to partially increase the scale of management.



equitable distribution of land and promoting social development through closer settlements throughout regional Australia (Fig. 3B).

However, the scale of climatic variation in these rangelands is large, both temporally and spatially. Therefore, when enterprises were scaled down in size, the mismatch between the scale of grazing enterprises and the ecological processes that underpin the system increased. Agistment is the temporary movement of cattle between properties in exchange for financial reward. Agistment networks evolved to allow enterprises to redress this scale issue in two ways (Fig. 3C). First, they allow cattle to be shifted around the landscape in response to spatially and temporally variable rainfall patterns

(McAllister et al., *in press*); second, they allow enterprises seeking to increase the spatial scale of their operations to stagger their investment, so that pastoralists can either purchase land and accept agistment cattle or purchase cattle and agist the cattle on land belonging to other ranches. Staggering investment is important because it often happens that individual pastoralists can borrow enough capital to buy either cattle or land but not both.

In addition to providing a buffer against regional variations in precipitation, the agistment of livestock in Australia, which is made possible by the availability of cheap transport, builds relationships of mutual trust between pastoralists with matching requirements. To determine the role of agistment networks in system resilience, we need to define and understand their social and physical structure. Social nodes are composed of pastoralists, who are physically linked to the pastoral properties they manage. One enterprise may own several spatially dispersed properties, but, even though stock can be transported between the various properties belonging to a single enterprise, agistment implies some financial transaction that does not occur within the enterprise itself. Links are created when stock are agisted between nodes. Another type of link is created when one node exhibits a degree of trust toward another node. In terms of analyzing resilience, using the less quantifiable notion of trust to define links is more useful. This is because it is the potential for agistment interactions that contributes to system resilience. In fact, when an agistment interaction occurs between two nodes, the link that connects the two nodes may subsequently disappear if the trust invested in the interaction was dishonored by either party, which seems to be a relatively common occurrence in agistment arrangements (R. R. J. McAllister, M. A. Janssen, M. Nicholas, and I. J. Gordon, *unpublished manuscript*). Agistment interactions test the broader agistment network, which is based on trust built up not just as the result of direct interactions between individual pastoralists but also via the testimony and preconceptions of others. In addition, this broader network contains what are known as “sleeping links,” because most pastoralists only ever engage a fraction of the directly connected nodes in their individual networks. It is this complete network of potential agistment opportunities that is important in fostering resilience. Actual agistment patterns depend largely on the patchy distribution of rainfall, because spatial rainfall patterns affect who is able to accept additional livestock and who may need to reduce the grazing pressure on his or her land.

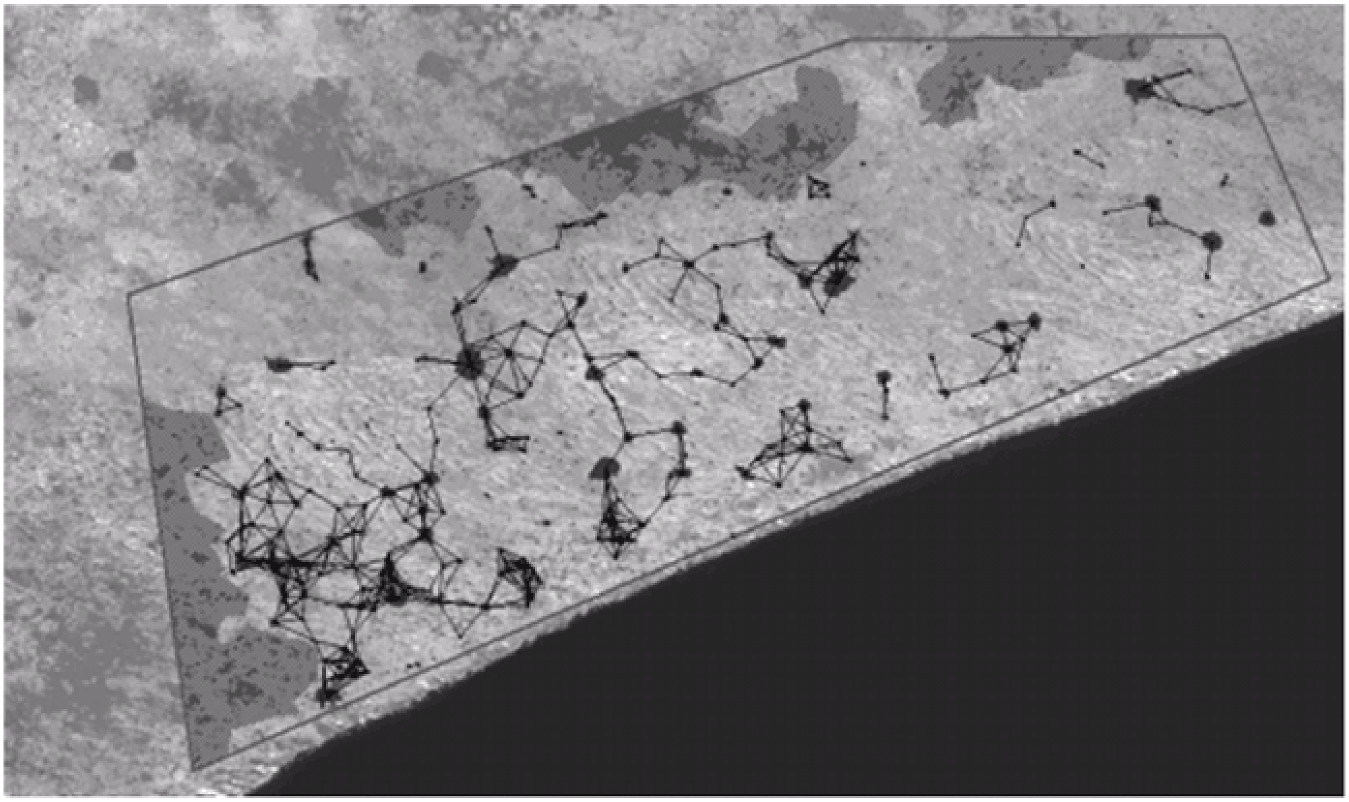
People disconnect ecological networks: the case of sacred forests in Madagascar

The sacred forests in southern Androy, Madagascar, offer an example of a fairly well connected landscape in terms of the aspects described in this article, although the forest is severely fragmented, with several hundred forest patches < 1–95 ha in size constituting islands in a sea of agriculture (Clark et al. 1998; M. Tengö, K. Johansson, F. Rasoarisela, J. Lundberg, J. A. Andriamaherilala, E. Andersson, J. A. Rakotoarisoa, and T. Elmqvist, *unpublished manuscript*). It has been argued elsewhere that, when fragmentation reduces a specific habitat to less than 30% of the landscape, the spatial arrangement of patches becomes more important for species survival than total habitat area (Andrén 1994). In the area described here, the forest coverage is only approximately 3.5 %. Most patches are protected by local taboos that restrict entrance and resource extraction (M. Tengö, K. Johansson, F. Rasoarisela, J. Lundberg, J. A. Andriamaherilala, E. Andersson, J. A. Rakotoarisoa, and T. Elmqvist, *unpublished manuscript*). These taboos have protected the forest patches for a long time (Heurtebize 1986).

We have focused on one essential ecosystem service supported by the forest patches, the seed dispersal services of the forest-dwelling ring-tailed lemurs (*Lemur catta*), and used this as a model for understanding some of the dynamics of the agri-forest system (see Bodin et al., *in press*). The analysis particularly addressed how further loss of forest patches by successive removal of the smallest patches affects landscape connectivity, in particular reachability, and the generation of ecosystem services.

A graph-theoretical landscape modeling approach was applied (Urban and Keitt 2001), in which the forest patches were represented as a graph, i.e., as a set of nodes connected by links. Using this approach, any two nodes, i.e., forest patches, are considered as connected, i.e., linked, if *L. catta* is presumed to be able to move between these habitat patches by traversing the landscape matrix. In other words, the graph encapsulates the potential for *L. catta* to traverse the whole landscape by moving from patch to patch (see Fig. 4).

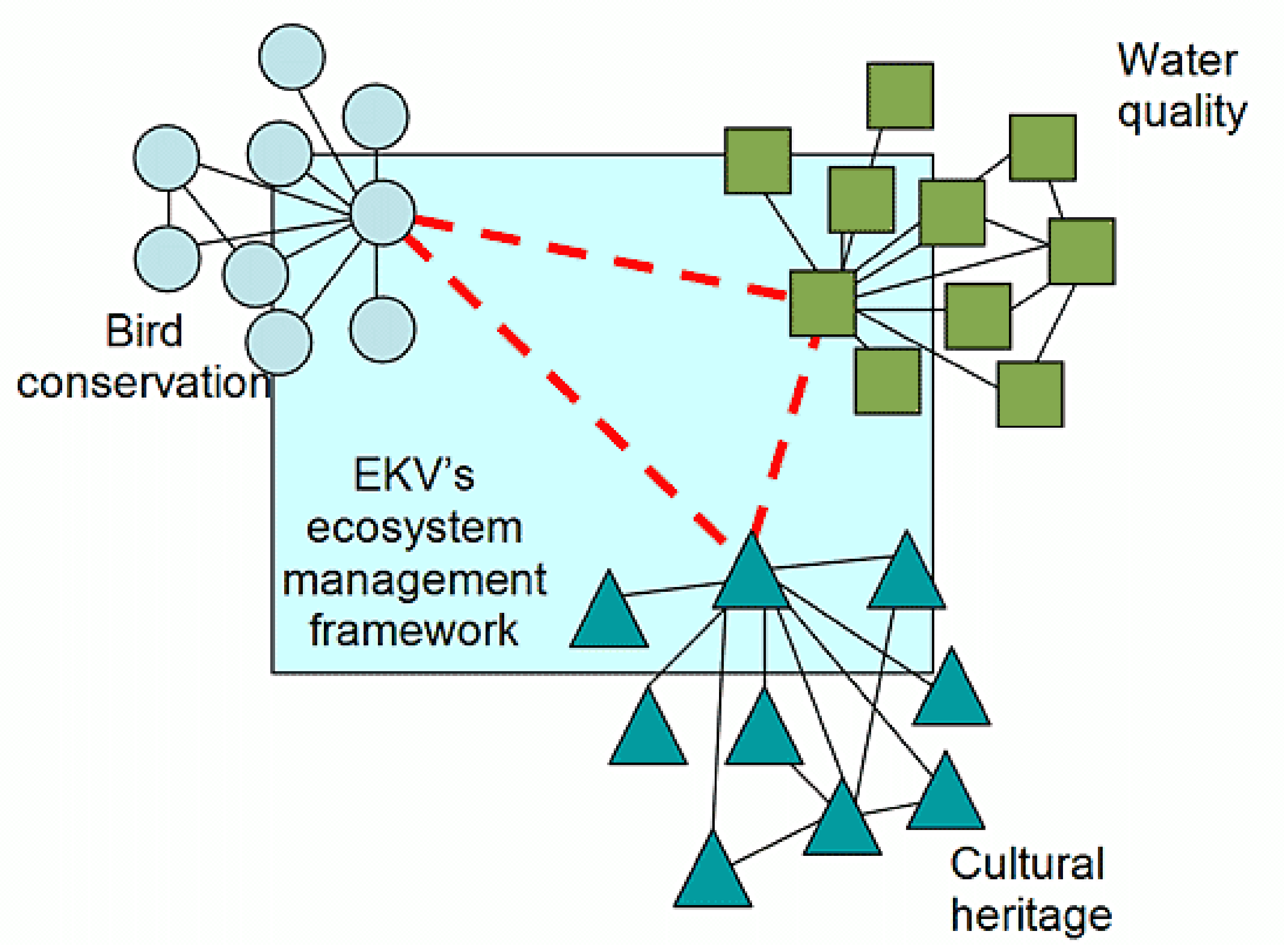
Fig. 4. Southern Androy, Madagascar, as seen in a Landsat image from May 2000 (adapted from Bodin et al. 2005). The study area is defined by the rectangular box. The isolated forest patches are distinguished by the separate dark spots situated within the light gray matrix of cultivated land. Patch sizes range from 1 to 95 ha, and the patches are fairly evenly distributed in the landscape. Areas classified as source areas are marked in the western and northern parts of the studied area. The spatial structure of connectivity of the present landscape, including forest patches measuring 1 ha or larger, as expressed through the graph theoretical model is shown when the vagility of *Lemur catta* is set to 1000 m.



The simplest graph that can be constructed is based on a maximum geographic distance between habitat patches in the landscape, i.e., any two habitat patches that are separated by a distance less than a defined threshold distance are considered connected, and thus they will be connected by a link. More advanced procedures to define links, although based on the same principle, are possible (for details see Bodin et al., *in press*). We defined the vagility of *L. catta* as the distance an individual is likely to move in search of food, and we concluded that 1000 m is a reasonable estimate in this study area. This estimate was used to construct the graph in Fig. 4. The components of the graph-theoretical model of the landscape are subsets of nodes in the graph in which there is a path between any two nodes; these represent a subset of habitat patches that are interconnected and, therefore, within reach of each other. Thus, by measuring the size of the largest component while simultaneously simulating the successive removal of the smallest patches, we can model the effect on the landscape's connectivity as experienced by *L. catta.*

The modeling results reveal that, although the decline in total forest area was found to be rather constant with successive losses of patches, the landscape also experienced varying rates of sudden drastic changes and thresholds in connectivity as expressed through the size of the largest component.

Fig. 5. Social network of different resource users of Kristianstads Vattenrike (P. Olsson, L. Schultz, C. Folke, and T. Hahn, *unpublished manuscript*). EKV stands for Ecomuseum Kristianstads Vattenrike.



The thresholds derive from the rapid break-up of the largest components when certain patches are successively lost and/or vagility declines (Bodin et al., *in press*). The thresholds are generated by changes in the spatial configuration of patches rather than by reduction of the area per se. These findings add to the growing evidence that in a landscape perspective, and especially when addressing ecological functions other than biodiversity conservation, small patches can, in spite of their limited size, play a significant role (Turner and Corlett 1996, Fischer and Lindenmayer 2002, Götmark and Thorell 2003). This spatially explicit model can be used to analyze and identify both "keystone patches," i.e., patches with high centrality that have a disproportionately strong negative effect on connectivity when removed, and areas suitable for restoration, i.e., an added patch that has a disproportionately high positive effect on connectivity.

In terms of resilience, landscape connectivity and the potential for seed dispersal services are very vulnerable to the removal of additional forest patches. From an ecological standpoint, it would be desirable to increase the density and/or reduce the level of centrality of the ecological network, i.e., to reduce the importance of a few critical forest patches. This could be done by, e.g., creating new patches carefully placed in the vicinity of the critical patches. Such ecological restoration attempts must, however, be embedded in the management system and incorporated into the social structure of the local communities who monitor compliance with the taboo associated with a particular patch.

Coordination in social-ecological networks

Co-management in Kristianstad, Sweden

The case study of the Kristianstads Vattenrike (Kristianstad Water Realm) described in Walker and Lawson (2006) is here used as an example of a system in which there exist linkages between different ecological components, but whose social components have not previously been interconnected to the same extent. The essential ecological components of interest, given the scope of this study, are basically areas of cultivated land, wetlands, and a river.

The circles, triangles, and squares in Fig. 5 represent social actors in different networks related to the various initiatives that existed in the area prior to the change in management regime in 1989. The nodes represent members of different interest groups, whereas the links refer to social interactions and information exchange. Although they included actors at several levels, they were often narrow in focus. Because declining bird populations, the abandonment of management practices for cultivating flooded meadows, and problems related to water quality and overgrown lakes were interrelated and connected, one actor, who was later to become the director of the Ecomuseum Kristianstads Vattenrike (EKV), saw the need to connect ongoing projects to match the scale of the problem and manage the area at a landscape level (Olsson et al. 2004). This actor played a key role in establishing links between the other important actors in those projects, shown as dotted lines in Fig. 5. He was also instrumental in developing a framework, including a vision and goals, for managing the flooded meadows in the area, illustrated as the larger blue square in Fig. 5. This framework is part of the arena for collaboration that helped to guide the interactions among actors (T. Hahn, P. Olsson, C. Folke, and K. Johansson, *unpublished manuscript*).

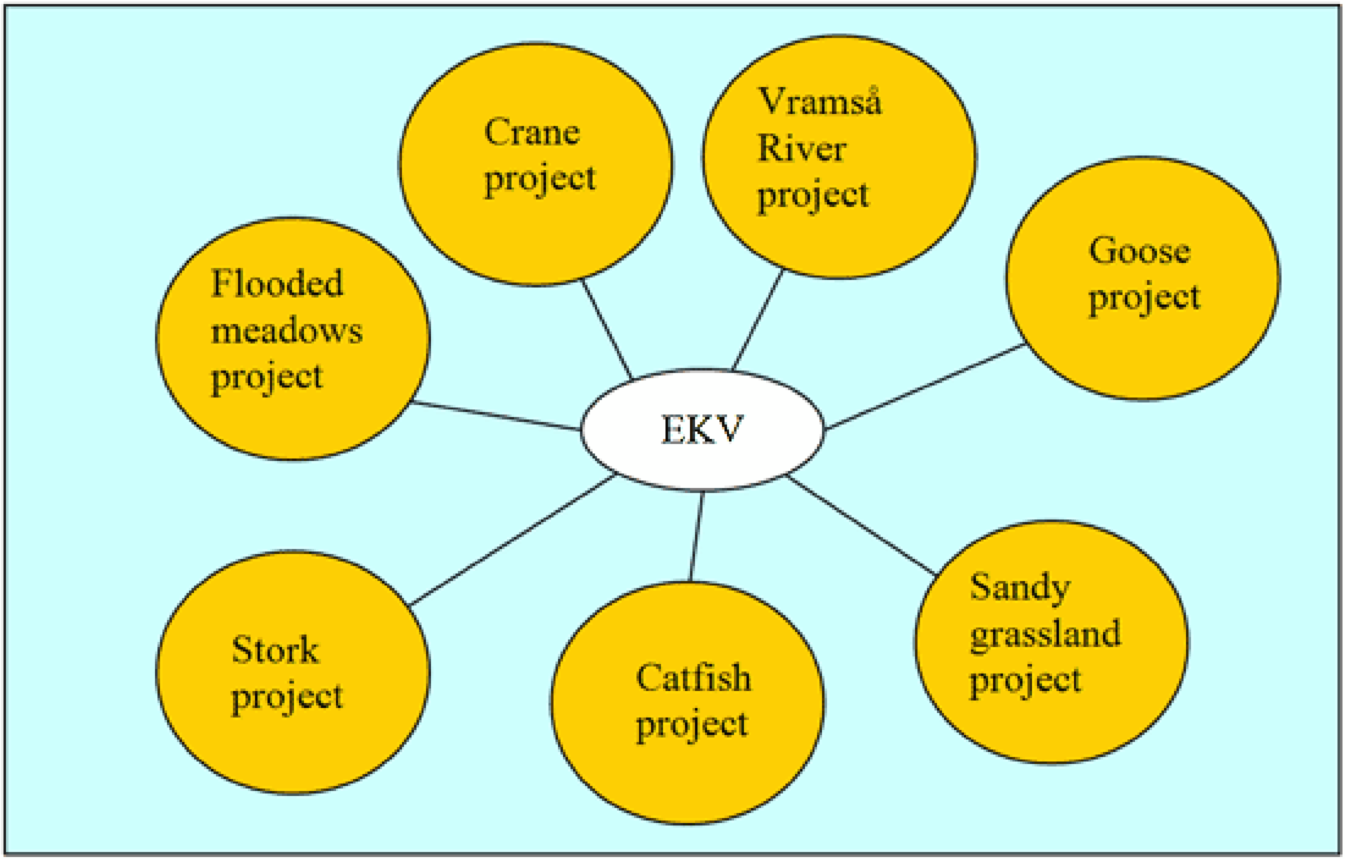
The EKV is important in the process of expanding management structures to meet the new challenges of matching social and ecological dynamics. Such expansion is needed when prevailing management structures are unable to address functional links in the landscape, for example, between sandy grasslands and flooded meadows (Olsson et al. 2004). These used to be connected by grazing but are not any longer, a situation that is similar to the preliminary stage of the agistment network in Australia.

As mentioned above, influential actors from different networks and ongoing projects in the Kristianstads Vattenrike (KV) were linked to manage the flooded meadows. The flooded meadows project thus became a node of social-ecological activity embedded in the overall network as depicted in Fig. 5. The establishment of the links between ongoing projects was to overcome the problem of ecological nodes that were functionally linked but whose managers, i.e., social agents, were not. It was a way to match ecological and social processes across scales (P. Olsson, L. Schultz, C. Folke, and T. Hahn, *unpublished manuscript*).

At another scale, the flooded meadows project becomes a node in the network of projects assigned to the nature conservation section of the EKV (Fig. 6). The EKV, which is a key actor in all of these projects, thus also links the other projects by acting as an intermediary. The other projects are also to some extent linked, because several actors are part of more than one project.

The management of the flooded meadows also illustrates a more complex picture that includes the interplay between different types of social-ecological relationships. Different layers, i.e., types of relations, of the social network are important for making the adaptive co-management of the KV robust (P. Olsson, L. Schultz, C. Folke, and T. Hahn, *unpublished manuscript*). There are, for example, the information layer, in which links increase the knowledge pool for decision making at different levels, and the commercial layer, in which links provide access to markets for farmers and goods for consumption. It is suggested that the interactions between the network layers make the system more robust, implying that the failure of a link in one layer can be buffered by links in other layers.

Fig. 6. The framework for the nature conservation section of Ecomuseum Kristianstads Vattenrike (EKV).

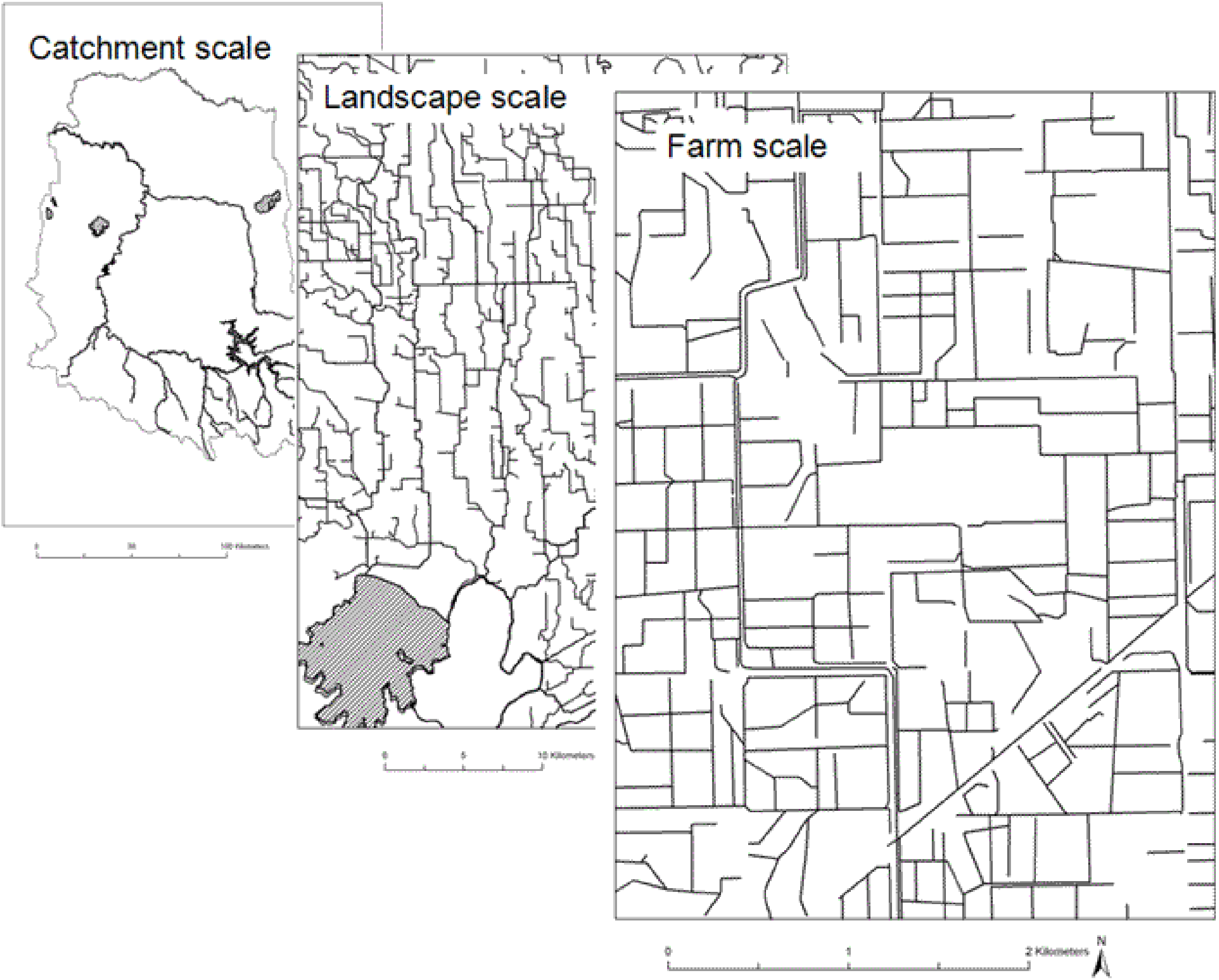


From Fig. 6, it seems quite clear that the EKV plays the role of coordinator and that the social-ecological system is very vulnerable to the removal of the EKV. However, this network structure has been very beneficial in the creation of the adaptive co-management regime. The key individual, later the director of EKV, could, by being the most central actor, coordinate and to some extent control other projects and groups of actors in the initial creation phase, thus bringing about a change in management practices. The high centrality of the EKV is, however, less resilient in the long run and could by its highly influential position contribute to a lack of diversity. From a resilience perspective, therefore, there is a need to increase the level of interconnectedness among the other actors, thus bypassing the EKV, and to take steps to make the EKV less dependent on the key individual. Such changes seem to be under way.

Irrigation in the Murray-Darling Basin, Australia

Irrigation networks generally consist of infrastructure that captures and/or diverts water and canals, ditches, or piping that distribute water resources in spatial and temporal patterns that enhance and manipulate production to suit human requirements. This spatial and temporal redistribution of water resources reduces the natural fluctuations and seasonality of rain-fed agriculture, allowing greater production per unit area of agricultural land over time. The Shepparton Irrigation Region is a 500,000-ha gravity-fed irrigation system in the Goulburn Broken Catchment (GBC) in northern Victoria, Australia (Fig. 7). The clearing of more than 90% of its native vegetation and the application of irrigation water have disrupted the natural hydrological cycle of the region; this caused water tables to rise and, in turn, triggered large-scale soil

Fig. 7. Nested structure of the irrigation infrastructure network in the Goulburn Broken Catchment. At the catchment scale, there are a small number of large dams, i.e., nodes, with sections of natural waterways and large canals, i.e., links, are used to capture and transport water. At the irrigation region, a landscape-scale network of infrastructure transfers water between temporary storages or nodes and to irrigation properties via open channels or edges. At the farm scale, the irrigation network connects intermittently to canals, i.e., the links of the landscape-scale network above, when irrigation water is required for pastures and crops.



salinization. Salinity now threatens the long-term viability of irrigated agriculture in the region (SPAC 1989).

The historical structure of the network, particularly the landscape-scale network, was determined by a mix of topography to ensure efficient flow and social policy that was designed to facilitate the development of the rural communities in the region. This dual-purpose approach to design resulted in a dense network that is highly inefficient in terms of network function. Approximately 30% of water is lost from the system between the catchment and farm-scale networks (Langford et al. 1999). Further, the fixed infrastructure means that, during peak periods, the demand for irrigation exceeds the maximum capacity of the canal network, delaying the irrigation of valuable crops and pasture. The irrigation network also makes it possible to transmit a range of undesirable products and organisms, including solutes such as salt, nutrients and pollutants; pests, including weeds, freshwater crayfish, and introduced fish; and pathogens, throughout the built infrastructure and the ecological network of rivers and streams (Sampson 1996).

An emerging issue in the GBC, and one common to irrigation systems, is the asymmetry of power and competing demands between upstream and downstream users. The GBC irrigation network is governed by property rights determined historically though a formal institutional process with little regard for the social or ecological impacts of these decisions. In the GBC, all surface-water and groundwater resources are “owned” by the state, which gives the network a high level of centrality, and are granted to individual irrigators under license, so that downstream irrigators have a legally recognized right to the rainwater that falls on the properties of upstream landowners. This limits the capacity of upstream communities to expand and develop economically, and, as a result, property rights to water are being continually tested, often through expensive legal processes, which creates tension and conflict between the social networks in the GBC (Langford et al. 1999). Additionally, the capture and storage of water high in the catchment, where more than half of all river flows are diverted for irrigation, affects the ecology of the entire downstream river system and the adjoining floodplains. The release of water down the system is determined by irrigation demand, which peaks during mid-summer, the period when natural flows would be at their lowest, disrupting the reproductive cycles of icon species of flora and fauna.

The vulnerabilities in the irrigation system are caused by its high centrality, which leads to inequalities in power and knowledge, and high connectivity, which requires detailed coordination of water use and results in the unanticipated diffusion of undesirable products.

DISCUSSION

We proposed a network perspective for the analysis of the resilience of social-ecological systems. A network perspective focuses on the structure of such systems and the importance of structure for their resilience. So far, theoretical studies on the robustness of networks have focused on static networks in rather homogeneous systems, and applying this perspective to more heterogeneous and dynamic systems is more difficult. Nevertheless, we were able to identify three types of social-ecological networks and their effects on resilience, and discuss this typology using illustrations from various case studies.

A social-ecological system can be represented as a social-ecological network by the different attributes of the system that would be used to draw a structural map, e.g., trust, information, power, movement of cattle, contamination, seed dispersal. For each network of particular attributes, we can analyze the properties of the network. The network consists of both human or social nodes and nonhuman or ecological nodes, plus their connections, which represent the various attributes. We propose that the level of connectivity, i.e., reachability and density, and the level of centrality are comprehensive, but still relevant, measures that encapsulate the structural aspects of a social-ecological network, and as such should be used when assessing its resilience. There is no simple relationship between connectivity and resilience. It depends on the specific characteristics of the various metrics of the network. For one particular social-ecological system, resilience can be increased by increasing the density of some attributes, such as the exchange of experience in Kristianstad, but decreasing the density of others to reduce the spread of viruses.

An important problem in resilience assessment is the lack of clear indicators that can be used to monitor the properties of social-ecological systems such as reachability, centrality, and density. A network perspective provides a tool that might be instrumental in deciding which information to collect. The case studies in this paper have not been selected for their network properties, nor do they share specific network characteristics. Nevertheless, we have been able to perform some analyses from a network perspective to show the various possibilities of this approach. An interesting observation is that there was an increase in the number of links during periods of reorganization in the various case studies. Sleeping links were activated during periods of crises to exchange information or to exchange livestock. Another interesting observation is that there is no clear indication of how connectivity is related to resilience, in contrast to the adaptive cycle proposed by Holling (1986).

The consequences of the structural properties of systems are context-dependent, and we are only in the initial phase of unraveling the specifics. We see a need for two important developments before a network perspective of the resilience of social-ecological systems becomes really useful. The first requirement is for the systematic collection over time of network relationships in social-ecological systems from different case studies. Second, model studies of theoretical social-ecological systems are necessary to reach a rough understanding of the expected importance of various characteristics of network structures, e.g., connectivity and centrality, for different archetypical social-ecological networks and their derivatives. The model exercises may also provide useful guidelines for systematic data collection.

Responses to this article can be read online at:
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