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# Disentangling intangible social–ecological systems

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ABSTRACT

Contemporary environmental challenges call for new research approaches that include the human dimension when studying the natural environment. In spite of the recent development of several conceptual frameworks integrating human society with nature, there has been less methodological and theoretical progress on how to quantitatively study such social–ecological interdependencies. We propose a novel theoretical framework for addressing this gap that partly builds on the rapidly growing interdisciplinary research on complex networks. The framework makes it possible to unpack, define and formalize ways in which societies and nature are interdependent, and to empirically link this to specific governance challenges and opportunities using a range of theories from both the social and natural sciences in an integrated way. At the core of the framework is a set of basic building blocks (motifs) that each represents a simplified but non-trivial social–ecological systems (SES) consisting of two social actors and two ecological resources. The set represents all possible patterns of interdependency in a SES. Each unique motif is characterized in terms of social and ecological connectivity, resource sharing, and resource substitutability. By aligning theoretical insights related to the management of common-pool resources, metapopulation dynamics, and the problem of fit in SES with the set of motifs, we demonstrate the multi-theoretical ability of the framework in a case study of a rural agricultural landscape in southern Madagascar. Several mechanisms explaining the inhabitants' demonstrated ability to preserve their scattered forest patches in spite of strong pressures on land and forest resources are presented.



## 1. Introduction

The magnitude of environmental impacts caused by human activities makes it difficult to justify disregarding social systems in any kind of scientific inquiry about the functioning of the natural environment (e.g. Clark et al., 1999; Lubchenco, 1998; Stafford et al., 2009). This widely accepted recognition of the need to think beyond the borders of scientific disciplines has led to the recent developments of several integrated transdisciplinary conceptual framework (e.g. Collins et al., 2011; Folke, 2006; Turner et al., 2003). These frameworks largely build on the assumption that societies and nature are inevitably interdependent and should be viewed upon as integrated social–ecological systems (SES) (Berkes and Folke, 1998). However, there has been less methodological and theoretical progress on how to, in detail, quantitatively study these social–ecological interdependencies (but see Ostrom, 2009). This is in part a consequence of the lack of common methods shared between the natural and social sciences but it is also a consequence of the inherent limitations of many traditional research approaches in studying highly complex and dynamic systems such as SES (Young et al., 2006). Furthermore, one fundamental question that is not unique for this context, but accentuated when studying integrated SES, is how do we account for the vast amount of variables without falling into the traps of either being too narrow in scope, thus risking missing the big picture, or too broad and therefore losing scientific depth and precision (see e.g. Romero and Agrawal, 2011). Balancing this trade off between embracing all possible explanatory variables and theories versus giving high attention to a limited set of hypothesized variables of importance naturally gets more challenging if theories from both the social and the natural sciences are used to define the pool of potentially relevant variables to chose from. In other words, we need to develop new transdisciplinary research approaches that make it possible to (1) choose, align, combine and integrate different social and natural science theories and assumptions in a coherent way, and (2) use that to quantitatively analyze empirical data in a generic, transparent and informative way.

In order to partly meet this challenge, we propose a framework that builds on the assumption that a SES can be modeled as a social–ecological network. Our framework is conceptually more

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narrowly defined in comparisons to other SES frameworks (see list above), however for the SES and the social–ecological problem domains where it is applicable, the framework can be utilized in a direct, explicit and quantitative way. The framework is first and foremost intended for analyzing empirical data, and its basic modeling approach is not hard-wired any specific theories although it is based on the assumption that the study object lends itself to an abstraction of a complex system consisting of many different parts and relations. In our approach, the social actors and the ecological resources, along with their interdependencies, are conceptualized and modeled as the nodes and the links of a social–ecological network that altogether constitutes a SES. A social actor may be an individual, a group of individuals (e.g. a community), an organization, or a state. An ecological resource may be a herd of grazers, a species, or a spatially explicit resource or ecosystem such as a forest patch or a fishing site. The patterns of interactions among social actors and ecological resources, respectively, can be assessed and studied using approaches that are well established within the social and the natural sciences (e.g. social network- and food web analysis), however for this framework we also consider interdependencies between social actors and ecological resources. Extraction of ecological resources, such as when a fishermen harvest on a fish stock, is probably the most straightforward way to define social–ecological interdependencies, but one could also apply a broader ecosystem service perspective and define social–ecological interdependencies based on recreation or regulation of environmental disturbances (e.g. Bennett et al., 2009). How to define relevant nodes and links depends on the research question, theoretical assumptions, and the characteristics of the studied SES. The framework itself is essentially a structured and transdisciplinary way to describe and organize various components of a studied SES, along with its ability to reveal and assess the frequency distributions of potentially important and re-occurring patterns of social–ecological interdependencies as described below.

The complete patterns of interdependencies (or topology) of a SES are the focus when using our framework. Hence, defining and conceptualizing a SES as a social–ecological network is the first basic step that is followed by an in-depth investigation of the patterns of interdependencies characterizing the network. This is accomplished by defining a finite set of basic SES configurations, or building blocks, that each retains some important and irreducible characteristics of a SES. By using this as an analytical point of departure, we are able to describe any SES in terms of how frequently these different building blocks occur in the larger system. Our approach thus makes it possible to unpack and precisely define and formalize in what ways societies and nature are interdependent in specific settings, and to start developing theory on how these patterns of interdependencies reflect important characteristics of these SES. The approach draws from the rapidly growing interdisciplinary research field of complex networks (e.g. Saavedra et al., 2009), and in particular it draws from earlier work on social networks ('triad census', see Davis and Leinhardt, 1972). Borrowing from recent terminology (e.g. Milo et al., 2002), we call these basic building blocks SES motifs.

Linking the framework with theory essentially require the researcher to translate theorical insights into a social–ecological relational context. In effect, the process of theory translation requires the alignment of various governance challenges, and the theoretically informed potential outcomes of these challenges, with a set of motifs. By governance we refer to the management of natural resources, as well as the structures and processes that provide the social and institutional environment in which the management can take place. As described in more detail further on, a goverance challenge could be a need for different resource beneficiaries sharing a common resource to coordinate their resource extractions, and the potential outcome (if this challenge is not addressed) could be overharvesting. The framework allows the incorporation of several different theories in parallell, thus making quantitative, integrated and multi-, inter- and transdisciplinary studies possible and feasible.

The paper is organized as follows. We start by describing the basis for the framework, i.e. the SES motifs and how they can be classified and clustered into a typology of families that correspond to some key governance challenges of SES. In doing so we thus start to fill our skeleton framework with some theories of key importance in SES research. This should only be seen as a start, and we argue that this framework could and should accommodate more and/or different social and ecological theories and conceptualizations.

A subsection where we present a heuristic approach for modeling a SES as a social–ecological network then follows (see also Cumming et al., 2010; Butts, 2009; Janssen et al., 2006). We then demonstrate the applicability of the suggested framework by analyzing social–ecological interdependencies in a rural agricultural landscape in southern Madagascar, and we conclude with a discussion on how this framework contributes to SES research.

## 2. The framework

The SES motifs are constructed following the basic assumption that any non-trivial SES must consist of multiple social actors and multiple ecological resources that are all potentially interdependent. A minimal set of social and ecological entities representing any non-trivial SES should therefore consist of two social actors and two ecological resources; i.e. a four-node representation of a social–ecological system (Fig. 1). Such a set of two plus two nodes can be interconnected in a finite number of ways, and each specific pattern of interconnecting links among the four nodes correspond to a uniquely configured SES (i.e. a SES motif). Each SES motif has six potential links (Fig. 1), thus the number of possible SES motifs is $2^6 = 64$. However, many of these motifs are equivalent, and the number of structurally unique SES motifs is 28 (Appendix A).

A real SES is, however, typically much larger and more complex than what could be captured by a small SES motif. However, by extracting all possible combinations of two social and two ecological nodes from a large social–ecological network characterizing a real SES, the frequencies of all the different SES motifs in the real SES can be quantified. The outcome of this frequency analysis thus reveals the relative abundances of the different SES motifs and their associated governance challenges (as described in

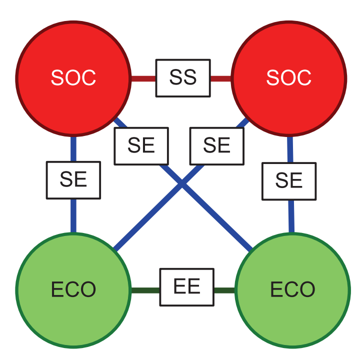


**Fig. 1.** A SES motif, i.e. a four-node representation of a social–ecological system. The top nodes represent social actors (SOC), and the bottom nodes represent ecological resources (ECO). Three types of links illustrate the potential interdependencies between the different nodes: social-to-social (SS), ecological-to-ecological (EE), or social-to-ecological (SE). Each structurally unique configuration of these types of links corresponds to a specific SES motif. Note that all links are undirected. The framework could be extended to account for directed links as well.

detail below). The frequency analysis can also be used to infer whether mechanisms exist in the larger SES that favor the emergence of some SES motifs over others; potentially highlighting key social and ecological processes. Hence, the framework is also useful when investigating dynamics of complex SES (as will be further elaborated in the concluding discussion).

To assess whether if there are more of less of a certain SES motif than would be expected by chance in the network, an appropriate null model is useful. A straightforward baseline approach to construct a null model is to generate a large set of randomly generated social-ecological networks that are created with the same number of social-to-social, social-to-ecological and ecological-to-ecological links, and nodes, as in the real network. Which SES motifs that occur more or less frequently than by chance, along with measures of significance, can be assessed by comparing the frequency of the different SES motifs in the real network, one by one, with the frequency distribution of the SES motifs among the randomly generated networks (preferably >1000).

### 2.1. A classification and interpretation of SES motifs

For the framework to be of real use in linking patterns of interdependencies to substantive insights about the SES, the 28 different SES motifs need to be interpreted in terms of possible governance implications. In order to do so, we need theory. The framework conceptually derives from two broad areas of research within the social and the natural sciences; namely the interdisciplinary research field of social network analysis (SNA) (e.g. Freeman, 2004), and the different subfields within ecology where network approaches are commonly applied. The latter includes community ecology where the use of network-based analyses of food webs is growing very rapidly (Bascompte, 2009). It also includes studies of species dispersals in a landscape context where nodes typically represent spatially distinguishable patches of habitat (Urban and Keitt, 2001; Bodin and Norberg, 2007; Cumming et al., 2010; Gonzalez et al., 2011). SNA encompasses and relates to a range of different disciplines within the social sciences such as social capital, organizational theory, and social psychology just to name a few (e.g. Borgatti and Foster, 2003; Freeman, 2004). The use of SNA in studying natural resource governance is growing, and it advances this line of research by explicitly drawing on a range of different social theories of relevance for this field (Crona et al., 2011). There are thus plenty of theories to draw from, which are all well developed from a relational (network) point of view, when interpreting the different SES motifs in terms of possible governance implications. However, in this work we constrain the analysis to basically two broad fields of theories of particular importance in resource governance: common-pool resources management (e.g. Ostrom, 1990), and the problem of fit in SES (Folke et al., 2007). From an ecological perspective we draw from the overarching insight within ecology that the levels of interdependencies among ecological components have substantial functional implications not only for the components themselves, but also for the larger ecosystem wherein these components are embedded (e.g. Allen and Hoekstra, 1992).

Guided by these broad theories, we classified and subdivided these SES first into two different groups and then into seven different families (Table 1). This subdivision is largely based on if and how the social actors access the ecological resources (i.e. the social–ecological links). Having access or not to ecological resources, at what levels, in which configurations, and for what purposes have, for example, huge livelihood implications in natural resource dependent societies and could be described as a research field in itself (e.g. Lund and Marcussen, 1994; Ribot and Peluso, 2003). In this work, we will by necessity leave out most of the contextual richness of this research, however we will explicate

**Table 1**
A classification of two groups and seven different motif families based on an alignment of insights from common-pool resources management, the problem of fit in SES, and ecological connectivity, in a social–ecological relational context.

| |
|---|
| **Symmetric access to ecological resources** |
| I. *One-to-one resource access* |
| In this family, each social actor has exclusive access to one ecological resource (Fig. 2, family I). Hence, there is no direct resource sharing taking place between the social actors, for example as when farmers own and control the fields they cultivate themselves. None of the actors are able to substitute one resource with another |
| II. *Shared single resource access* |
| In this family, both social actors have access to one single ecological resource (Fig. 2, family II). In other word, all configurations within this family are characterized by resource sharing/competition and with no possibilities for substitution. An example of this system would be two fishing communities that fish the same stock |
| III. *Multiple shared resources* |
| Both social actors have access to both ecological resources (Fig. 2, family III). This implies substitutability of resource utilization for both actors, but also sharing/competition between the two social actors. An example of this system could be two fishing communities fishing on two different species or on two different fishing sites. Both fishing communities could therefore redirect their fishing effort to either of the different species or sites at their own will |
| *IV. Separated social and ecological systems* |
| The lack of links between the social and the ecological nodes characterizes this family (Fig. 2, family IV). Hence, this family is of limited interest from a SES point of view, although the very existence of such motifs in a larger SES system informs the extent to which social actors are disconnected from the ecological resources |
| **Asymmetric access to ecological resources** |
| V. *One exclusive, one shared resource* |
| In this family, one of the social actors has access to both ecological resources while the other can only directly access one (Fig. 2, family V). Thus, one social actor experiences ecological substitutability, while the other does not, and sharing/competition is relevant for one ecological resource but not for the other. Similar to the case above, this could be exemplified by a SES consisting of two fishing communities and two fishing sites, but where only one community has the right and/or ability in extract fish at both sites |
| VI. *Mediated resource access* |
| In this family, the only way for one of the social actors to access an ecological resource is through the other (Fig. 2, family VI). This configuration suggests power asymmetries in terms of resource access, and it is plausible to assume that the actor with direct resource access are typically in a more favorable position than the other (e.g. Crona and Bodin, 2010). One might however, in other cases, envision the opposite relationship, i.e. that the social actor harvesting the resources is dependent on the other actor to get access to appropriate gear and capital to do so (Crona et al., 2010). Which of these scenarios applies for any given system depends on the context and on what types of relationships are being studied |
| VII. *Isolated social actor* |
| In this family, one of the social actors is decoupled from the other actor and the ecological resources (Fig. 2, family VII). Hence, this family is of limited interest although its prevalence can inform the level of social isolation in the larger SES |

the structural configuration on how different social actors access (or not) a set of common ecological resources. It should also be mentioned that even though we argue that our classification is broadly applicable, aligning other theories to the social-relational context of our framework might require changing the classification scheme.

The first group consists of all motifs where the social actors are connected to the ecological resources in structurally identical ways, and the second group when they are not (i.e. symmetric and asymmetric resource access, respectively). The rationale for this division is that in the former group, where there are no structural differences between the social actors, none of the actors could be said to be in a more favorable position than the other. The opposite applies for the latter group. Whether such imbalances exist or not will likely affect the actors' ability to act collectively, although if, how and in what direction depends on the specifics of the SES being studied (e.g. Crona and Bodin, 2010; Janssen et al., 2011).

The motifs in these two groups are further subdivided into seven different families (Table 1, I–VII in Fig. 2) based on whether the social actors are sharing one or more ecological resources (*resource sharing*), and/or whether the social actors have access to just one or both of the ecological resources (*ecological substitutability*). *Resource sharing*, i.e. shared access among the social actors to one or several ecological resource, implies some level of competition for the resources that can lead to over harvesting (the tragedy of the commons, see Hardin, 1968) and therefore this arrangement typically needs institutions to regulate resource extraction (Ostrom, 1990). *Ecological substitutability*, i.e. when a social actor has access to more than one ecological resource, potentially increases a social actor's ability to compensate for resource fluctuations. For example, if one resource falters, the other resource might still provide good harvests, thus increasing the actor's livelihood resilience in terms of more diversified sources of income (e.g. Cinner and Bodin, 2010). Ecological substitutability may also reduce incentives for engaging in long-term common-pool resource management since an actor has access to a portfolio of resources, and therefore each individual resource might be perceived as less important (cf. Berkes et al., 2006). Depending on how the ecological resources are defined, substitutability might not necessarily mean that a social actor can choose which resource to utilize; it could also be that both resources are needed in parallel. In such cases, other potential governance implications of this structural characteristic should be elaborated.

The motifs within the seven different families can be further differentiated based on their level of *social* and *ecological connectivity* (A–D in Fig. 2). *Social connectivity*, i.e. when there is a link between the social actors, can potentially provide for communication, learning, coordination, mediated resource access, collective action and common agreements among the social actors (e.g. Crona et al., 2011; Bodin and Crona, 2009). The assumption that the existence of social relations comes with large implications for individuals, groups and whole societies actually constitutes the very foundation of the social relational approach of SNA (Freeman, 2004). It can also be seen as a prerequisite for successful common pool resource management since social actors lacking any means for communications would have difficulties agreeing upon, maintaining or enforcing any common institutions regulating resource use (Ostrom, 1990). The actors in family II, III, and V share at least one ecological resource and therefore risk ending up with a tragedy of the commons. However, in motif II.B or D, III.B or D and V.B or D the social links between the social actors indicate that the actors could communicate and agree on common measures to regulate resource use and thus avoid a tragedy of the commons. For example, two fishing communities that are communicating may agree on a temporary or spatial ban on fishing to restore a common fish stock.

*Ecological connectivity*, i.e. when there is a link between the ecological resources, to some extent defines the very nature of something being *ecological*. Without ecological connectivity, there would not be any ecosystems (cf. Odum, 1953). Increasing the levels of ecological connectivity among different ecological components, however, generally increases the level of ecological complexity and typically makes governance more challenging since predicting responses to different management options becomes more difficult (cf. Ostrom et al., 1999; Bodin et al., 2011). Ecological connectivity can also affect ecosystem stability, and recent studies of interacting predator and prey species have shown that the effects depend on, for example, levels of connectivity and modularity of the food web (Stouffer and Bascompte, 2011). It can also lead to unintended side effects. For example, farming can lead to nutrient leakage affecting adjacent and therefore connected ecological resources such as rivers and wetlands.

Finally, level of social and ecological connectivity, in combination, relate to the "problem of fit" between ecological processes and the mechanisms for governing them (Folke et al., 2007; Ekstrom and Young, 2009; Borgström et al., 2006). Ideally, a governance system should be configured so that the temporal and spatial scales of both the ecological and governing processes are in agreement. This suggests that the level of fit, in general, is better in motifs where the level of social and ecological connectivity is the same (e.g. I.A and I.D are better than I.B and I.C; see Fig. 2). In particularly it might be problematic if lack of social connectivity prevents relevant social actors from managing ecological processes encompassing several ecological resources in a coordinated way (e.g. I.B is better than I.C).

### *2.2. Defining a SES as nodes and links*

As stated, defining a SES as a social-ecological network consisting of appropriate nodes and links is in most cases a non-trivial task, and any plausible interpretation of the patterns of interdependencies revealed by the framework is inevitably linked to how this has been done. As is often the case in SES research and when using models in general, there are no "one-size-fits-all" solutions to this problem. Acknowledging this, we propose an integrated and iterative step-wise heuristic approach to define a SES as a social–ecological network. The different steps should be sequentially repeated until the defined nodes and links fulfill two criteria described below. If this seems not to be possible, the applicability of the framework for the specific research questions and/or the study system is probably quite limited. In other words, our proposed framework is not a panacea that is applicable for analyzing any kind of SES and/or problem domain. The iterative procedure requires some basic knowledge of the SES beforehand, although the iterative approach allows for further refinements alongside the acquisition of more detailed empirical data. Hence, the approach can also be used as a guide on where to focus further empirical investigations. Also, the approach does not impose any restrictions on how the social-ecological network is being assessed. Everything from a rather simplistic network model of the SES encompassing only some few presumed key components and relationships (cf. Ekstrom and Young, 2009) all the way up to much more detailed, systematic and accordingly more data demanding models can be accommodated (cf. Fath et al., 2007). This high level of generality comes with a prize: our heuristic approach requires the researcher to define appropriate social and ecological entities and relations him/herself. This should be done in a theoretically informed way, i.e. all assumptions about what constitute a social actor, an ecological resource, and all possible links between and among these entities should be linked to the specific SES and the issues under investigation. Our case study described further down illustrates how this can be done, although

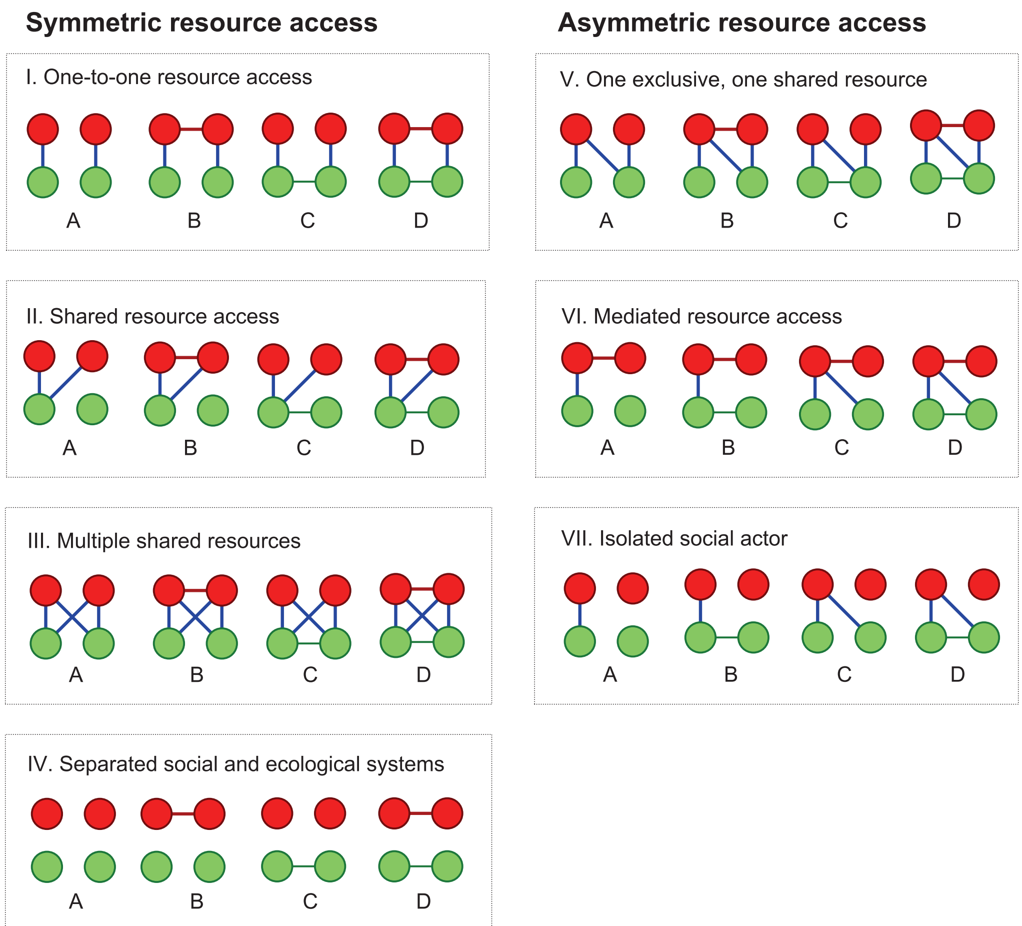


**Fig. 2.** Seven different SES motif families (I–VII). The different motifs in each family are, where applicable, sorted according to their level of social, ecological and social and ecological connectivity (A–D). Families I–IV on the left are characterized by symmetric resource access, while the resource access for the families V–VII on the right is asymmetric.

other SES and problem domains would require other conceptualizations of appropriate nodes and links.

The first step is to define the social–ecological interdependencies, i.e. what types of social–ecological linkages are the focus of the specific study? These links could be based on direct resource extraction such as harvest of fish or crops, but they could also be defined using an ecosystem service framework (e.g. Bennett et al., 2009) allowing for a broader definition of social–ecological interdependencies. The next step involves defining appropriate social actors and ecological resources given these social–ecological interdependencies. For example, if the focus of the research is fisheries, the social actors could be defined as individual fishermen or as individual fishing vessels, and the ecological resources as different fishing sites. Since the framework does not differentiate between different kinds of social actors or ecological resources, it is in general advisable not to mix completely different kinds of social actors or ecological resources within the same network. Instead, in such cases it may be better to define two or more social–ecological networks of different kinds. Alternatively, a study object encompassing different types of actors could be divided into smaller subsystems. An example of such approach would be to define a set of small-scale fishermen as a subsystem being part of a larger resource governing setting that involves state- and regional authorities, various nongovernmental organizations, and other fishermen utilizing large fishing vessels. Then, the framework presented here could be used to only study the subsystem of the small-scale fishermen, whereas an integrated system-wide analysis of the whole problem domain might utilize other research approaches as well.

Defining appropriate social-to-social and ecological-to-ecological links is the third step. These links should relate to the defined social actors and the ecological resources, and they should, through indirect effects, be able to have an impact on the chosen types of social–ecological interdependencies. For example, if the social–ecological links have been defined as extraction of fish and the social nodes as individual fishermen, it makes less sense to define social links based on fishermen being members of the same ethnic group if such membership does not involve any exchange of resources related to fishing. Rather, it makes more sense, in this case, to for example define a social link based on reported exchanges of fishing gear since such exchanges might affect how, where and when fish extractions takes place.

Following this step, the resulting social-ecological network should be evaluated according to two key criteria. The first criterion is about scale matching. Matching scale implies that the interdependent social actors and the ecological resources should both be defined at such scales that their ability to impact on each other is comparable in strength. For example, if a whole watershed including a set of inshore lakes is defined as just one ecological resource (node), the social counterparts (i.e. the social actors) should be operating on a comparable level of scale. Thus, in this case it would be inappropriate to define the social actors as individual fishermen only fishing in a geographically limited part of one particular watershed. Instead, it makes more sense to define the social actors as aggregates of inshore fishermen that

**Table 2**
Types of linkages among clans and forest patches.

| Type | Linkages | Description |
|---|---|---|
| Social–ecological | Ownership | Established by customary law. The owner is in charge of rule enforcement and in most cases uses the forest as burial ground (Tengö et al., 2007) |
| | Ceremony officiate | In charge of important ceremonies in the forest such as burials (Tengö and von-Heland, 2011) |
| | Appointed manager | In charge of monitoring |
| | Neighbor | Has settlement or fields in proximity of forest, held accountable for forest disturbance |
| Social | Kinship relation | Based on shared ancestry, agreed kinship, or historical dependencies that is manifested in forest related ceremonies such as burials |
| Ecological | Seed dispersal | Based on assumed regular movement of key seed disperser, *Lemur catta*, in the landscape (Bodin et al., 2006) |

(potentially) operate across different watersheds. In this context it is important to point out that neither the framework as a whole nor this approach in defining a social–ecological network are bound to any specific scale but are equally applicable across different scales.

The second criterion focuses on the presumed patterns of links of the social-ecological network. To make maximum use of the framework, the network should be defined in such a way that all three types of links are possible (social-to-social, ecological-to-ecological, or social-to-ecological; see Fig. 1), and that these links, in theory, potentially could occur across all or most of the nodes in the network. The latter implies that no significant subsets of either the social or ecological nodes should be defined beforehand in such a way that certain types of links are excluded by design. For example, if all the ecological resources (nodes) were defined as a set of widely distributed inshore lakes lacking any substantial ecological interdependencies, the level of complexity of the modeled SES would be reduced to such a level that the proposed framework would be of limited value.

## 3. Studying social–ecological interdependencies in southern Madagascar

To illustrate and to some extent assess the applicability of the framework along with our theory alignment (Table 1, Fig. 2), we used it to study small-scale forest governance in a rural agricultural landscape in southern Madagascar. The area belongs to a key ecoregion for global biodiversity with high levels of endemism (Olson and Dinerstein, 1998). Forest patches, ranging in size from <1 to more than 90 ha, are scattered across the studied agricultural landscape of small fields and pastures. The landscape has been well preserved in spite of strong pressures on land and forest resources (Tengö et al., 2007; Tengö and von-Heland, 2011). The forest patches are protected by taboos restricting access and use, and the patches generate essential ecosystem services such as micro-climate regulation and crop pollination (Bodin et al., 2006). Furthermore, the forests are culturally important as ancestral burial grounds, sites for ceremonies, and as symbols of the link between people and the land (Tengö and von-Heland, 2011).

The social–ecological interdependency at focus here is the control and use of the ecosystem services, including cultural services, stemming from the forest patches. Thus, we frame this primarily as a common-pool resource problem where multiple actors utilize and to some extent compete for a limited set of ecological resources. We defined the set of forest patches being interspersed in a geographically well-defined village as the ecological resources (nodes) in a social-ecological network. The village has ca. 9000 inhabitants who are primarily agropastoralists. They are organized and settled in the landscape according to clan affiliation, which also matter for forest ownership and management (Tengö and von-Heland, 2011). Thus, our social actors (nodes) were defined as the six land-holding clans in the village, alongside two additional clans residing elsewhere but with a stake in the forests of concern. The social-to-ecological and social-to-social links were assessed for each specific forest patch and clan through semi-structured interviews with clan authorities and forest managers. The definition of the links are presented in Table 2, The ecological-to-ecological links were defined and assessed based on the potential for seed dispersal among the forest patches (Table 2), which is essential for the scattered forest patches' ability to sustain metapopulations of plant species over time (Gilpin and Hanski, 1991; Bodin et al., 2006). In all, the social-ecological network describing the study system consists of 14 ecological and eight social nodes that are comparable in scale, and where all types of interdependencies are possible between all nodes (Fig. 3). Hence, the defined social-ecological network fulfills the criteria defined earlier.

The frequency analysis of how often the different SES motifs occur in the social-ecological network of forests and clans is shown in Fig. 4. This pattern of frequencies can be thought of as a "fingerprint" of the SES. The figure also shows the frequencies for a set of 10,000 randomly generated networks with the same

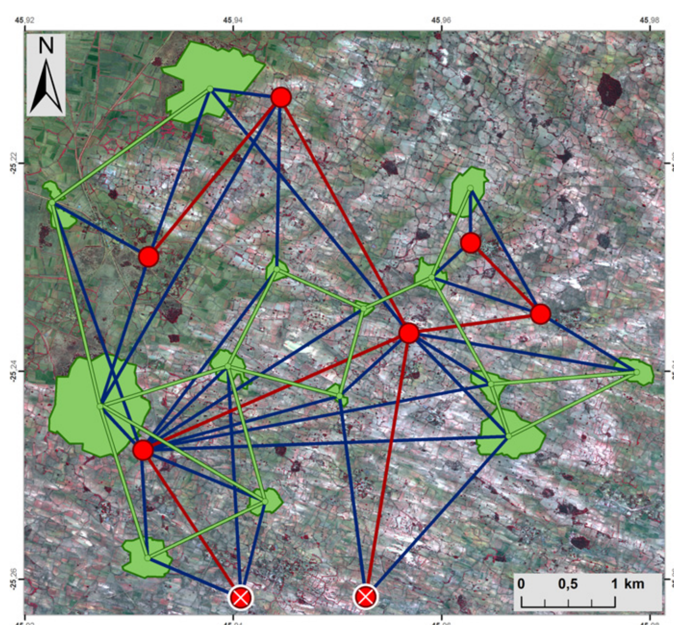


**Fig. 3.** A rural agricultural system in Madagascar described as a social–ecological network. The map shows where the different clans are located in the landscape along with their social relationships (circular nodes and grey links [red in the web version]). Each clan is represented as a single settlement. The two nodes with a white cross represent clans without any clearly defined physical location in the landscape. The forest patches and the ecological links are shown as light grey nodes and links (green in the web version). The social–ecological links (described in Table 2) are dark grey (blue in the web version).

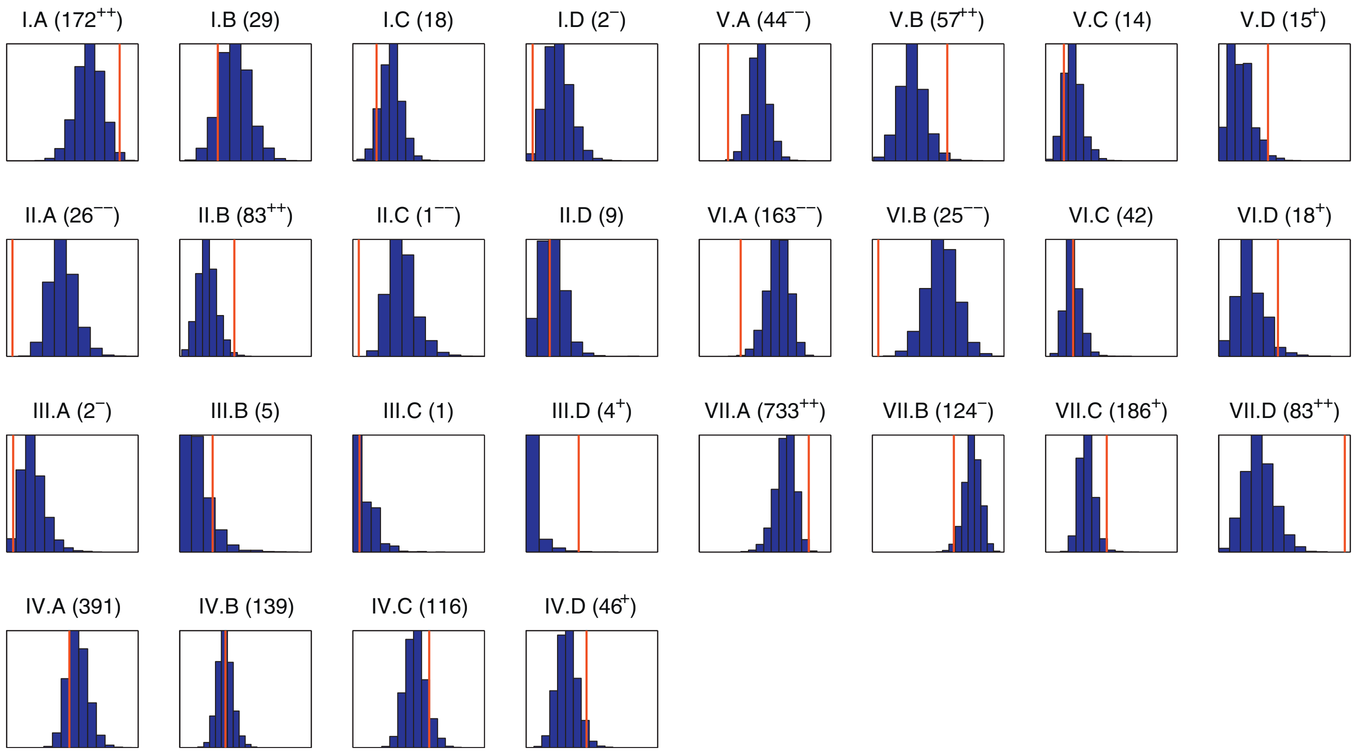


**Fig. 4.** Frequency of SES motif occurrences in the studied social–ecological network. The solid line corresponds to the real social–ecological network, whereas the bars come from 10,000 random networks. If the solid line significantly deviates from the distribution of bars (e.g. II.A), the title is marked with one or two plus or minus sign (5 and 1% significance levels, respectively). The numbers in the titles refer to the number of motifs in the real social–ecological network.

composition of nodes and linkages. We find that in most motif families, some motifs are significantly more or less frequent in the real network compared to the random networks (i.e. <5% of the random networks have more or less of these motifs compared to the real network). In the following, we will explore these divergences and discuss potential implications. First, we find that shared forest access (competition) generally implies social connectivity (II.B, III.D, V.B and V.D are overrepresented whereas II.A, II.C, IIIA, and V.A are underrepresented). This can be interpreted as resource sharing and competition is, in this study area, often accompanied with social connectivity that increases the potential for negotiating and regulating resource use.

Secondly, the motif with all possible connections among the four nodes being realized (III.D) is also overrepresented. Hence, if the clans are sharing two patches, these patches are relatively often also ecologically connected, as are the clans. Thus, highly interconnected clusters of clans and forest patches are relatively common in the network.

Thirdly, SES motifs with ecological but no social connectivity are either underrepresented or neutral (I.C, II.C, III.C and V.C), and those with both social and ecological connectivity are more often overrepresented than underrepresented or neural (I.D, II.D, III.D and V.D). Furthermore, the symmetric pair-wise coupling of the social and ecological nodes is overrepresented (I.A). This indicates a tendency that unconnected patches are divided between unconnected clans. All this indicates a fit between social and ecological connectivity in the network.

Finally, mediated resource access occurs rarely (VI.A and VI.B) unless the clan with access to the ecological resource have links to both interconnected forest patches (VI.D). This could be interpreted to mean that most of the clans have relatively equal forest access, however there may be one or just a few socially well connected clans that also have access to a relatively large set of interconnected forest patches. This suggests there are some power asymmetries characterizing the relationships among clans.

Taken together, by analyzing the motif-based SES fingerprint of the social–ecological network defining the study area, we were able to come up with some pending hypotheses that could partly explain the successful governance of the biodiversity rich forest patches. The clans are organized in relation to the forest patches so that shared forests are combined with social connectivity, which is a cornerstone of successful common-pool resource management as discussed earlier. Furthermore, there are several indications of a good fit in terms of social and ecological connectivity although this pattern is less pronounced. Based on the findings above, one could argue that the clans *either* divide access to patches among each other, *or*, if a patch is shared, the clans are also socially linked to each other. All these configurations are likely to contribute to the successful resource governance in this area. Although we should refrain from drawing far-reaching conclusions from this single case study, the results are indeed in good agreement with our theoretical assumptions and therefore give support to the usefulness and validity of the suggested framework.

## 4. Concluding discussion

In using our network approach, we have initiated the development of an integrated methodological and theoretical framework that makes it possible to start disentangling the complex web of social, ecological and social–ecological interdependencies characterizing SES. Our framework thus lays a foundation for the development of an interdisciplinary 'language' for describing and analyzing SES characterized, or partly characterized, by large numbers of fairly homogenous actors and resources interconnected through complex webs of interdependencies. These complex patterns of social–ecological interdependencies bridge over disciplinary borders, and in doing so they challenge traditional and intra-disciplinary research approaches. In contrast, our framework focus on these cross-disciplinary patterns of interdependencies and use them as a point of departure for linking empirical work with theory in expanding our understanding of social–ecological systems. The framework is not inevitably bound to any specific theories, rather we argue it is able to accommodate and integrate a range of different social and ecological theories.

Furthermore, interesting and relevant results can be obtained even when the framework is used to analyze rather coarse-grain data. The Madagascar case study illustrates this point. Using a fairly limited set of data, we were able to expose some important patterns of interdependencies that helped us to pose informed hypothesis on why the social actors in the studied SES have been able to preserve the integrity of their landscape through time. To further investigate these hypotheses, more elaborated theoretical assumptions as well as more elaborated sets of data involving detailed assessment of various flows and interdependencies between both ecological resources (cf. Fath et al., 2007) as well as social actors can be developed, gathered and analyzed at a later stage.

In other words, the framework could favorably be used in a multi-stage and iterative approach. At a basic level it could be seen as a vehicle to generate informed hypothesis about key characteristics of complex SES. These issues could then be investigated further and more in-depth using more specified hypotheses, assumptions and refined datasets. For example, in our analysis of the clans and the forest patches in southern Madagascar, the revealed patterns of social–ecological interdependencies indicate asymmetry in terms of power and influence among the different clans. Power and influence is in itself a huge and multi-facetted research area. To investigate these issues more in-depth, the framework therefore needs to be charged with more specific and theoretically grounded assumptions about how power and influence relate to specific patterns of social–ecological interdependences. Since our framework takes a stance in a social relational approach that has been used for several decades to investigate aspects of power and influence (e.g. Cook et al., 1983), we think our framework would be well suited for such endeavor (although being beyond the scope of this work). Furthermore, in-depth investigations of these issues could be done in combination with, or based solely on other research approaches since the framework, as with all other research approaches, can only provide insights on an inherently limited set of aspects of a complex reality.

In other words, the framework is quite flexible in terms of its ability to accommodate different theories within the social and natural sciences, and it seems to provide a favorable trade-off between how well it is able to explore complex SES and the data it require to do so. It can be used for exploratory work as well as for detailed in-depth analysis, in parts depending on how coarsely the nodes and links are defined. In this context we think its important to point out that the framework does not provide any shortcut to circumvent the need for the groundwork of scientific inquiries. The quality of the results will, for example, not be any better than the quality of the gathered empirical data. Fortunately, since the framework is utilizing the relational approach that defines the broad field of social network analysis, as well as it indirectly draws from several different fields within ecology where network-based approaches are commonly applied, knowledge on such issues has accumulated over long time. Hence, guidance on how to gather data of sufficient quality, how to define and operationalize relevant systems boundaries, and how to analyze data are readily available.

Our analyses of the clans and the forest patches in southern Madagascar implicitly assume relationships between processes and structures. For example, the relative abundances of the SES motifs where two social actors sharing an ecological resource are also socially connected (Fig. 4) was not only attributed to have reduced the risk of a tragedy of the commons, it was also implicitly suggested that the clans tend to configure themselves in such way. Hence, the analysis of the patterns was also used to infer potential processes, or mechanisms that influence different ongoing processes. This dynamic perspective could be much further elaborated. For example, the most straight forward way to explicitly study dynamics and evolution of SES using the suggested framework would be to assess the frequency distributions of SES motifs at different points in time, and relate this to various types of governance outcomes. Such analysis of longitudinal data could potentially infer causal relationships among and between processes, mechanisms, patterns and governance outcomes. In particular, if the framework is used to test and elaborate different hypothesis and assumptions related to different governance challenges with partly overlapping outcomes, a longitudinal analysis could help to map out different cause and effect relationships. Using cross-sectional data, several different cases would be needed for that purpose, and relationships between variables would typically still be based on associating rather than causality.

Gathering longitudinal data to study dynamic processes is however not always possible. In such cases we suggest another approach. In this study, we generated a large number of random social–ecological networks that we used as a baseline null model to assess if any SES motifs in the real social-ecological network appeared more or less often than expected by chance. An alternative approach would be to (1) assume that links are generated and distributed among social actors and ecological resources as a result of some hypothesized process or mechanism, (2) use and implement that assumption when generating a large number of "semi-random" social-ecological networks, and finally (3) compare the distribution of SES motifs in the real network with the distributions of the generated networks. For example, our results suggest that shared resource access increases the likelihood that the corresponding social actors will connect to each other (or that social connectivity increases the likelihood that the social actors will eventually agree to share a ecological resource). This assumption could be used and implemented when creating a large set of semi-random social-ecological networks (although this would be a non-trivial task). This would be followed by an assessment of to what extent the frequency distributions of the SES motifs of the real network and the set of generated networks correspond. If there is a high level of correspondence, the hypothesized process is supported. Such elaborations of the suggested framework could and should build on recent work on exponential random graph models by social network analysts (see e.g. Snijders et al., 2006; Robins et al., 2007), although it is beyond the scope of this paper to discuss how. In comparison with analyzing real longitudinal data, analyzing cross-sectional data however is inherently limited, although we argue it could still be useful when inferring relationships between processes and the observed structures of social-ecological networks.

Our initial and rather coarse-grained analysis of the relationships between some relational characteristic of SES and governance challenges would clearly benefit from further theoretically and empirically driven elaborations. Furthermore, although the main argument in this work has been that the framework can be used to first translate theories and hypotheses about SES into an integrated social–ecological relational context and then use the framework to test and elaborate these assumptions, the opposite direction of reasoning is also possible. In other words, another point of departure in using this framework could be an observation that certain motifs occur more or less often in certain settings, presumably in conjunction with some notable differences in terms of governance outcomes. Hence, in such cases the frequency analysis of the motifs could drive the process of recombining and reinterpreting existing social and ecological theories into a relational context. Such process could even initiate the development of new and integrated social–ecological theories, explicitly expressed in a social–ecological relational context. The network-centric approach of our framework supports and encourages such endeavors. It provides a platform that can be used to develop, with conceptual clarity and methodological rigor, new and novel theories linking different patterns of social–ecological interdependencies, expressed as SES motifs, to the behaviors and dynamics of coupled social–ecological systems. Also, the framework does not preclude or prescribe the use of other SES frameworks. On the contrary, using it in conjunction with more broadly defined frameworks helps to embed the issues under investigation in a larger SES context. Finally, the framework is independent of scale and is equally applicable for studying small-scale SES, such as the system studied here, as it is for studying global ecosystems operating on a planetary scale where the most relevant social actors could be of the size of nations.

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## Appendix A

Here we describe all possible four-node configurations of a social–ecological network. The four nodes could be interconnected by six links, and therefore the possible number of configurations is $2^6 = 64$. However, many of these configurations are equivalent (e.g. if the social nodes in a specific configuration are interchanged, and the resulting pattern of links would be the same as in another configuration, these two configurations are equivalent). In the tables below, we group all possible configurations into sets of structurally unique configurations (which we call motifs). Each configuration is defined by a six-digit number, and each digit is set to 0 or 1 depending on whether if the corresponding link is realized or not (see Fig. A.1). Although the focus of our framework is set on motifs consisting of two social and two ecological nodes (Table A.1), we also show how other configurations consisting of four nodes but with different compositions could be grouped into structurally unique configurations (Tables A.2 and A.3).

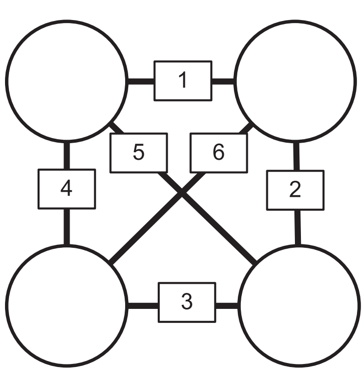


**Fig. A.1.** A four-node network. The numbers on the links refer to their positions in the six-digit representation of a certain configuration. A fully connected configuration would, for example, be named "111111" since all possible links are realized.

**Table A.1**
Two ecological nodes, two social nodes.

| Unique motif | Equivalent configuration(s) | Accumulated sum of configurations |
|---|---|---|
| 000000 | – | 1 |
| 000100 | 010000, 000001, 000010 | 5 |
| 001000 | – | 6 |
| 100000 | – | 7 |
| 000101 | 010010 | 9 |
| 000110 | 010001 | 11 |
| 010100 | 000011 | 13 |
| 001100 | 011000, 001010, 001001 | 17 |
| 100100 | 100001, 100010, 110000 | 21 |
| 101000 | – | 22 |
| 001101 | 011010 | 24 |
| 100101 | 110010 | 26 |
| 101100 | 111000, 101001, 101010 | 30 |
| 001110 | 011001 | 32 |
| 010110 | 010011, 010101, 000111 | 36 |
| 100110 | 110001 | 38 |
| 011100 | 001011 | 40 |
| 110100 | 100011 | 42 |
| 010111 | – | 43 |
| 101101 | 111010 | 45 |
| 011110 | 011011, 011101, 001111 | 49 |
| 101110 | 111001 | 51 |
| 110110 | 110011, 110101, 100111 | 55 |
| 111100 | 101011 | 57 |
| 011111 | – | 58 |
| 110111 | – | 59 |
| 111110 | 111101, 101111, 111011 | 63 |
| 111111 | – | 64 |

**Table A.2**
Four out of four nodes being of the same kind.

| Unique motif | Equivalent configuration(s) | Accumulated sum of configurations |
|---|---|---|
| 000000 | – | 1 |
| 100000 | 000010, 000100, 001000, 010000, 000001 | 7 |
| 100100 | 001100, 000101, 000110, 011000, 110000, 010010, 010001, 001010, 100010, 001001, 100001 | 19 |
| 101000 | 010100, 000011 | 22 |
| 100101 | 001110, 011001, 110010 | 26 |
| 100110 | 001101, 110001, 011010 | 30 |
| 101100 | 011100, 111000, 110100, 010101, 010110, 000111, 101010, 101001, 010011, 100011, 001011 | 42 |
| 110110 | 101101, 101110, 011101, 110101, 111010, 111001, 011110, 100111, 110011, 011011, 001111 | 54 |
| 111100 | 101011, 010111 | 57 |
| 111110 | 111011, 101111, 111101, 011111, 110111 | 63 |
| 111111 | – | 64 |

**Table A.3**
Three out of four nodes being of the same kind.

| Unique motif | Equivalent configuration(s) | Accumulated sum of configurations |
|---|---|---|
| 000000 | – | 1 |
| 001000 | 010000, 000001 | 4 |
| 100000 | 000100, 000010 | 7 |
| 100100 | 100010, 000110 | 10 |
| 011000 | 010001, 001001 | 13 |
| 101000 | 000011, 010100 | 16 |
| 110000 | 000101,100001,010010, 001010, 001100 | 22 |
| 100101 | 110010, 001110 | 25 |
| 011001 | – | 26 |
| 110001 | 011010, 001101 | 29 |
| 100110 | – | 30 |
| 110100 | 100011,101010, 000111, 101100,010110 | 36 |
| 111000 | 001011,101001, 010011, 011100, 010101 | 42 |
| 111001 | 011011, 011101 | 45 |
| 110110 | 100111, 101110 | 48 |
| 111010 | 011110, 110011, 001111, 110101, 101101 | 54 |
| 111100 | 101011, 010111 | 57 |
| 111101 | 111011, 011111 | 60 |
| 111110 | 110111, 101111 | 63 |
| 111111 | – | 64 |

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