Title: Synthesizing theories of natural resource management and governance

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Integration of social-ecological knowledge from different disciplines is lacking

Without such integration, previous work is under-leveraged and progress is stymied

We present the results of a collaborative effort to achieve such integration

We do so by formalizing theories of natural resource governance from multiple fields

We conclude by discussing these theories and their relationships with each other

1. Introduction

Understanding how human-environment interactions can generate more sustainable outcomes remains one of the key challenges for contemporary scientific inquiry (Clark 2007; DeFries et al. 2012). For this, the integration of knowledge from different disciplines has been recognized as key (Newell et al. 2005; Ostrom 2007). However, despite calls for a unified "sustainability science" (Clark 2007), the analysis of human-environment interactions remains dispersed across a wide range of fields, each with their own set of theories (VanWey et al. 2005; Armitage 2007; Turner and Robbins 2008). These fields include the study of social-ecological systems, coupled-natural-human systems, resilience, common-pool resources, environmental, resource and ecological economics, environmental anthropology, psychology and sociology, political ecology, sustainability science, conservation biology, and land-use and land cover change, among others. Collectively, these fields have produced an impressive amount of knowledge regarding the factors affecting human behavior and subsequent environmental outcomes.

To date, however, no formal effort has been made to consistently express the theories developed within these disciplines in a way that could both document the body of accumulated theory and specify testable hypotheses. Theories are a critical way of representing scientific knowledge by expressing important causal relationships among a set of related concepts. In the absence of such an effort, several problems persist.

First, to the extent that progress in sustainability science (or any science) should, at least in part, be measured by the accumulation of empirically supported theoretical statements, progress in the study of human-environment interactions cannot be easily evaluated and understood. Relatedly, meaningful discussions regarding the level of evidentiary support for various theories in the relevant fields are needed, but are difficult to have in the absence of a repository of such theories.

Second, empirical work cannot be as effective or efficient without a thorough understanding of the theories that could be used to deductively generate relevant hypotheses for a particular study area. Because of the diversity of disciplinary perspectives represented in human-environment studies, as well as the lack of cross-disciplinary engagements between different approaches, many scholars are simply unaware of alternative hypotheses or theoretical perspectives from other fields. What researchers measure and analyze in a particular case, then, may not reflect the full body of knowledge within the literature. Indeed, in much empirical work on human-environment interactions, even in articles that employ a standardized framework such as the one introduced by Ostrom (2007), the common practice is to under-explain the (presumably theoretical) reasons for which variables examined were chosen (Thiel et al. 2015). As a result, researchers may continue to collect facts and document patterns inductively, without testing theories generated by their colleagues, and the science of sustainability may perpetually remain in an exploratory phase.

An under-emphasis on theoretical consolidation has been a challenge to the practice of science for some time. Forscher (1963, 339) remarked on this problem in his brickmakers parable: "The brickmakers became obsessed with the making of bricks. When reminded that the ultimate goal was edifices, not bricks, they replied that, if enough bricks were available, the builders would be able to select what was necessary and still continue to construct edifices...and so it happened that the land became flooded with bricks." For the study of human-environment interactions, this is a practical problem as well as an academic one. A synthesis of knowledge on human-environment interactions will enable policy analysts and policymakers to more effectively diagnose particular problems and bring to bear the relevant knowledge to explore possible solutions.

The purpose of this paper is to present the results of a collaborative effort to consistently document theories from several fields focused on human-environment interactions. This work is inspired by, but ultimately quite distinct from, a framework for the study of social-ecological systems developed by Ostrom (2007, 2009). Our research is part of a larger project known as the Social-Ecological Systems Meta-Analysis Database (SESMAD) project (Cox 2014). Within this database, we document many important sustainability-oriented theories generated by scholars across multiple disciplines and perspectives.

2. Materials and Methods

2.1. Preliminary work

Prior to coding theories into the SESMAD database, the SESMAD team members met multiple times at in-person workshops to establish the overall approach and a common understanding of the main concepts and protocols to be used. In order to facilitate the storage of the data needed to express theories and variables, we constructed a relational database, with a table for each necessary object: theories, variables, and studies, as well as several others less relevant for this paper. Data entry forms for each object were also constructed to guide data entry.

The structure of the database reflects several previous synthetic, comparative efforts, especially the International Forestry Resources and Institutions (IFRI) Project (Gibson et al. 2000; Poteete and Ostrom 2004) and Ostrom's (2007) SES framework. This previous work established protocols for exploring human impacts on the environment as interactions between an environmental resource, one or more actor groups, and an overarching governance system. Starting with this conceptualization, we collaborated with a team of database experts to produce the digital infrastructure needed to consistently code information on interactions between humans and their environment. The data are currently stored on a server as an Oracle database and are publicly accessible via the SESMAD website (https://sesmad.dartmouth.edu).

To support the coding of the SESMAD theories, we populated the database with all of the variables that the group agreed to be relevant for the analysis of social-ecological systems. This was in fact done to support the coding of empirical cases of social-ecological systems, which the database also supports. Each group member was asked to come up with a list of the most important concepts from their field and draft an entry in the database for a corresponding variable. This coding included identifying what the primary coder perceived to be the most prominent studies relevant to the meaning of this variable. During several in-person meetings, these drafts were then reviewed in sub-groups to ensure that the variables were described according to their most widely understood meaning and usage. During the theory coding process new variables were added and reviewed as necessary for particular theories.

2.2. Sampling and coding steps

To bound our inquiry we developed the following formal criteria for inclusion in the SESMAD database. To be included, each theory had to (1) be prevalent in at least one relevant scientific field, (2) include both social and ecological variables, (3) point to a relatively clear causal chain between one or more independent variables and an outcome for a natural resource (e.g., a forest or a fishery), and (4) be described in at least one peer-reviewed study.

We were unable to sample theories in the traditional sense because there is no bounded sampling frame or population from which to select, which is part of the problem we are attempting to address. Thus instead of trying to include all environmental resource governance theories, we focused on an important subset of governance theories which deal primarily with rational choice models of human decision making and the role of collective action and compliance in affecting environmental outcomes. Most of these theories were developed from studies of relatively small to regional-scale systems, and were the core theoretical approaches that underlay Ostrom's SES framework (Ostrom 2007), although they have recently also been applied to larger-scale systems (Cox 2014; Fleischman et al. 2014).

Adopting this approach meant leaving out several sets of theories, including those that do not focus on local-to-regional contexts or do not rely on rational choice models of human decision making, but are still widely used to study environmental governance. Thus, we did not include theories developed by international relations scholars to study international environmental regimes (Young 2011). We also do not include behavioral theories that focus on norms and perceptions, as opposed to economic incentives and collective decision-making, like the theory of planned behavior (Fishbein and Ajzen 2010). Additionally, we did not include many theories used in political ecology, which often focus on factors that are difficult to operationalize as we have in the database, or seek to explain how important categories come to be socially constructed, and how power mediates this process (Goldman et al. 2011). Finally, following criterion number three above meant that we did not include theories that involved recursive relationships involving mutual feedback between two or more variables. This led theories such as the adaptive cycle (Gunderson and Holling 2002) and co-evolutionary arguments to be excluded.

The first step in the sampling process was to have the group brainstorm the most relevant theories in the disciplines they knew best. This created an initial list of theories from multiple disciplines. For each theory, a member of the team entered a first draft of the theory into the shared database using the standard data entry forms. This member was the "expert" for this theory, and was primarily responsible for its coding. For each theory so created, the expert for each theory led a discussion amongst members of the larger group. If the larger team decided that a theory could be effectively formalized by entry into the SESMAD database, a second draft was produced that was then reviewed one final time by the lead author to ensure that it complied with the coding protocols, to which we now turn.

2.3. Coding protocols

To aid in and standardize theory formalization, we developed a basic coding protocol that was implemented in a set of online data entry forms. The most important element of this protocol is its definition of a "theory." This term does not have one universal meaning across (or sometimes within) scientific disciplines. Our own working definition of a theory is based on the discussion of theories and two closely related concepts, frameworks and models, in McGinnis and Ostrom (2014):

"A framework provides the basic vocabulary of concepts and terms that may be used to construct the kinds of causal explanations expected of a theory. Frameworks organize diagnostic, descriptive, and prescriptive inquiry. A theory posits specific causal relationships among core variables. In contrast, a model constitutes a more detailed manifestation of a general theoretical explanation in terms of the functional relationships among independent and dependent variables important in a particular setting. Just as different models can be used to represent different aspects of a given theory, different theoretical explanations can be built upon the foundation of a common conceptual framework."

Frameworks then populate the scientist's world with a set of conceptual objects and (non-causal) relationships among them. Theories are statements that stipulate causal interactions among these objects, and models formalize theories mathematically, generally for the purposes of testing them. Based on this and similar work, we have adopted the following definition of a theory, or theoretical statement:

Theory: A statement that describes (1) a relationship between an outcome and a set of independent variables, the values of which are argued to be *sufficient* for predicting the outcome, and (2) a mechanism by which this relationship occurs.

We interpret theories to express sufficient conditions rather than necessary conditions. For example, the theory of the Tragedy of the Open-Access Commons argues that open-access conditions and low property security are sufficient for environmental deterioration. This would predict that for every case of open-access and low tenure security, the condition of the commons will suffer. It does not mean that every case of environmental degradation involves an open-access property regime and low tenure security (which would be a necessary relationship). To the extent that the logical inverse of a theory can be meaningfully expressed, this complementary theory would express a necessary relationship: some type of property regime with high property security is necessary for environmental sustainability.

This definition closely ties theories to another important scientific object: variables, and we have adopted the following working definition of variables:

Variable: A scientifically important concept that has been assigned a level of measurement and range of possible values.

A variable defines an attribute of a particular object. The objects that our variables describe are components of a social-ecological system, roughly based on Ostrom's social-ecological framework. The three components that SESMAD variables can describe are (1) actor groups, (2) governance systems, and (3) environmental commons.

Variables can take on multiple roles in a theory (Table 1): dependent variables are the outcomes that a theory explains, and independent variables do the explaining. An independent variable can be specified as an underlying or proximate variable, depending on its immediacy to the final outcome (Geist and Lambin 2002). For theories with multiple independent variables, such variables are essentially INUS conditions: see Ragin's (2000) discussion of INUS conditions originally developed by Mackie (1965).

Outcomes can similarly be specified as intermediate or final. Each theory must have at least one final outcome that describes the predicted result for a natural resource commons, and an intermediate outcome is specified if there is an outcome of interest (e.g. collective action from the commons literature) that is seen as facilitating the final outcome. Finally, a third type of independent variable that is available is a moderating variable. A moderating variable influences the strength of a relationship between two other variables in a theory.

Any variable that contributes to a theory is assigned one of these roles as well as a qualitative explanation of its role. It is also assigned a value, which can be either (1) one or more values from its range of allowable values, or (2) a descriptor of a change in its value. This way of formalizing theories is consistent with the hypothetico-deductive approach to scientific practice, whereby theories are developed and enable predictions that are then tested via the deductive specification of their observational implications (what we would expect to see in the world if they were true). The value of each variable in a SESMAD theory is one such observational implication that can be used to test the theory in an empirical setting (King et al. 1994).

Each SESMAD theory has an open text field which summarizes the causal narrative that links each of the variables together. We also considered the ways in which theories could be simple vs. complex based on the variables they contain. A simple theory specifies a relationship between one independent variable and an outcome, where this relationship is not seen to be contingent on any third moderating variable (no interaction effects). We recorded multiple ways in which theories could depart from this simplicity. First, we recorded how many steps they involved (with the maximum being four for theories that involve underlying and proximate independent variables and intermediate and final outcomes). Theories with four steps were informally labeled as "process" theories. A process theory, such as Gilded Traps (Steneck et al. 2011) describes a sequence of related events that culminate in one or more related outcomes. A theory can also gain complexity by containing many variables at a single step. Such "list" theories list out many facilitating conditions needed in order to produce a particular outcome. Finally, complex theories are characterized by interaction effects created by moderating variables.

In addition to connecting to variables, theories can be connected to published studies (articles, books). This association can record whether the study empirically supports or contradicts the theory with which it is being associated, or simply describes it. At least one such study was recorded for each SESMAD theory.

Finally, theories can have one of three types of associations to each other: nested, related and contradictory (Table 2). Table 2 shows three types of relationships. These relationships vary in the extent to which the relationships involved are symmetric, and in the extent to which they confer transitive relationships among theories. The only asymmetric relationship type is nested, in that A containing B does not imply that B contains A.

The nested relationship is fully transitive: if A contains B and B contains C, then theory A contains theory C and all of its variables. Moreover, because theory A contains all of the variables (with the same, or when appropriate, opposite, values) as theory B, this also means that theory A inherits all of the other relationships held by theory B. These inherited relationships are implicit in the variables that theory A contains and are not formally coded for theory A. For example, if theory A contains theory B and theory B contains theory C and is contradictory with theory D, we did not code that theory A had any formal relationship with theories C or D.

Related relationships are partially transitive. If theory A is related to theory B and theory B is related to theory C, whether or not theory A is then related to theory C depends on whether this relationship also satisfies the conditions for the related association. Theories that are related to the same theory are more likely to be related to each other in this way, but are not always related. Contradictory relationships are not transitive at all. However, if A and B are both contradictory to C, then it is likely that they are related to each other.

2.4. Analysis

To analyze the coded theories, we first statistically summarized the results (Table 3), and then summarized the results by the scientific fields from which the theories were derived (Table 4). Following this, we examined the relationships between theories and variables (Figure 1) and with each other. To examine the theory-to-theory network, we used the Excel extension NodeXL. This produced visualizations of the theory-to-theory network (Figures 3, 4, 5) as well as distributions of the number of connections between theories by type of connection (Figure 6). We also examined the extent to which theories tended to associate more or less with theories from their own or other scientific fields (Table 5). Finally, we conducted a basic correlational analysis and an exploratory cluster analysis to examine the extent to which different coded attributes of the theories tend to create different classes of theories (Table 6).

3. Results

Drawing upon 117 published studies, we inductively coded 63 theories using 81 variables (Table S1). All of the theories and variables are publicly viewable at the SESMAD website.

3.1. Scientific fields and variables

Table 3 defines the numerical attributes that were coded or calculated for each theory and provides summary statistics for each. Table 4 summarizes the results for each of the fields from which the theories were taken (see Appendix A for a full description of the fields). It also provides a brief description of each of these fields as they pertain to the environmental sector. The field with the most theories was Collective Action and the Commons, followed by a closely related field, Political Economy. Because our sample of cases cannot be said to be representative of a broader, ill-defined population of theories, we note that the distribution of theories across the different fields does not reflect the extent of theoretical content of different fields. We list it here merely to characterize our own sample of theories.

Seven theories were recoded as Interdisciplinary. This somewhat understates the highly interdisciplinary nature of the majority of the theories that were coded. Also many theories could have been formally associated with an additional field. Those coded as interdisciplinary were coded as such because they could not be coded as belonging to one field over all others among the experts of the respective fields.

While there was a fair amount of diversity in the variables used by the theories, as reflected in the distribution of the number of theories using each variable, several variables were used much more than others (Figure 1). The most used variable was Commons Condition Trend, which was used by 59 theories. This variable was the final outcome for all theories with the exception of those from the resilience literature, which instead use Basin Switch as the final outcome variable. The second most common variable was Collective Action. This was used mostly as an intermediate outcome to explain environmental outcomes in the Commons literature (see Table 4). Next, the variable Compliance is used as an intermediate outcome in several other literatures, and also as a moderating variable (i.e., in theories that focused on the importance of policy instruments). The main difference between Compliance and Collective Action as intermediate outcomes is subtle, yet important. Theories emphasizing Compliance tend to view actors as the recipients of environmental policies imposed by external actors; while those emphasizing Collective Action highlight the role of those actors in the design and enforcement of environmental policies. The other important intermediate outcome variables were the level of Social-Ecological Fit between institutions and ecological systems and the Resilience of Ecosystems, which was unique to the resilience literature.

Finally, the fields differed in the primary independent variable they used. Policy Instrument and Centralization were used in many theories because they were the primary independent variables in one or more fields. Centralization is used by many of the Political Economy theories, while Policy

Instrument is used mostly by the Environmental and Resource Economics and Conservation Biology fields (Table 4).

3.2. Network results

Figures 2, 3 and 4 contain diagrams that depict all of the theories and their relationships to each other, using abbreviations of the theory names. Figure 5 provides a legend for each of the other figures. Figure 2 shows the theories involved in "related" and "contradictory" relationships, while Figure 3 shows the theories involved in "nested" relationship. Figure 4 shows all theories and all relationships. This figure shows a network with 63 nodes and 137 connections, with 56 being "related", 59 being "nested" and 22 being "contradictory." The connections between the theories are color-coded, as are the theories themselves based on the literature they were drawn from.

Figure 4 shows some degree of clustering by scientific field as well as the presence of theoretical "hubs", or highly connected nodes. This first feature is unpacked further in table 5, which shows the counts of connections between theories of different fields. Overall 59 out of 137 (43%) connections in the full network (Figure 4) were between theories of the same field. The second feature is shown in figure 6, which contains the degree distributions for the full network and each of the three link types. Like many networks, the full network is right-skewed with a small number of theories having dis-proportionally large numbers of connections to other theories. The figure also shows that this skew comes primarily from the "nested" connections, and secondarily from the "related" connections, with the "contradictory" distribution being only slightly skewed.

The two largest network clusters are associated with the Commons and Political Economy fields (Figure 4). The main hub in the network, the theory Community Based Natural Resource Management (CBNRM), connects these two clusters. The clustering of the Political Economy theories reflects that most of these theories include the Centralization variable and make either similar or contradictory arguments with it. Closely related to this cluster are several theories from the Conservation Biology literature. The Commons cluster, meanwhile, has several connections to the Resilience theories at the bottom of the diagram. The final cluster (of four theories) using these links is located in the upper right, containing theories that argue about the role that technology plays in affecting environmental outcomes.

The theories from different fields differ in the extent to which they use the different types of theory-to-theory relationships (Figures 2, 3, 4, 5 Table 4). The Commons field relies almost exclusively on nested relationships, creating three highly connected hubs. One of these, Collective Action and the Commons, is used by all of the theories that assume a connection between collective action and positive commons outcomes. The other two hubs in this literature, Community Based Natural Resource Management (CBNRM) and CBNRM Design Principles, use many of the theories that attempt to explain collective action outcomes in mostly local contexts. The Resilience theories are similar in this regard, with one main hub (Conditions for General Resilience) containing the majority of the other resilience theories, as well as several from the Commons literature. The other two theories that were used by several others were Enforcement and Social-Ecological Fit Theory. The former is used as a pre-condition for success of theories that argue for the desirability of policy regimes (such as Individual Transferable Quotas), while Social-Ecological Fit (as a variable described in the theory of a similar name) is an intermediary outcome for many of the theories advocating for decentralized governance regimes.

3.3. Correlational results

Table 6 shows a basic correlation matrix between all of the attributes contained in Table 3. Here we see several things that further unpack results just presented. Least surprisingly, larger theories (theories with more variables) tend to have more theories nested in them, and partially as a result are more highly connected and more complex as measured by the final three dimensions. Theories that have "related" connections also tend to have "contradictory connections and to not be nested within other theories. Finally, list theories tend to have multiple steps as well, but tend not to have moderators. A cluster analysis was also conducted that showed two basic groups of theories: a small group of larger, more complex theories, and a large group of simpler ones. It is important to note that these correlational results are disproportionately driven by the large theories which appear as outliers in Figure 1.

4. Discussion

4.1. Important elements and controversies

As the results show, some variables and theories are much more widely used than others. The full network degree distribution is widely skewed, largely as a result of some theories containing or being contained by many other theories. It's worth reiterating that the "contradictory" distribution does not indicate that there are particularly controversial theories, but this masks the importance of a particular variable that is behind the majority of these connections: the Centralization variable. The results indeed show that this variable is one of the more controversial in terms of the theoretical predictions made with it. At the same time, this analysis does not necessarily reveal other controversies within the literature by not recording situations of equifinality as contradictions. For example, many different arguments are made with the Policy Instrument variable, and controversies regarding what are the most effective instruments are widespread. This is not something the SESMAD database is currently well equipped to detect, however.

4.2. Empirical utility of the database

There are several ways in which researchers can use this database to support their empirical work. First, the SESMAD theory database can help researchers identify the most important variables to measure and theories to test for a particular empirical context or set of research questions. Through an iterative process, a researcher can combine their knowledge of a particular social-ecological system with the theories database to develop a list of variables that they want to measure to test the theories that are most relevant for their system.

For example, if a researcher is examining a case in which a group of local resource users are nested within a set of large-scale governance arrangements, s/he could examine the Multiple Levels variable and see what theories it is involved in. Each of these theories contains additional variables, and the value predicted for each of these variables is an observational implication that can be tested empirically (King et al. 1994). This functionality will only increase as additional theories are added to the database, with some being made specific to particular environmental sectors such as fisheries. The database currently supports this function, but it has not yet been implemented for more than a few theories, such as Forest Transition Theory. This function has been more thoroughly implemented for variables, with a subset of variables describing attributes and outcomes specific to marine protected areas (MPAs). These variables have not yet been used to formalize MPA-specific theories.

Additionally, the researcher can use the theory-to-theory relationships to explore what types of theories (and their associated variables) might be most relevant. For example, if a researcher is interested in testing the theory of Failure of Centralized Control in a particular case or set of cases, he or she could examine other theories that are associated with this theory (such as Centralization and Corruption, or Technical Solutions and Shifting the Burden and Gilded Traps) as they might also be relevant.

Finally, because the SESMAD theories link to similarly formalized variables, which themselves are explicitly and systematically documented, researchers can use the database to help them decide how they want to measure the variables in the most relevant theories. Currently such details are poorly specified in much of the empirical social-ecological literature (Thiel et al. 2015).

4.3. Testing theories

Whereas the reviewed literatures appear to have little difficulty in generating new theories, strong empirical tests of many of these theories are lacking beyond the cases in which they were developed. This likely results from several factors. First, many scholars may simply not be aware of many of the relevant theories they could test in their work. Second, it is analytically difficult to empirically test the complex theories that have come to dominate the literature on natural resource management and governance. Simple theories, which propose a direct relationship between a primary cause and an outcome, have been well-studied and enjoy considerable empirical support from both case-based analysis and large-n statistical studies (Gibson et al. 2005; Chhatre and Agrawal 2008; 2009; Cox et al. 2010; Persha et al. 2011; Villamayor-Tomas 2014). As represented in the total number of variables they used (Figure 1), the majority of the theories we coded were fairly simple, with the median number of variables used being four (Table 3).

In contrast, there is far less broad, quantitative empirical support for more complex theories (such as Gilded Traps or the Failure of Centralized Control) that use many variables and which now dominate much of the discourse on sustainability. While the historical absence of formalization certainly impedes this goal, so has the absence of suitable methods to interrogate a large body of theory that is difficult to test (Poteete et al. 2010).

The distinction between process vs. list-oriented theories has implications for empirical evaluation. List theories, such as CBNRM Design Principles, Polycentric Co-management and Conditions for General Resilience, are those which combine a set of simple theories into a list which generally predict success on the basis of adherence to that list. List theories do not necessarily contain interaction effects, but the presence of many variables as say proximate causes can imply a level of dependence among these variables in their effects on an outcome. For instance, Ostrom (1990, 90-91) speculates that something similar to her design principles might ultimately constitute a set of necessary or sufficient principles for robust community-based natural resource management; or that some combination of the design principles increases the likelihood of success. However, because there are thousands of possible combinations of the eight original design principles, it is effectively impossible to apply conventional statistical methods to test which combinations of these factors are likely to contribute to success. Other types of analysis suggest that the exact combination of sufficient conditions in a list theory may not matter, only that a minimum number of factors are present (Gutierrez et al. 2011). Nevertheless, the default approach to analyzing complex list theories is to effectively treat them as sets of simple theories, which are then tested individually (Quinn et al. 2007; Cox et al. 2010).

A number of theories involved many (up to four) steps. These process-oriented theories are those that propose the mechanism by which a set of initial conditions affect changes in social-ecological systems. The most prominent (or at least most complicated) examples of these in the database are the Failure of Centralized Control and Gilded Traps theories, each of which details a fairly intricate process by which their causal narratives unfold. The methodological implications for process-based theories are somewhat different than list theories, in that they cannot as easily be decomposed into semi-autonomous sub-theories. There are both qualitative (process-tracing) and quantitative (structural and simultaneous equation modeling, mediation analysis) approaches to examining these kinds of dynamics (Young et al. 2006), although to date these are not common methodologies in the literatures we examined.

Finally, there are interaction-based theories, which suggest that the effects of variables are contingent upon the state or magnitude of other factors. For instance, the Decentralization and Local Capacity theory (Garces-Restrepo and Muñoz 2007) suggests that decentralization efforts are unlikely to contribute to sustainable use of natural resources unless groups have the capacity to undertake management responsibilities. In other words, the effects of decentralization are contingent upon the presence of a group with high levels of social capital. Although interaction-type theories are easier to test than list or process theories, and indeed several recent studies have done so (Andersson and Agrawal 2011; Coleman 2011), they present their own analytical challenges. First, models which include interaction terms will always have higher levels of multicollinearity than models which do not, which reduces the power of statistical tests. Second, in a field where scholars are often limited by small samples sizes (Poteete et al. 2010), the likelihood of developing a strong empirical test involving more than two factors is unlikely.

Two final comments on this issue are warranted. First, our distinction between simple vs. complex theories raises questions about the direction of theory development in sustainability science. Simple theories explain highly general relationships that make sense only in probabilistic terms, while complex theories are more specific about the conditions under which one can observe certain outcomes, and thus are more deterministic in their predictions. The trade-off between developing simple vs. complex theories resonates with that between the accuracy and meaning of predictions (Cox 2008). Simple theories prioritize predictability (i.e., across different contexts), while complex theories value meaning (i.e., to the contexts to which theories apply). Theory testing can advance the field of sustainability science in both directions. Simple theories that are tested in new types of contexts can result in new complex theories, while variables that fulfill similar roles in two or more complex theories can inspire new simple theories.

Second, our analysis emerges from an effort to formalize theories; we have not systematically looked at how the theories are used by scholars and policy makers. This distinction is not trivial, as theories, particularly popular ones involving particular governance arrangements (primarily via the Policy Instrument and Centralization variables), run the risk of being applied as "panacea" prescriptions across diverse contexts (Ostrom 2007), or as blueprints against to which evaluate the supposed sustainability of human-environment interactions. Anecdotally, we would say that some list theories are becoming increasingly popular among scholars and policy makers. An example is Polycentric Co-management. The ideas this theory expresses come from both a segment of the Commons and Political Economy fields, which have discussed the benefits of polycentricity, and the Resilience literature, where cross-scale adaptive co-management arrangements are frequently lauded (Chaffin et al. 2014). Given its widespread support despite the challenges in testing this theory across contexts, we suggest, with some hesitation given that this is a controversial argument, that this theory increasingly resembles a "panacea", as this is how we see its arguments playing out in the literature. Several other theories we reviewed, such as Community-Based Natural Resource

Management (CBNRM) and Individual Transferable Quotas, have faced similar speculation (Bromley 2009; Dressler et al. 2010).

4.4. What counts as evidence?

Testing complex theories is not only a tricky analytical issue, but a tricky philosophical one. Scientists must consider what counts as evidence for or against such theories. The fact that complex theories support the generation of multiple observational implications and empirical hypotheses is a double-edged sword. On the positive side, it allows for more Popperian-like tests of theory, which, as Cox (2015) explains, is the very condition that can enable strong small-n, case-based causal inference:

"If the properties of a case are highly congruent with the expectations generated for it by a certain theory, and there are no alternative theories with which the case is also congruent, we may conclude that the results of the case are very unlikely except if they are explained by the theory, and this can be seen as strong evidence in support of the theory. As George and Bennett (2005, 117) put it: 'an explanation of a case is more convincing if it is more unique, or if the outcome it predicts could not have been expected from the best rival theory available.' This is made possible by having well-established theories with many independent predictions for a case. The more predictions, the more points of congruence can potentially be established and the less likely it is that a confirmatory case could be explained without the theory in question. 'This process relies on Bayesian logic-the more unique and unexpected the new evidence, the greater its corroborative power' (George and Bennett 2005, 219)."

On the other hand, it is unclear what constitutes a critical test for a theory. If a case affirms five out of six observational implications (hypotheses) for a theory, is this confirmatory or contradictory? A statistical perspective would probably dictate that it is more confirmatory than not. And many scientists will feel comfortable in many circumstances to simply adjust a theory in light of new evidence. On the face of it this is reasonable and acceptable practice. But the line between this and simply making ad hoc changes to a cherished theory is fuzzy at best, and increasing analytical and technological sophistication will not resolve this issue.

5. Conclusion: limitations and future directions

5.1. Limitations

There are several limitations to the approach we have taken. The first of these is the non-exhaustive "sampling" process we used to produce our list of theories. The distribution of the number of theories across the fields reflects the experiential bias of the researchers involved in this project, rather than the actual extent of theoretical knowledge accumulated in these fields. As we are not trying to generalize our results from our sample in the traditional way, this is not exactly an inferential problem, but it is an important limitation nonetheless. Our intention is for our formalization of theories to serve as a starting point to enable other researchers to add theories as well.

Second, the way in which we have formally expressed the theories is not the only way of expressing them. Particularly for the more complex theories, there is no standard understanding of their arguments. Even for simple theories, we were sometimes challenged to arrive at a common understanding of a rigorous formal expression. Relatedly, the three types of relationships between theories presented in this study do not necessarily capture the full universe of potential relations amongst theories.

Third, while this project benefited from the infrastructure of an online relational database management system, other tools are possibly superior in recording scientific knowledge. Technologies associated with the semantic web such as the Resource Description Framework (RDF) and Web Ontology (OWL) ontology language, for example, are explicitly designed to store fields of knowledge, including scientific knowledge (Frey and Cox 2015). A disadvantage of those technologies is that they tend to be less well developed and have much less technical support and available expertise than those associated with the dominant relational database paradigm.

5.2. Future work

The SESMAD database is not a final product. Rather, additional theories, variables, and connections will be added to it over time. This process will only increase the need for a complementary process to be undertaken, one which would document the extent of empirical support for the theories that have been coded. This is particularly salient for pairs of theories that are coded as being mutually contradictory. One promising approach is a type of vote-counting-based meta-analysis of empirical analyses to document the extent to which different theories are supported or refuted. Without the database it is difficult to see how this could be done systematically. Nevertheless, even with the database to support such an effort, several challenges must be addressed.

The first of these is how to defensibly sample from the highly diffuse literatures that contribute to these theories in a way that is representative of a hypothetical population of studies. Whereas in this paper we were less concerned with obtaining a technically representative sample, to compare different theories based on the amount of support in the literature would require such a sample of hundreds to thousands of studies.

A second challenge is how to validly and reliably measure (and thus weight) the "level of empirical support" offered for theories by different types of studies (e.g. case studies vs. large-n statistical analyses) conducted at different levels of analysis and with different measurements of important outcomes. This is a particularly challenging question for more complex theories as previous discussed. This is also not purely a technical question, but rather one that strikes at the heart of multiple fields and the philosophy of science behind many of our activities as researchers. It is a challenge for the conduct of social-ecological science as a whole, for without addressing it sooner or later, theoretical progress will by stymied as theories are essentially allowed to persist in a cloud of incomplete mutual understanding among the relevant research communities.

There are several ways in which this challenge can be addressed. First, it could become a standard practice in future empirical work to report the extent to which such work supports or contradicts certain SESMAD theories. This would require a community-level agreement on how this relationship is recorded, but if this were possible, it could greatly ease the burden on subsequent efforts to code for such a relationship between empirics and theory after the fact. Second, and relatedly, we can try to increase the comparability of empirical measurements, particularly on dependent variables, in future work. The SESMAD theories as we have coded them reflect a standard practice in much of the commons literature to conflate multiple ways of measuring outcomes for environmental commons and the communities that depend on them. One way forward here will involve the introduction of new variables to further specify what exactly is meant by Common Condition Trend as the primary outcome used in SESMAD theories. Our group is already engaged in such efforts with respect to outcomes specific to forest and fisheries governance.

To conclude, research in sustainability science will continually be faced with the challenge of synthesizing and comparing numerous case studies and theories. We hope our research encourages the social-ecological research community to value the importance of reliability and consistency in the measurement and expression of the concepts and theoretical statements they use to guide their work.

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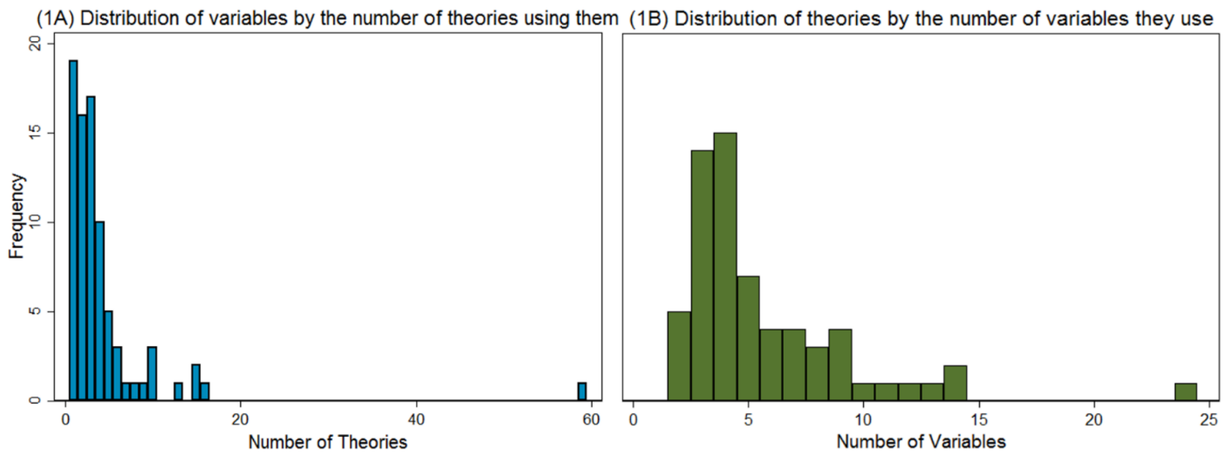

Figure 1: Relationships between variables and theories

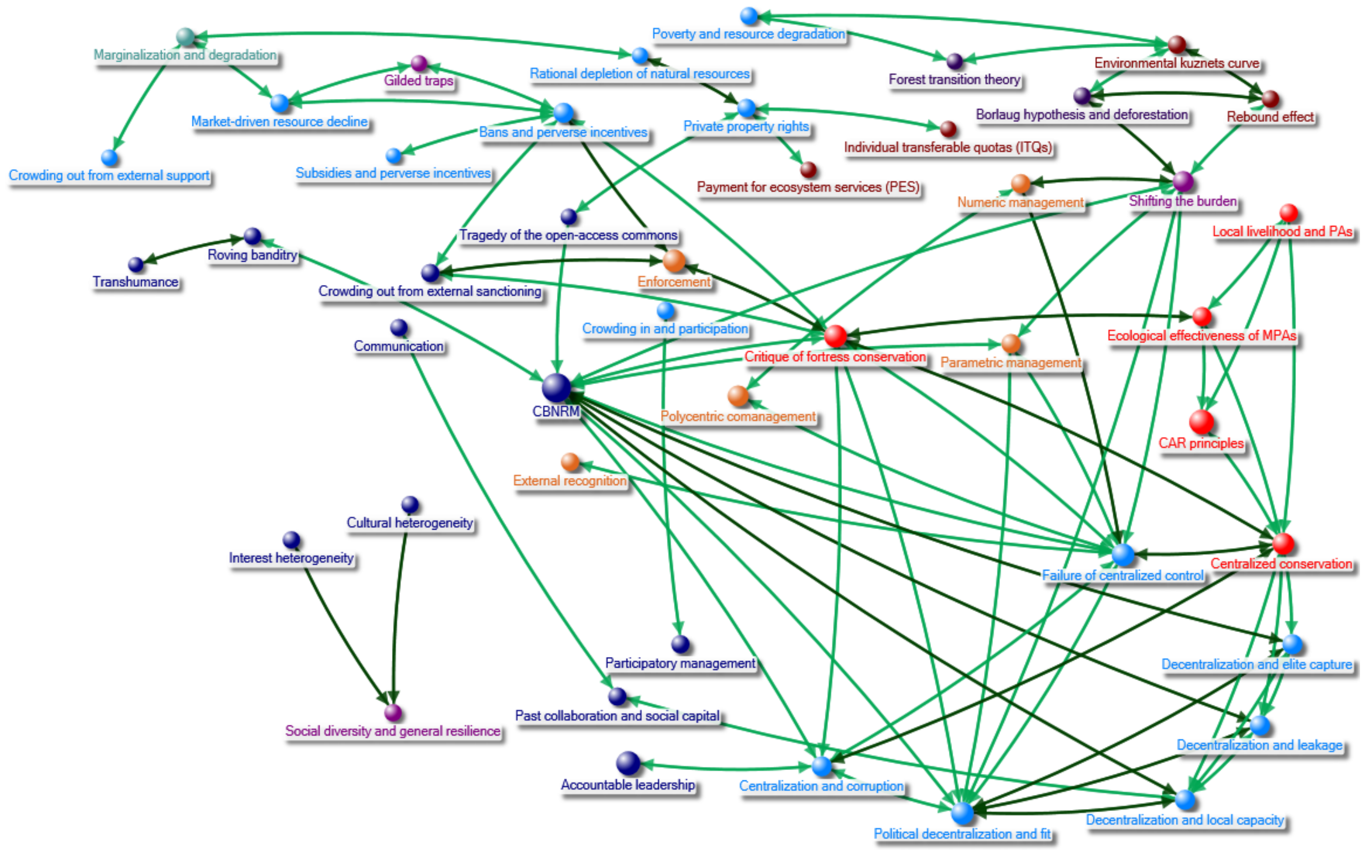

Figure 2: Network diagram of related and contradictory theory-to-theory connections

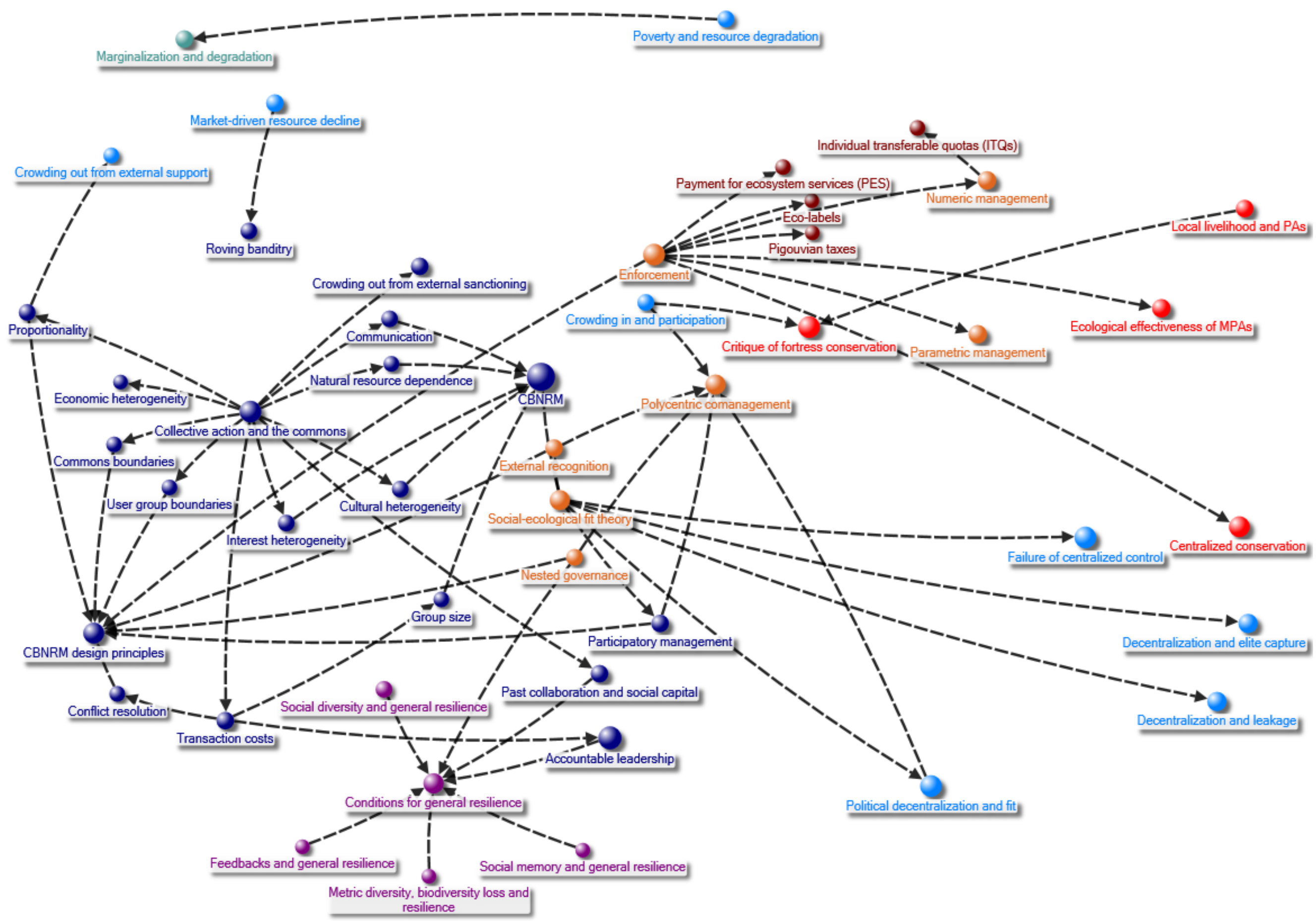

Figure 3: Network diagram of nested theory-to-theory connections

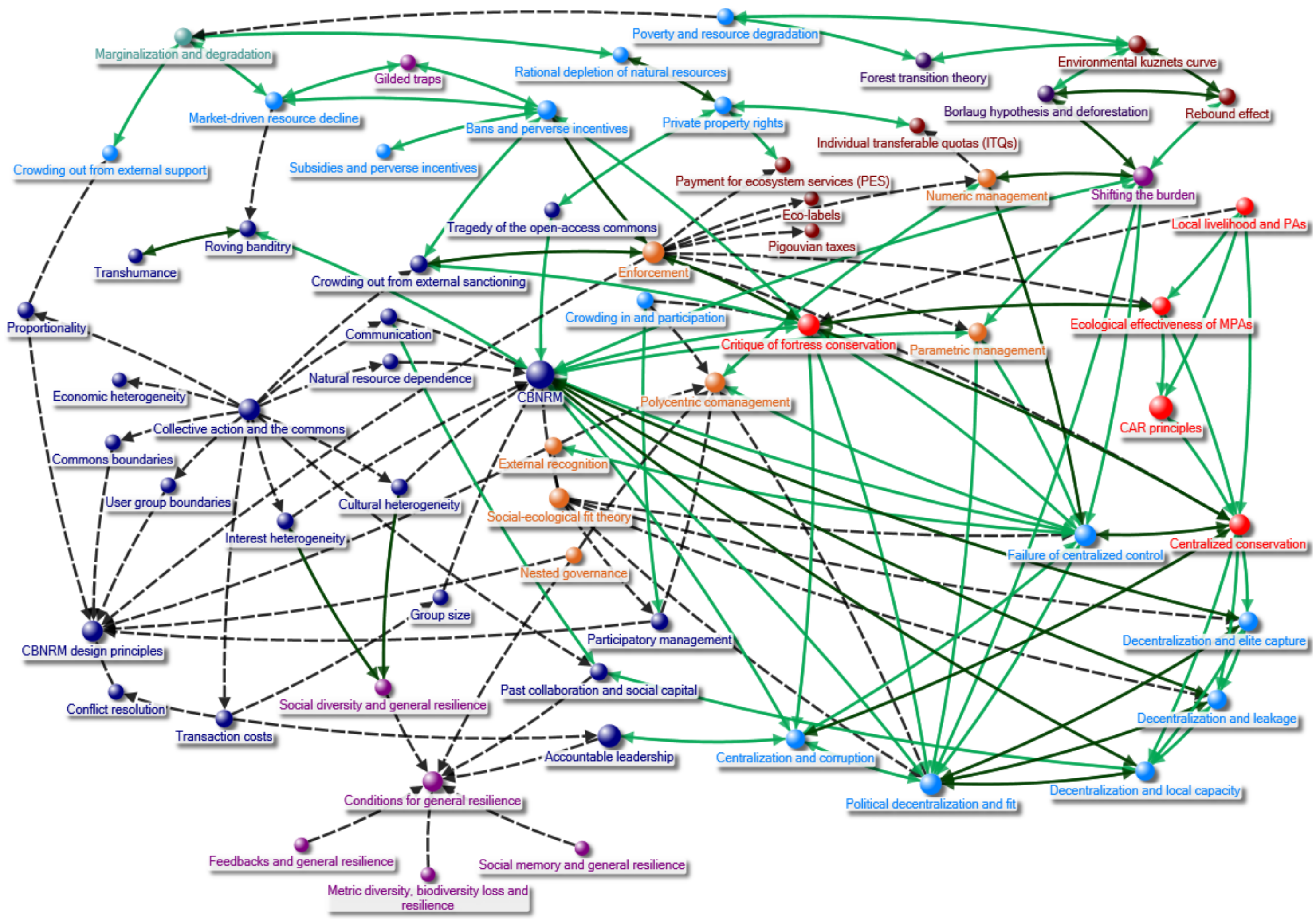

Figure 4: Network diagram of all theory-to-theory connections

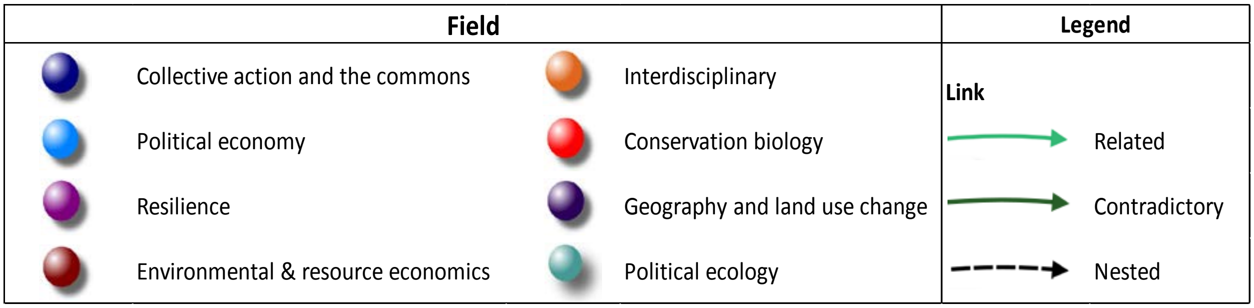

Figure 5: Legend for theory-to-theory network diagrams

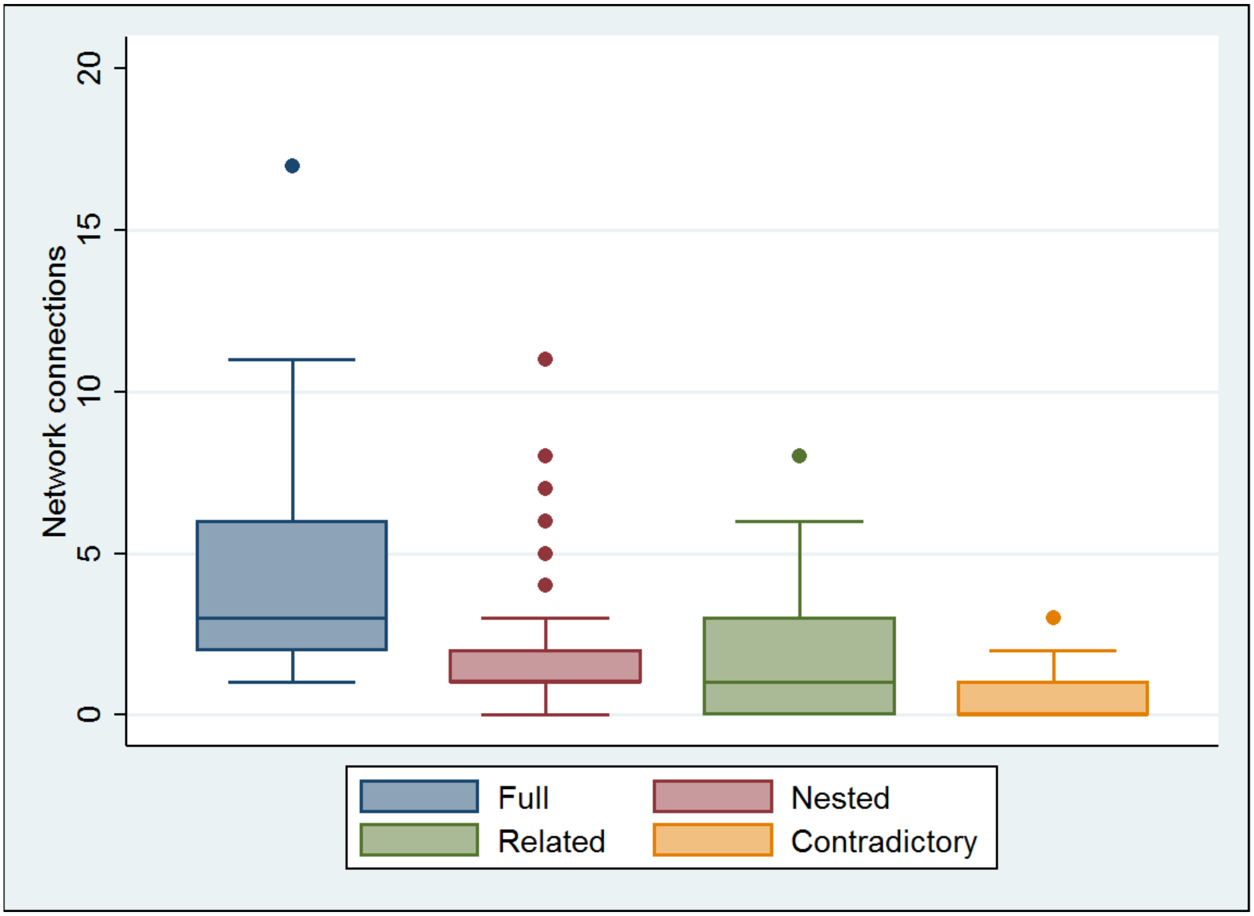

Figure 6: Distributions of theory-to-theory connections by connection type

Table 1: Summary of variable roles

Type	Subtype	Description
Independent	Underlying	An independent variable that affects an outcome by affecting another, more proximate cause. Also referred to as a distal cause.
	Proximate	An independent variable that directly affects an outcome without the help of an intermediary variable.
	Moderating	An independent variable that affects an outcome by affecting the relationship between another independent variable and this outcome. This creates what is commonly referred to as an "interaction effect."
Outcome	Intermediate	An outcome that is affected by the independent variables in a theory, that in turn affects the final outcome (e.g. collective action of a commons user group)
	Final	The final outcome in a theory (e.g. the condition of an environmental commons as it is affected by levels of the intermediate outcome such as collective action)

Table 2: Types of theory-to-theory relationships.

Relationship	Transitivity	Symmetry	Conditions and notes
Nested	Fully	Asymmetric	1) Theory A contains all of the variables that theory B contains, with either the same* values or the opposite* set of values. 2) These variables do not need to have precisely the same roles in the larger theory as they do in the nested one (e.g. a proximate cause may become an intermediate outcome depending on its place in the larger theory).
Related	Partially	Symmetric	1A) Theory A and B have the same* value for the same independent variable and predict the same value for the same final outcome. 1B) OR theory A and theory B have opposite* values for the same independent variable and thus predict opposite values for the same final outcome, 2) AND the two theories do not share the common independent variable via a shared theory that is nested within each.
Contradictory	Not	Symmetric	1) Theory A and B have the same* value for the same independent variable but predict a different value for the same final outcome. 2) Because of the principle of equifinality, theories that have different values for the same independent variable and the same value for the same final outcome are not considered to be contradictory.

The table shows three types of relationships. These relationships vary in the extent to which the relationships involved are symmetric, and in the extent to which they confer transitive relationships among theories. The only asymmetric relationship type is nested, in that A containing B does not imply that B contains A. Otherwise the relationships are symmetric. The nested relationship is fully transitive: if A contains B and B contains C, then theory A contains theory C and all of its variables. Moreover, because theory A contains all of the variables (with the same, or when appropriate, opposite, values) as theory B, this also means that theory A inherits all of the other relationships held by theory B. These inherited relationships are implicit in the variables that theory A contains and are not formally coded for theory A. For example, if theory A contains theory B and theory B contains theory C and is contradictory with theory D, we did not code that theory A had any formal relationship with theories C or D. Related relationships are partially transitive. If theory A is related to theory B and theory B is related to theory C, whether or not theory A is then related to theory C depends on whether this relationship also satisfies the conditions for the related association. Theories that are related to the same theory are more likely to be related to each other in this way, but are not always related. Contradictory relationships are not transitive at all. However, if A and B are both contradictory to C, then it is likely that they are related to each other.

*Two variables have the same value if the value each of is on the same side of the median value (e.g. both are “high” for an ordinal variable). They have opposite values of their values are on the opposite side of the median value.

Table 3: Numerical summary of theories

Attribute	Definition	Mean	Median	SD
Variables	Number of variables used	5.63	4.00	3.79
Connections	Number of connections to other theories	4.35	3.00	3.21
Related	Number of "related" connections to other theories	1.78	1.00	2.06
Nested in	Number of theories a theory is nested in	0.94	0.00	1.92
Contains	Number of theories a theory contains	0.94	1.00	1.56
Contradictory	Number of "contradictory" connections to other theories	0.70	0.00	0.99
Steps	Number of steps (up to 4) a theory contains in its process	2.97	3.00	0.78
List	Maximum number of variables at one step a theory contains	2.29	1.00	2.58
Moderators	Number of moderator variables a theory contains	0.95	0.00	1.56

Table 4: Results by scientific field

Field	Description and focus	Theories	Primary link type	Final outcome	Intermediate outcomes	Main Independent variable
Collective Action and the Commons	Explain the outcomes of emergent collective action among natural resource-users.	21	Nested	Commons condition trend	Collective action	Transaction costs
Political Economy	Explain how institutions and political contexts affect environmental outcomes across multiple scales	14	Related	Commons condition trend	Compliance and Social-ecological fit	Centralization
Interdisciplinary	Theories that were closely related to multiple disciplines	7	Nested	Commons condition trend	Compliance and Social-ecological fit	Governance knowledge use
Resilience	Explain conditions under which ecosystems retain their current structure and function and avoid a phase shift to an alternative stable state in the face of *unspecified* perturbation	7	Nested	Basin switch	Ecological resilience	Actor adaptive capacity
Environmental Economics	Focus on environmental policy instruments	6	Related	Commons condition trend	None	Policy instrument
Conservation Biology	Focus on conservation-based policies and governance regimes (e.g. protected areas)	5	Related	Commons condition trend	Compliance	Policy instrument
Geography and Land Use	Focus on spatial land use dynamics as affected by institutions and technology	2	Related	Commons condition trend	None	Technology role
Political Ecology	Focus on power dynamics and how these affect social and environmental outcomes	1	Related	Commons condition trend	Economic dependence	N/A

A scientific field is characterized by a suite of factors, namely: (1) a topic of study with a characteristic set of research questions and methods designed to answer these questions; (2) an identifiable community of scholars, usually organized around membership in one or more professional or academic societies, a set of conferences, and the set of journals they publish in."

Table 5: Connections between theories by field

	Commons	Con. Biology	Env. Economics	Geography	Interdisciplinary	Political ecology	Political economy	Resilience
Commons	27							
Con. Biology	3	9						
Env. Economics	0	0	1					
Geography	0	0	3	0				
Interdisciplinary	8	3	4	0	6			
Political ecology	0	0	0	0	0	0		
Political economy	13	10	3	1	12	4	12	
Resilience	5	0	1	1	3	0	4	4

Table 6: Correlation matrix of theory attributes

	Variables	Connections	Related	Nested in	Contains	Contradictory	Steps	List	Moderators
Variables	1.00								
Connections	0.44	1.00							
Related	0.27	0.66	1.00						
Nested in	-0.26	0.28	-0.32	1.00					
Contains	0.73	0.43	0.07	-0.18	1.00				
Contradictory	0.22	0.65	0.58	-0.07	0.02	1.00			
Steps	0.36	0.11	0.07	-0.16	0.29	0.09	1.00		
List	0.87	0.48	0.21	-0.19	0.85	0.14	0.30	1.00	
Moderators	0.31	-0.02	0.06	-0.19	0.04	0.10	-0.40	0.00	1.00

1. Collective action and the commons

Collective action and the commons, or the literature on common pool resources emerged during the 1980s and 1990s as a response to the view that embodied natural resource management until that time. According to this view, sustainable use of natural resources could only be achieved through privatization or centralized management by an external authority. However, research on the topic of collective action and small-scale environmental management revealed that local groups of people, such as communities, can self-organize and sustainably manage their resources (1-3). These findings have had a significant impact on the theory and practice of natural resource management around the world.

Through the use of laboratory and field experiments, case studies, and large-n datasets, this body of literature identified over 30 variables potentially affecting sustainable resource management (4). Some of the more recent advances in the field of collective action and the commons try to assess how some of these variables interact to produce sustainable resource outcomes. This is evident in most of the theories in our database that are related to this field.

2. Political economy

Political economy is the study of the interrelationships between political and economic processes, and is thus pursued by a broad array of scholars from multiple disciplines and traditions. Within sustainability science, prominent political economic theories draw from both Marxist (see discussion under political ecology) and neoclassical roots (e.g., 18, 19, 20). Although these traditions work from different assumptions and have different concerns, they share a focus on understanding the impacts of institutions and governance on economic and ecological change, as well as understanding the ways that economic forces constrain institutional change.

Theories that we coded from this body of literature are in large part centered on the decentralization of natural resource management. Although decentralization as a concept has taken on different meanings in different contexts (21-24), we use it here to refer to the process of transferring authority over resources from central governments to lower level units. On the one hand, the literature on decentralization argues that these transfers in management authority are superior to centralized management approaches because greater local involvement in decision-making improves the fit between resources and users, aligning the incentives between the costs and benefits of resource management. On the other hand, it highlights the problems associated with decentralization by examining leakage and elite capture; all of which can result in the degradation of resources they are meant to protect.

3. Interdisciplinary

Several theories coded in our database could not be easily assigned to any one of the literatures described in this section. This is largely because the theories in this group constitute building blocks for many of the other theories in our database and cross disciplinary boundaries. For instance, enforcement is classified as an interdisciplinary theory because there is widespread agreement across most disciplines that enforcement plays an important role in generating desirable behavior and outcomes in social-ecological systems. Given the close relatedness among the examined literatures in terms of their origins and theoretical underpinnings this situation is not entirely surprising.

4. Resilience

Resilience can be defined as the ability of a system to maintain its function, processes, and structure, and to persist in the presence of disturbance (6-8). This definition, according to Gunderson (7), implies the existence of multiple stable states of a given system. Once a resilience threshold has been reached, a system may lose its ability to maintain adequate structural processes and function and may switch to an alternate stable state. Despite significant global declines in environmental conditions, examples of systems that have undergone a basin switch remain relatively rare. This means that empirical evidence supporting resilience theory is derived from the few cases that have crossed resilience thresholds and switched to an alternative state (9) and from regimes that remain within their current configuration but that are seemingly better able to recover from disturbance events (10).

A more recent shift towards resilience theories underpinned by social-ecological systems science has led to a burgeoning of interdisciplinary research in this area and the positing of many principles for enhancing ecological or SES resilience (e.g., 11, 12). Some principles like the “Rule of Hand” which posits that at most five slow variables drive a particular system’s resilience are difficult to formalize because these slow variables are context dependent and specific to a particular system and set of perturbations (13). Regardless of these challenges, resilience theories have substantially contributed to natural resource governance by informing more adaptive, flexible forms of environmental management and by altering key management practices, such as fire management regimes in forests and savannahs (11) or the systematic design of protected area networks (14).

5. Environmental and resource economics

Environmental and resource economics is a distinct branch of economics that utilizes economic theory and methods to evaluate both the economy and the environment in which it is embedded. Evaluations are used to develop policy prescriptions for environmental problems such as pollution, waste, overharvesting, and to measure the costs and/or benefits that result from such activities. A common theme of environmental and resource economics is to incorporate costs associated with natural resource pollution or depletion into the model (i.e. externalities) and in that way correct price signals in the most efficient manner. It relies on a number of policy instruments, such as taxes, emission licenses, quotas, or technology control among others to achieve this goal (5).

The theories we coded include a number of different policy instruments including information provision, market-based instruments, payment for ecosystem services, and taxes. The effects of these policy instrument are typically based upon a presumption that external monitoring and sanctioning mechanisms exist to influence compliance with those policy instruments. Two of the coded theories from this literature (Environmental Kuznets Curve and Rebound Effect) do not include policy instruments. Instead, they explain the role of economic status and technological advances, respectively, on the use of the commons.

6. Conservation biology

Conservation biology is a mission-driven discipline, aiming to reduce or stop biodiversity loss caused by human activities (25). Key threats to biodiversity include direct mortality by people (e.g., hunting, fishing), habitat degradation, pollution, and climate change, among others (26, 27). Although conservation biology is deeply rooted in Western science and thought (28, 29), it also reflects and incorporates some of the traditional ideas and knowledge related to resource conservation and ecology in general (30). The main approach by which conservation biology seeks to promote biodiversity conservation is through protection of diverse habitats and maintenance of key ecological processes. Within this context, selection and protection of geographic areas that have high biodiversity value is of utmost importance.

The theories we coded from this body of literature rely on protected areas as a main policy instrument, although they apply this instrument within different governance models. One theory is that effectively designed networks of conservation areas will be effective at protecting biodiversity (comprehensive, adequate, representative principles for conservation area design). Similarly, another identified characteristics of effectiveness of marine protected areas (MPAs) (ecological effectiveness of MPAs). Earlier conservation views treated humans as an exogenous component of the natural system that should, to the highest extent possible, be removed from the conservation initiatives (i.e. fortress conservation, or centralized conservation). Based on largely negative outcomes of those early conservation efforts, more recent theories view humans and human-related activities as an important determinant of successful conservation outcomes (critique of fortress conservation). Similarly, another theory posits a relationship between positive cultural and livelihood impacts and positive conservation outcomes (local livelihood and protected areas). An important distinction among these latter three theories is in their depiction of humans' role in resource and biodiversity conservation.

7. Geography and land use change

Land use change literature investigates how human activities, such as forestry and agriculture, transform the landscape and in that way affect the natural exchange rate of greenhouse gas emissions between the atmosphere and land (31, 32). Such transformations and alterations of the landscape can potentially have substantial impact on regional and global climates (33).

The theories that we coded from this body of literature focus on the role of technology and economic status in reducing deforestation. In the agricultural context, technological improvements lead to higher productivity per unit of arable land and thus minimize conversion of forests to agricultural land. The effect of a rising economic status on the level of deforestation follows a Kuznets curve.

8. Political ecology

Political Ecology (PE) is an emerging supra-disciplinary approach to study human-environment interactions with a critical lens. PE analyzes the causes and outcomes (incl. the distribution of costs and benefits) of environmental changes in relation power relations in turn associated to the existing political economy (15-17). A central feature of political ecology is the *politicization* of environmental problems.

This means that environmental problems are understood as rooted in political clashes over alternative futures and clashes between alternative values and imaginaries. Therefore, there is a crucial distinction between what PE calls *political* explanations of environmental problems and *apolitical* ones. Apolitical explanations ‘naturalize’ certain conditions; these include explanations that mainly attribute environmental changes to geographical factors, population, poverty, technology and market failure. It is arguably not (mainly) an academic discipline but *an approach* to doing research and writing which shares some central propositions (theses).

Political ecology consists of five key “critical tools” or fields of study, which serve as pillars and which contribute important concepts and theories (17): Marxist political economy (also “green materialism”); peasant studies; feminist development studies; critical environmental history; and postcolonial studies. Drawing from these critical tools, PE has developed four main “theses” (or for the purpose of this paper, theories) which compose the broad research agenda of the field: (1) the systematic relation between processes of social-ecological marginalization and degradation; (2) the link between the unequal appropriation and metabolization of ecological resources for economic activities, socially-produced scarcities, and the emergence of environmental conflicts (also linked to the concept of environmental injustice); (3) the relation between environmental conservation initiatives and governmental or corporate control over territories and peoples; and (4) the role of social movements in achieving more just and sustainable socio-ecological conditions (17).

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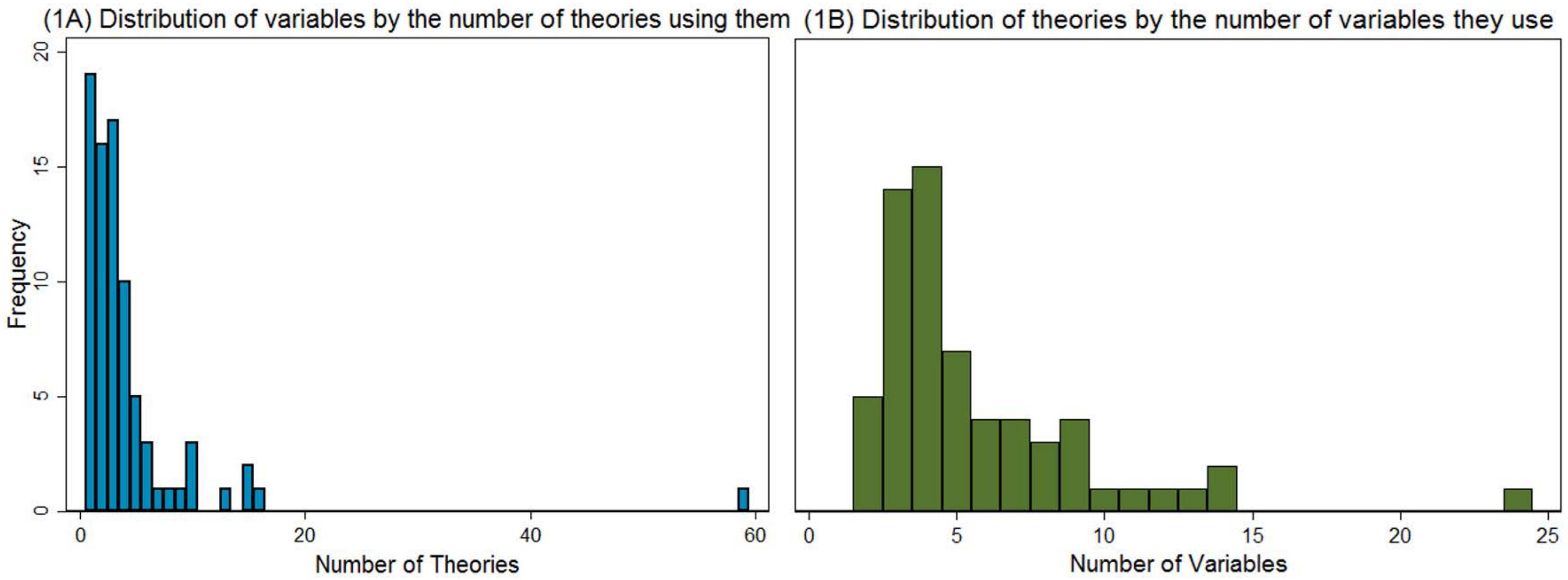
Figure 1: Histograms of the number of variables used by theories and theories using variables.

Figure 2: Theory-to-theory network of related and contradictory relationships

Figure 3: Theory-to-theory network with nested relationships

Figure 4: Theory-to-theory network with all relationships

Figure 5: Network legend



(1A) Distribution of variables by the number of theories using them
(1B) Distribution of theories by the number of variables they use
Frequency
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Number of Theories
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5
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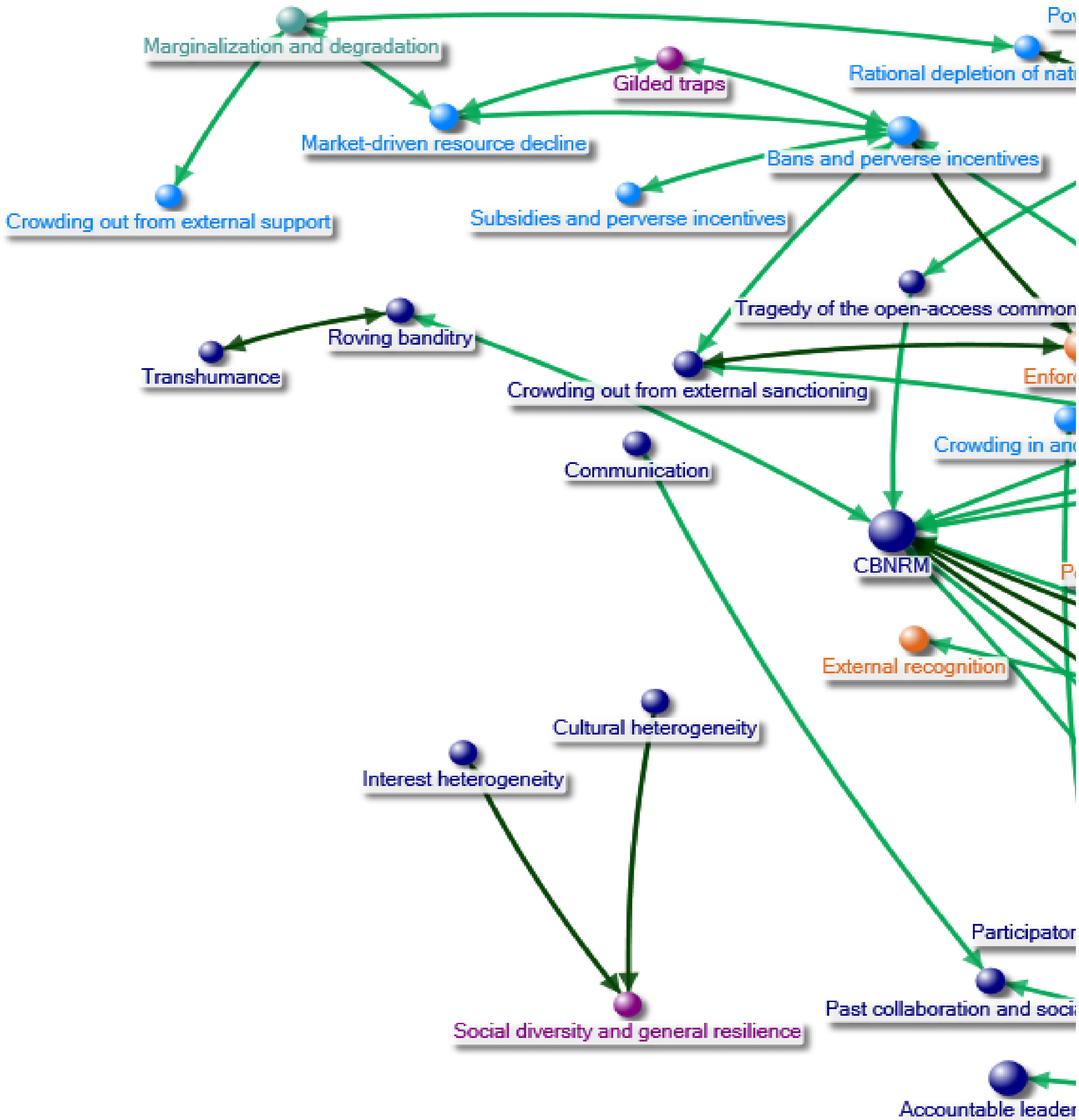
20
25
Number of Variables



Marginalization and degradation
Gilded traps
Rational depletion of natu
Market-driven resource decline
Bans and perverse incentives
Crowding out from external support
Subsidies and perverse incentives
Tragedy of the open-access common
Roving banditry
Transhumance
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Interest heterogeneity
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Social diversity and general resilience
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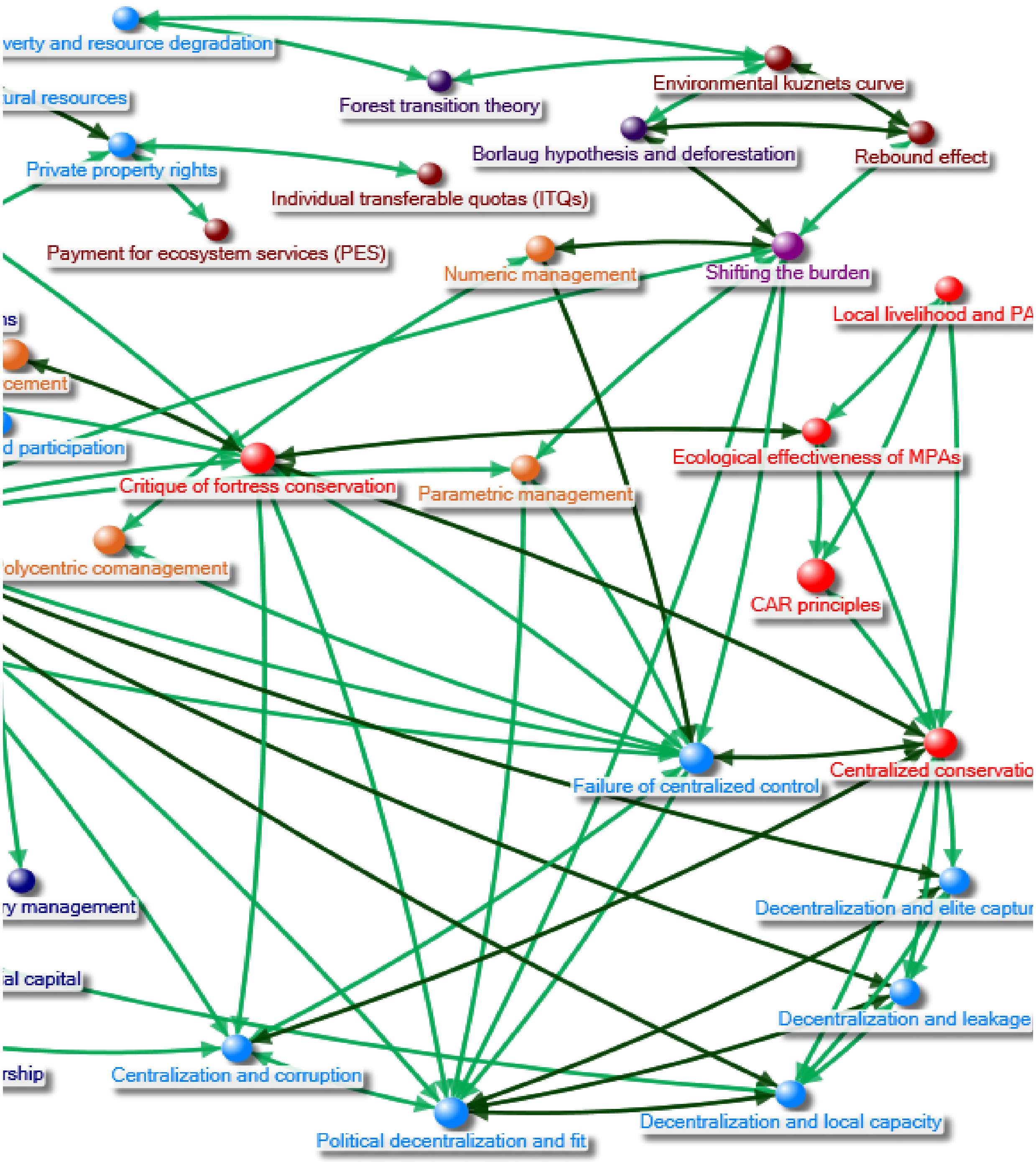

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Borlaug hypothesis and deforestation
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Payment for ecosystem services (PES)
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Shifting the burden
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Decentralization and local capacity
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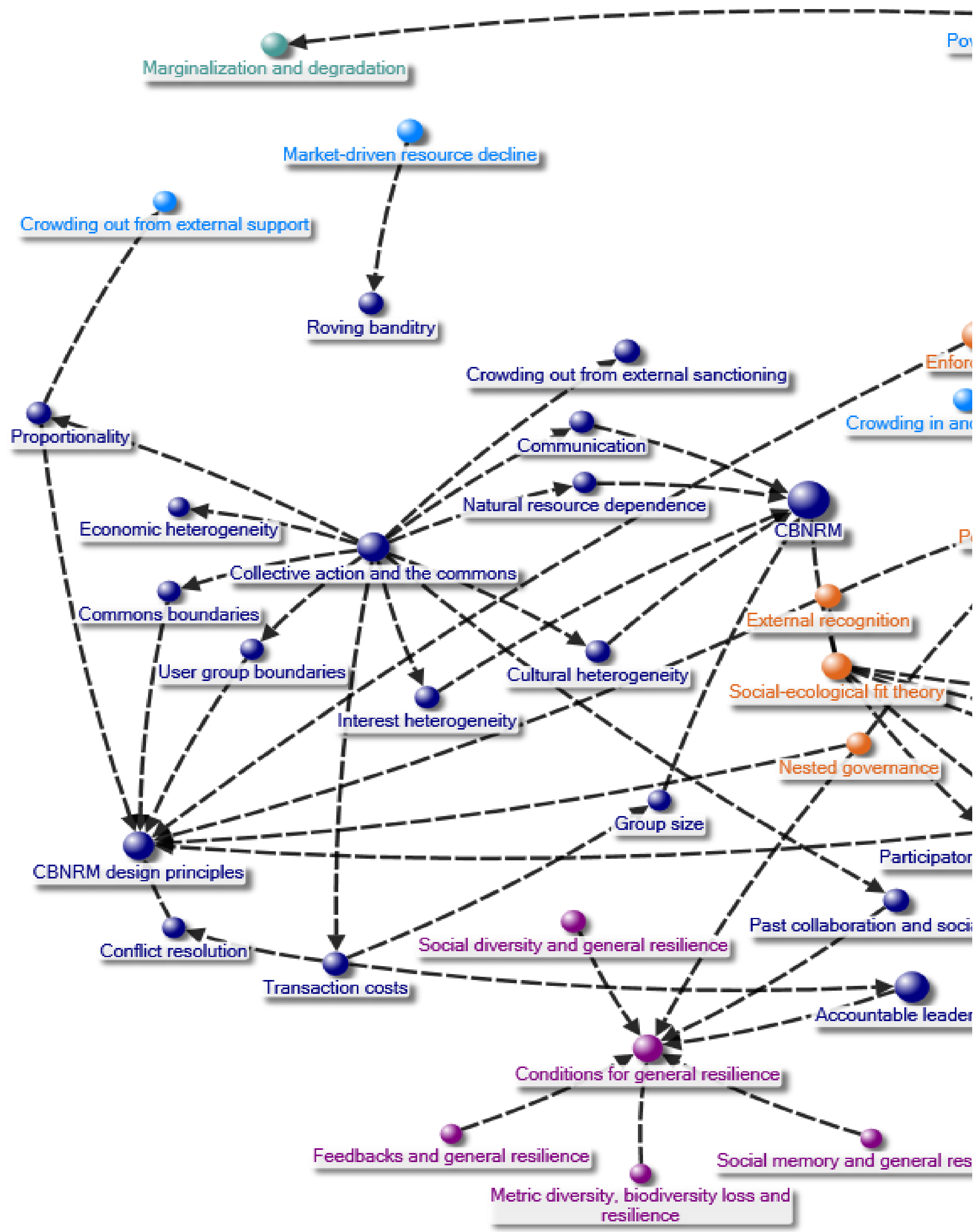
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Commons boundaries
External recognition
User group boundaries
Cultural heterogeneity
Social-ecological fit theory
Interest heterogeneity
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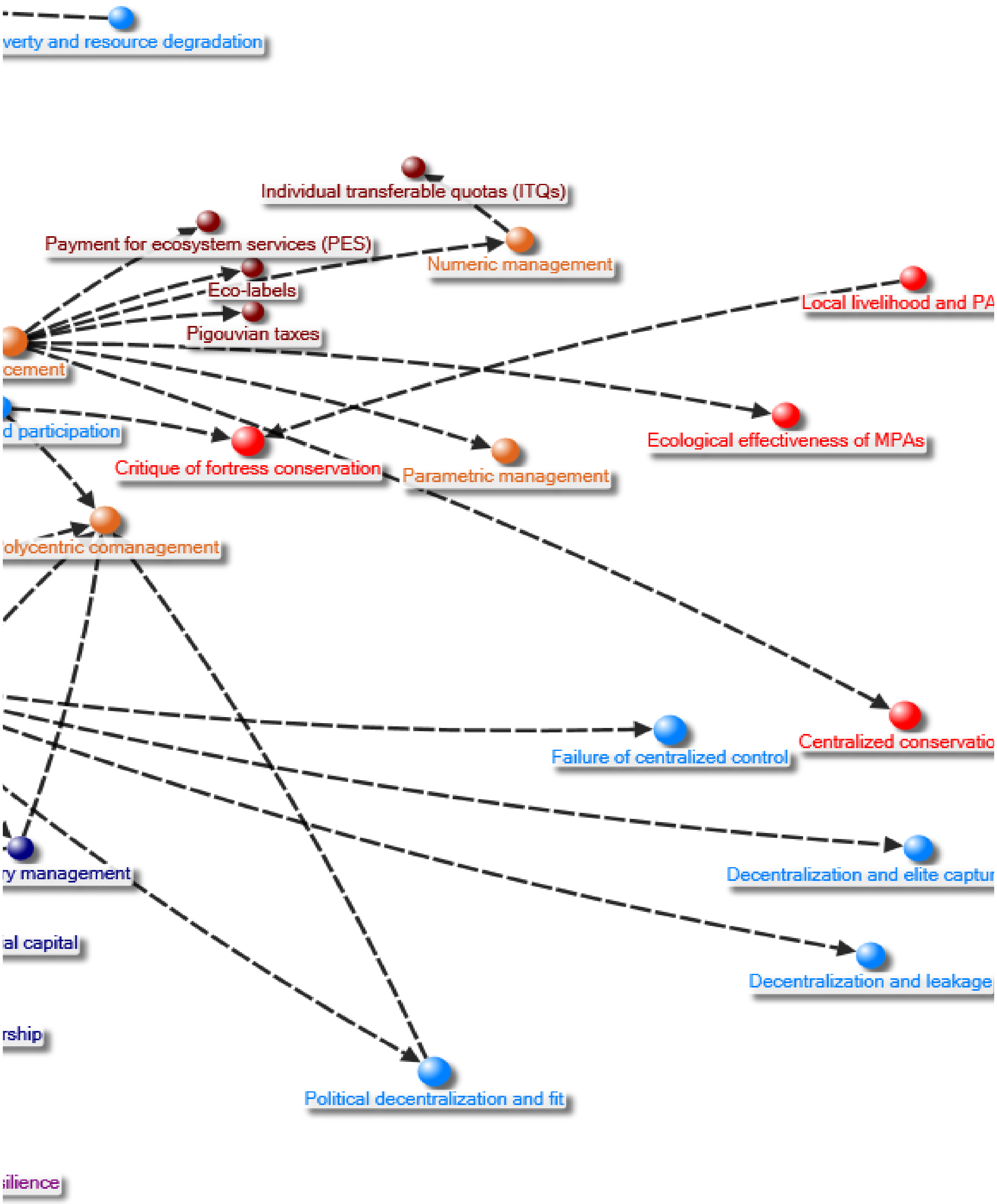
Group size
CBNRM design principles
Social diversity and general resilience
Conflict resolution
Transaction costs
Conditions for general resilience
Feedbacks and general resilience
Metric diversity, biodiversity loss and resilience



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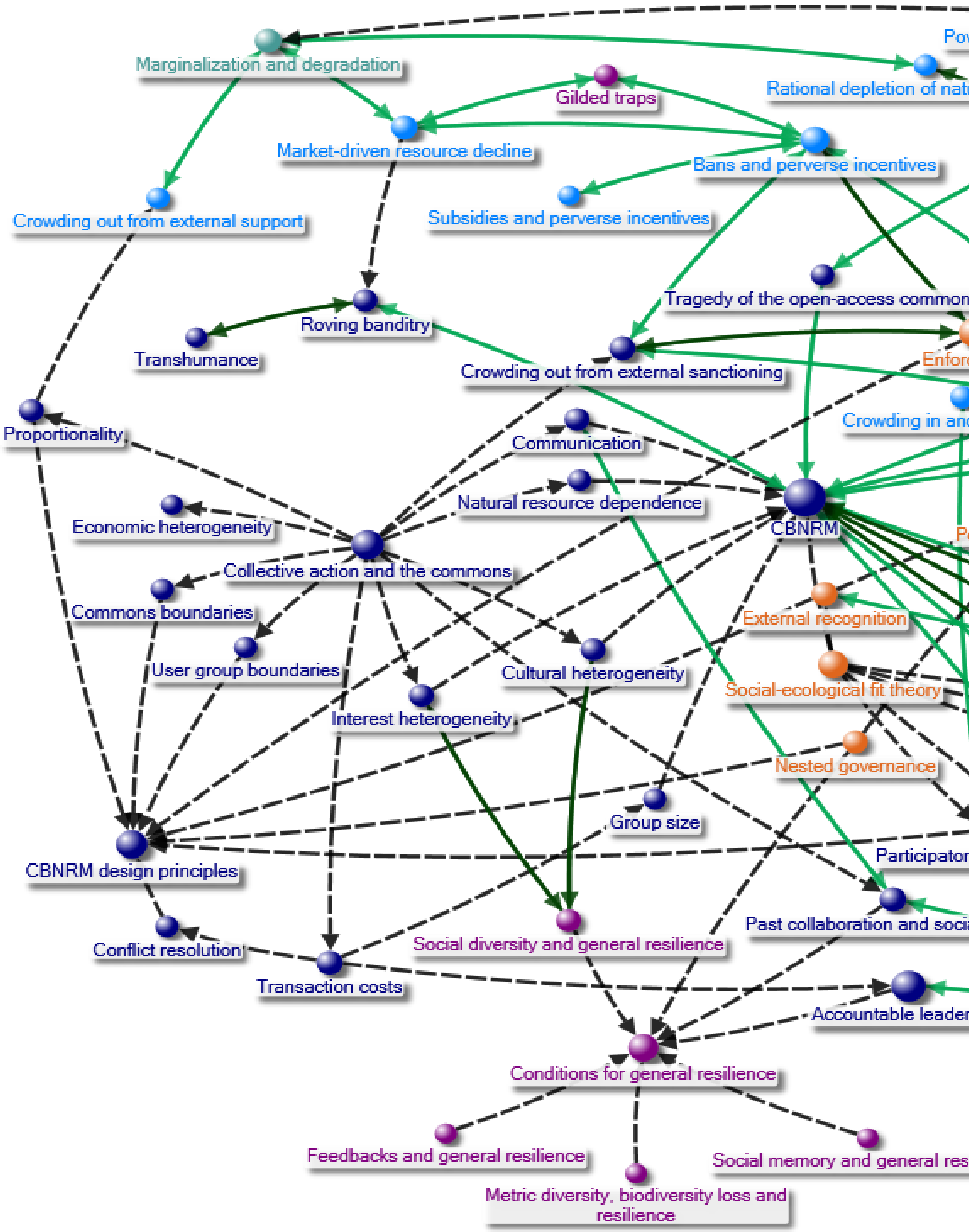

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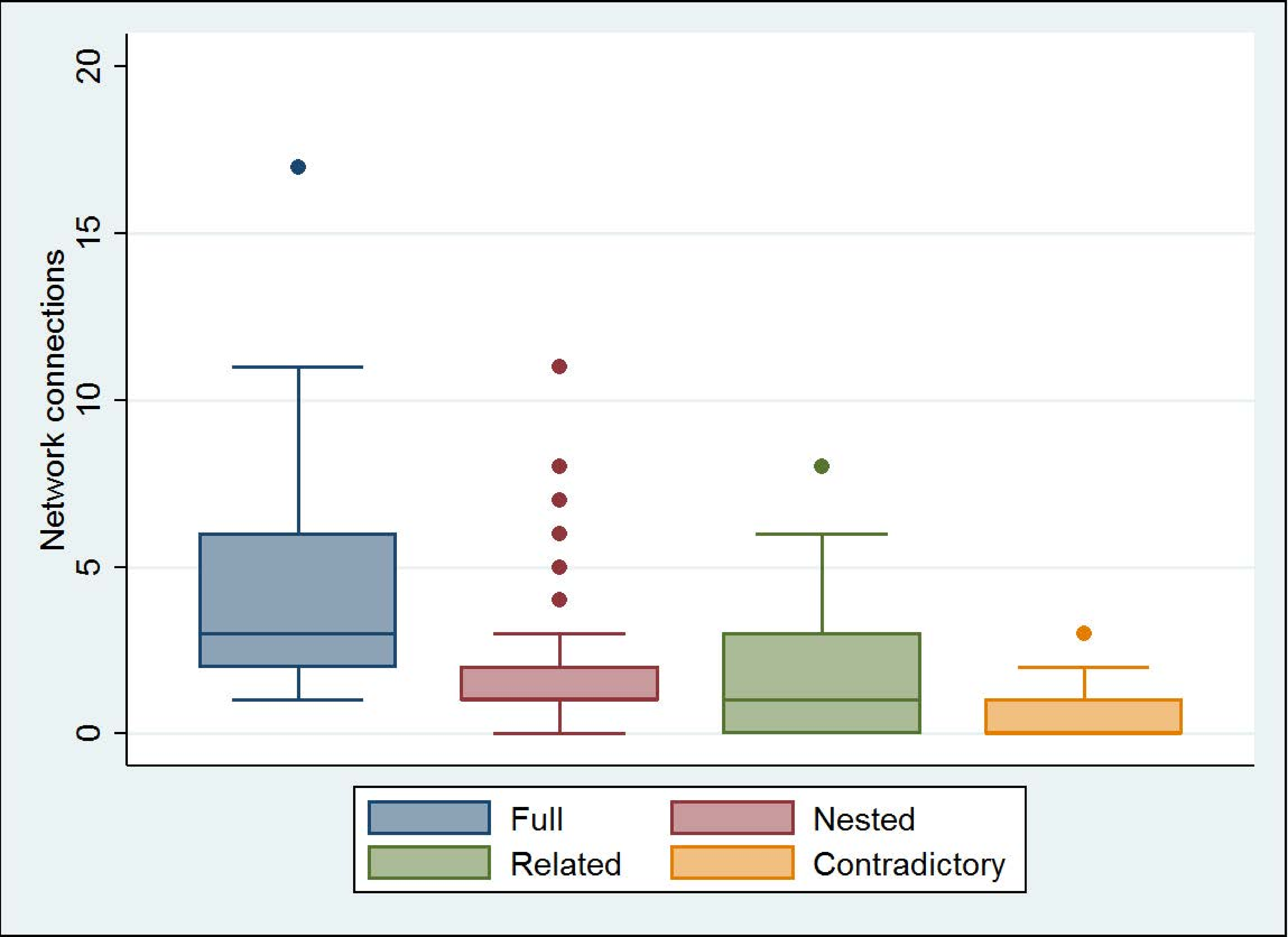
Field		Legend	
Collective action and the commons	Interdisciplinary	Link	
Political economy	Conservation biology		Related
Resilience	Geography and land use change		Contradictory
Environmental & resource economics	Political ecology		Nested



Network connections
0
5
10
15
20
Full
Nested
Related
Contradictory

Table 1: Summary of variable roles

Type	Subtype	Description
Independent	Underlying	An independent variable that affects an outcome by affecting another, more proximate cause. Also referred to as a distal cause.
	Proximate	An independent variable that directly affects an outcome without the help of an intermediary variable.
	Moderating	An independent variable that affects an outcome by affecting the relationship between another independent variable and this outcome. This creates what is commonly referred to as an “interaction effect.”
Outcome	Intermediate	An outcome that is affected by the independent variables in a theory, that in turn affects the final outcome (e.g. collective action of a commons user group)
	Final	The final outcome in a theory (e.g. the condition of an environmental commons as it is affected by levels of the intermediate outcome such as collective action)

Table S2: Types of theory-to-theory relationships

Relationship	Transitivity	Symmetry	Conditions and notes
Nested	Fully	Asymmetric	1) Theory A contains all of the variables that theory B contains, with either the same* values or the opposite* set of values. 2) These variables do not need to have precisely the same roles in the larger theory as they do in the nested one (e.g. a proximate cause may become an intermediate outcome depending on its place in the larger theory).
Related	Partially	Symmetric	1A) Theory A and B have the same* value for the same independent variable and predict the same value for the same final outcome, 1B) OR theory A and theory B have opposite* values for the same independent variable and thus predict opposite values for the same final outcome, 2) AND the two theories do not share the common independent variable via a shared theory that is nested within each.
Contradictory	Not	Symmetric	1) Theory A and B have the same value for the same independent variable but predict a different value for the same final outcome. 2) Because of the principle of equifinality, theories that have different values for the same independent variable and the same value for the same final outcome are not considered to be contradictory.

The table shows three types of relationships. These relationships vary in the extent to which the relationships involved are symmetric, and in the extent to which they confer transitive relationships among theories. The only asymmetric relationship type is nested, in that A containing B does not imply that B contains A. Otherwise the relationships are symmetric.

The nested relationship is fully transitive: if A contains B and B contains C, then theory A contains theory C and all of its variables. Moreover, because theory A contains all of the variables (with the same, or when appropriate, opposite, values) as theory B, this also means that theory A inherits all of the other relationships held by theory B. These inherited relationships are implicit in the variables that theory A contains and are not formally coded for theory A. For example, if theory A contains theory B and theory B contains theory C and is contradictory with theory D, we did not code that theory A had any formal relationship with theories C or D.

Related relationships are partially transitive. If theory A is related to theory B and theory B is related to theory C, whether or not theory A is then related to theory C depends on whether this relationship also satisfies the conditions for the related association. Theories that are related to the same theory are more likely to be related to each other in this way, but are not always related. Contradictory relationships are not transitive at all. However, if A and B are both contradictory to C, then it is likely that they are related to each other.

*Two variables have the same value if the value each of is on the same side of the median value (e.g. both are “high” for an ordinal variable). They have opposite values of their values are on the opposite side of the median value.

Table S3: Summary of variables

Variable	Component type	Type	Theories	Question	Range
Commons Condition Trend	Environmental commons	Ordinal	59	Based on your answers to the Beginning Condition and End Condition variables, would you say that the condition of this commons has improved, remained the same, or worsened during this snapshot?	1 Worsened; 2 Remained the Same; 3 Improved
Collective Action	Actor group	Ordinal	16	What is the current level of collective action within the members of this actor group with respect to the use or management of this commons?	1 Low; 2 Medium; 3 High
Compliance	Actor group	Ordinal	15	Do members of this actor group follow the rules of this governance system with respect to the emission or appropriation of this commons?	1 No; 2 Somewhat; 3 Yes
Transaction Costs	Governance system	Ordinal	15	How high (or low) are the transaction costs of monitoring and enforcing the rules that this governance system involves in managing this commons?	1 Low; 2 Medium; 3 High
Policy Instrument	Governance system	Categorical	13	Does this formal governance system apply any of the following policy instruments to this commons?	Proportional outcome-based performance standard; Absolute outcome-based performance standard; Technological prohibition; Technological mandate; Temporal standard; Ban; Price ceiling ; Price floor ; Tax ; Subsidy; PES scheme; Joint tax-subsidy; Market-based instrument; Information provision; Insurance provision; Protected area
Centralization	Governance system	Ordinal	10	Is this governance system highly centralized or highly decentralized?	1 Highly decentralized; 2 Somewhat decentralized; 3 Somewhat centralized; 4 Highly centralized

External sanctions	Actor group	Binary	10	Are sanctions applied by other actor groups to the members of this group for violations of rules regarding extraction or emission? And if so, are these sanctions graduated (increasing with severity and repetition of offenses)?	Yes; No
Social-Ecological Fit	Governance system	Ordinal	10	To what extent (low, medium, or high) do the institutional arrangements of this governance system fit well with the ecological or physical features of the commons on which they are implemented?	1 Low; 2 Medium; 3 High
External Monitoring	Actor group	Binary	9	Do external actors/organizations monitor the activities of this commons using actor group with respect to the use of this commons?	Yes; No
Governance Knowledge Use	Governance system	Categorical	8	What type(s) of knowledge does this governance system employ in its management of the commons it governs?	Scientific knowledge; Local/traditional knowledge
Actor Adaptive Capacity	Actor group	Ordinal	7	How would you rate the adaptive capacity of this actor group with respect to large changes in the availability or concentration of the commons they rely on in this snapshot?	1 Low; 2 Medium; 3 High
Ecological Resilience	Environmental commons	Ordinal	6	Given the current state of the system, how ecologically resilient is this commons to the threats that it can be expected to face?	1 Poorly resilient; 2 Moderately resilient; 3 Highly resilient
Property Regime	Actor group	Categorical	6	What property regime does this actor group apply to this commons?	Private property; Common property; Public property; Corporate property; Open-access
Actor Traditional Knowledge	Actor group	Ordinal	5	What is the level of traditional or local knowledge this actor group has regarding the condition of this environmental commons?	1 Low; 2 Medium; 3 High
Basin Switch	Environmental commons	Categorical	5	Does this natural resource show evidence of switching stable states during this snapshot? If not, is the current stable state considered to be in a desirable / undesirable state? If yes, is the new stable state considered to be desirable / undesirable?	Yes desirable; Yes undesirable; No desirable; No undesirable; Unclear - system may be transitioning; N/A
Commons Feedback Visibility Use	Actor group	Ordinal	5	How visible are the effects of commons use to this actor group?	1 Low; 2 Medium; 3 High

Metric Diversity	Governance system	Ordinal	5	Does this governance system focus exclusively on one target outcome, or on a range of metrics that are interrelated?	1 Low: One metric for success; 2 Medium: Few metrics for success; 3 High: Many metrics for success
Participation in Rule Making	Actor group	Ordinal	5	How high is the level of participation of this actor group in the process that determines how this environmental commons is governed?	1 Low; 2 Medium; 3 High
Actor Group Trust	Actor group	Ordinal	4	How high is the level of trust between members of this group?	1 Low; 2 Medium; 3 High
Actor Scientific Knowledge	Actor group	Ordinal	4	What is the level of scientific knowledge this actor group has regarding the condition of this environmental commons?	1 Low; 2 Medium; 3 High
Cultural Heterogeneity	Actor group	Ordinal	4	How high is the level of variation in the cultural identity of the group members?	1 Low; 2 Medium; 3 High
Economic Dependence	Actor group	Ordinal	4	How dependent are the members of the group on this commons for their economic well-being?	1 Not dependent or Slightly dependent; 2 Moderately dependent; 3 Very dependent
Economic Status	Actor group	Ordinal	4	What is the average economic status of the group? (Does not refer to variation within the group – see ActorEconomicHeterogeneity).	1 Low; 2 Medium; 3 High
External Recognition	Governance system	Ordinal	4	Within this governance system, do larger governmental jurisdictions (i.e. International agreements, Nation states) recognize the autonomy of lower-level jurisdictions (States, regions, communities), and their right to make decisions regarding this commons?	1 Low - no recognition; 2 Moderate - some recognition; 3 High - complete recognition
Interest Heterogeneity	Actor group	Ordinal	4	How much do the interests of the members of this group diverge from each other?	1 Low; 2 Medium; 3 High
Multiple Levels	Governance system	Categorical	4	Does this governance system contain multiple levels, with each level having a set of actors who conduct tasks with respect to the management of this commons? If so, is there active coordination across these levels, or not?	Single-level governance; Coordination among multiple levels; Multiple levels but no coordination
Productivity	Environmental commons	Ordinal	4	How productive is the commons? For renewable commons this is often positively associated with levels of rainfall and solar radiation. (e.g., Amazon rainforests have very high	1 Poorly productive; 2 Moderately Productive; 3 Very productive

				productivity, while deserts have low productivity).	
Resource Market Value	Environmental commons	Ordinal	4	If it is traded in a market, how high is the market value of this resource?	1 Low; 2 Medium; 3 High
Technology Role	Actor group	Categorical	4	How has technology affected the relationship between this actor group and the commons it uses in this interaction?	Increased commons conservation; Increased commons use; Increased productivity
Biodiversity Trend	Environmental commons	Ordinal	3	What is the trend in biodiversity of this natural resource system during the time frame for which the governance system has been in place?	1 Worsened; 2 Mixed effects or remained the same; 3 improved
Commons Alternatives	Actor group	Ordinal	3	In addition to this particular commons, does this actor group have access to other commons of the same type (e.g. if the commons in use is a forest, other forests) that would serve the same function?	1 Easily access other commons; 2 Can access other commons with some difficulty; 3 Cannot access other commons
Commons Feedback Speed Use	Actor group	Ordinal	3	How quickly does this actor group experience the effects of its own use of this environmenal commons?	1 Low; 2 Medium; 3 High
Commons User Mobility	Actor group	Ordinal	3	Does this commons user group have a large amount of mobility to move within this system and between this system and other systems?	1 Low; 2 Medium; 3 High
Conflict Resolution	Actor group	Binary	3	Are mechanisms in place to address conflicts that arise over the use of this commons by this actor group?	Yes; No
External Support	Governance system	Ordinal	3	Within this governance system, do larger governmental and/or non-governmental organizations actively support (e.g. through the supply of physical or financial resources, information) lower level jurisdictions (States, Regions, Cities)?	1 No support; 2 Some support; 3 Extensive support
Institutional Diversity	Governance system	Ordinal	3	How diverse are the institutions that are implemented by this governance system on this commons? Do these institutions vary systematically with natural variations in properties of this commons?	1 Low; 2 Medium; 3 High
Leadership Accountability	Actor group	Ordinal	3	How accountable are the leaders to the other members of the	1 Low; 2 Medium; 3 High

				group?	
Market Scale	Environmental commons	Categorical	3	If there are markets for goods produced by or associated with this resource, what is the largest scale at which they operate?	local; sub-national; national; international; global; other
Markets	Environmental commons	Binary	3	Are there well-articulated markets for goods produced by or associated with this commons that affect this particular commons?	Yes; No
PA IUCN Strict Zones	Governance system	Interval	3	What percentage of the area of this PA is covered by no take zones (IUCN Ia, Ib, and II)?	Real numbers between 0 and 100
Past Collaboration	Actor group	Ordinal	3	How high is the level of past collaboration within this group?	1 Low; 2 Medium; 3 High
Property Security	Actor group	Ordinal	3	How secure are the rights that this commons user group has with respect to this environmental commons?	1 Low; 2 Medium; 3 High
Proportionality (of costs and benefits)	Actor group	Binary	3	Is there general proportionality between the amount of costs group members incur and the amount of benefits received?	Yes; No
Self-Monitoring	Actor group	Binary	3	Does this actor group monitor its own activities with respect to the use of this commons?	Yes; No
Self-Sanctions	Actor group	Categorical	3	Are sanctions applied by and to the members of this group for violations of rules regarding extraction or emission? And if so, are these sanctions graduated (increasing with severity and repetition of offenses)?	Graduated sanctions; Non-graduated sanctions; No sanctions
User-Commons Proximity	Actor group	Binary	3	Does this actor group reside within or adjacent to the primary resource in this interaction?	Yes; No
Actor Group Boundary Clarity	Actor group	Categorical	2	Are there clear rules that are followed about who and who isn't a member of this group?	No boundaries; Unclear boundaries; Clear boundaries
Actor Group Size	Actor group	Interval	2	For this variable either enter the number of actors (e.g. 30), or if the number of actors is very large and essentially uncountable, enter “Many.”	Positive whole numbers or "Many"
Actor Vulnerability	Actor group	Ordinal	2	How how would you rate the vulnerability of this actor group to changes with respect to the commons that they depend on?	1 Low; 2 Medium; 3 High
Commons Boundaries	Environmental commons	Ordinal	2	Are the boundaries that define the spatial extent of this commons clearly defined and highly visible?	1 Very unclear boundaries; 2 Somewhat unclear boundaries; 3 Clear boundaries

Commons Political Power	Actor group	Ordinal	2	How much power does this actor group have in the process that determines the governance of this commons?	1 Low; 2 Medium; 3 High
Cultural Services Condition	Environmental commons	Ordinal	2	What is the general trend in the condition of cultural services (e.g. spiritual, aesthetic, recreation, education) derived from this commons during the time frame of this snapshot?	1 Worsened; 2 Mixed effects or remained the same; 3 Improving
Environmental Monitoring	Actor group	Ordinal	2	How much environmental monitoring of this commons does this actor group engage in?	1 Low; 2 Moderate; 3 High
Leadership	Actor group	Categorical	2	What type of leadership does this group have, if any?	No leader; Formal leader; Informal leader
Leadership Authority	Actor group	Ordinal	2	How much authority does the leader of this group hold?	1 Low; 2 Medium; 3 High
Leakage	Environmental commons	Categorical	2	Has the governance of this commons led to the leakage of costs or benefits onto other systems? In terms of costs, has the governance of this commons increased extraction or pollution pressures on other similar resources?	Yes, leakage of benefits; Yes, leakage of costs; No leakage
Livelihood Alternatives	Actor group	Ordinal	2	Other than this commons, does this actor group have access to alternative sources of economic livelihood or cultural well being?	1 Easily access other alternatives; 2 Can access other alternatives with some difficulty; 3 Cannot access alternatives
Outsider Exclusion	Actor group	Ordinal	2	To what extent are members of this commons user group able to exclude non-members (outsiders) from using this commons?	1 No exclusion; 2 Some exclusion; 3 Total exclusion
Over-Capitalization	Actor group	Binary	2	Is overcapitalization (e.g. excessive fishing capacity that overwhelms renewal rates of fish or another natural resource) a problem for this user group?	Yes; No
Personal Communication	Actor group	Ordinal	2	How frequently do the actors within this group, or individual representatives, communicate in person?	1 Never; 2 Less than once every 2 years; 3 Once every 2 years; 4 Once a year; 5 More than once a year
Perverse Incentives	Actor group	Binary	2	Do higher levels of governance in this system provide this actor group incentives to over-appropriate or over-emit? For example, through subsidizing fishing fleets or agriculture crops?	Yes; No

User Group Well-Being Change	Actor group	Ordinal	2	How has the well-being of this commons user group changed during the time period identified in this interaction?	1 Worsened; 2 Remained the Same; 3 Improved
Actor Debt	Actor group	Ordinal	1	Has this commons user group had to leverage their assets and take on debt in order to establish and continue their use of this commons?	1 Little to no debt; 2 A moderate level of debt; 3 A high level of debt
Black Markets	Environmental commons	Binary	1	Are there well-articulated illegal markets for goods produced by or associated with this resource that affect this particular commons?	Yes; No
Causal Level	Governance system	Ordinal	1	Would you say that the governance system associated with this commons is addressing the more proximate causes, or addressing the more ultimate, underlying causes of the environmental and social problems that can be associated with this commons?	1 Proximate; 2 Between proximate and ultimate; 3 Ultimate
Commons Boundary Negotiability	Actor group	Ordinal	1	How negotiable is access by non-members of this actor group to this environmental commons?	1 Rigid ; 2 Moderate; 3 Negotiable
Commons Scarcity	Environmental commons	Ordinal	1	How scarce is this resource?	Not scarce -- abundant; Moderately scarce; Highly scarce
Economic Heterogeneity	Actor group	Ordinal	1	How heterogeneous are the members of this actor group in economic terms (wealth, income)?	1 Low; 2 Medium; 3 High
External Ecological Connectivity	Environmental commons	Ordinal	1	How high is the level of ecological connectivity of this natural resource system?	1 Low; 2 Medium; 3 High
Governance System Age	Governance system	Interval	1	How old is this governance system at the beginning of this interaction?	Positive real numbers
Governance System Spatial Extent	Governance system	Interval	1	What is the approximate spatial extent of this governance system (put in terms of square kilometers)?	Positive real numbers
Horizontal Coordination	Governance system	Categorical	1	What type of coordination do the members of this actor group engage in with members of other actor groups that are also involved in the use and/or management of the resource?	No coordination; Informal; Formal; Both formal and informal
Inter Annual Predictability	Environmental commons	Ordinal	1	How predictable is the availability or prevalence of this commons from year to year?	1 Low; 2 Moderate; 3 High
Intra Annual Predictability	Environmental commons	Ordinal	1	How predictable is the availability or prevalence of this commons within years?	1 Low; 2 Moderate; 3 High

Internal Ecological Connectivity	Environmental Commons	Ordinal	1	How high is the level of ecological connectivity between this natural resource system and its external environment?	1 Low; 2 Medium; 3 High
MPA Internal Natural Boundaries	Governance system	Ordinal	1	Does the marine protected area protect an ecologically coherent area (i.e., limited or protected by deep water or sand) within no-take zones?	1 Low; 2 Medium; 3 High
PA CAR Principles	Governance system	Ordinal	1	Were the ecological principles of Comprehensive, Adequate, Representative considered in the design of this MPA?	1 No; 2 Partially; 3 Yes
Participation in PA Siting	Actor group	Ordinal	1	How high was the level of participation of this actor group or their representatives in siting of the marine protected area?	1 Low; 2 Medium; 3 High
Rights Granting Process	Actor group	Categorical	1	Which of the following characterizes the process by which property rights to extract or emit this resource were granted to this actor group?	Based on historic extraction/emission rates; Based on current extraction/emission rates; Based on amount of land owned; Based on rights in another resource; Based on need; Based on political dynamics (power); Based on ethnic group; Based on gender ; Based on nationality; Based on sale or auction; Based on random assignment or lottery
Roving Bandit	Actor group	Binary	1	Would you say that this actor acts like a "roving bandit" (moving from place to place and degrading resources along the way)?	Yes; No
Scale Match	Governance system	Binary	1	Does the scale of this governance system match the scale of the commons that it is governing?	Yes; No

Table 2: Types of theory-to-theory relationships

Relationship	Transitivity	Symmetry	Conditions and notes
Nested	Fully	Asymmetric	1) Theory A contains all of the variables that theory B contains, with either the same* values or the opposite* set of values. 2) These variables do not need to have precisely the same roles in the larger theory as they do in the nested one (e.g. a proximate cause may become an intermediate outcome depending on its place in the larger theory).
Related	Partially	Symmetric	1A) Theory A and B have the same* value for the same independent variable and predict the same value for the same final outcome, 1B) OR theory A and theory B have opposite* values for the same independent variable and thus predict opposite values for the same final outcome, 2) AND the two theories do not share the common independent variable via a shared theory that is nested within each.
Contradictory	Not	Symmetric	1) Theory A and B have the same value for the same independent variable but predict a different value for the same final outcome. 2) Because of the principle of equifinality, theories that have different values for the same independent variable and the same value for the same final outcome are not considered to be contradictory.

The table shows three types of relationships. These relationships vary in the extent to which the relationships involved are symmetric, and in the extent to which they confer transitive relationships among theories. The only asymmetric relationship type is nested, in that A containing B does not imply that B contains A. Otherwise the relationships are symmetric.

The nested relationship is fully transitive: if A contains B and B contains C, then theory A contains theory C and all of its variables. Moreover, because theory A contains all of the variables (with the same, or when appropriate, opposite, values) as theory B, this also means that theory A inherits all of the other relationships held by theory B. These inherited relationships are implicit in the variables that theory A contains and are not formally coded for theory A. For example, if theory A contains theory B and theory B contains theory C and is contradictory with theory D, we did not code that theory A had any formal relationship with theories C or D.

Related relationships are partially transitive. If theory A is related to theory B and theory B is related to theory C, whether or not theory A is then related to theory C depends on whether this relationship also satisfies the conditions for the related association. Theories that are related to the same theory are more likely to be related to each other in this way, but are not always related. Contradictory relationships are not transitive at all. However, if A and B are both contradictory to C, then it is likely that they are related to each other.

*Two variables have the same value if the value each of is on the same side of the median value (e.g. both are “high” for an ordinal variable). They have opposite values of their values are on the opposite side of the median value.

Table 3: Numerical summary of theories

Attribute	Definition	Mean	Median	SD
Variables	Number of variables used	5.63	4.00	3.79
Connections	Number of connections to other theories	4.35	3.00	3.21
Related	Number of "related" connections to other theories	1.78	1.00	2.06
Nested in	Number of theories a theory is nested in	0.94	0.00	1.92
Contains	Number of theories a theory contains	0.94	1.00	1.56
Contradictory	Number of "contradictory" connections to other theories	0.70	0.00	0.99
Steps	Number of steps (up to 4) a theory contains in its process	2.97	3.00	0.78
List	Maximum number of variables at one step a theory contains	2.29	1.00	2.58
Moderators	Number of moderator variables a theory contains	0.95	0.00	1.56

Table 4: Results by scientific field

Field	Description and focus	Theories	Primary link type	Final outcome	Intermediate outcomes	Main Independent variable
Collective Action and the Commons	Explain the outcomes of emergent collective action among natural resource-users.	21	Nested	Commons condition trend	Collective action	Transaction costs
Political Economy	Explain how institutions and political contexts affect environmental outcomes across multiple scales	14	Related	Commons condition trend	Compliance and Social-ecological fit	Centralization
Interdisciplinary	Theories that were closely related to multiple disciplines	7	Nested	Commons condition trend	Compliance and Social-ecological fit	Governance knowledge use
Resilience	Explain conditions under which ecosystems retain their current structure and function and avoid a phase shift to an alternative stable state in the face of *unspecified* perturbation	7	Nested	Basin Switch	Ecological resilience	Actor adaptive capacity
Environmental Economics	Focus on environmental policy instruments	6	Related	Commons condition trend	None	Policy instrument
Conservation Biology	Focus on conservation-based policies and governance regimes (e.g. protected areas)	5	Related	Commons condition trend	Compliance	Policy instrument
Geography and Land Use	Focus on spatial land use dynamics as affected by institutions and technology	2	Related	Commons condition trend	None	Technology role
Political Ecology	Focus on power dynamics and how these affect social and environmental outcomes	1	Related	Commons condition trend	Economic dependence	N/A

A scientific field is characterized by a suite of factors, namely: (1) a topic of study with a characteristic set of research questions and methods designed to answer these questions; (2) an identifiable community of scholars, usually organized around membership in one or more professional or academic societies, a set of conferences, and the set of journals they publish in.

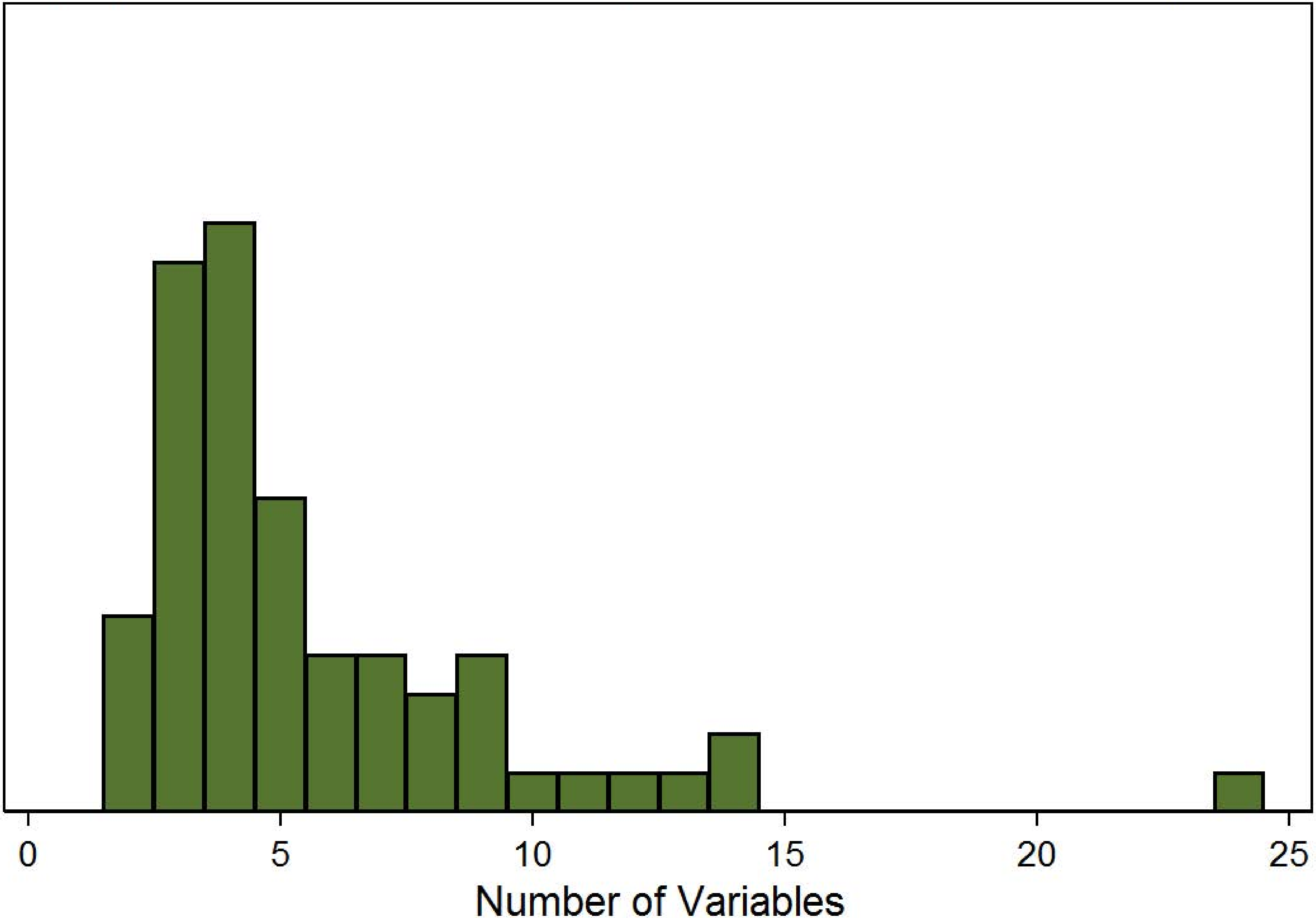
Table 4: Connections between theories by field

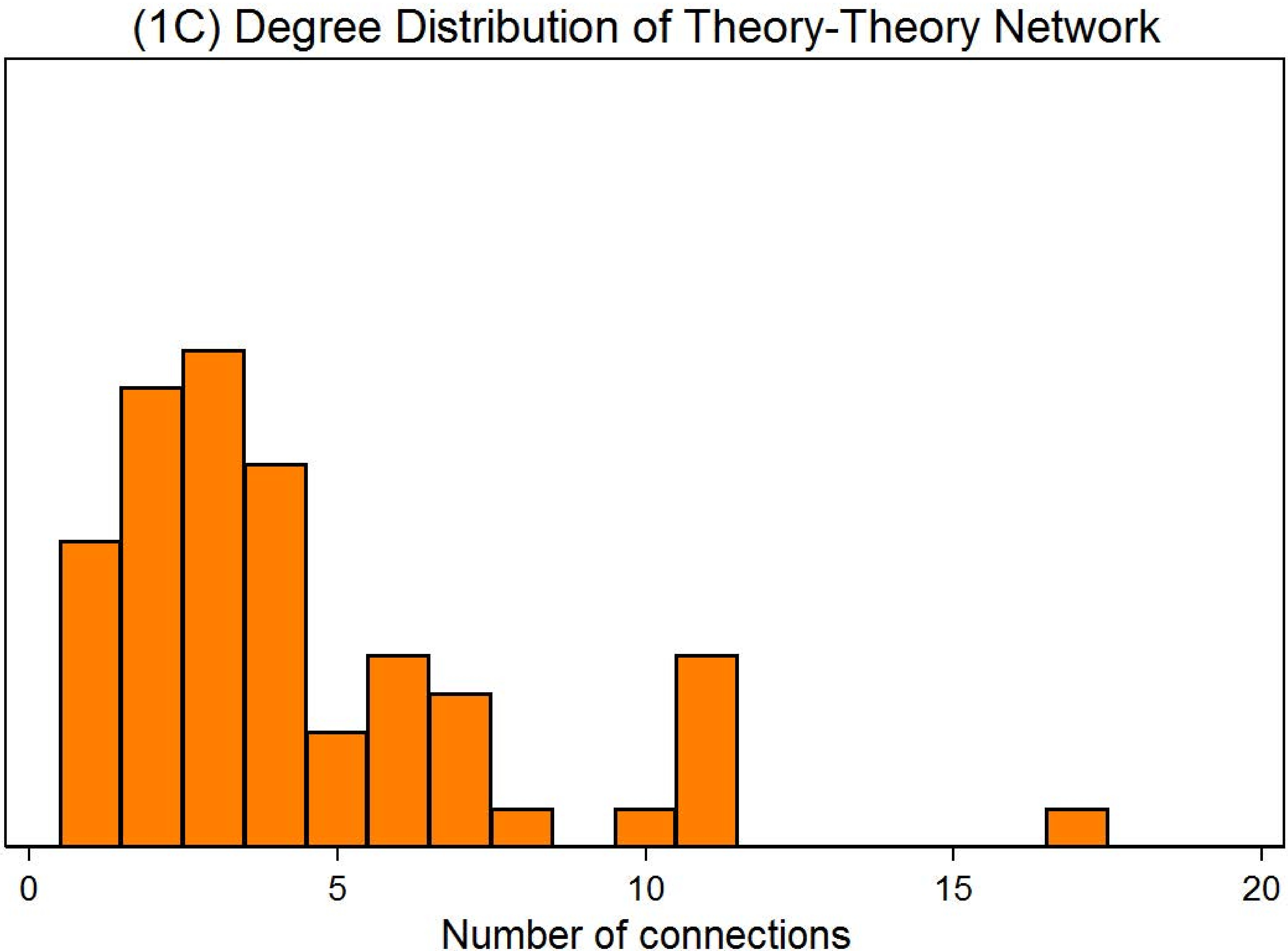
	Commons	Con. Biology	Env. Economics	Geography	Interdisciplinary	Political ecology	Political economy	Resilience
Commons	27							
Con. Biology	3	9						
Env. Economics	0	0	1					
Geography	0	0	3	0				
Interdisciplinary	8	3	4	0	6			
Political ecology	0	0	0	0	0	0		
Political economy	13	10	3	1	12	4	12	
Resilience	5	0	1	1	3	0	4	4

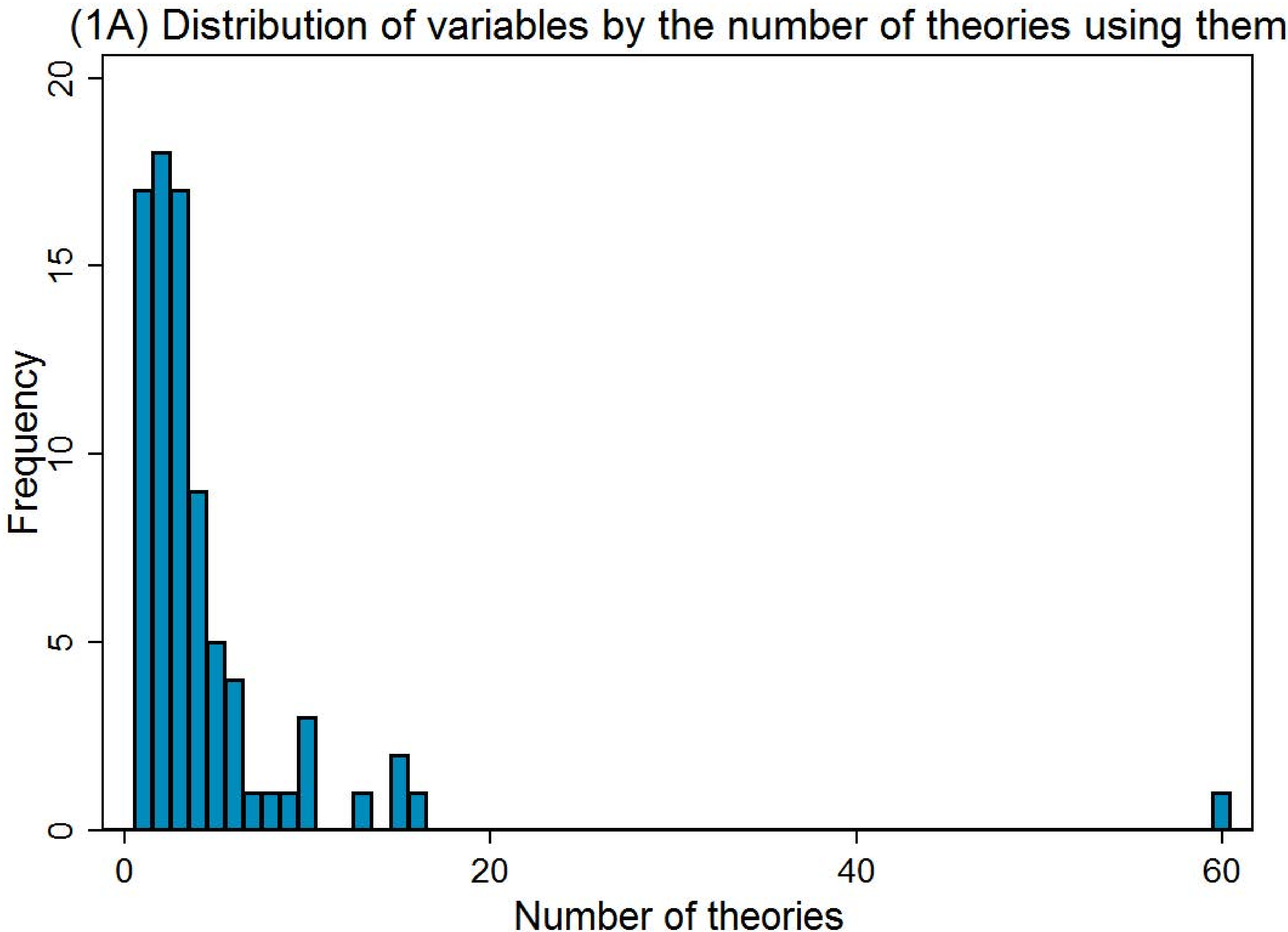
Table 6: Correlation matrix of theory attributes

	Variables	Theories	Related	Nested in	Contains	Contradictory	Steps	List	Moderators
Variables	1.00								
Theories	0.44	1.00							
Related	0.27	0.66	1.00						
Nested in	-0.26	0.28	-0.32	1.00					
Contains	0.73	0.43	0.07	-0.18	1.00				
Contradictory	0.22	0.65	0.58	-0.07	0.02	1.00			
Steps	0.36	0.11	0.07	-0.16	0.29	0.09	1.00		
List	0.87	0.48	0.21	-0.19	0.85	0.14	0.30	1.00	
Moderators	0.31	-0.02	0.06	-0.19	0.04	0.10	-0.40	0.00	1.00

(1B) Distribution of theories by the number of variables they use




(1C) Degree Distribution of Theory-Theory Network
0
5
10
15
20
Number of connections



(1A) Distribution of variables by the number of theories using them
Frequency
0
5
10
15
20
0
20
40
60
Number of theories