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RESEARCH ARTICLE

A meta-analysis of SES framework case studies: Identifying dyad and triad archetypes

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Abstract

1. There is a need to synthesize the vast amount of empirical case study research on social-ecological systems (SES) to advance theory. Innovative methods are needed to identify patterns of system interactions and outcomes at different levels of abstraction. Many identifiable patterns may only be relevant to small sets of cases, a sector or regional context, and some more broadly. Theory needs to match these levels while still retaining enough details to inform context-specific governance. Archetype analysis offers concepts and methods for synthesizing and explaining patterns of interactions across cases. At the most basic level, there is a need to identify two and three independent variable groupings (i.e. dyads and triads) as a starting point for archetype identification (i.e. as theoretical building blocks). The causal explanations of dyads and triads are easier to understand than larger models, and once identified, can be used as building blocks to construct or explain larger theoretical models.
2. We analyse the recurrence of independent variable interactions across 71 quantitative SES models generated from qualitative case study research applying Ostrom's SES framework and examine their relationships to specific outcomes (positive or negative, social or ecological). We use hierarchical clustering, principal component analysis and network analysis tools to identify the frequency and recurrence of dyads and triads across models of different sizes and outcome groups. We also measure the novelty of model composition as models get larger. We support our quantitative model findings with illustrative visual and narrative examples in four case study boxes covering deforestation in Indonesia, pollution in the Rhine River, fisheries management in Chile and renewable wind energy management in Belgium.

3. Findings indicate which pairs of two (dyads) and three (triads) variables are most frequently linked to either positive or negative, social or ecological outcomes. We show which pairs account for most of the variation of interactions across all the models (i.e. the optimal suite). Both the most frequent and optimal suite sets are good starting points for assessing how dyads and triads can fulfil the role of explanatory archetype candidates. We further discuss challenges and opportunities for future SES modelling and synthesis research using archetype analysis.

KEYWORDS
archetypes, cluster analysis, common-pool resources, environmental governance, governance theory, social-ecological systems

1 | INTRODUCTION

Social-ecological systems (SES) research aimed to understand how configurations of social and ecological variables interact, and how those interactions could be governed to achieve outcomes of interest such as environmental sustainability or human well-being. A key question is: what variables interact most frequently and how? There is a large amount of data and knowledge available, some as context-specific case studies and in the form of a relationship between one variable (e.g. group size or leadership) to an outcome (e.g. reef health, forest cover or income; Casari & Tagliapietra, 2018; Nagendra & Ostrom, 2014; Schmitt-Harsh & Mincey, 2020; Yandle et al., 2016). Others describe more detailed interactions, but tend to be qualitative in nature (Carrillo et al., 2019; Palomo & Hernández-Flores, 2019; Partelow et al., 2018), requiring secondary interpretations of relationship strength and casual pathways among numerous variables that are difficult to quantity and compare for meta-analysis (Villamayor-Tomas, Oberlack, et al., 2020). Understanding the nuanced interactions to disentangle multiple or even single variable relationships is often fuzzy. For example, we know that smaller groups of resource users tend to be better able to manage shared local resources like forests and fisheries than larger groups (Casari & Tagliapietra, 2018), but empirics and theory are less conclusive about this in the presence of strong leaders or expensive infrastructure (Epstein et al., 2021). How do we generalize such nuanced and context-specific findings when they each need to be individually interpreted?

Consolidating case studies with many variables into a rich and complex systems theory remains a challenge (Cumming et al., 2020). Many frameworks have attempted to do this by synthesizing variables that are important across cases (Agrawal, 2003; Binder et al., 2013; Pomeroy et al., 2001; Pulver et al., 2018). However, nearly all frameworks in the field (e.g. ecosystem services, resilience and DPSIR) tend to provide a general list of variables and their broad conceptual relationships rather than specify the types of interactions and relationships among those variables that would be observed in a real case. The benefit of frameworks, however, is that they can be used to guide new case study research using a common set of variables to identify those case-specific variable interactions (Partelow, 2023).

Variable standardization can then facilitate more accurate and methodologically sound meta-analyses of the specific variable relationships. This process is necessary to build more meaningful SES theory that helps inform governance towards intentional goals such as social justice and ecosystem resilience which could inform the design of place-based solutions to complex sustainability problems. However, the field struggles with aggregating diverse case study data due to the need to tailor methods to specific projects. This leads to diverse variable definitions, indicators for measurement, measurement and analysis methods, even when using the same framework (Nagel & Partelow, 2022; Partelow, 2018). We argue that if the SES field wants to advance its claim that SES are complex and comprised of many variables that interact dynamically, then there is a need to analyse their interactive effects among each other from a systems perspective (Elsawah et al., 2020), and thus, there is a need to develop innovative methods to do that in synthesis research (Villamayor-Tomas, Oberlack, et al., 2020).

The SES framework developed by Elinor Ostrom and colleagues (McGinnis & Ostrom, 2014; Ostrom, 2009) is arguably the most comprehensive framework in the field alongside the Ecosystem Services or DPSIR frameworks (Binder et al., 2013; Partelow, 2023; Pulver et al., 2018). The SES framework identifies 54 empirically supported variables that influence the ability of communities to govern their resources sustainably. These variables range from considerations of the size and diversity of the groups of resource users, to the predictability and market value of the resource, or the existence of leaders. The framework is broadly applicable to nearly all natural resources or commons governance contexts such as fisheries, forestry, water management, agriculture, climate, public goods and infrastructure provision, as well as knowledge, digital commons and pollution (Meinzen-Dick, 2007; Nagel & Partelow, 2022; Young et al., 2018). While the framework is broadly applicable, it provides little insight into how any of the 54 variables interact. As a result, we understand that each of the 54 variables can play a role in shaping the outcome, but we know far less about how the 54 variables interact with each other, or if recurring groups of variables are linked to the probability of realizing certain outcomes.

The few available studies addressing SES variable interaction analyse what groups or pairs of variables recur across cases, and then have assessed whether those groupings or pairs are linked to certain outcomes (Cumming et al., 2020; Villamayor-Tomas, Oberlack, et al., 2020). Historically, most empirical evidence in the field has attempted to identify variables and then isolate an association between those independent variables (e.g. number of resource users, economic value and specific rules) and one dependent outcome (e.g. collective action, forest cover, water quality and income; Barnett et al., 2020; Cox et al., 2010; Oberlack & Eisenack, 2018). In doing this, we are assuming that complexity is a simple aggregation of single variable outcome relationships. For example, Ostrom's Design Principles are typically studied this way, as well as most studies using Ostrom's SES framework (Cox et al., 2010; Partelow, 2018; see Baggio et al., 2016 for an exception). We do know, however, that there are interactive effects between independent variables (Epstein, 2017; Epstein et al., 2021; Kellner, 2023), but synthesizing them across diverse cases to infer causality is challenging and requires methodological innovation to solve. Current approaches are time intensive and can create methodological challenges because they often require either re-coding qualitative data manually, interpreting and transforming qualitative causal statements into quantitative values, or transforming quantitative values into standardized units. This is needed even when standardized conceptual variables from the same framework are used, due to the need for individual studies to adapt indicators and measurement methods to context (Nagel & Partelow, 2022; Partelow, 2018). Another challenge for theoretical synthesis is the crowding out of theoretical discussions in papers with limited word counts and discussions of policy and practical relevance instead. For example, during the coding process to acquire the data for the analysis in this project, model descriptions and associated data were often split between paper sections, annexes and supplementary files, which makes secondary data reuse and the identification of archetypes difficult.

Archetypes are characterizations of the generic structures and behaviours of a system, usually shown as causal graphs, that may recur across cases (Oberlack et al., 2019). Archetype analysis investigates these recurrent patterns of the phenomenon of interest at an intermediate level of abstraction to identify multiple models that explain the phenomenon under particular conditions (Eisenack et al., 2019) and offers a useful conceptual framing and set of methodological tools to make progress on bridging the gap between synthesis and empirical research (Eisenack et al., 2019; Oberlack et al., 2019). Archetypes help specify what Merton (1968) referred to as middle-range theory. Geels (2007) characterizes middle-range theory as contextualized generalizations, that is, general propositions that apply only within specific conceptual and empirical boundaries. For example, highly efficient irrigation technologies allow Spanish farming communities to better cope with droughts. This, however, does not apply to communities that are small and less productivity-oriented: it only applies to larger, professionalized irrigation systems that have the means to operate and maintain such technology (Villamayor-Tomas, Iniesta-Arandia, et al., 2020).

Archetypes fill a niche in providing a specific set of analytical tools for developing middle-range theory in practice. Eisenack et al. (2019) note that archetypes 'generally reject a single universal model [but rather] identify multiple recurrent patterns that function as building blocks to explain outcomes in multiple, more or less heterogeneous cases'. Archetypes thus extract patterns of regularity while remaining grounded to context. Many different methodologies have contributed to archetype analysis such as social-ecological network analysis (Bodin et al., 2019; Kluger et al., 2020; Sayles et al., 2019), formal concept analysis (Oberlack et al., 2016), qualitative comparative analysis (Crona et al., 2015; Villamayor-Tomas, Iniesta-Arandia, & Roggero, 2020) and other specific quantitative (e.g. machine learning, clustering, process or variable centric meta-analysis) and qualitative approaches (e.g. classification and expert assessment; Sietz et al., 2019). However, very few SES framework applications have pursued an archetype approach (Nagel et al., 2024; Nagel & Partelow, 2022; Oberlack et al., 2016; Rocha et al., 2019). The theoretical contribution this paper aims to make is to identify the foundational units (pairs of dyads and triads) that can then be used to identify sets of cases that have models and outcomes within them. Within these cases—as a next step beyond this paper—qualitative mechanisms can then be examined to construct archetypes that are on one hand abstracted to build theory, but on the other hand linked to context. This paper is a necessary first step towards middle-range theory building using the archetype lessons.

The purpose of this paper was to examine whether interaction patterns among the 54 variables of the SES framework can be identified and to assess whether they are linked to specific outcomes. Furthermore, we ask the question of whether interacting variable pairs of two (i.e. dyads) or three (i.e. triads) can be used as archetypal building blocks. This would mean that the identified dyads or triads tend to have the same sets of causal mechanisms when we look back at the case studies they come from, and that they would be a in part explanatory of larger models in other cases with those pairs as well (Figure 2). In other words, if we can identify recurring dyads and triads, would it be possible to combine them, as a way of explaining the dynamics of larger models? Simply identifying the existence of recurring dyads and triads—and then trying the explain their causal mechanisms—is a necessary first step. To do this, however, innovative case study synthesis methodologies are needed given the data diversity and interpretation challenges. This includes the need for effective tools for aggregating and analysing diverse case study data into standardized formats (Baggio et al., 2016; Lambert et al., 2021; Sietz et al., 2019; Villamayor-Tomas, Oberlack, et al., 2020). Our approach suggests that new tools such as machine-learning techniques can facilitate and provide new insights for exploratory analysis.

2 | METHODS

This study uses a systematically generated quantitative data set that was created by coding qualitative SES case studies (i.e. written mostly in the form of narratives) in the peer-reviewed SES framework literature into models, that is, a database where the rows are explanations and the columns are variables that are present or absent in the explanations (Villamayor-Tomas, Oberlack, et al., 2020). The coding process followed standard practices for evidence synthesis and, more generally, thematic analysis (Braun & Clarke, 2021; Haddaway et al., 2015; James et al., 2016). Peer-reviewed studies were coded independently by two people (i.e. two different coders) and then compared. Any differences in the coding were resolved through discussion among coders. If necessary, the lead author (i.e. Villamayor-Tomas, Iniesta-Arandia, et al., 2020) of the meta-analysis study (Villamayor-Tomas, Oberlack, et al., 2020) was consulted as a third party to ensure standardization of the coding procedure across all coding teams and models. In this study, a 'model' is an explanation that includes a set of independent variables and an outcome. The simplest model in the data is one independent and one outcome variable. The coded models reflect causal explanations as stated by the authors of the case studies in the text. The variable was only coded as part of a model, if it described a causal influence on the outcomes (either in qualitative text or in a quantitative data table), as represented by the authors in the original paper. For example, a paper may have examined 10 independent variables, but only found four that have a causal influence on two different outcomes. The authors of Villamayor-Tomas, Oberlack, et al. (2020) would then have coded two different models, one for each of the different outcomes, and each containing the same four variables. This reflects the fact that case studies may identify several models for the same outcome (i.e. equifinality), or one model could lead to multiple different outcomes (i.e. social and ecological impacts). The authors coded all configurations of models with causal relationships to single outcomes (as stated by the original authors) as separate models. They focused on models that explained 'final outcomes' as specified in the SES framework, as either Social Outcomes (O1) or Ecological Outcomes (O2). While the dataset includes 125 models in total, this study examined the 71 models with explicit final outcomes in the data (e.g. livelihoods and sustainable development), excluding models with only intermediary outcomes (e.g. cooperation, conflict resolution and monitoring) or with both intermediary and final outcomes for simplicity, which enabled the use of standardized analysis methods. The context of the models is diverse, originating from case studies on the governance or management of fisheries, aquaculture, agriculture, irrigation, water use, renewable energy, outdoor recreation and pollution.

All original qualitative case studies used the SES framework, which facilitated the coding. The SES framework organizes variables into first-tier categories (Actors; Governance; Social, Economic & Political settings; Interactions) and second-tier variables (the 35 variables studied) (Table 1, Figure 1). Independent variables in this data are coded as being 'present' or 'absent'. It was not possible to accurately and consistently determine the strength of effects, or substantive significance, of each independent variable on the outcome for two reasons. First, not all case studies detailed this relationship in a quantifiable way that allowed for consistent coding. Second, the presence–absence approach enables far more case studies and variables to be included (the trade-off being fewer more detailed explanations). This approach suits the purpose of our analysis, which is most importantly to identify the most frequent variable groupings (i.e. dyads and triads). Including more models and variables increases the likelihood that our configurations are representative of the broader literature, even at the cost of losing contextual detail. Furthermore, it is often unclear how to assign a quantitative value from a qualitative narrative with causal statements while maintaining methodological integrity and replicability. This would require a large degree of assumption by the coders, where the translation of qualitative significance into either categorical, ordinal or continuous quantitative data has different challenges and assumptions. Our approach minimizes these interpretation risks because all SES framework variables used were explicitly stated in the studies, and therefore simple to identify and include as present or absent. Clear outcomes were also stated in the original studies, even if the explanation of the causal link describing the relationship between the independent variable and outcome was ambiguous. If further research were to include the coding of causality, methodological innovation would be needed with particular attention given to transparently describing the decisions and trade-offs being made in the coding process. Another challenge is how differing degrees of directionality, intermediary outcomes or degrees of significance could be, or are, handled within the current statistical analysis tools used in this study (i.e. clustering methods, principal component analysis [PCA]) described below.

We examined the frequency of groups of two and three variables (dyads and triads) across all models and the four possible outcome group combinations (positive social, negative social, positive ecological and negative ecological). As a starting point, analysing two and three variable groupings is necessary before moving to larger groupings because if dyads and triads comprise the majority of model complexity, then explaining casual relationships will be easier and may not need more complex configurations to make progress. We also limit this study to dyads and triads, rather than displaying and including quadrads (i.e. four variable groups) to focus the study. To do this, dyad and triad edge lists were generated, aggregated and ranked by frequency. Then, we identified the set of dyads and triads which optimized the coverage of models in the dataset. In addition, we only selected dyads (or triads) which appear at least once as a 'stand-alone' set in at least one model, that is, the triad is the model, and not only as a part of a larger model.

We further analyse the relationship between dyads and triads to model outcomes. The data were aggregated at the first-tier level of the SES framework in order to simplify the observed relationship between social and ecological variable composition to the four possible outcomes (social negative, social positive, ecological negative and ecological positive). A hierarchical cluster analysis was performed by calculating the Euclidean distance and clustering with Ward's method. Using the NbClust package in R (Charrad et al., 2014), we tested the optimal number of clusters using nine different techniques for our data, which indicated either two or four clusters as optimal. The cluster analysis is used to identify groupings of similar

TABLE 1 First- and second-tier variables of the social-ecological systems (SES) framework developed by Ostrom and colleagues. Each variable has an assigned code for reference to its first tier and was included in the framework based on evidence from prior empirical studies demonstrating the potential role each plays in shaping management and governance outcomes in SES.

Social, economic and political settings (S)	
S1—Economic development. S2—Demographic trends. S3—Political stability. S4—Other governance systems. S5—Markets. S6—Media organizations. S7—Technology	
Resource Systems (RS)	**Governance Systems (GS)**
RS1—Sector (e.g., water, forests and pasture)	GS1—Government organizations
RS2—Clarity of system boundaries	GS2—Non-governmental organizations
RS3—Size of resource system	GS3—Network structure
RS4—Human-constructed facilities	GS4—Property-rights systems
RS5—Productivity of system	GS5—Operational rules
RS6—Equilibrium properties	GS6—Collective choice rules
RS7—Predictability of system dynamics	GS7—Constitutional rules
RS8—Storage characteristics	GS8—Monitoring and sanctioning
RS9—Location	
Resource Units (RU)	**Actors (A)**
RU1—Resource unit mobility	A1—Number of relevant actors
RU2—Growth or replacement rate	A2—Socioeconomic attributes
RU3—Interaction among resource units	A3—History or past experiences
RU4—Economic value	A4—Location
RU5—Number of units	A5—Leadership/entrepreneurship
RU6—Distinctive characteristics	A6—Norms (trust-reciprocity)/ social capital
RU7—Spatial and temporal distribution	A7—Knowledge of SES/mental models
	A8—Importance of resource (dependence)
	A9—Technologies available
Interactions (I)	**Outcomes (O)**
I1—Harvesting	O1—Social performance measures
I2—Information sharing	O2—Ecological performance measures
I3—Deliberation processes	O3—Externalities to other SESs
I4—Conflicts	
I5—Investment activities	
I6—Lobbying activities	
I7—Self-organizing activities	
I8—Networking activities	
I9—Monitoring activities	
I10—Evaluative activities	
Related Ecosystems (ECO)	
ECO1—Climate patterns ECO2—Pollution patterns ECO3—Flows into and out of SES	

models, both in the total number of variables (i.e. model size) and the model composition (i.e. which specific combinations of social and ecological variables). This was coupled with model outcome groups to examine whether there is a relationship between model composition and size with outcome groups. Principal component analysis was also performed with first-tier variable counts across outcome model groups in R package 'Vegan' (Oksanen et al., 2022). The PCA was performed to examine which first-tier variable groups of the SES framework drive the variation in cluster group formation. Dyad and triad frequency and percentage recurrence across models were calculated by generating edge lists of the two and three variable pairings across all models, using network analysis software (Csardi & Nepusz, 2015).

3 | RESULTS

Below, we detail a series of cumulative findings using different analysis methods. We first show the descriptive frequencies of single variables and outcomes in the data. The next step is to assess whether there is any relationship between outcome classes (positive, negative; social, ecological) and model composition. This is done with a cluster analysis which enables us to see which models are grouped (i.e. cluster) together by similarity of features (i.e. size and/or variable composition), and whether those groups are explained by their relationship to outcome classes or not. A PCA was then used to better understand which aggregate first-tier variables of the SES framework drive variation in model composition that led to the formation of the groups in the cluster analysis. We then create edge lists of dyads and triads (the recurring pairs of two and three variables across all models), to measure their frequency and links to outcome classes. With the dyad and triad frequency data, we can then compare whether smaller models are contained within the larger models and at what frequency (i.e. as potential building blocks), as well as test which specific dyads and triads explain the most coverage (i.e. represent the highest diversity of models) across all models.

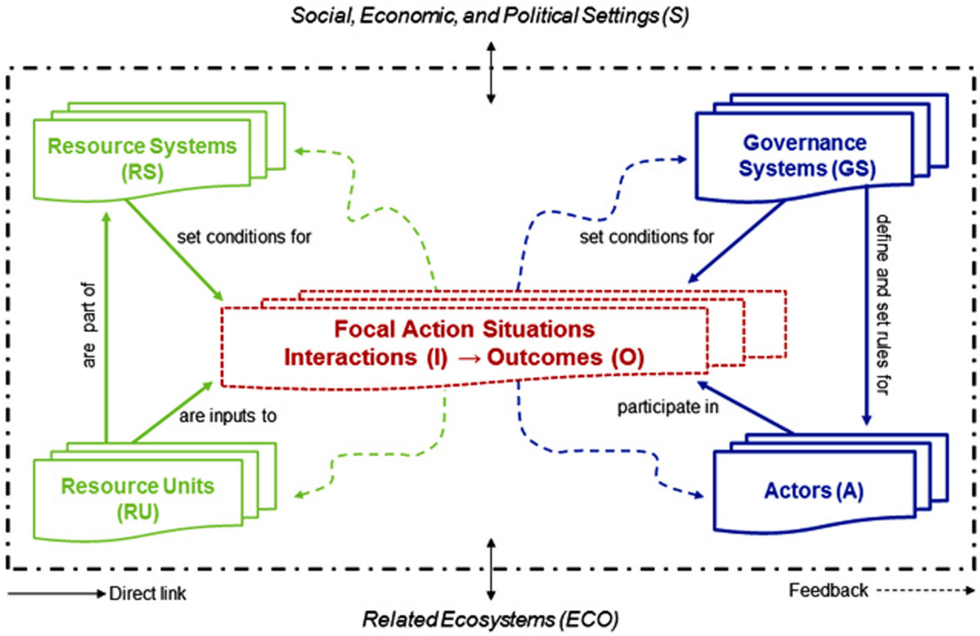


FIGURE 1 Conceptual organization of the social-ecological systems framework first-tier variables (McGinnis & Ostrom, 2014). Each first-tier variable has more specific second-tier variables shown in Table 1.

3.1 | Model and variable descriptions

Our main interest is in recurrence of dyads and triads. Before addressing them, examining the distribution of individual variables (and their association with outcomes) is useful. The 14 most frequent variables in the models are social (Figure 3). The most frequent are 'A6 Norms and social capital', 'GS5 Operational rules', 'A5 Leadership', 'GS4 Property rights', and 'A8 Importance of resource'. The most frequent ecological variables are 'RS4 Human-constructed facilities' (rank 15), 'RS3 Size of resource system' (rank 18) and 'RU4 Economic value' (rank 23) (Figure 3). Thus, either social variables tend to contribute more to explaining model outcomes across all groups (+16%), particularly social outcome models (+20%), or there is a bias towards examining the social variables in empirical applications of the SES framework (Vogt et al., 2015; Table S2). There is no clear relationship between any single variable and a specific outcome group or cluster. Even correcting for the smaller number of ecological variables in the SES framework (only 19 compared with 35 social), the focus on social variables is still dominant.

Social outcome models have a larger number of variables (total 259; average 6.4) than ecological outcome models (total 177; average 5.7), when the sum of all variables in all models contributing to those outcome groups are calculated (Table S2). However, when accounting for unique variables (i.e. whether a variable is mentioned or not in any of the models), social and ecological models are more even. Positive social and ecological outcome models have more overall and unique second-tier variables (Tables S2 and S3) than negative outcome models (Table S3), and have a higher mean number of second-tier variables (Table S4). Positive social outcome models include a total of 43 (out of 54) unique second-tier variables across all 27 models, with a mean of 7.4. Positive ecological outcome models have a total of 38 (out of 54) unique second-tier variables across all 18 models, with a mean of 6.1.

3.2 | Clustering models by size and composition

Four clusters were identified as the optimal way to categorize all models. Cluster 1 contains 36 models averaging 1.8 variables each. Cluster 2 contains 23 models averaging 6.1 variables each. Cluster 3 contains 8 models averaging 13.3 variables each. Cluster 4 contains 4 models averaging 30.2 variables each. All cluster groups have a mix of models with all four outcome possibilities. There is no observed relationship between model composition and model outcomes (Figure 4a). The main factor underlying cluster formation appears to be model size (i.e. the number of variables in the model), and the social and ecological mix of specific variables (Figure 4b).

The hierarchical cluster analysis determines model groupings by balancing the number of individual clusters with their internal diversity. However, it does not provide information about which specific variables differ across clusters and therefore influence cluster formation and model heterogeneity. We conducted a PCA to assist in interpreting drivers of cluster formation. The PCA helps us identify differences in variable composition across models (at the first-tier level), and when paired with the cluster groups, provides information about variation across the groups. The first two principal components explain 81.2% of the variation across all models, PC1 63.5% and PC2 16.7%. The clusters have clear groupings (Figure S2). Cluster 1 and Cluster 2 contain many relatively simple models, with a likely aggregate composition of first-tier level variables that are similar and mostly social. As the models in Cluster 3 and Cluster 4 become larger, more variation is observed. Variation in Cluster 3 seems to be driven by increased social variable heterogeneity, while Cluster 4 contains more ecological variables. Differences in the mean social variables per model per cluster group (Social-Economic-Political settings (SEP), Actor, Gov., Interactions) and mean ecological variables are clear between Cluster 3 and Cluster 4 (Figure 4b).

3.3 | Recurring dyads and triads in cluster groups

We identified the recurrence of dyads and triads across all models. Fifty-four variables allow for 1413 unique combinations of two (dyads) and 24,804 combinations of three (triads) variables. Our data contains 1020 unique dyads (72% of all possible) and 12,015 unique triads (48% of all possible). As one might expect, the distribution of dyads and triads is skewed, with 300 dyads and 5500 triads occurring only once, and three dyads / five triads appearing more than 15 and 10 times, respectively (Figure S3, see Tables 2 and 3 for a list). All of the most frequent dyads involve social variables, specifically from the Actor and Governance tiers of the SES framework. The most frequent triads are also composed of social variables from the SES framework Actors and Governance tiers; however, there are also frequent triads with Resource System (RS3, RS4) and Interaction (I7, I8) tier variables (Table 3). None of the most common triads appear in Cluster 1, which is reasonable since the average number of variables per model in Cluster 1 is 1.8. Two triads occur once each in Cluster 1, and eight times in total.

We tested the number of unique dyads per cluster group as a measure of how unique the composition of each cluster group is (Table S5). The main finding is that as models get more complex (i.e. more variables), the majority of the dyads and triads are repeating until you get to the most complex models. We observe that, as the number of variables per model increases across the four cluster groups, the number of unique dyads increases despite the fact that the number of models per cluster group decreases. For example, Cluster 2 has 14 unique dyads (7.3%), and Cluster 3 has 48 (12.9%). Cluster 4 only has four models; however, 60% of the dyads are unique. This is likely because the mean number of variables per model in Cluster 4 is 30.2 (out of 54) (i.e. the more variables models include, the higher the possible dyad combinations with other variables). Similar patterns are observed for triads, although Cluster 2 has a slightly lower percentage of unique triads than Cluster 1.

As a measure of the similarity in model composition, we conducted additional tests on the percentage recurrence of dyads and triads

TABLE 2 Most frequent dyads across cluster and outcome groups.

Dyads		Cluster frequency					Outcome frequency			
		Total	C1	C2	C3	C4	Soc+	Soc−	Eco+	Eco−
A5 Leadership	A8 Importance of resource	17	0	6	7	4	8	2	5	2
A6 Norms/social cap.	GS5 Operational rules	16	0	11	2	3	7	4	3	2
A7 Know. of SES	GS5 Operational rules	15	0	9	3	3	5	4	4	2
A6 Norms/social cap.	GS4 Property rights	14	1	8	2	3	8	1	3	2
GS5 Operational rules	GS8 Monitoring/ sanctioning	14	1	5	5	3	5	2	4	3
A5 Leadership	A6 Norms/social cap.	13	0	5	5	3	7	2	3	1
A5 Leadership	GS5 Operational rules	13	0	5	5	3	6	1	5	1
A5 Leadership	A7 Know. of SES	12	0	6	3	3	5	2	3	2
A6 Norms/social cap.	A8 Importance of resource	12	0	4	5	3	6	2	3	1
GS4 Property rights	GS5 Operational rules	12	1	7	1	3	5	2	3	2
A5 Leadership	GS6 Collective choice rules	11	0	1	6	4	5	1	4	1
A6 Norms/social cap.	A7 Know. of SES	11	0	5	3	3	3	4	2	2
A2 Socioecon. attributes	A6 Norms/social cap.	11	0	7	1	3	7	1	2	1
I7 Self-organizing	A6 Norms/social cap.	11	1	3	3	3	6	2	3	0

across clusters (Table 4). If understanding system complexity is in part a function of model size, we are testing whether we can identify how small sets of repeating dyads and triads interact as a representation of the larger model. We find support for this in the observation that there is little dyad and triad composition novelty as model size increases. Cluster 1 which only has dyads and triads as the full model, already comprise 93% of the dyads and 75% of the triads in the most complex models. This provides strong support for starting with dyads and triads as a basis of building blocks for understanding the aggregate configurations of more complex models. Only with the most complex models (i.e. in cluster 4) does novelty slightly increase. Pairing this observation with the variable frequency across cluster groups (Figure 2b) and the PCA (Figure S2), we can see which variables are driving the unique and recurrent variation. For example, Cluster 4 models have more ecological variables, but also a very high percentage of the same social variables appearing in the other clusters.

3.4 | Outcome groups with dyads and triads

Dyad and triad pairs relate to either social or ecological outcomes, and they can be either positive or negative (Tables S6 and Table S7). Dyads have stronger relationships with specific outcomes than triads, even after controlling for the total number of dyad and triad models linked to each outcome group, which is uneven. This means that there is a clearer association among dyads with a specific outcome (e.g. social positive) compared with many of the triads which have less obvious relationships to the four possible outcomes. This may suggest that dyads could be reasonable starting points for archetypes. As models get more complex (from dyad to triad to multi-dyad-triad model), the strength of the relationship to a specific outcome seems to decrease due to less certainty given the multiple variable relationships.

3.5 | Optimal suite of dyads and triads

The optimal suite is a minimum diversity metric that aims to maximize the coverage of models with a small number of dyads or triads. We do not consider outcome groups in this analysis. There is a set of 10 dyads which appear in 84% of all models (46) in the data coded (Table 5). The highest number of triads, meanwhile, is 8, covering 88% of all models in the data coded with at least three variables. Adding one more set to both the dyad and triad suites only increases the coverage in each set by one model, suggesting a plateau. The dyads and triads in the optimal suites are overlapping with the most frequent dyads and triads, but not entirely. For example, the frequent triad of 'Leadership A5—Social capital A6—Importance of resource A8' is needed in the optimal set of triads in order to cover many models. On the other hand, the nearly as frequent triad 'Knowledge of SES A7—Operational rules GS5—Monitoring and sanctioning GS8' does not appear here, because it overlaps quite frequently with other triads. Focusing on the optimal suites seems to be more important for theorizing archetypes that cover a larger diversity of potential cases than focusing on the most frequent dyads and triads only.

4 | DISCUSSION

4.1 | Implications of specific findings

We set out to identify patterns of SES framework variable interactions and assess their relationships to specific outcomes. Such patterns could be identified in the form of recurring variable dyads and triads. However, we show no definitive links to either positive or negative, or social or ecological outcomes. Before discussing the meaning of these findings, we address some limitations of our study. The first and most obvious limitation is the use of secondary data. As such, it inherits the limitations of and challenges faced in the original study about interpreting causal statements in peer-reviewed scientific publications that were written with other objectives in mind and belong to different epistemic communities with different transparency and reproducibility norms. A second limitation is the relatively small number of models available to analyse (i.e. from the SES framework literature) compared with the number of possible dyads and triads that could be configured from the 53 SES variables likely occurring in non-documented cases or other literature with different frameworks. A related limitation stems from the choice to limit cases to those applying Ostrom's SES framework. While Ostrom's framework enables relatively rapid synthesis, it does not incorporate all variables and assumptions present across other types of SES studies. Third, our study is limited to assessing presence or absence and does not capture directional or value metrics, including on outcomes. Numerous other meta-analysis efforts have used similar presence-absence coding procedures, including on outcome variables (Baggio et al., 2016; Barnett et al., 2020; Cox et al., 2010). This highlights the need for a three-sided approach that includes (1) exploring new tools and approaches for data integration (e.g., mixed qualitative and quantitative coding) and synthesis (e.g. unsupervised and supervised machine-learning tools), (2) incentives for transparency in empirical research designs (where the adoption of frameworks can assist) and (3) clear statements about the levels of theory the study contributes to informing.

Setting aside these limitations, we observed a certain skewedness in our results towards social variables, with Actor and Governance variables characterizing the most frequent dyads and triads across the 71 models. This may seem puzzling, given that the broader SES modelling literature tends to neglect social variables and dynamics (Stock et al., 2023). Then again, our analysis is based on the SES framework literature, where social aspects are a key concern—regardless of the biophysical system at stake: fisheries comanagement (Gutiérrez et al., 2011), recreational fisheries (Fujitani et al., 2020), coral reef conservation (Cinner et al., 2018), marine protected areas (Edgar et al., 2014) and forestry (Epstein et al., 2021; Hajjar et al., 2016, 2021; Persha et al., 2011).

The most frequent dyads include 'A5 Leadership' and 'A8 Importance of resource'. A possible explanation is that high stakes in

TABLE 3 Most frequent triads across cluster and outcome groups.

Triads			Cluster frequency					Outcome frequency			
			Total	C1	C2	C3	C4	Soc+	Soc−	Eco+	Eco−
A5 Leadership	A6 Norms/social cap.	A8 Importance of resource	12	0	4	5	3	6	2	3	1
A7 Know. of SES	GS5 Operational rules	GS8 Monitoring/sanctioning	11	0	5	3	3	4	2	3	2
A5 Leadership	A8 Importance of resource	GS5 Operational rules	10	0	3	4	3	4	1	4	1
A5 Leadership	A8 Importance of resource	GS6 Collective choice rules	10	0	1	5	4	4	1	4	1
A6 Norms/social cap.	GS4 Property rights	GS5 Operational rules	10	0	6	1	3	5	1	2	2
I7 Self-organizing	A5 Leadership	A8 Importance of resource	10	0	1	7	2	5	2	3	0
A1 Number of users	A5 Leadership	A8 Importance of resource	9	0	2	3	4	4	1	3	1
A1 Number of users	A5 Leadership	RS3 Size of resource system	9	0	2	3	4	4	1	3	1
A1 Number of users	A8 Importance of resource	RS3 Size of resource system	9	0	2	3	4	4	1	3	1
A5 Leadership	A7 Know. of SES	GS5 Operational rules	9	0	3	3	3	4	1	3	1
A5 Leadership	A8 Importance of resource	RS3 Size of resource system	9	0	2	3	4	4	1	3	1
A5 Leadership	GS5 Operational rules	GS6 Collective choice rules	9	0	1	5	3	4	1	3	1
A5 Leadership	GS5 Operational rules	GS8 Monitoring/sanctioning	9	0	1	5	3	4	1	3	1
A5 Leadership	GS6 Collective choice rules	GS8 Monitoring/sanctioning	9	0	1	5	3	4	1	3	1
A6 Norms/social cap.	A7 Know. of SES	GS5 Operational rules	9	0	5	1	3	2	3	2	2
A6 Norms/social cap.	GS5 Operational rules	GS8 Monitoring/sanctioning	9	0	4	2	3	3	2	2	2
A6 Norms/social cap.	GS5 Operational rules	RS4 Human-constructed fac.	9	0	4	2	3	4	2	2	1
GS5 Operational rules	GS6 Collective choice rules	GS8 Monitoring/sanctioning	9	0	1	5	3	4	1	3	1
I8 Networking activities	A5 Leadership	A6 Norms/social cap.	9	0	3	4	2	5	1	3	0

TABLE 4 Recurrence rates of dyads and triads across clusters. For example, 40.9% of the dyads in Cluster 1 recur in Cluster 2.

	Recur in Cluster 2	Recur in Cluster 3	Recur in Cluster 4
Dyads in Cluster 1	40.9%	45.4%	93.2%
Dyads in Cluster 2		67.0%	85.8%
Dyads in Cluster 3			84.1%
Triads in Cluster 1	14.60%	24.40%	75.60%
Triads in Cluster 2		48%	71.30%
Triads in Cluster 3			68.70%

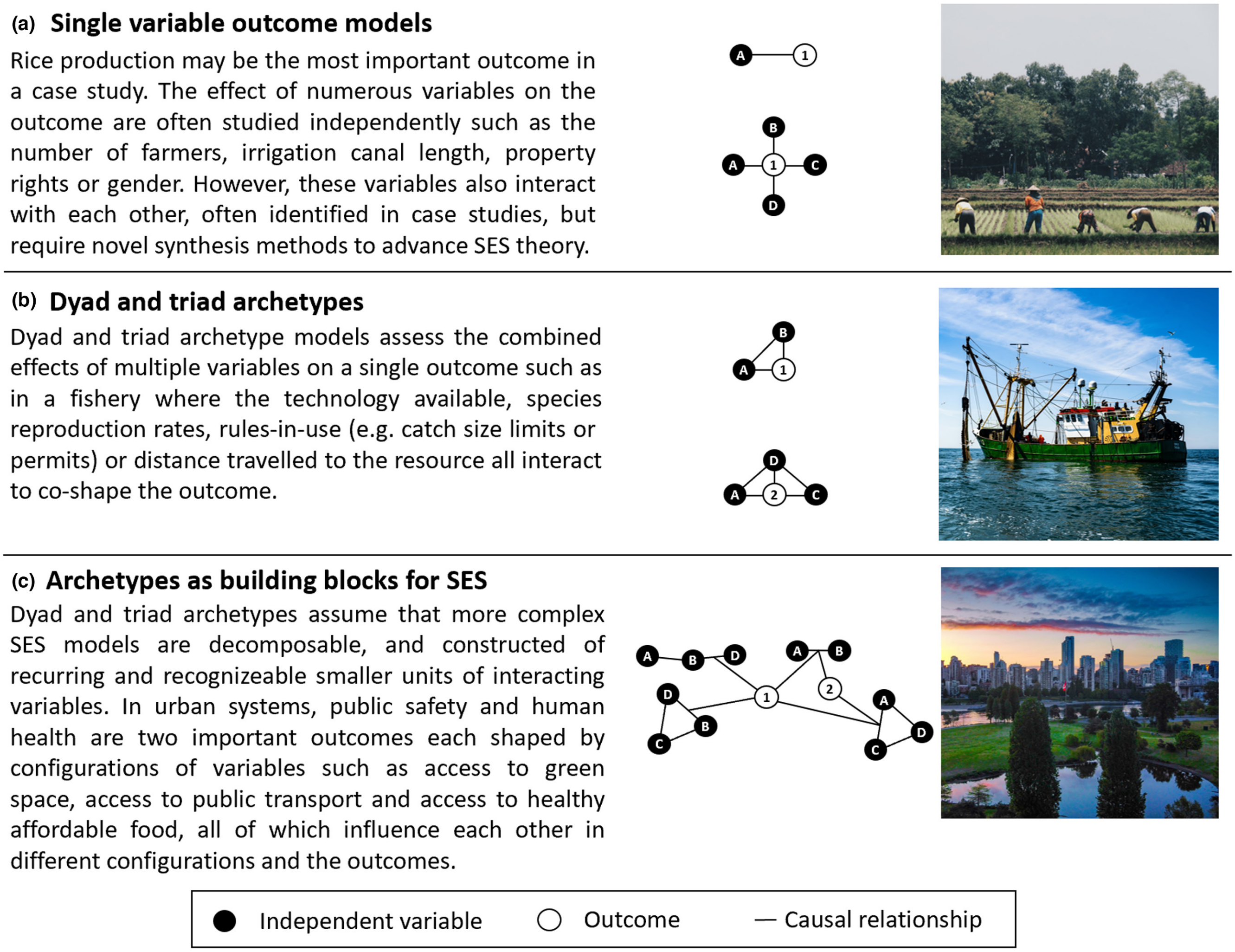


FIGURE 2 (a) Single variable outcome models assume no interactive effects among independent variables but are the current standard for building theory in social-ecological systems (SES). (b) Archetypes, starting with dyads and triads, consider interactive effects of independent variables in recurring and identifiable clusters. (c) The combination of multiple dyads and triads can be the building blocks of more complex SES.

the long-term survival of a shared resource (A8) create fertile ground for leadership (A5) to emerge. This resonates well with the extant literature on SES (Crona et al., 2017; Gutiérrez et al., 2011; Imburgia et al., 2021; Vedeld, 2000). The second most recurring dyad captures instead the co-occurrence of 'A6 Norms/social capital' and 'GS5 Operational rules'. This pattern is an important reminder that those rules determining how actors go about implementing governance and harvesting common-pool resources (GS5) is embedded in a broader set of norms shaping community interactions (A5). This resonates well with those branches of CPR research addressing the role of reciprocity and community in collective action (Lobo et al., 2016; Partelow, 2020; Partelow & Nelson, 2018; Tadie & Fischer, 2017), showing how the same rules can perform differently in different communities (Carrillo et al., 2019; De Moura et al., 2021; Wallrapp et al., 2019).

The most frequently observed triads are the co-occurrence of 'A5 Leadership', 'A6 Norms/social capital' and 'A8 Importance of resource', and 'A7 Knowledge of SES', 'GS5 Operational rules', and 'GS8 Monitoring/sanctioning'. Social capital likely interacts with leadership

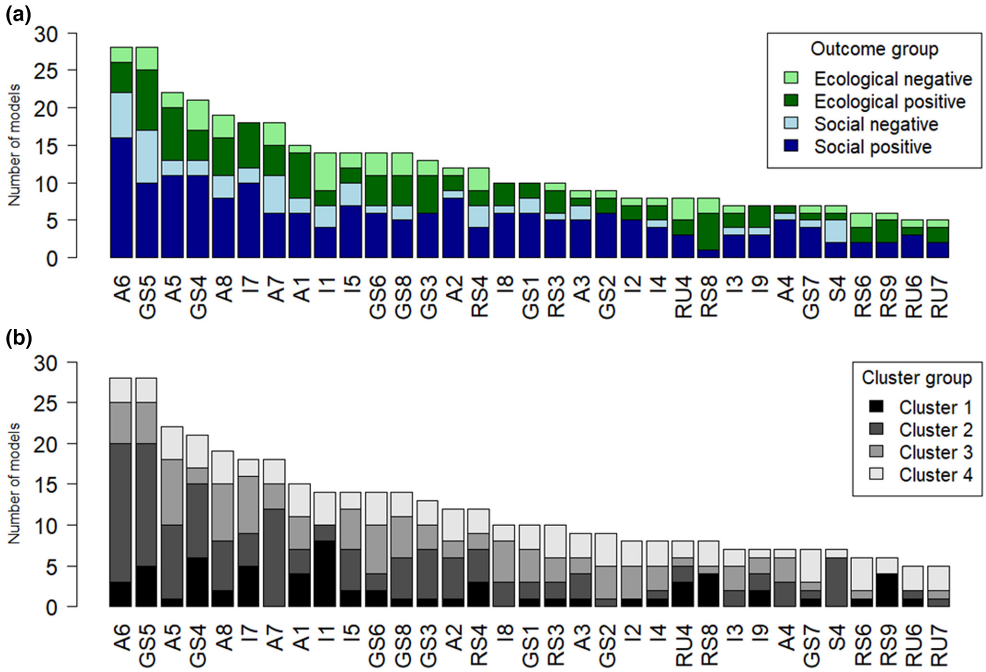


FIGURE 3 (a) Frequency of SES framework second-tier variables across all models and model outcomes groups. There are four combinations of outcomes that a model influences (positive social, negative social, positive ecological, negative ecological). Only variables that appear in at least five models are shown. Variable root codes refer to A, Actor; GS, Governance; RS, Resource systems; RU, Resource units and I—Interactions. For full specific second-tier variable reference codes, see Table 1. A full plot including variables occurring in less than five models is available in Figure S1. (b) The variable frequency by cluster group (see Figure 4).

in a context characterized by high stakes in the long-term survival of the resource at hand (Partelow, 2020). We can thus speculate that, in SES, the salience of leadership (A5) for sustaining important resources (A8) depends on community attributes (in this case social capital A6) and not only on individual entrepreneurship, aligning with the above-cited literature. Furthermore, we observe that the combination of 'A7 System knowledge', 'GS5 Operational rules' and 'GS8 Monitoring and sanctioning' interact in a way that suggests that community knowledge may more effectively inform local rule designs that are easier to manage and enforce, as shown in the literature (Benyei et al., 2022; Rathwell et al., 2015; Raymond et al., 2010).

Finally, we observed no systematic link between recurring dyads/triads and the outcomes. This is not surprising: It would be naïve to expect that the complexity of SES systems can be captured with bundles of two or three variables. This was not our aim. Rather, archetype analysis relies on the concept of 'building blocks': decomposing complex processes into smaller functional units (i.e. dyads and triads) that recur across cases. From this perspective, the broader aim becomes one of assessing how archetypes interact with further, contextual variables (including other archetypes) in order to determine the outcomes of interest. This question of how to pursue this is discussed below.

4.2 | Advances in archetype analysis

We have identified patterns of SES framework variable interactions (as dyad and triad models) and their relationships to specific outcomes. One question that arises is: are they archetypes? We argue they are archetypal candidates. Established archetypes would need to prove consistency against new data and would also require explanations of why variables co-appear together (mechanisms), that is, whether they interact with each other or have independent effect on the outcomes. Our analysis does not provide details on those mechanisms, but does provide the first step towards getting there, which is arguably a first necessary step (i.e. case standardization and synthesis into patterns of triads and dyads). As such, this study provides a baseline assessment and potential agenda for guiding future SES middle-range theory research following an archetype approach. The ambition is that this type of synthetic research can help future research sort through the complexity of SES models in their case context and make sense of variable interactions by breaking them down into understandable units or building blocks. Selected models from our data have been selected to exemplify how single models from more complex case studies can provide useful narratives about causal mechanisms when coupled with the qualitative data from the original studies (Boxes 1–4). Each of the boxes indicates one specific case context and does not intend to demonstrate how the models can be fully extrapolated to develop a grand theory of SES interactions. The next step, building on this analysis, would be to identify sets of cases with the same models and outcomes, and then to examine whether the qualitative mechanisms explaining them are similar or not. This would make concrete progress towards middle-range theory building—as an archetype—that is generalized but remains contextually meaningful.

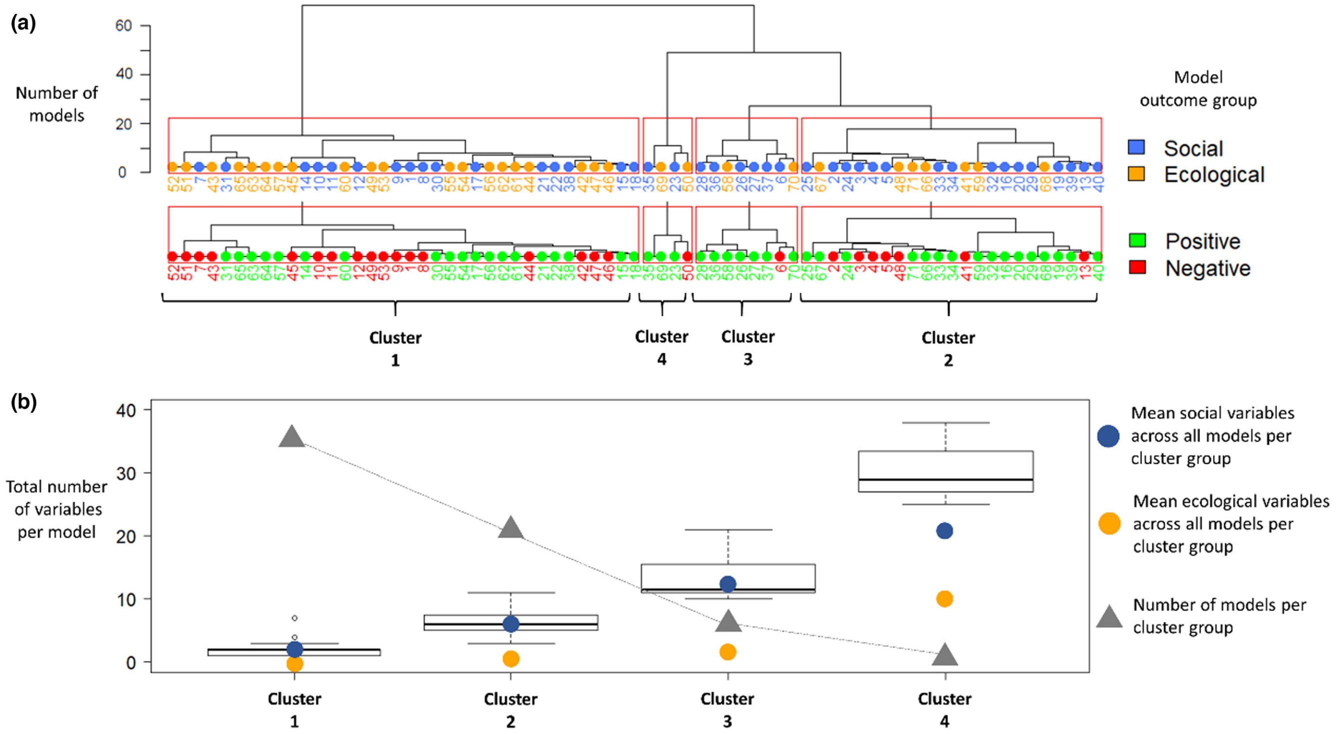


FIGURE 4 (a) Dendrogram with four groups from a hierarchical cluster analysis of all models. The clustering reveals that outcome groups are not driving clustering, rather model size (number of variables) and independent variable composition. Clusters indicate models that have similar size and composition of SES Framework variables. Models are coloured by their social or ecological outcome (top) and positive or negative outcome (bottom) to examine whether model similarity has a relationship with model outcomes. We observe no significant statistical relationship between them. (b) The boxplots show the range of and mean number of variables per model in each cluster group, as well as the mean number of social (blue nodes) and ecological variables (yellow nodes) across models in each cluster group. The number of models per cluster group is also indicated (triangle nodes).

TABLE 5 Optimal suites of dyad and triad sets. The optimal suite is a minimum diversity metric that aims to maximize coverage with the lowest number of sets.

Dyads—optimal model coverage, 10 dyads with 84% coverage		
GS5 Operational rules	GS7 Constitutional rules	
A7 Knowledge of SES	GS5 Operational rules	
A6 Norms/social capital	GS4 Property rights	
A5 Leadership	GS3 Network structure	
A5 Leadership	A8 Importance of resource	
A1 Number of users	RS9 Location	
I5 Investment activities	S6 Media organizations	
I4 Conflicts	A6 Norms/social capital	
I1 Harvesting activities	RU4 Resource unit value	
I1 Harvesting activities	A8 Importance of resource	
Triads—optimal model coverage, Eight triads with 88% coverage		
A6 Norms/social capital	GS4 Property rights	GS5 Operational rules
A5 Leadership	A7 Knowledge of SES	GS5 Operational rules
A5 Leadership	A7 Knowledge of SES	GS3 Network structure
A5 Leadership	A6 Norms/social capital	A8 Importance of resource
A2 Socioeconomic attributes	A6 Norms/social capital	GS4 Property rights
A1 Number of users	RS8 Storage characteristics	RS9 Location
I5 Investment activities	GS5 Operational rules	S4 Other governance systems
I5 Investment activities	GS1 Government organizations	GS2 Non-governmental orgs.

BOX 1 **Single model from the data is selected to exemplify how each model represents a qualitative narrative and series of causal mechanisms derived from the original study. This model is embedded within the case study of deforestation processes in Indonesia (Fleischman et al., 2014).**

Deforestation in Indonesia

Narrative and causal mechanisms

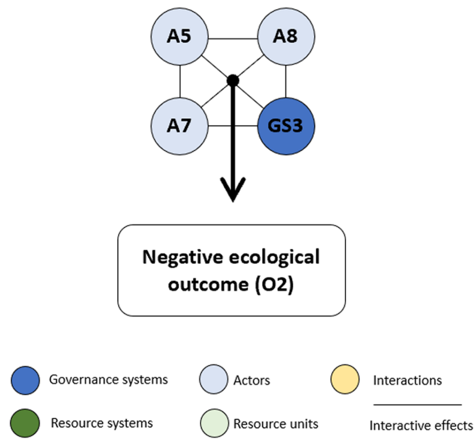
Between 1965 and 1998, Indonesia incurred substantial deforestation rates. Suharto's 32 year strong leadership (A5) encouraged logging for vibrant international markets (A8), The network structure (GS3) of so called 'dark' leadership can drive top-down environmental impacts even when international agreements and NGO advocate and pursue conservation initiatives. The mental models (A7) of central government actors sought collected tax revenue and advocated the flow of benefits to large companies without having to bear the costs of forest degradation (O2) and social disruptions that local and regional governments face. These interacting variables form a model within the more complex case contributing to a negative ecological outcome.

Key dyads

Leader (A5) – Network structure (GS3)

Key triads

Leadership (A5) – Network structure (GS3) – Mental models (A7)



Fleischman et al. (2014). Evaluating the utility of common-pool resource theory for understanding forest governance and outcomes in Indonesia between 1965 and 2012. *International Journal of the Commons*, *8*, 304–336.

Eisenack et al. (2019) outline four quality criteria that can be used to guide continued SES archetype research. These are: (1) specify the domain of validity for each archetype, (2) ensure that multiple archetypes can be combined in different ways to characterize single cases, (3) the proposed archetypes should explicitly navigate through different levels of abstraction and (4) each archetype (or set) should obtain a fit between its configuration of attributes, theory and empirical evidence. The concept of 'building blocks' is a common approach to archetype analysis: it suggests that more complex models can be understood by decomposing them into smaller functional units (i.e. dyads and triads). The logic of building blocks is that no archetype is mutually exclusive, but that multiple archetypes can contribute to and overlap within a case study or model. For example, a more complex SES model may consist of three dyads and two triads which all interact to shape the final outcome. This helps the field move beyond single variable outcome relationships, but also assumes that more complex models can be decomposed.

A key question for future research is how multiple dyads and triads become interactive in more complex models, both among themselves and with other individual variables. A further question is how to test candidate archetypes against other cases. To do this, we propose identifying case studies with the same models and outcomes (and perhaps the same models with different outcomes) to (1) confirm that there is indeed a causal mechanism that links each of the independent variables with the outcomes and (2) to identify interactions between the independent variables. The recurrence of mechanisms across cases would indicate strong support for the

BOX 2 **Single model from the data is selected to exemplify how each model represents a qualitative narrative and series of causal mechanisms derived from the original study. This model is embedded within the case study of pollution management in the Rhine River, Europe over time (Villamayor-Tomas et al., 2014).**

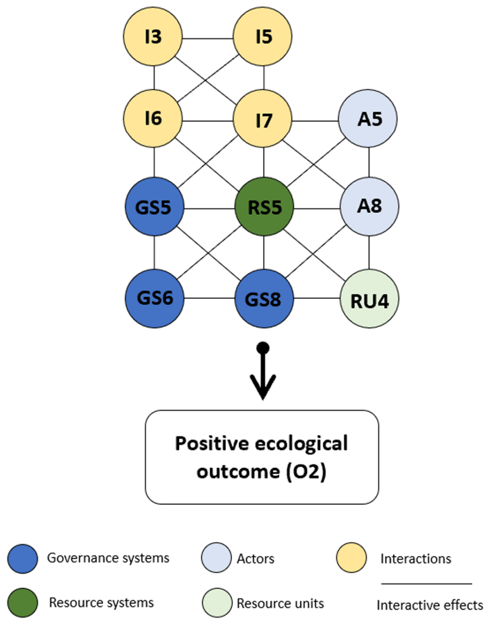
Pollution in the Rhein River, Europe

Narrative and causal mechanisms

Pollution management in the Rhine River is considered a success. Low water quality in the 1960s from pollutants such as lead, mercury, cadmium and zinc led to species extinctions and ecosystem collapse. The International Commission for the Protection of the Rhine (ICPR) was created along with pollution management agreements in the 1970s and 1980s. The Sandoz chemical spill (1986) is considered a further catalyst for collective action, and the river's productivity (RS5) enabled recovery over time once governance improved following investments (I5) into an integrative bargaining approach (GS6) that allowed for trade-offs. By the mid-1990s, water quality improved by 50%, and fish stocks were recovering. Success is attributed to national governments and big industry efforts to align vertical and horizontal interests (A5, I3, I6) due to the river's high value (RU4). Homogeneous political interests (A8) led to clear regulations (GS5) with monitoring (GS8), and the possibility of side agreements (I7).

Key dyads
Leader (A5) – Importance of resource (A8)
Operational rules (GS5) – Monitoring & sanctioning (GS8)

Key triads
Leadership (A5) – Network structure (GS3) – Mental models (A7)



Villamayor-Tomas, S. et al. (2014). From Sandoz to Salmon: Conceptualizing resource and institutional dynamics in the Rhine watershed through the SES framework. *International Journal of the Commons*, *8*(2).

model acting as an archetype. If there are differences (perhaps most likely) in the mechanisms, the emerging archetype would need further specification by examining more cases to explore those different causal explanatory pathways. This has yet to be fully realized or explored, and is only beginning to gain traction in the broader SES literature due to the need for sufficient case knowledge, available data, analysis techniques and conceptual framings as a precondition.

Numerous archetype scholars are beginning to unpack causal mechanisms and their cumulative impact pathways (Eisenack et al., 2021; Oberlack et al., 2019; Sietz et al., 2019), proposing different approaches. Both qualitative and quantitative efforts being made in three categories: data-driven classifications of models or cases, theory-driven models and empirical synthesis of building blocks. Important for advancing all three are detailed and transparent case study research, where using common frameworks such as Ostrom's SES framework can help structure case data into aggregate models. Future qualitative research is encouraged to provide detailed single and small-n qualitative case studies as the foundation for aggregate modelling efforts, validate existing ones or provide narrative explanations of the mechanisms that link variables together in complex systems. The SES framework is a very useful coordination tool for structuring comparable case study research, among other prominent theories and frameworks in the SES field

BOX 3 Single model from the data is selected to exemplify how each model represents a qualitative narrative and series of causal mechanisms derived from the original study. This model is embedded within the case study of lobster fisheries management in Chile (Ernst et al., 2013).

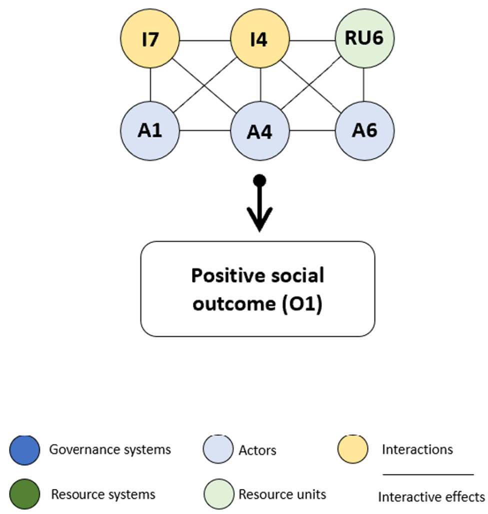
Small-scale fisheries in Chile

Narrative and causal mechanisms

In the Juan Fernandez Archipelago off the coast of Chile, small-scale lobster fishing has been governed by traditional tenure access and self-organized rules. Positive social outcomes in the form of fair allocation of benefits have been attributed to the homogeneous fleet (A1) and the informal 'marcas' tenure system allowing fishers to more efficiently manage their fishing spots. Self-organization (I7) has built social capital and trust (A6) overtime to strengthen the tenure system, which reduces interference among fishers, conflicts (I4) and transaction costs. The remote location of the islands (A4) and the distinctive characteristic of lobsters (RU6) has allowed isolation and management to be largely uninterrupted from outside influences.

Key dyads

Self-organization (I7) – Norms and social capital (A6)
Conflicts (I4) – Norms and social capital (A6)
Number of actors (A1) – Actor location (A4)



Ernst, B., et al. (2013). Sustainability of the Juan Fernández lobster fishery (Chile) and the perils of generic science-based prescriptions. *Global Environmental Change*, *23*(6), 1381–1392. https://doi.org/10.1016/j.gloenvcha.2013.08.002

(Binder et al., 2013; Partelow et al., 2020; Pulver et al., 2018). However, using common frameworks effectively has challenges. The contextual focus, scale, number of variables and the balance between social and ecological variables are highly diverse among case studies. Even the use of common frameworks creates heterogenous data, making secondary re-use and comparability challenging. Focus on methodological transparency can avoid these challenges, and methodological innovations in qualitative coding can help bypass some of these issues. To help this process, scholars can start by better understanding the frameworks they use. Four factors can be considered when using a framework, outlined by Partelow (2023): (a) who developed it, (b) the values being put forth by those researchers, (c) the research questions engaged with and (d) the field in which it is embedded.

Lastly, modelling approaches themselves require further advancements to make progress on archetypes. Methods to include and evaluate value and directionality of the relationship between the variables in dyads and triads is an essential next step. More broadly, the SES modelling literature has recognized eight key challenges (Elsawah et al., 2020). Here, we briefly outline five of those challenges relevant for this research. The first is bridging epistemologies across disciplines or at least recognizing limitations and differences, which is critical for archetype analysis that adopts a system perspective and aims to understand different types of archetypal

BOX 4 **Single model from the data is selected to exemplify how each model represents a qualitative narrative and series of causal mechanisms derived from the original study. This model is embedded within the case study of wind energy cooperatives in Belgium (Bauwens et al., 2016).**

Wind energy cooperatives in Belgium

Narrative and causal mechanisms

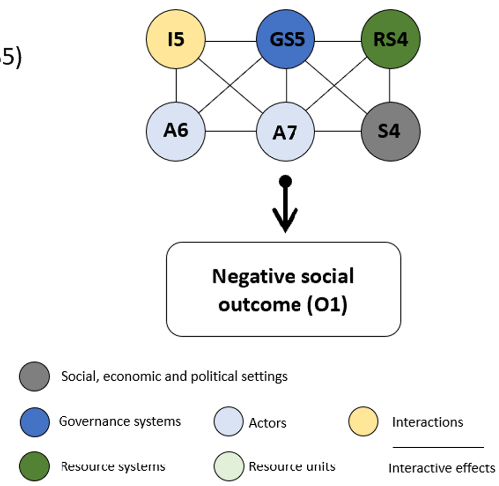
In Belgium, renewable energy cooperatives are community energy projects offering collaborative solutions toward low-carbon energy systems while enhancing social acceptance of technologies (RS4) at the local level. However, the Belgian institutional context is not conducive to cooperative initiatives, stifling progress. The scarcity of suitable sites, the increasing number of wind developers and the zoning policies (GS5) have created a highly competitive environment and encouraged a 'wind rush' on the available locations (A7). Cooperatives lack the time and resources (I5) to act as fast as large-scale wind power producers. Furthermore, cooperative members do not actually co-own wind turbines, which remain the property of operating companies, forcing cooperatives to justify their value (A6). As such, less new wind projects exist, driven in tangent by increasing juridical appeals against wind power projects (S4).

Key dyads

Norms/social cap. (A6) – Operational rules (GS5)
Norms/social cap. (A6) – Knowledge of SES (A7)

Key triads

Human- constr. fac. (RS4) – Norms/social cap. (A6) – Oper. rules (GS5)



Bauwens, T. et al. (2016). What drives the development of community energy in Europe? the case of wind power cooperatives. *Energy Research and Social Science*, *13*. https://doi.org/10.1016/j.erss.2015.12.016

narratives. The second is the need to better combine qualitative and quantitative methods and data sources. The third is dealing with scales and scaling. If archetypes should be applicable to multiple levels of abstraction, then the scales at which they are relevant should also be made clear. The fourth is capturing systemic changes in SES. Moving beyond static representations of system dynamics requires more comprehensive data collection and analysis techniques. Few archetype studies have time-series data and future work is encouraged to better understand changes and adaptations over time. The last challenge is elevating the adoption of SES models and impacts on policy. Important practical gains can be made from future archetype and modelling efforts if models pursue the integration of impact pathways, where causal mechanisms and trade-offs can be better illuminated (Mach et al., 2015).

5 | CONCLUSION

This article identified patterns of SES framework variable interactions (as dyads and triads) and their relationships to specific outcomes. The analysis of 71 SES framework models suggests that identifying recurrent two (i.e. dyad) and three (i.e. triad) variable groupings is a useful step towards better understanding more complex SES dynamics. We show that dyads and triads are the building blocks of larger SES, and are therefore helpful seeds for theory building. We refer to the dyads and triads as candidate archetypes. The framing of dyads and triads as archetypes is useful because it allows us to position findings as a bridge between narrative-rich empirical case studies and the often abstracted and context-neutral claims about SES complexity in the conceptual and perspective literature. Meeting in the middle is where archetype models can help reveal the causal mechanisms and impact pathways in SES that so much of the SES field attempts to unmask but struggles with, either in moving beyond their single cases or grounding larger scale often abstracted models to local problems in practice. The dyad and triad groupings should be tangible to both communities. Our study constitutes a first step towards synthesizing existing qualitative case studies into quantitative models, extracting dyads and triads archetype candidates, and then exploring causal narratives of those groupings in the case narratives. Further research can build upon this and identify full archetypes of SES variable interactions, adding empirical validation and exploring frequent and optimal dyad and triad groupings as building blocks of future SES theory.

AUTHOR CONTRIBUTIONS

Stefan Partelow, Sergio Villamayor-Tomas, Graham Epstein, Elke Kellner, Matteo Roggero and Maurice Tschopp were part of the original data collection team, led by Sergio Villamayor-Tomas. Stefan Partelow designed the study and analysed the data with assistance from Klaus Eisenack. Stefan Partelow led the writing of the paper, and all authors contributed to the interpretation of the results, writing and editing the paper.

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CONFLICT OF INTEREST STATEMENT

Stefan Partelow has recently been appointed a Lead Editor of the journal, but was not part of the editorial board during the submission period, and was not involved in the peer review and decision-making process of a paper. All other authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data for this study will be made available on the GitHub account of the lead author (SP) and are available on request. https://github.com/sbpartelow/SESFmodels.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supporting Information S1. Methods extension.

Supporting Information S2. Additional tables and figures.

Figure S1. Full plot of all models frequencies to outcomes (above) and cluster groups (below).

Figure S2. Principal Component Analysis (PCA) of independent model variables aggregated at the 1st tier of the SES Framework (interaction, governance, actor, socio-economic and political system, resource unit, and resource system variables).

Figure S3. Dyad and triad recurrence across all models.

Table S2. Combined second tier variables contributing to each model outcome group.

Table S3. Unique 2nd-tier variables contributing to at least one model per outcome group.

Table S4. Statistics on the number of 2nd tier variables in models per outcome group.

Table S5. Dyad and triad composition across clusters.

Table S6. Out of the highest total frequency dyads (>7), this table shows the pairs with the largest social and ecological outcome skews (>=15%).

Table S7. Out of the highest total frequency triads (>6), this table shows those with the largest social and ecological outcome skews (>=10%).

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