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Refinements of the Robustness Framework: Towards a Standardization of SES Adaptation Analysis

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Abstract:
There are numerous frameworks for studying the governance of shared resources. The basic structure of these frameworks has been articulated many times in the literature. Although they have been applied to multiple cases, these applications are idiosyncratic, subject to the interpretation of the user, and raise concerns regarding the operational use of frameworks for case-study comparisons. As a result, insights from these studies do not live up to the aspirations of the frameworks to generate generalizable knowledge. Here, based on several case studies and our experience using various frameworks for analyzing social-ecological systems, we undertake the task of generating a verb list meant to qualify interactions represented in the Robustness of Coupled Infrastructure Systems (CIS) Framework. This list is a first step in laying the foundation for a general typology of and a standardized protocol for representing dynamics of CISs.

Keywords:
Robustness, Coupled Infrastructure Systems, Coastal Settlements, Climate Adaptation

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Introduction

The study of how societies interact with their environments is extraordinarily challenging. First, it is difficult to define and conceptualize a useful unit of analysis when societies consist of hundreds, thousands, or even millions of individuals each making decentralized decisions. "Environments" are equally complex. When conceived of as ecosystems, environments, like societies, consist of millions of interacting agents. When "environments" are conceived of as including chemical processes, physical processes, and technology as they interact with ecological processes, system complexity increases even further. So how do we begin to study such complexity? What can we say about it?

Past research suggest the obvious first step: divide and conquer. This is typically achieved by identifying different temporal or spatial scales on which processes play out. For example, we might assume that decisions about how much bread the baker makes today are not impacted by soil fertility decline over the last decade in the wheat fields that supply her grain. The baker takes soil fertility, as embodied in the price of flour, as a constant in her decisions. This division between fast and slow variables is very powerful. To study the fast variables, we treat all the slow ones as constant (or more technically as parameters), and focus on how the fast variables change. Similarly, to study the slow variables, we may assume that the fast variables equilibrate so rapidly as to track the slow variables. This allows us to represent fast variables as algebraic functions of the slow ones (that adjust instantaneously), and focus on how the slow variables change. This technique is quite common both in the natural and social sciences.

However, this separation of key processes across temporal and spatial scales also divides the attention of researchers. In order to make progress on understanding and designing governance regimes for the interaction between people and the environment (both natural and built) we need to be able to 1) effectively communicate across disciplines, 2) systematically gather data across instances/examples of social-ecological systems (SES or, more broadly, coupled infrastructure systems "CIS"), 3) translate data into conceptual and formal models, and/or 4) qualitatively compare multiple SESs or CISs. For this, we need a tool such as a framework with a language, a set of terms, and a set of rules to link them. There are several useful frameworks in this space, but none has so far been able to address all of these issues for reasons we discuss in more detail below.

For an example familiar to the readers of this journal, the Institutional Analysis and Development Framework (IAD) (Kiser and Ostrom, 1982; Ostrom et al., 1994) is based on this division of temporal scales. The IAD Framework takes the biophysical context, attributes of the community, and rules-in-use as fixed external variables. The IAD focuses on the action situation, a context in which people come together to exchange information, materials, and make decisions, as it is conditioned by the external variables. What are the external variables? Examples include forests, watersheds, culture, belief systems, legal structures and norms. These change much more slowly (2 or 3 orders of magnitude) than a water user group meeting plays out or market transactions occur. This allows economists, for example, to assume that preferences (attributes of the community) and technology (biophysical context) are fixed in order to compute market equilibria. They even distinguish further, and define partial equilibria which treats some parts of the economy as fixed (slow) as distinct from general equilibria. Ostrom used the IAD Framework to great effect in organizing her research of small-scale SESs (Kiser and Ostrom, 1982; Ostrom, 2011; Poteete et al., 2010; Ostrom et al., 1994) that focused on understanding what constellation of external variables (slow) enabled groups of people to effectively engage in collective action to address problems associated with governing shared resources (fast). That is, the IAD Framework is a powerful tool to organize research around understanding the *static* relationship between external structuring variables and the capacity for collective action.

The obvious question that follows is what factors influence the capacity of the governance structures observed in long-lived small-scale social ecological systems to respond to changes in the slow variables? Specifically, the unit of analysis in the IAD is the action situation. It is structured by culture, technology, and ecosystems which, although they can exhibit rapid, punctuated change, tend to change slowly rela-

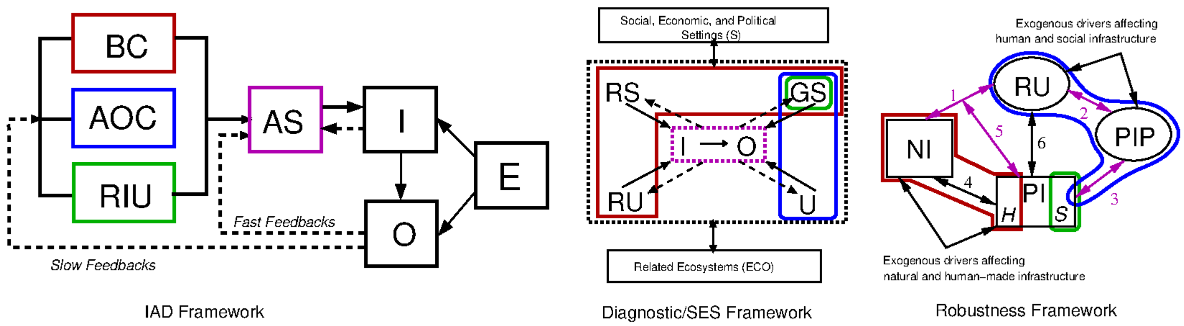


Figure 1: The IAD Framework on the left (adapted from Ostrom, 2011) is mapped on to the SES Framework in the center (adapted from Ostrom, 2007) and the Robustness of SES Framework on the right (adapted from Anderies et al., 2004). The color coding shows how the elements of the IAD framework, Biophysical Conditions (BC) in red, Attributes of the Community (AOC) in blue, and Rules-in-Use (RIU) in green are parsed in the SES and Robustness Frameworks. See text for further details.

tive to the information and material exchanges playing out within the action situation. To understand how emergent governance structures that enable agents to efficiently function *within the action situation* impact the capacity of the action situation itself to adapt to changes in slow variables requires that we unpack the IAD framework. We must look at how Ostrom's original classes of external variables: biophysical context (large scale ecological and technological processes), attributes of the community (culture, values, beliefs), and rules-in-use (legal and knowledge infrastructures) co-evolve over time. We must identify the larger-scale, slow feedbacks that give rise to persistent structures in which social interactions play out. Toward this end, Ostrom developed the closely-related diagnostic (Ostrom, 2007) and Social-Ecological Systems (SES) frameworks (Ostrom, 2009b). These frameworks really are diagnostic; they provide a taxonomic structure for identifying variables in SESs in 5 major groups: Resource Systems (RS), Governance Systems (GS), Resource Units (RU), Users (U), and Interactions and Outcomes (IO). The SES Framework re-parses the three broad categories of variables in the IAD as shown in Figure 1: biophysical context (BC, red) is parsed into RS, RU, parts of GS and parts of IO, attributes of the community (AOC, Blue) is parsed into U and parts of IO, and Rules-in-Use (RIU, green) is parsed into parts of GS. The Action Situation (AS, magenta) is mapped to the I $\rightarrow$ O box. Within these groups, the SES Framework identifies concrete examples for important variables that provide support for framing empirical research but provides little in the way of tools to understand how to frame questions about the *dynamics, resilience,* and *robustness* of SES.

Understanding this well, Ostrom collaborated on another framework to address these issues: the Robustness of SES Framework (Anderies et al., 2004). The Robustness of SES Framework focuses deeply on dynamics and feedbacks within SES with an emphasis on shared infrastructure. It provides a basis to visualize different possible links (rather than variables). This helps visualize how different parts of the system are "wired up" (or not) and thus what different feedbacks are or are not enabled in a given SES. The Robustness Framework is also a re-parsing of the IAD Framework as shown in Figure 1 where: 1) biophysical context is parsed into natural infrastructure (NI) and hard public infrastructure (PI), 2) attributes of the community is parsed into resource users (RU) and public infrastructure providers (PIP) and 3) part of PI, and Rules-in-Use (RIU, green) is parsed into soft public infrastructure (PI). In the Robustness Framework, there are multiple action situations that are actualized through the links. Links can also represent direct interactions between different governance levels indicating, for example, whether decision-making by PIPs affects the day-to-day activities of participants (operational level) or represents authoritative decisions that have an effect on the decision-making of others (collective choice level).

A comparison of the SES and Robustness Frameworks quickly reveals the different emphasis of the two. The SES essentially embeds action situations (I $\rightarrow$ O box) within a set of drivers (RS, RU, GS, U), emphasizing the nested nature of SES. This structure is then used to identify a set of "tiered" variables. The SES Framework, however, does not emphasize the structure of interactions. Rather, drivers enter the I $\rightarrow$ O box and return. The diagram provides no indication of how RS links to GS or U links to RS, etc. The Robustness Framework, on the other hand, emphasizes how subsystems articulate like puzzle pieces and how they are linked. Here, the geometry of the linkages and, with them, potential flows of material, information, and influence/authority are explicit. When a link or links are removed in the Robustness Framework, the impact on the function of the SES can be discerned. This is not the case for the SES Framework because all interactions are hidden within the I $\rightarrow$ O box. The essential difference is that the SES Framework emphasizes variables through nouns and their organization in a hierarchical structure while the Robustness Framework emphasizes relations through arrows and how key sub-structures are linked to generate dynamic processes and change.

The Robustness Framework has been used in a number of case studies to help develop (Anderies, 2006; Yu et al., 2015; Muneepeerakul and Anderies, 2018) and interpret (Anderies, 2006; Cifdaloz et al., 2010) models of SESs, as well as conduct comparative analysis (papers in this volume). As the community using the Robustness Framework expands, the greater the need for standardization of descriptions to avoid potential misinterpretation and to facilitate meta-analysis across case studies (Poteete et al., 2010). We identify a need for strengthening the description of links in the use of the RF.

As we mentioned earlier, we acknowledge there are numerous other frameworks in this space. For example, Ghorbani et al. (2013) extends the IAD Framework to develop the Modelling Agent systems based on the Institutional Analysis (MAIA) framework for agent-based simulation of SESs. Hinkel et al. (2014) attempt to enhance the SES framework through formalization in which the authors propose formal components to be included in description of SES using very low level language. The framework is well suited for formal analysis but difficult to operationalize for more empirical scholars. In a similar vein, Schlüter et al. (2014) link variables with processes and processes to outcomes using tools from the scientific computing and modeling community (e.g. universal modeling language) to add the dynamics that the SES lacks. However, the utility of this approach is limited to scholars familiar with scientific computing language conventions. There are dozens of similar applications and formalizations of the IAD and the SES frameworks all of which emphasize different points. We consider these as complementary to the Robustness Framework, but typically less general and/or more specific to particular research communities.

Applications of the Robustness Framework suggest that it is a convenient, general, and compact tool to describe, compare, and formalize many cases. However, it needs continued development and improvement. First, unlike Ostrom's SES Framework which provides a variable list based on her fieldwork over several decades, there is no such list to describe the interactions and processes for the Robustness Framework links which can be qualified by any type of expression. Ostrom's standardization of variables in the SES Framework motivates us to standardize the interactions (the meaning of the arrows) in the Robustness Framework. For us, this means developing a homogeneous way to qualify the arrows leading to a potential taxonomy of relations within the RF. Whereas nouns are used to qualify variables, we take verbs as candidates to qualify relations.

Second, the Robustness Framework has yet to be used to its full potential to identify a typology of SESs and their associated feedback structures based on empirical studies. This is especially true regarding the management of multi-scale and multi-level systems and analyzing linked action situations. Based on the studies presented in this special feature along with previous studies that used the Robustness Framework, we undertake the task of generating a preliminary verb list and associated CIS archetypes that lay the foundation for a general typology of CISs and a standardized protocol for representing them. Our goal in developing a list of verbs is to provide a mechanism to vastly reduce the number of equivalent descriptions of SESs or CISs so that these descriptions are more robust and comparable. Further, in many analyses of case studies, the regulatory feedback mechanisms that constitute 'governance' are often only described implicitly. Our hope is to enable researchers to more explicitly describe and classify these feedback structures. Finally, we hope to provide tools to move beyond describing the collections of links that make up key feedback structures, uncover key interactions, and better understand what is behind their operation (or failure to do so).

Standardizing and refining the Robustness Framework

Because SESs are comprised of connected subsystems that are part designed and part self-organizing, in recent work, we have shifted our view of coupled SESs to coupled infrastructure systems (CISs). On the one hand, this is a minor semantic issue in which we refer to all systems capable of processing mass and information flows as infrastructures (so a resource system is natural infrastructure as shown in Figure 1). On the other, using the term CIS acknowledges the importance of specific characteristics of infrastructure for generating both human well-being and problems for societies (Anderies et al., 2016). As such, in what follows, we are thinking in terms of the "Robustness of CIS Framework" (CIS-RF).

One approach to standardization of the CIS-RF is to list a set of potential verbs associated with each of the links 1-8 as Ostrom does in the SES Framework. However, because the CIS-RF emphasizes networks of material, information, and energy transformations (the arrows), any such list of verbs must be linked to feedback processes that give rise to persistent patterns over time. As such, we assume that these links can be reduced to verbs that represent **actual or potential transformation** (e.g. through influence) of the receiving element induced by the origin element. For example, the verb "extract" for link 1 has meaning beyond the removal of biomass because the extraction of fishing stocks will transform the availability of those fishing stocks to fishers, as well as other species who rely on that stock for their survival (link 1a RU to RS). Identifying a set of verbs in this way may help researchers focus on specifying the transformations rather than loosely acknowledging the existence of a link. As we are interested in using the CIS-RF to investigate dynamical SES, this focus on transformation helps us to articulate how dynamics in CISs are propagated. In a second step, a list of verbs (e.g. Table 1) can be used to create typologies of feedback processes and pave the way for elicitation of general patterns.

Toward this end, we will build up a number of examples of CIS elements and processes and derive a set of verbs that act as shorthand descriptors for these processes. Figure 2 shows the simplest case, i.e. a traditional open access natural resource (e.g. a fishery, forest, groundwater basin). Note, in this Figure and those that follow, the color coding follows Figure 1 with red representing natural and human-made infrastructure while blue represents human and social infrastructure. In the most general terms, RUs **expend effort** and **mobilize private assets** to **generate flows** of materials and information from the shared natural infrastructure. As a result of this effort, they transform RS in *collecting, extracting* or *harvesting* part of it. In the case in Figure 2, there is no governance. It is clear from the CIS representation that the only feedback is through flows from the RS to RUs via link 1b. This is the typical ecological feedback that stabilizes ecological systems. As resource flows (1b) per unit effort (1a) decrease, total effort stabilizes. This equilibrium is often not the most economically efficient or sustainable due to the unintended consequences of resource exploitation on resource availability (Gordon, 1954) and ecosystem structure and function (e.g. biodiversity loss) (Hooper et al., 2012; Worm et al., 2006).

The possible verbs in this case are limited given the narrow number of positions (or roles) specified. It is seldom the case that RUs assume only one position in relation to the resource system. Once we introduce the possibility for other positions, the number of possible relations increases considerably. Figure 3 shows one layer of complexity up from the most basic case: community governance. In this case, people can allocate assets to interacting with the resource system or participating in governance, i.e. as PIPs or as part of the PI. In the simplest case, the same people participate in both roles, transforming both the RS (link 1) and the PI (either through the PIPs via links 2 and 3 or directly as actors within the PI).

Note that the PIP oval and PI box in 3 are much smaller than RU and RS. This represents the rela-

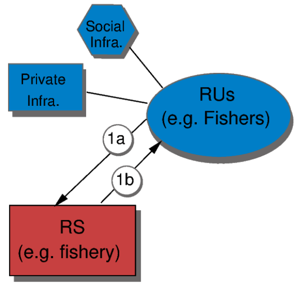
CIS Example 1	Core verbs and process details
	1a: Verbs: *Harvest, extract, collect*. Process details: RUs *expend* effort to mobilize assets (e.g. boats, knowledge) in the RS to *harvest, extract, collect* resource units. This activity includes *enhance*, e.g. the use of fire to clear brush by hunter-gatherers. 1b: Verbs: *flow*. Process details: As a result of expended effort and mobilized assets, resource units (e.g. fish, lumber, water, minerals) and information (stock status, forest cover) *flow* to RUs.

Figure 2: The most basic example of the use of a shared resource (e.g. a CPR). In this example, the resource is open access and there is no public infrastructure for governance of the resource. In such cases, the resource system is overexploited.

tive importance and complexity of PI in its diminished size in relation to the resource system. The PIPs (co)produce rules and norms along with monitoring and sanctioning capacity (3a) which allows them to *restrict/control* effort directed toward and/or flows from the shared resource system (5a) as well as to constrain the potential ways in which RUs may mobilize private infrastructure (6a). The CIS diagram highlights the tight feedbacks[1] that operate in such systems. In fact, systems with this configuration exhibit most of Ostrom's Institutional Design Principles and are very effective because of these tight feedbacks (Ostrom, 2005). However, such tight feedbacks can introduce fragilities (Anderies and Janssen, 2013) such as a lack of adaptability to exogenous drivers. For instance, in Indian community forests, historically the elected Van Panchayat (village forest governance board) took into account the community's timber needs (link 2b) when devising local timber harvesting rules. This changed when the national government imposed logging restrictions on local community forests. The logging restrictions deprived the Van Panchayat of its rule-making authority to regulate forest resources (5a) and community timber harvests (6a) resulting in increased illegal logging (1a) and disenchantment with the Van Panchayat governance system by the local community (6 to PI) (Balooni et al., 2007).

The next level of complexity in CIS emerges when the positions of RU and PIP are occupied by distinct people. In such cases, there is task specialization between activities directed at resource use and resource governance and there emerge specialist, if not professional, PIPs. Such a case is shown in Figure 4. Note that the relative size of the PIP entity has increased compared to community governance example but remains smaller than the RU entity; the *perceived or actual prominence, importance, or complexity* of the PIP entity is less than that of the RUs but considerably more prominent than in the case of community governance (cf. Figure 3). Examples of such a system include more formalized water user associations supported by formal government entities or jointly managed irrigation systems where RUs work with PIPs from a formal government agency. In both cases, examples of relevant government agencies include any number of national-level ministries or departments of water and irrigation in most countries around the world. If the RS is a fishery, forest, or groundwater system, similar instantiations of link 2 occur in the form of co-management where the formal governmental agencies are ministries or departments of fisheries, oceans, land, or forestry. CIS of this type are very common globally. The PI entity is depicted as larger than in the community governance example but still smaller than the RS. This suggests that co-management CIS are natural-resource-dominated, and the main objective of the PI is to improve the management of the RS. That is, the main focus of the system is the natural resource while human-made infrastructure plays a subsidiary

[1]A tight feedback is one in which high quality information is available and can be measured and translated into effective action with little delay

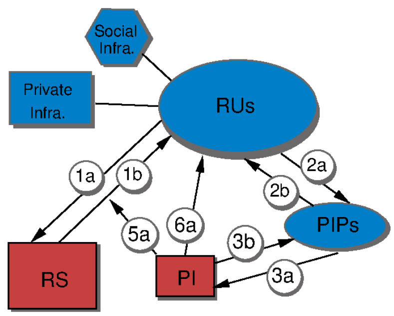
CIS Example 2	Core verbs and process details
	1: 1a and 1b same as Example 1 in Figure 2. 2a: Verbs: *control, assign, appoint*. Process details: RUs *control, assign, appoint* by drawing persons who will occupy PIP positions (e.g., via elections) from within the population of people holding a position of RU. 2b: Verbs: *inform*. Process details: PIPs provide all information regarding their activities and performance, as well as information about the condition/performance of the PI to RU's. 3a: Verbs: *provide*. Process details: PIPs *provide* resources (make allocation decisions) which are used to *produce, maintain* or *modify* PI. 3b: Verbs: *inform*. Process details: PI provides information regarding the performance of PI which PIPs may use to make decisions. 5a: Verbs: *restrict*. PI (rules, norms, monitoring, and sanctioning capacity) *restricts* effort (impacts 1a) or *restricts* mass flow (impacts 1b). An example of the former (latter) is a fishing season (quota). 6a: Verb: *constrain, enable*. Process details: PI (rules, norms, monitoring, and sanctioning capacity) *constrains* choice sets of RUs (e.g. gear restrictions, groundwater pump type restriction, no-take zones), or *enables* new actions.

Figure 3: Use of a shared resource (e.g. CPR) with community governance. In this example, the community provides public infrastructure for governance of the resource. The relative size of the RU, PIP, PI, and RS shown in the diagram reflect the relative perceived prominence, actual size and complexity, or perceived importance of the element. Here, resource users and the resource system (RU and RS) are the dominant features of the system. PIPs and PI are often embedded in the community and are not as prominent, at least when the system is viewed from the outside and in 'systems' terms. In such cases, overexploitation of the resource system can be effectively prevented because of tight feedback loops.

role. This is quite different to Example 4 discussed below.

Link 2 is now much more complex with more potential verbs as PIPs are characterized by more formal relations (defined by both formal and informal institutions) with RUs. RUs may try to provide PIPs with information (gathered through link 1), express concerns, lobby for particular infrastructure investment decisions (operationalized through link 3), or otherwise influence the actions of the PIPs. The PIPs, on the other hand, may provide information to or otherwise influence the actions of the RUs. Link 3 is similar to the community governance case except that now, the information and assessment in link 3b is much more sophisticated. For example the ministries and departments may invest in public infrastructure in the form of science bodies whose sole purpose it is to gather and process information to 1) generate new and/or inform existing instances of links 5 and 6 to control actions of RUs and the state of the RS and 2) inform PIPs regarding future investment decisions. This case is representative of the 'science-based management' model pioneered in western industrial countries and now exported to most countries of the world in which the PI equips the RS for monitoring, collects and processes information on the state of the RS which is used as a feedback to links 5 and 6.

If we compare this example to example 2, we see that the tight feedback between the RUs and RS in which information about RS flowing mainly through link 1 is translated into action in links 5 and 6 is replaced by one in which a formal PI processes information through link 4 to impact links 5 and 6. In theory, this system should function very well and be able to cope with larger-scale resource systems and user populations than the community governance model. However, in practice, the introduction of additional complexity in links 2, 3, and 4 brings with it at least three problems: 1) increased pressure for more and better information, 2) delays in decision making due to transaction costs associated with the functioning of each link, and 3) emergence of endogenous incentives within the RU (e.g. to free-ride), PIP (e.g. to

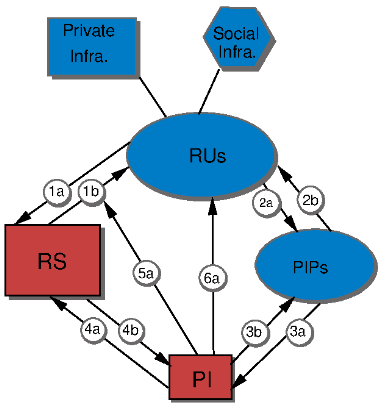
CIS Example 3	Core verbs and process details
	1: 1a and 1b same as Example 1 in Figure 2. 2a: Verbs: *petition, vote, lobby, influence*. Process details: RUs formally *vote for* PIPs or formally *petition or lobby* PIPs. They may informally *bribe* or *inform*. 2b: Verbs: *inform, persuade, empower, survey*. PIPs may gather information via surveys (hence modifying RUs mental representations and willingness to share information) or provide information to (*inform*) RUs. PIPs may *empower, instruct* or *persuade* RUs to change their choice sets thus restricting or biasing choices of RUs. PIPs may also invite RUs to participate in the definition of possibilities for choice sets. 3a: Same as Example 2 in Figure 3. 3b: Verb: *flow*. Process details: Information about the state of the resource system and the PI *flows* to PIPs. 4a: Verbs: *equip*. Process details: Actors in the PI system equip the RS with monitoring instruments to collect information which is analyzed within the PI system and passed on to PIPs through link 3b or deployed through links 5 and 6. 4b: Verb: *flow*. Information flows to PI system. 5a, 6a: Same as Example 2 in Figure 3.

Figure 4: Use of a shared resource with specialist or professional PIPs, such as shared natural resource co-management . In this example, a specialized/professional governance entity provides public infrastructure for governance of the resource. In such cases, overexploitation of the resource system can be effectively prevented because of tight feedback loops.

rent seek) and PI (e.g. principle-agent problems) elements. Unless links 2 and 6 are carefully designed to compensate, these problems can reduce the performance of the governance system.

Our final example illustrates the most common CIS in the modern context. Here, the PIP and PI elements are dominant (and thus are larger than the RU and RS elements). Examples include urban settlements and intensive agriculture. The activities in links 1 and 4 are more complex, involving activities beyond simple resource extraction. Specifically, links 1 and 4 involve *transforming* the RS through land development. Obviously, RUs can cause transformations in the RS as spillovers from their extractive activities. Here, we are referring to intentional transformations. The focus of such land development is to concentrate mass and information flows in space and time, either to *direct* them *towards* (e.g. irrigation) or *away from* (e.g. levee, dyke) human activities. Even though RUs might directly transform the RS, it is typically quite costly. As a result, RUs often need assistance from hard PI. People in position of RU will then lobby or demand people in positions of PIP for such infrastructures. Link 4a is then also characterizing this transformation of RS by PI. Further, because the PI is complex, link 3 involves more negotiation between the PIPs and actors in the PI system, leading PIPs to *reorient* or *adjust* the original aim and rules toward their own ends and vice versa. A by-product of this negotiation is that PIPs begin to leverage private and social infrastructures in their activities to negotiate with RUs and the PI system. These issues have obvious implications for the effective functioning of feedbacks in the system because, for example, this negotiation can cause severe delays and information distortion.

These four examples illustrate some of the verbs that can emerge in various archetypal CIS that have been studied extensively. In many cases, the examples that have been studied are assumed to be in a stable configuration (Cifdaloz et al., 2010) in the sense that the underlying structure of the CIS is assumed fixed for the timescale of interest. In the remainder of this paper, we extend these examples to situations characterized by structural change, as it is the most common situation under climate change. Specifically, the studies in this special feature in Cornwall, UK, Languedoc, France, and the Garden Route District, South Africa are all characterized by example 4 in which built infrastructure is dominant and links 3 and 4 are extremely

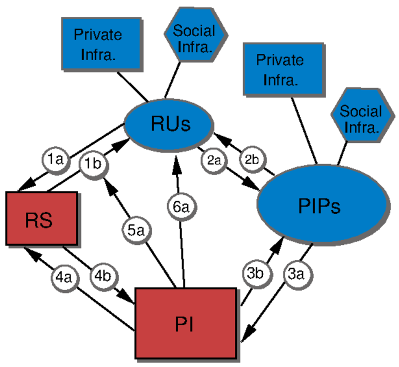
CIS Example 4	Core verbs and ancillary verbs
	1a: same as Example 1 in Figure 2, with the additional verb *transform*, as in modify the landscape for agriculture or settlement development. 1b: same as Example 1 in Figure 2. 2: 2a and 2b same as Example 3 in Figure 4. 3: 3a and 3b same as Example 3 in Figure 4. Additional verbs (3b): *reorient, adjust*. PIPs negotiate with actors in PI about how PI is produced and operated and how power is shared. In the negotiation process the PIPs are reorienting/adjusting the aims of PIs (3a) and vice versa (3b). 4a: Same as Example 3 in Figure 4. Additional verbs: *transform, concentrate.* Actors in the PI system mobilize assets and expend effort to *transform* the RS, typically to concentrate resource flows in space and time. 4b: Same as Example 3 in Figure 4. 5a, 6a: Same as Example 2 in Figure 3.

Figure 5: Use of a (or possibly multiple) shared resources with specialist or professional PIPs. This case differs from Example 3 in that PIPs are dominant and RUs are subsidiary. Further, PIPs mobilize significant private infrastructure in their roles.

complex. In this case, the potential for regulation and fast return to a stable configuration is low. In fact, these CIS are facing changes over which they have no control and to which they attempt to adapt, generating further instability. Thus, we want to investigate whether new verbs are required and whether there is a specificity in the types of verbs representing the links in CIS that are far from stable configurations.

Analyzing adaption pathways through identification and analysis of feedback networks in CIS

As we mentioned above, all stable structures are created and maintained by regulatory networks. These regulatory mechanisms enable systems to keep key variables within desirable (or safe) ranges. They also allow systems to cope with variability and shocks and maintain their structure. The first four cases discussed in the previous section provide a menu of verbs that, when assigned to appropriate links, can generate essential feedback loops. However these relations provide also potential pathways for transformation. Even those intended for regulation of stability may lead to structural transformation due to unintended consequences of complex interdependencies.

In the remainder of this section, we examine three coastal case studies in France, Great Britain, and South Africa in depth in order to add a new layer of verbs to those in examples 1-4 (Figs. 2 - 5) that focus on *maintaining an existing system*, in the face of exogenous (perhaps highly variable and uncertain) drivers, to verbs that focus on changing the system itself as an adaptation to new sets of exogenous drivers on longer timescales (e.g. climate change versus weather variability). In addition to identifying new sets of verbs, our analysis suggests that such adaptation processes should focus more on avoiding missed opportunities for coordination and information sharing rather than modifying existing feedback loops. The main risk is that the efforts of actors who do not coordinate and/or communicate are not only ineffective, they may, in fact, cancel one another, and weaken critical feedbacks. The more complex the system, the more difficult coordination and information sharing becomes, and the regulatory feedback networks that hold the system together become fragile.

Insights from the MAGIC[2] case studies: Openness, reflexivity, and evolution

While most examples using the Robustness Framework are concerned with systems with a dominant resource use focus (e.g. an irrigation system or a fishery) functioning in a relatively stable period, the case studies described through the CIS-RF here focus on systems in periods of significant change driven by sources of change mainly external to the system. We focus not on what factors may enable systems to sustain coordination and cooperation and, with them, the function of shared infrastructure but, rather, how (complex) systems may continuously adapt to exogenous change. With case studies from the MAGIC project described in this special issue, we incorporated the CIS characteristics of multi-level governance: subjectivity (environment as a social construct depending on representations and intention), system openness (no clear and meaningful boundaries), and evolution (Armitage, 2008; Barreteau et al., 2016). They constitute a fifth category of CIS, that could be designated as "joint resource planning for multiple users at multiple scales in a changing context". These attributes are depicted by the multiple overlapping and nested governance units, resource users, and resource systems in Figure 6, respectively. Openness is captured by the exogenous drivers affecting social and biophysical systems while subjectivity is captured by a focus on intention and inclusion of information flows that help in building social representations.

Coastal systems are in constant interaction with their hinterland, e.g. coastal dynamics with dune mobility, the existence of a logistical basis for sea product commercialization, the provision of freshwater and raw material from river basins, etc. The literature on ICZM describes these interactions that act as the vectors through which interdependencies are realized in detail (Mazouni et al., 2006; European Commission, 2016). As places with multiple uses, coastal systems attract different stakeholders, each with their own perspective, willing to close the system according to their own view: biodiversity conservation with a focus on water exchanges and faunal habitats, sea surge protection and potential for strategic retreat, tourism development and conformance to social expectations from far away. Given that coastal systems are sensitive to the global changes now underway, they are now and into the future far from any stable configuration, whatever the chosen time scale. They keep evolving either according to the variation in the location of the seashore, the core cluster of economic activities, or land uses. Whatever adaptation strategy is adopted by any community related to one of these issues, the potential to significantly reorient the whole system development pathway is high.

The use of verbs aims at improving the robustness of descriptions of CIS which, in turn, will further our capacity for meaningful case study comparison. Most examples in cases 1 to 4 fall within a rather homogeneous academic community and homogeneous domain: common pool resources (CPRs) and natural resource management (NRM). However, the extension of case studies by scholars interested in governance and institutions to situations in which the built environment plays a key role (e.g. the CIS archetype in Example 4 (Figure 5) and issues of adaptation in Example 5 (Figure 6) is stretching this community. We argue that comparison should still be an objective. Classical NRM cases are well described in the literature and could be considered as reference points. As the community using the CIS-RF framework expands, the greater the need for standardization of descriptions to avoid potential misinterpretation and to facilitate meta-analysis across case studies (Poteete et al., 2010).

Expanding the verb set based on the MAGIC Cases

We elicited verbs relating to Example 5 (Figure 6) in two ways: (1) during a workshop of the MAGIC project from colleagues who elaborated the CIS-RF description of case studies, (2) analysis of verbs used in papers describing case studies in this special issue. Then we extrapolated from that set of verbs (workshop and paper analysis) a set of verbs that we suggest may meaningfully describe CIS-RF interactions across a

[2] Multi-scale Adaptations to Global change In Coastlines (MAGIC) is a project funded by the Belmont Forum. See www.belmontforum.org for further details.

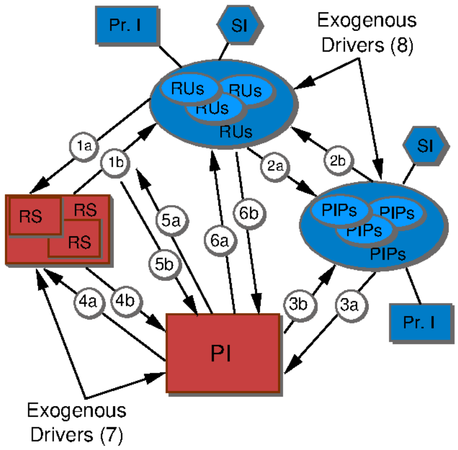
CIS Example 5	Core verbs, process details, and ancillary verbs (extrapolated from key verbs described by study participants in the three case study areas)
 	1a: *value, pollute, take ownership, appropriate, care for, steal, exploit, waste, extract, demand, cultivate* 1b: *support, provide, flood, enrich* 2a: *criticize, petition, fund, lobby, influence, blame, complain, bribe* 2b: *idealize, survey, empower, responsibilize, involve, consult, engage, inform, protect, adapt, facilitate, advise, make promises to, exclude, include, provide* 3a: *provide, deny, shape, repair, maintain, fund, invest, coordinate, adapt, redefine* 3b: *responsibilize, shape, distract, challenge, advise, inform, appoint, support* 4a: *modify, concentrate, designate, protect, preserve, augment, invest, prioritize, restore, sell, control, influence* 4b: *supply, erode* 5a: *regulate, restrict, plan, relax, coordinate, control, authorize, mitigate, inform, influence, value* 5b: *adjust, stimulate, inform* 6a: *limit, control, legitimize, enable, help, grant, deny, approve, disapprove, educate, regulate, incentivize, sanction* 6b *take ownership, appropriate, influence, vandalize, value, utilize, enjoy, appropriate, expect, resist, blame, sue, pressurize, protest, implement, responsibilize* 7: (impact on RS) *disturb, invigorate, destroy, change, pressurize* (impact on PI) *destroy, justify, damage, obsoletize, pressurize* 8: (impact on RU) *attract, value, change, scare, legitimize, migrate in* (impact on PIP) *discourage, help, aid, constrain, compete for, invest*

Figure 6: Complex coupled infrastructure system in a changing environment. These case studies differ from Example 4 (Fig. 5) in that they consist of an assortment of users with varying interests and public infrastructure providers (PIPs) organized by legislative mandate, e.g., PIPs tasked with environmental governance, development, risk management, public health, etc. These systems often appear to be polycentric in design, yet the lack of systematic coordination mechanisms undermines effective information flows, rule application, and task delegation, perpetuating compartmentalized decision-making without overarching goals.

variety of complex CIS-RF scenarios (Figure 6).

The verbs in Figure 6 describe actions or process descriptions related to specific links in the CIS-RF, not unlike the aim syntax in the institutional grammar (Crawford and Ostrom, 1995; Ostrom, 2005, p. 140). To be precise, the verbs actually provide shorthand categories for how we experience the very general processes of mass/energy and information transformations. It is just easier to say "cook" than to say "transform fuel (mass) into heat energy and concentrate it (transform it again) to transform (breakdown/create) molecular compounds in biomass." But the latter is actually what is happening. In every case, the verbs in Figure 6 involve mass/energy and/or information transformations of some kind. While natural language verbs help convey the ideas quickly and roughly, the latter is what may be required to formalize the notion of "governance of CIS" and analyze it in general terms. In addition, verbs may convey indications of the intention behind the action, while the process of transformation itself does not. This indication is important for systems in which subjectivity plays a major role as mentioned earlier.

The verbs in Figure 6 can be classified in different ways in order to build comparisons of CIS and provide insights regarding the main processes at stake in the dynamics of these CISs. Here we establish a first categorization according to the potential outcomes they may generate on the destination entity. First, we identify three broad categories according to the type of modified characteristics of destination entities: (1)

Table 1: Verb categories for supporting or inhibiting adaptive capacity.

Quantity	Positive	Provide, enrich, fund, inform, supply, invest, attract
(20 verbs)	Negative	Extract, steal, survey, augment, destroy, waste, compete for, exploit, flood
	Change characteristic	Concentrate, migrate in, constrain, modify
Quality (28 verbs)	Positive	care for, repair, protect, enjoy, idealize, invigorate, restore, coordinate, relax
	Negative	pollute, erode, vandalize, scare, blame, pressurize, demand, damage
	Change characteristic	Maintain, resist, utilize, preserve, adapt, take ownership of, appropriate, sell, exclude, include, change
Capacity to modify	Positive first order	Support, aid, help, mitigate, adjust, advise, authorize, appoint, grant
(50 verbs)	Positive second order	Lobby, empower, responsibilize, legitimize, value, reinvigorate, educate, implement, petition, stimulate, expect, involve, consult, incentivize, influence, make promises to
	Negative	Criticize, ignore, distract, restrict, limit, obsoletize, disturb, bribe, complain, deny, sanction, sue, protest, challenge
	Change conditions	Enable, shape, regulate, control, justify, engage, facilitate, redefine, designate, prioritize, plan

quantitative state (the process increases or decreases something in the destination entity, e.g., fishing effort, water availability in a main canal, CO_2 emissions); (2) qualitative state (the process positively or negatively affects the quality of something in the destination entity, e.g. repair a broken canal headgate; or (3) capacity to modify, (the process described by the verb modifies the destination entity's capacity to take control of its own dynamics or another entities' dynamics either directly (first order) or indirectly (second order). Table 1 provides an overview of this categorization of verbs.

Second, for each class we consider subclasses related to the direction of changes that are induced. For verbs describing a modification of state, we introduced three subclasses: positive, negative or related to other changes in characteristics, including spatial repartition or resistance. For verbs describing a modification of capacity to modify, we considered four subclasses: positive first order, positive second order, negative, change conditions of action. Positive first order means that the origin entity adds its own capacity to its destination entity for a bigger modification. Positive second order means that the origin entity increases the destination entity's capacity to modify. The fourth subclass, change conditions, tackles the efficiency of modifications that might be perpetrated further by the destination entity. Table 1 provides an overview of this verb categorization at the level of subclasses.

Based on this categorization, we can begin to understand how the presence of certain action verbs in CIS-RF links facilitates the development of processes that can either support or undermine robust CIS. For example, the second order reputational risks of Cornish PIPs incentivizes them to ignore non-mandatory Shoreline Management Plans in favor of inappropriate coastal redevelopment projects (link 3 interaction) (see Cornwall case study, this issue). This also helps us understand and link the processes and interactions to the presence/absence of certain design principles (Ostrom, 1990; Cox et al., 2010) that are indicative of more or less robust governance systems.

We find 20 verbs in the first class, 28 in the second, and 50 verbs in the third (cf. Table 1). Although our analysis is qualitative, based only on interviews of colleagues and a meta-analysis of 3 cases, we observed that public infrastructure providers are predominantly willing to first seek control over paths of change directed toward lower governance levels rather than taking action at their own level. This often results in cascading effects that extend beyond the original authority domain making coordination and management of the system increasingly difficult. For example, all three case studies are engaged in political restructuring activities that deliberately shed authority and responsibility from national to local governance levels without putting in place funding mechanisms to give local authorities the financial ability to act on their newfound authority (Languedoc, Cornwall, and Garden Route publications in this issue). In these unstable systems with multiple perspectives, actions are first targeted towards increasing control over the whole system. Figure 7 posits the verbs according to their category for each case. The key role of PI in controlling the whole system's dynamics appears through the number of arrows leaving the PI components, mainly in link 5. However PIs appear to be controlled by RU and PIP. Both modify PIs capacities to control RS and regulate the relation between RS and RU. These controls, both justified in the analysis presented in Therville et al.'s paper (this issue) as adaptation to global changes, are not necessarily coordinated and may generate a lack of efficacy at the CIS scale. More than reinforcing negative feedbacks, the risk here is more of cancellation of efforts due to lack of coordination.

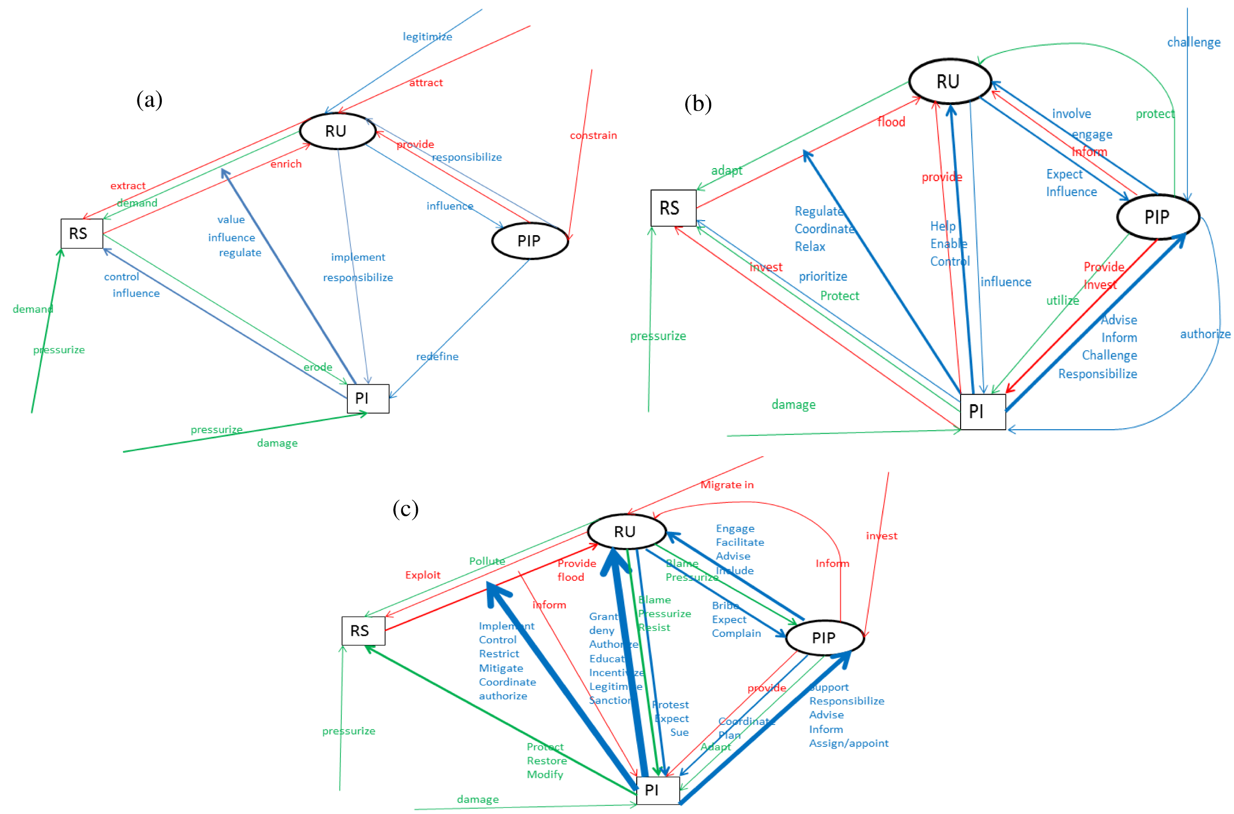


Figure 7: Representation of actual verbs for each case study (a: French case, b: Cornish case, c: South African case). Red arrows are for quantitative transformation, Green arrows are qualitative transformations, Blue arrows are for changes in capacity to change. Thickness of arrows depends on number of verbs for each subclass.

The framework we propose is intended for comparative case-study analysis. Although it is not yet well enough developed for proper use in this capacity, we can already observe some interesting points. The South

African case looks much more autonomous to external drivers but with much more complex connections along the pathway from RU to PI. The French case is characterized by the paucity of connecting pathways from RS to RU. Rather, direct flow of resources is regulated in many ways by PIs which seems awkward for establishing suitable feedback loops. Such assumptions built on comparison constitute a valuable initial step to return to the cases and investigate further to test these observations and elaborate on their consequences for the governance of these systems.

Conclusions

This paper is a first step in strengthening the CIS Robustness Framework through the development of a list of transformative verbs to characterize links represented by arrows. This format to characterize links can be applied to abstract archetypes of CIS, from the simple case of a single shared resource to the more complex, multiple-resource co-management case. It could also be applied to the analysis of the three case studies in this issue. As a result, we developed a list of candidate verbs for characterizing processes in CIS dynamics. Our characterization of links with verbs usefully complements the characterization of variables with nouns as established with the SES framework (Ostrom, 2009b).

Ostrom identified eight design principles found in long-enduring small-scale resource SES (Ostrom, 1990). The design principles (DPs) have found widespread support among institutional analysts (Agrawal, 2002; Ostrom, 2009a; Araral, 2014) and have been utilized to examine a variety of resource governance systems (Ostrom, 2009b; Cox et al., 2010), including more recently at higher governance scales (Gibson et al., 2005; Epstein et al., 2014b,a). However, they have also been criticized for, among others, (1) their incompleteness, including their failure to investigate critical social and ecological variables and to consider external factors important to sustainable natural resource management; (2) their limited applicability to more complex governance systems; and (3) their narrow focus on formal rules and strategies which ignores complexity that extends beyond the institutional framework (Cox et al., 2010). The CIS-RF can help address these shortcomings by connecting the DPs to the processes in the CIS-RF identified by the verbs. Both the DPs and the verb ontology represent infrastructure in the CIS-RF context. The verbs describe the processes and feedback structures in a CIS and are an effort to better understand and classify these phenomenon. The DPs "describe characteristics of the information processing infrastructure that is essential for feedback systems to function" (Anderies et al., 2016) and, as such, the DPs are "an effort to understand why the results [of certain governance processes] are robust in some cases but fail in others" (Ostrom, 2009b, p. 38). In essence, the two ontologies are complementary and in combination can provide a greater understanding of the governance structures, interactions, and feedbacks in CIS.

We suggest that utilizing verbs to identify sub-processes and feedback systems within CISs is an important consideration in an institutional analysis which can then be further deepened by an exploration as to how these processes may be indicative of design principle configurations or more fine-grained structures of which Ostroms design principles are coarse descriptors. Our work here is a first step in this direction. The next step is to complete this list of verbs through other case studies and then to extend it in two directions: generalization and classification.

In this first step based on three case studies, we did not pay strict attention to potential synonyms within the list. The number of different verbs for a given link in a case study (as represented by thickness of arrows in figure 7) is merely indicative and should not be over-interpreted. With a larger set of cases and a cautious analysis of verbs, generalization of the verb list should enable quantitative analysis thanks to a complete and unambiguous list. The eventual goal is to come up with a list of generic verbs without overlaps between them. As for potential categorizations, we have suggested one based on changes induced in the destination entities. Other categorizations of verbs might be meaningful to interpret the dynamics of CIS. For example, the nature of what is conveyed in the transformation is an interesting candidate to analyze how information transfer intensive a CIS might be.

Finally, and perhaps most importantly, this add-on to the CIS-RF is an attempt to provide shared knowledge infrastructure that can provide a platform for coordinating the systematic analysis conducted by large teams of researchers that will be necessary to fully understand the robustness, resilience and sustainability of human well-being within the large, complex coupled infrastructure systems we create and inhabit.

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