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ORIGINAL ARTICLE

A synthesis of key factors for sustainability in social–ecological systems

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Abstract Attempts to identify relevant variables for the success or failure of sustainable management of social–ecological systems seem to be constrained by the inconsistent organization of the variables and the difficulties arising from their lack of comparability; both of these reduce generalizability to other systems. Therefore, to date, only a few comprehensive lists of attributes relevant to the performance of socio-ecological systems exist for sustainable management. This paper integrates such lists into a synthesis of 24 concepts. The scattered evidence of why each factor is important for sustainability has been compiled through a literature review. This concept synthesis may help to overcome some of the constraints of SES research by increasing the comparability of research designs and extending analyses from that of a few concepts for a few systems to widely applicable approaches in sustainability science.

Keywords Sustainability · Design principles · Success factors · Common-pool resources · Social-ecological systems · Framework

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Introduction

Since the seminal work of Elinor Ostrom on design principles for robust institutions in social–ecological systems (Ostrom 1990), there has been a wealth of research on factors that may help to improve sustainability, equity, and efficiency in social–ecological systems (SES). However, up to now, few consistent relations between any single variable and sustainability have been found in this mostly case-study-based research. Exceptions are some biological or physical attributes, such as population size or regeneration rate.

Consequently, researchers have changed their analysis from specific implementations to more abstract concepts: performance should be related to a certain set of *concepts* (e.g., the aforementioned design principles), but not single variables. One such concept relating to the performance of SES is, for example, adapting rules to the local conditions. In communities managing natural resources, whether rules are adapted by implementing a rotation scheme, lot drawing or any other method is not the primary concern for the analyst at this level of abstraction. Each concept may, in turn, be measured (proxied) by one or many variables.

However, case-study-based research is impeded by two characteristics. The first is the multitude of methods, concepts, and variables used that prevent the research community from arriving at testable and generalizable conclusions. One main reason is that research is scattered across disciplines, although sustainability has served as a core unifying concept (Partelow 2016). Second, there seem to be very few comprehensive lists of concepts that may be used by the empirical case studies as a guide.

The aim of this article is to present a comprehensive list of relevant concepts for natural resource management building upon the previous efforts (e.g., Agrawal 2001;

Ostrom 2009). Such a synthesis provides a consistent and encompassing set of concepts relevant for the sustainability of SESs. This paper draws on research efforts in sustainability science (Kajikawa 2008), both on the empirical case studies as well as theoretical syntheses on enabling factors for sustainable, equitable, and economically efficient outcomes. It also helps to connect different research strands in sustainability science (e.g., as pointed out by Loring 2016) and advance transformations towards more sustainable management (Miller et al. 2008).

By defining each concept and summarizing why each factor may be relevant for the success of community-based management (see Table 3), this article also addresses the lack of explicit theoretical explanations of concepts and variables.

Towards higher comparability

Often, researchers have a highly specific aim and possess detailed knowledge of a particular case. Therefore, it is not surprising that single-case studies use different methodologies, concepts, and variables. These analyses are the basis for any work hoping to find patterns to improve sustainable management. However, even in meta-analyses, there is a staggering diversity of concepts within the fields of SES research, e.g., in the fields of sustainability science (Partelow 2016), community-based management (Berkes 2007), (adaptive) co-management (Plummer and Fitzgibbon 2004), and common-pool resource management (Schlager et al. 1994).

Many of these concepts have been organised into hierarchical structures, *frameworks* (Ostrom 2008, 2009). Frameworks provide several advantages, for example, a common language and logical consistency. By integrating sets of variables from different research strands, they enable researchers to use many variables in a structured manner. There are different frameworks for SESs, e.g., Hagedorn (2008) or Young (1989); for a comparison of 12 frameworks, see (Binder et al. 2013).

Although there are some concepts that are used by these frameworks and a larger number of studies, like “number of actors”, “level of participation”, or “fairness”, there are many differences regarding their use and their operationalization. In effect, these differences prevent what would be highly desirable: *comparisons* and *generalizations*. The following two sections discuss the two most important obstacles for advancing comparability.

Defining concepts and variables

The large variety of case-study approaches has sometimes lead to some confusion with a different terminology for identical theoretical concepts. This article points to some potential pitfalls, since even theoretically very sophisticated studies like the SES framework (Ostrom 2009) use variables and concepts (e.g., trust-reciprocity) or processes (e.g., interaction among resource units) interchangeably. Mixing concepts and variables may lead to problems in converting theoretical analyses to practical implementation. To begin, we distinguish between *concepts* and *variables*. A *concept* is a more general combination of ideas, i.e., a construct. Frequently used concepts in SES research are equity, trust, or social capital. Concepts (or constructs) are, as a rule, not directly measurable. They are often complex and may be abstractions. They are useful for analytical purposes, if the exact implementation of a certain concept (e.g., fair rules) does not matter, as long as the abstract purpose is achieved (here: fairness). This is most useful if case studies are compared that use different methodologies and operationalizations. Usually, a concept consists of sub-concepts describing its respective dimensions; two possible dimensions for “clear boundaries” may be the spatial clarity itself and the knowledge of users about the boundaries.

A *variable*, in contrast, is more concrete and may be measured directly, e.g., “Is there an equal distribution of benefits?”. Sometimes, a variable expresses a concept that is practically identical (e.g., number of actors). One or more variables act as proxies to measure concepts or sub-concepts.

Another source of confusion may stem from the inconsistent use of nomenclature when comparing the SES case-study literature. Two possibilities have to be distinguished: First, the concept is the same, but the terminology is different. One example is the number of actors in a community. Whether they are called users, stakeholders, community members, or actors does not matter, as long as this particular parameter of a SES is measured. For this example, what is meant is the number of members of the local community. Even if this is a minor problem, it takes a special effort to make cases comparable, because it is not always clear whether the same concept is measured, e.g., if several groups are combined.

Second, the terminology is the same, but the concept is not. For example, the concept “social capital” (defined, e.g., by Pretty 2003) figures prominently in many studies as important for different outcomes. It is highly problematic if central concepts like “social capital” are used widely differently, since even in meta-analyses, there are notable differences: While one meta-analysis (Pagdee et al. 2006, p. 42) defines it as “[…] traditional knowledge, common practices and beliefs toward the resources (e.g., forest-spirit, offering ceremony, and medicine man)”, another meta-study (Gutiérrez et al. 2011, p. 388) mainly sees it as “Community cohesion founded on norms, trust, communication, and connectedness in networks and groups […]". Still another study (Brooks et al. 2012, p. 21266) uses this concept as enhancing "[…] community pride, empowerment, and cohesion", while for (Gruber 2008), p. 55, social capital "[…] is used to describe robust local social networks, strong community norms and trust between community members […]", including participatory management.

While the overlap can be seen clearly, there are major differences as well. Sometimes, concepts are *only* defined over their operationalization (e.g., in Cinner et al. 2012). These operationalizations are often very different (see the next section) and, hence, add to the non-comparability of SES research.

Operationalizing concepts

Perhaps the major obstacle for comparing case studies is that concepts are *differently operationalized*. This means that although studies appear to talk about the same concept, in effect, they do not, because the same concept is measured in different ways. This may be illustrated by comparing operationalizations of social capital of the meta-studies used in this study (Table 1) and discussed above:

- "Whether the project created or enhanced attributes like community pride, empowerment, or social capital, two categories: no [attributes not created or enhanced or attributes eroded (loss of pride, empowerment, social capital)], yes (attributes created or enhanced)." (Brooks et al. 2012, SOM).
- A second operationalization consists of three subcategories (Cinner et al. 2012, SOM):
    1. *Levels of trust*: "We asked resource users to describe their level of trust of other community members on a 5 point Likert scale."
    2. *Frequency of participation in community events*: "We also examined how frequently resource users participated in community events, such as feasts, ceremonies, celebrations, etc."
    3. *Group homogeneity*: "[…] we also examined the proportion of resource users that were migrants. Migration was examined by asking respondents where they were born. Respondents born in other communities were considered migrants."
- A third operationalization has four subcategories (Gutiérrez et al. 2011, SOM), coded as present or absent:
    1. Unity of user groups, cooperatives, or committees
    2. Trust among users
    3. Communication and cooperation among users
    4. High degree of homogeneity in the community (political, religious, socio-economic, etc.)

The other studies in Table 1 do not use any explicit operationalization (Gruber 2008; Pagdee et al. 2006) or split up social capital in different aspects belonging to several distinct other concepts (Pomeroy et al. 2001).

As a result, even prominent concepts like social capital, are usually made up of *different* sub-concepts, which, in

Table 1 Summary description of the nine meta-analyses, large *N* studies, and literature syntheses used

Study	Sector	Type	Number of case studies	Most important factors
Brooks et al. (2012)	Forestry, grasslands, wildlife, and fisheries; community-based conservation	Meta-analysis	136	High level of participation, engagement with local institutions
Gutiérrez et al. (2011)	Fisheries; co-management	Meta-analysis	130	Leadership, social cohesion
Pagdee et al. (2006)	Forestry; community-based management	Meta-analysis	69	Social norms and rules, effective enforcement
Agrawal (2001)	No specific sector	Literature-synthesis	3 syntheses	–
Gruber (2008)	No specific sector	Literature-synthesis	23 research groups	–
Ostrom (2009)	No specific sector	Literature-synthesis	Based on several 100 case studies	–
Cinner et al. (2012)	Fisheries; co-management	Large *N* study	42	Distance to market, primary marine livelihood
Lam (1998)	Irrigation; farmer- and government- managed systems	Large *N* study	127	Tpe of management, engineering infrastructure
Pomeroy et al. (2001)	Fisheries; co-management	Large *N* study	45	Clear boundaries, participation

turn, are measured *differently*. These examples are typical for many other concepts in SES research.

Lacking comparability and generalizability

As an effect, results from the rich case-study literature and even SES meta-analyses are hardly comparable. This is problematic for generalising case-specific policy advice. Therefore, this paper addresses the problem of lacking comparability to improve the generalizability of propositions about sustainable natural resource management. Certainly, there are large *N* studies, applying a consistent research design to many cases. These studies can, in principle, overcome the problems mentioned above (Poteete et al. 2010; Poteete and Ostrom 2008). However, there are very few such studies due to costs and other constraints. Worse, there is a lack of studies with robust statistical support of factors that may influence outcomes in SES.

In sum, the relevance for performance is largely unclear even for concepts that are thought to be central in SESs, like equity, participation, or social capital. Therefore, it remains doubtful whether results may be generalized to other sectors; monitoring seems to be of paramount importance in forestry (van Laerhoven 2010), but is this true for irrigation as well?

While we use meta-analyses (see Table 1) to make the point that concepts are often defined and operationalized differently, they are, in fact, a big step towards a higher comparability of case studies. This is also true for literature reviews trying to build a synthesis of concepts in the SES literature (Agrawal 2001; Ostrom 2009). All these studies aim for the same goal as this article does—higher comparability among case studies. The intention of this article is to build on these efforts by providing, first, a synthesis of concepts related to the successful management of natural resources; second, a working definition for each concept; and third, a discussion of reasons why a particular concept is relevant for sustainable management.

Methods

To create a comprehensive synthesis of concepts relevant for the success of SESs, a literature review was performed. Using large *N* studies, meta-analyses, and syntheses of concepts in the literature as a starting point (see Table 1), the references cited therein were followed and complemented by a keyword search on Google Scholar, using as search terms "social–ecological systems", "sustainable management", and "natural resource management". The resulting hits and the selection process are described in detail in the ESM, (section 2).

This process resulted in 32 studies that discuss influences on sustainable SES-management outcomes in more detail. A list of these studies can be found in the ESM (Section 4). In the ESM (Table S2), further information for each study is given on sector, country, number of empirical cases within the study and whether results are presented with statistical tests. A concept is included in the synthesis if it is discussed as influencing performance in at least four peer-reviewed articles based on the empirical case studies.

Table 2 shows the 24 concepts of our synthesis of empirical and theoretical works on sustainable SESs. The organization of the concepts follows the SES framework (Ostrom 2009) with the addition of external influences as fifth top tier (Agrawal 2001). While there are many other frameworks (see Binder et al. 2013 for an extensive comparison), the SES framework is most suited, since it provides a well-balanced synthesis of biophysical and social attributes. In addition, it is in active development, e.g., concerning its concepts (McGinnis and Ostrom 2014), its use as a diagnostic instrument (Hinkel et al. 2015), or its formalization as an ontology (Frey and Cox 2015).

To arrive at a synthesis that is consistent in terminology, as well as the level of abstractness and the scope of concepts, several steps were necessary. First, the slight variations of concepts had to be merged into one (e.g., number of users/actors).

Table 2 in the ESM (Section 6) shows how the 24 concepts relate to the variables of the studies used.

Second, the concepts themselves had to be chosen, so that they do not overlap. Consider the two concepts "There is a common information base that is accessible and useful." and "Economic evaluation of environmental assets is a valuable information base." (Gruber 2008, p. 56). The second statement is a subset of the first one and should, therefore, not be a different factor on the same level but a sub-factor of the first one.

Third, decisions had to be made whether to merge two concepts or to treat them separately. This step was guided by theoretical discussions in the literature and according to the overall importance of a concept. One example is "clear boundaries", a well-known design principle (Ostrom 1990). However, it has often been suggested to separate this concept into resource boundaries and group boundaries (cf. Cox et al. 2010). Another example is control (often called monitoring), compliance (sanctions), and conflict management, which are—analytically speaking—three separate concepts, but they are often treated together due to their close causal relationship.

A fourth difficulty is the place of a concept in the hierarchy of our synthesis. Since it is as valid to say that location determines accessibility, as that accessibility is determined by location, the question remains which concept to use as the top category. In difficult cases, the

Table 2 Synthesis of concepts relevant for outcomes in SESs

Resource system		Resource units		Actors		Governance system		External influences	
RS1	Resource size	RU1	Manageability	A1	Number of actors	GS1	Group boundaries	EI1	Exclusion
RS2	Resource boundaries	RU2	Regeneration of RU	A2	Group composition	GS2	Participation of users	EI2	Relations
RS3	Accessibility			A3	Social capital	GS3	Legal certainty and legitimacy	EI3	Capabilities to adapt to change (resilience)
RS4	Initial ecological condition			A4	Dependency on resource	GS4	Administration		
				A5	Dependency on group	GS5	Information		
						GS6	Characteristics of rules		
						GS7	Fairness		
						GS8	Monitoring		
						GS9	Compliance		
						GS10	Conflict management		

concept chosen for the top level is more directly linked to outcomes. Since it is not location per se that is relevant for sustainability, but the attributes that go with it, accessibility would be chosen here.

Fifth, some concepts had to be excluded. There are three main reasons for exclusion: a concept may be a meta-concept (e.g., positive cost-benefit-analysis of users), it may be too fuzzy (e.g., appropriate number of users to solve problems), or concepts may be too broad (e.g., stable political, economic, and ecological environment). Sixth, the level of abstraction has to be chosen carefully. The more abstract, the fewer the number of concepts which, if taken to an extreme, yield catch-all concepts only. Such a choice would be impractical from the standpoint of an empirical researcher, since their fuzziness would make operationalization practically impossible. The opposite extreme—very concrete and specific concepts—would lead to concepts that are indistinguishable from variables. This approach would result in unwieldy lists with little generalizability between cases. The level chosen here is a middle ground, similar to the level used in the literature (Ostrom 2009), with concepts typically subsuming two to five sub-concepts that, in turn, can be operationalized through one or two variables each.

It is, of course, perfectly possible to organize the hierarchy according to other principles—there is no single right way to do it. Our purpose is to provide a guiding framework for future SES case studies. For this synthesis, the concepts selected are of potential relevance to *sustainability* of SESs, but not about enhancing the probability of self-organizing. The specific purpose implies that even specific concepts may move up in relevance, if many case studies consider them important.

Results

The following section provides a definition or description of all 24 concepts (Table 3), followed by reasons why a concept may contribute to the sustainability of SES based on the literature review described in the "Methods" and the ESM (Section 2). The concepts and the reasons given are organised according to the SES framework—resource system, resource units, actors, and governance system. Due to the number of studies treating these concepts, they must remain incomplete. There is a particular focus on the various connections *between* concepts. For space reasons, the three concepts subsumed under external influences (exclusion of third parties, relations with external parties, and capabilities to adapt to change (resilience) can be found in the electronic supplementary material (Section 1)).

Full definitions for all concepts can be found in the ESM (Section 3).

Resource system (RS)

Concepts: RS1—Resource size, RS2—Resource boundaries, RS3—Accessibility, RS4—Initial ecological condition.

Sustainable management of natural resources by implication depends on the resource system itself: First, it is affected by its *size* (RS1), since the costs for a community to organize often exceed the management benefits. If a resource is large, it is difficult and costly to collect knowledge (GS5), monitor withdrawal (GS8), and control boundaries (Ostrom 2009). In short: organization will be

Table 3 Concepts, their definitions, connections to other concepts, and their relevance for sustainability (partly adapted from Frey and Rusch 2014)

Concept		Definition	Connections	Relevance for sustainability	Reference
RS1	Resource size	Physical size of the resource system	RS2, RS3, A1, GS8	Cost of organization	Ostrom (2009)
RS2	Resource boundaries	Geographical limits to the outside	RS1, EI1, GS3	Transparency	Wade (1994)
RS3	Accessibility	Time to travel to key system locations	GS8, RU1, RU2	Costs of extraction	Nagendra (2007)
RS4	Initial ecological condition	State of resource system before appropriation	A4, GS5, GS2	Condition of RS and RU	Ostrom (2009)
RU1	Manageability	Ease of handling resource units	RS3, GS5, GS8	Costs of extraction	Ostrom (1992)
RU2	Regeneration of RU	Replacement rate of resource units	GS5, RS4, A1	Robustness against overharvesting	Baland and Platteau (1996)
A1	Number of actors	Number of actors	RU2, A3, A2	Cost of organization	Olson (1968)
A2	Group composition	Heterogeneity of actors' group	A3, GS5, GS7	Coordination	Agrawal (2007)
A3	Social capital	Social networks, norms and trust	EI2, A1, GS6	Coordination	Gruber (2008)
A4	Dependency on resource	Dependency on resource for survival	RU2, RS3, GS2	Willingness to invest	Agrawal (2007)
A5	Dependency on group	Dependency on group for collective action	A1, A4, GS2	Willingness to invest	Pagdee et al. (2006)
GS1	Group boundaries	Who belongs to the actors' group	A1, GS8, A2	Exclusion of third parties	Ostrom (1990)
GS2	Participation of actors	Involvement of actors in collective action	A3, GS6, GS7	Adapted rules	Ostrom (1990)
GS3	Legal certainty and legitimacy	Recognition of rights by other groups	EI2, GS9, GS6	Willingness to invest	Schlager and Ostrom (1992)
GS4	Administration	Organisation of actors' group	GS9, EI2, GS5	Cost of organization	(Tang 1989)
GS5	Information	Information flow within community	EI2, RU1, RS1	Harvesting decisions	Sandström and Widmark (2007)
GS6	Characteristics of rules	Adaptedness of local rules	A3, GS8, EI1	Adapted rules	Meinzen-Dick (2007)
GS7	Fairness	Just actions, behavior and rules	A3, GS8, A4	Willingness to invest	McKean (1992)
GS8	Monitoring	Information to control rule compliance.	GS9, GS10, GS5	Deterrence of free-riders	Ostrom (1990)
GS9	Compliance	Level of rule-following	GS8, GS10, RS1	Deterrence of free-riders	Pagdee et al. (2006)
GS10	Conflict management	Ways of treating disagreements	GS9, A1, A2	Ccoordination	Ostrom (1990)
EI1	Exclusion of third parties	Prevent other groups from appropriating	RS2, GS1, GS3	Harvesting decisions	Feeny (1992)
EI2	Relations with external parties	Interactions with other groups	GS3, GS2, GS4	Willingness to invest	Berkes (2007)
EI3	Capabilities to adapt to change	Ability to cope with sudden changes	RS4, RU2, GS5	Stability	Agrawal (2002)

more difficult (Baland and Platteau 1996) and transaction costs will be higher (Shiferaw et al. 2008).

Second, it is affected by the *resource boundaries* (RS2), since clear boundaries facilitate the exclusion of third parties (EI1) (Baland and Platteau 1996) and are a prerequisite for clear property rights (Schurr 2006). Clear boundaries facilitate the initial efforts to cooperate and function as the demarcation of externalities (Gruber 2008). Without clear boundaries protection against potential damage from the outside is difficult or impossible (Acheson 1987).

Third, sustainable management is affected by the *accessibility* (RS3) of the system. Appropriation costs are lower if appropriators live nearby the resource, which, in turn, depends on the spatial and temporal distributions of resource units within (RU1). A close distance also facilitates monitoring and thus improves compliance with rules (GS8, GS9) (Ostrom 1992, Nagendra 2007, Baland and Platteau 1996). An easily accessible resource decreases the cost of resource unit extraction (Nagendra 2007). This may have negative effects too (Ostrom 2009; Pagdee et al.

2006), since the exclusion of third parties may be difficult or impossible (EI1).

Fourth, the *initial ecological condition* (RS4) plays a role for sustainability: If the resource is heavily exploited, there is a little future prospect, which also prevents organization (Shiferaw et al. 2008; Pagdee et al. 2006). If an actors' group has experienced a certain lack of resource units, they understand better that cooperation is necessary to ensure sustainable management (Thomson et al. 1992; Ostrom 2009). A long-term perspective assessing the past, present, and future of the condition of the resource is essential, especially in slowly renewable resources, such as forests (Nagendra 2007). As a result, the initial state of the resource is critical, because duration and scope of measures for sustainable management depend on it.

Resource units (RU)

Concepts: RU1—Manageability, RU2—Regeneration of resource units.

Especially relevant for sustainability is the *manageability of resource units* (RU1), involving predictability, complexity, and dynamics, as well as the ease of harvesting, storage, and transportation. Since biological populations fluctuate in abundance over time, predictability is especially important for resource flows (Pagdee et al. 2006). It may be difficult in a very unpredictable system for actors to allocate resources or coordinate activities (Agrawal 2001). If resource units' predictability is low, it becomes hard for communities to draw together observations to a mental model of the system (GS5) (Baland and Platteau 1996). The unique distribution of units in time and space directly influences the costs of appropriation (Pagdee et al. 2006).

Among the key parameters for sustainable management is the *regeneration of resource units* (RU2). The growth or replacement rate describes how fast resource units that are extracted replace themselves (Dietz et al. 2002) influencing many other critical concepts (Pagdee et al. 2006). If regeneration capability is slow, even a low rate of use may not be sustainable (cf. Agrawal 2001). Thus, regeneration time and capability have a direct and large effects on the condition of the resource (RS4) (Wade 1992). Regeneration, in turn, is itself influenced by many concepts. (Chhatre and Agrawal 2008) suggest that rule enforcement (GS9) is important—lacking enforcement leads to degradation. Group size (A1)—at least in forestry—seems to have a curvilinear effect on regeneration rates (Nagendra 2007): both too few and too many individuals per hectare of forest are not optimal for regeneration.

Actors (A)

Concepts: A1—Number of actors, A2—Group composition, A3—Social capital, A4—Dependency on resource, A5—Dependency on group.

Sustainable management also depends on the actors' group. For example, *large groups* (A1) increase the pressure on resource units (RU2) by their very number (Baland and Platteau 1996). In some cases, though, costs for management and monitoring (GS8) are higher for smaller groups (Ostrom 2009). In addition, trust (A3) builds up more easily in smaller groups and rule violations are more easily detected (GS9), especially third parties without rights to appropriate (EI1).

Moreover, the *group composition* (A2), i.e., the level of heterogeneity, regarding different sub-concepts, such as ethnicity, socio-economic standing and many others, influences group cohesion, which, in turn, negatively influences coordination. High heterogeneity may also impede fair distributions and collective action (Gruber 2008). Since heterogeneity may refer to many aspects, such as ethnic group, culture, gender, wealth, or interests (Baland and Platteau 1996), it is difficult to subsume it under one concept, because while heterogeneity in one aspect may be positive, it may well be negative in another. Therefore, group composition is a mixture of highly context-dependent variables (Agrawal 2007).

A third aspect of the community which influences sustainable management is *social capital* (A3). Trust is, perhaps, the most essential part of social capital. It may be increased by already established norms, availability of arenas for collective action, and past experiences of groups with collective action. Building trust takes time (Olsson et al. 2004) and works best when groups are not too large (A1). In general, high trust means less monitoring (GS8) and a higher compliance with rules (GS9), which is a condition for sustainability (Gibson et al. 2005). Group cohesion increases with trust as well (Gutiérrez et al. 2011). Therefore, the loss of reputation can be an important part of sanctioning in a well-functioning society (Wade 1992). Another significant aspect of social capital is good leadership (Gutiérrez et al. 2011; Scheberle 2000).

The community is, furthermore, *dependent on the resource* (A4) and on the *group itself* (A5), which, in turn, influences decisions concerning sustainability. For example, appropriators who depend heavily on the resource, because they have no alternatives, are more likely to invest in the resource system and to manage it sustainably. This is particularly true for dependencies that extend over several generations (Bischoff 2007). Resources that are critical for subsistence are, on average, better maintained, because of their inherent high value (Ostrom 2009). Nevertheless, a high dependency is often a key for the initiation of self-organization (Pagdee et al. 2006; Gruber 2008; Ostrom 2009; Agrawal and Chhatre 2006). There is also a correlation between tenure regime and dependency (Nagendra 2007). One of the main reasons, individuals join communities, is their desire to minimize risks, because often only a community can buffer high and unpredictable risks like crop failures (Wade 1992).

Dependency on the group is often crucial for the initiation of a community-wide system of rules and regulations (Ostrom 1992), since group formation often starts with the insight or compulsion that successful and sustainable operations are only possible in groups (McKean 1992). This may also mean that exploitation of a resource by a single individual is not possible. A strong dependency among group members, e.g., by common purpose, geographical isolation or strong cultural traditions can also be a prerequisite for collective actions to prevent third parties from entering the system (Berkes 1986). If dependency on other group members is high, members are anxious to maintain reciprocity and trust. This contributes to a long-term view of actors on resource exploitation and increases the willingness to invest in the resource (A4) as well as social sustainability (Pagdee et al. 2006). If the dependency on the *resource* is high (A4), the dependency on the *group* is often high as well, since strong fluctuations in the flow of resource units or losses from disasters can only be overcome together (Wade 1992).

Governance systems (GS)

Concepts: GS1—Group boundaries, GS2—Participation of actors, GS3—Legal certainty and legitimacy, GS4—Administration, GS5—Information, GS6—Characteristics of rules, GS7—Fairness, GS8—Monitoring, GS9—Compliance, GS10—Conflict management.

When managing natural resources, rules, regulations, and institutions play an important role for sustainability. First, *group boundaries* (GS1) are crucial. Group membership is defined by *boundary rules* which can be implemented in many different ways (Tang 1991). Group boundaries are, on average, clearer in small groups (A1) with a common history of use (A3). They become especially important with highly mobile or scattered units (RU1). Clear boundaries of the appropriating group are an essential prerequisite for reaching decisions on a common system of rules. In addition, clear boundaries facilitate the monitoring of compliance with rules (GS8, GS9), since rights can be assigned clearly (Pomeroy et al. 1998; Schlager and Ostrom (1992).

Second, *participation of actors* (GS2), one of the most discussed concepts in the literature, is considered very relevant. Opportunities for the participation of the involved actors are a prerequisite for the process of crafting rules (Gutiérrez et al. 2011). The costs for rule changes decrease when the majority of those affected created the rule-system themselves, thus being in an optimal position to change or enforce it, too. In addition, rule compliance (GS8) is higher when rules have been crafted by the actors' group itself (Kosfeld et al. 2009). With high participation, rules can be adapted quickly and targeted precisely (Ostrom 1990). A high dependency on the resource system (A4) increases the likelihood of participation (Agrawal and Chhatre 2006). Participation of the majority involved ensures fair and open processes.

Third, *legal certainty and legitimacy* (GS3), i.e., the acceptance of the local community, as authority in regard to local jurisdiction and local legislative authority is a key prerequisite for long-term planning and, thus, sustainability (Ostrom 1990). In particular, property rights must be safe and stable (Schlager and Ostrom 1992). If such security is given, the willingness to invest in the resource increases considerably (A4). Legal certainty is the basis for long-term management policies which, in turn, are important for ecological success (Gutiérrez et al. 2011).

In other cases, the state regulations *replace* existing local rules—sometimes with the best intentions, sometimes not (Ostrom 1992), but often destroying existing locally adapted rule systems (GS6). In general, many authors see a clear relationship of this factor to success (e.g., Pagdee et al. 2006; Tucker 2010; Tang 1989).

Fourth, implementing rules that are agreed upon and organizing the community are the task of an *administration* (GS4), which is thus central to many processes (Pomeroy et al. 1998). A local administration has to be legitimized, enjoy the confidence of the actors, and assign clear responsibilities. If this is the case, compliance will benefit (GS9). To be effective, individuals within an administration must make fair decisions and must not be corrupt. Ideally, employees take part in local life and know appropriation problems from their own experience (Ostrom 2009). Efficient management lowers the costs of organization (Tang 1989). A well-functioning administration ensures that organizational decisions are, indeed, implemented (Gruber 2008). Thus, an administration helps to translate institutional decisions into efficient and actual facts.

Fifth, the *information and communication flow* (GS5) within the community is relevant for sustainability, since only after information on, e.g., the condition of the system is acquired, it becomes possible to adapt rules and to control monitoring and appropriation (Sandström and Widmark 2007; Ostrom 2009). Good information is particularly important in systems with a high resource unit's mobility, a heterogeneous distribution, and unpredictable system dynamics (RU1) and a large size (RS1). A strong information system generates knowledge about all parts of the system. It may also strengthen the cohesion of the social network (A3) (Gruber 2008).

Sixth, it is important to *adapt rules to local conditions* (GS6; Baland and Platteau 1996; Pagdee et al. 2006). (Pomeroy et al. 1998) emphasizes cultural and social environmental parameters that have to be considered; failure is inevitable if local customs are ignored or contradictory actions are taken. Ideally, rules integrate seamlessly into cultural and ideological givens and traditions (A3) (Cox 2010). Flexibly adapted rule sets have to be easily understandable, clear, transparent, and simple (Berkes 1992).

Seventh, actions, behavior, and rules should be just and promote *fairness* (GS7). It is well documented that fairness is a basic condition for the motivation of people to constructively participate in community actions (e.g., Falk et al. 2003). If institutions are unfair, they will already be rejected in the start-up phase (Kosfeld et al. 2009). Fairness emerges in rules crafted by those in authority (Baland and Platteau 1996), but it is also reflected in voting rights (Scheberle 2000). Moreover, inequalities can be compensated with appropriate, skillfully selected rules. For example, in Japan, harvested grass of differing quality is divided into clusters and distributed by lot (McKean 1992). In fisheries, where some spots are known to be better than others, as well as in irrigation systems, rotating systems are common to ensure fairness (e.g., Berkes 1987).

Eighth, *monitoring,* especially the environmental aspects of appropriation (GS8), enhances sustainable use by improving rule compliance. Monitoring in SESs is typically either performed by the actors themselves or by appointed guardians accountable to the actors (Gruber 2008). In agency-managed SESs, the lack of guardians' motivation is often a problem. Such problems may be resolved in local systems with additional incentives (Wade 1992). Since SESs are, by definition, always at risk of free riders, monitoring seems to be necessary, in general. If actors succeed in effectively deterring free riders through checks and penalties (GS9), the effectiveness of the system can be greatly increased (Gutiérrez et al. 2011). The costs of monitoring are usually relatively small if the appropriators themselves monitor (Ostrom 1990; Tucker et al. 2007) or through appropriate arrangements (Cox 2010). Summing up many other studies, (Tucker 2010) concludes that monitoring (at least for forests) is one of the key factors for ecological success.

Ninth, *compliance* with established rules (GS9) helps to avoid the exploitation of the resource (cf. Vollan 2008). It is essential for compliance that penalties are *actually* and *effectively* enforced and do not only exist on paper (Pagdee et al. 2006; Ostrom 1990; Gibson et al. 2005).Compliance strongly depends on whether rules and enforcing institutions are perceived as legitimate (Baland and Platteau 1996).

In many social–ecological systems, *graduated sanctions* (Ostrom 1990) have a proven track record, building up on reputation. Sanctions also prevent abuse, which adversely affects the condition of the resource (Cox et al. 2010). Rule enforcement is linked to resource size (RS1)—very small communities may not need material sanctions at all relying instead only on reputation losses and gains (Agrawal and Chhatre 2006). The positive correlation between compliance and condition remains statistically reliable even with larger samples in forests world-wide, demonstrating the importance of this concept (Tucker 2010; Gibson et al. 2005).

Finally, *conflict management* (GS10) both inside the group and with other stakeholders is important: solving conflicts contributes to the stability of rule systems and, thus, a stable use of the resource (Ostrom 1990). It is important that conflicts are resolved quickly at low cost and by a jurisdiction which is locally available, works fairly and without corruption, and is easily accessible for everyone. If conflicts do not escalate, cooperation and trust are strengthened, coordination is furthered, and efficiency is increased. Typical causes for conflicts are a rapidly growing population (A1) which increases the pressure on the resource (RU2), a high heterogeneity of actors (A2; Baland and Platteau 1996), or new migrants demanding the same rights as long-term residents.

Discussion

Some limitations of this synthesis have to be pointed out. First, there is a certain bias towards the concepts discussed in the SES literature, i.e., relatively little importance is attributed to economic indicators, such as income, poverty level, market access, or GDP. A user of such a synthesis has to be aware that these factors may explain a large share of variability in some cases. This shortcoming in SES research has already been pointed out by Agrawal (2001). A second bias identified within social–ecological systems research is towards social attributes, neglecting ecological ones (Vogt et al. 2015). Second, indicators on a national basis, such as the human development index (HDI), the GINI coefficient, or the corruption perceptions index (CPI) provide additional information that should be considered (e.g., Brooks et al. 2012). Third, the context, i.e., framing conditions, such as major social, political, technological, or demographic changes, prior to any empirical analysis, is not covered by the concepts.

Fourth, these 24 concepts are organised in regard to sustainability. There are other outcomes of interest that may require a different set of factors. For example, the *resilience* of social–ecological systems has come into focus (Walker et al. 2004; Domptail et al. 2013; Folke et al. 2002; Anderies et al. 2004). Other important outcomes include social equity (Oberlack et al. 2015) and economic efficiency (Gutiérrez et al. 2011).

Fifth, robust statistical support for some of the concepts is sparse: only 17 out of 32 studies indicate statistical significance of concepts in some way (see ESM, Table 2).

Lastly, different contexts, such as urban environments (Muñoz-Erickson 2014) or shared infrastructure (Yu et al. 2015), should result in a different sets of concepts.

Nevertheless, we hope to provide a concise and manageable synthesis for sustainability science researchers. The 24 concepts introduced may serve as a guiding construct to structure data collection (e.g., surveys), to link previously unconnected concepts with sustainability as a linking hub (Kajikawa 2008) and to streamline the operationalizations of concepts. In this vein, this study would like to re-emphasize some points from Agrawal (2001), namely the call to intensify research on comparative case studies, to use broader research designs encompassing more variables, to move from correlational analysis to causal relationships and pathways, and to put more weight on statistical tests to validate findings.

Apart from discussing key concepts of research on the sustainable management of natural resources, this article links in some even more specific ways to sustainability research: many authors highlight one or more concepts as crucial for successful sustainable management. For example, Walker et al. (2004) sees adaptability (here: EI3) as central for the sustainable future development of social–ecological systems, distinguishing it from resilience. Another example is Mitchell (2006), who stresses partnerships and collaboration between stakeholders (here: GS2 and EI2).

Still another link is to research on coupled infrastructure or socio-technical systems (e.g., Markard et al. 2012), which is another aspect to integrate into social–ecological systems. In particular, transformations and transitions will play a major role (Geels 2002), while the connections between concepts provide a first step to possible pathways.

As long as the conceptualization that has been put forward in this article remains purely theoretical, its usefulness is limited. However, it has been tested with three large data sets of social–ecological case studies ($n = 794$), the CPR, the NIIS, and the IFRI database developed at the Ostrom Workshop. The goodness of fit of these models based on the 24 concepts is very good (Frey and Rusch 2013, 2014). This indicates that the 24 concepts are useful and broad enough to capture many major factors for sustainable management of natural resources.

As added value, these steps can be seen as building blocks to further understanding of natural resource management (Mitchell 1998). A comprehensive framework exposing relevant interactions between concepts is required for beginning to unravel the dynamics and complexity of social–ecological systems. This may serve as a starting point for a more comprehensive work with larger sets of concepts. Thus, it can help to unify field work by placing this synthesis at the disposal of sustainability researchers.

Finally, I would like to point out some possible further developments of the work presented here. It may serve as first step towards causal models of social–ecological systems by linking concepts for the sustainable management of natural resources. The presented network of interactions helps to indicate causal pathways. Unfolding these relationships may lead, e.g., to collect additional data on these factors or to specify a more precise causal model of the system in question. Structural equation modeling is one statistical tool to develop such models further. However, given the complexity of social–ecological systems, the "causes" of the described relationships are only sufficient, not necessary conditions, since a certain effect (outcome) can almost always be reached through multiple ways, while other factors may interfere as well.

Hopefully, this compilation also contributes to a more comprehensive work with concepts and variables. At the time of writing, many studies analyze only some variables in regard to the performance of SESs. This is perfectly understandable for practical reasons, but holds the danger of missing other vital factors, since even stable looking connections may break apart or reverse direction when another factor comes into play.

Conclusion

This article provides a synthesis of 24 concepts which are relevant for the sustainable management of social–ecological systems, building on the previous syntheses, meta-analyses, and case studies. A literature review for each concept summarizes the reasons why each is relevant, provides a definition and explores connections to other concepts.

Thus, the scattered evidence of *why* many concepts contribute to the performance of natural resource management and their interactions, which are largely unknown, is described. This synthesis should make it easier for the subdisciplines of sustainability research to communicate and design research, improving replicability and generalizability.

In conclusion, it would be optimal to study the sustainability of SESs accounting for all of the factors discussed. However, this would entail collecting empirical data on hundreds of variables which is not easily done (Poteete and Ostrom 2008; Agrawal 2001). Still, some attempts have been made to collect such data, for example, the IFRI data set on forestry or the NIIS data set on irrigation systems. By working with larger databases, precise quantitative models can be developed which would require combining large data sets with the data-mining methods.

To sum up, there have been few attempts in social–ecological systems research to organise potentially relevant variables for sustainable management in a consistent, comprehensive, and generalizable manner. This paper presents such a synthesis. It puts forward definitions for each concept and the reasons why each concept is important for sustainability. In addition, the interactions and connections between concepts relevant for the analysis are presented. Therefore, this effort may help to make research designs more comparable and thus more generalizable results and enabling a better detection of successful management patterns in the future.

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