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REVIEW

A Sustainability Agenda for Tropical Marine Science

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Abstract

Tropical coasts face unprecedented sustainability challenges for advancing human welfare and maintaining ecosystem functioning and diversity. These coupled social–ecological processes exist within interdependent relationships across multiple levels and scales. Reflection is needed on the knowledge tropical marine science generates to advance a research agenda for sustainability. In this article we systematically review 753 social and natural science articles conducted within the tropical coastal marine sector. Our results are organized in five themes. (1) The spatial distribution and disciplinary composition of research is not homogeneous across regions. (2) A third of all research lacks a stated problem orientation and coral reefs dominate the ecosystem focus. (3) Research is primarily conducted on selected subgroups of levels and scales. (4) The social and natural sciences focus on a varying diversity of system processes that indicate different degrees of inter- and intradisciplinary research. (5) Statistically clustered terminology usage across all articles indicates that distinct research communities exist across a social to natural science gradient. The social and natural sciences generate different types of knowledge associated with terminology at different scales. This analysis attempts to provide a guidepost for discussing the challenges and pathways forward to progress a sustainability agenda in tropical marine science.

Introduction

Tropical coasts contain the highest concentrations of biodiversity and people worldwide (Glaser *et al.* 2012; Bowen *et al.* 2013; McKinnon *et al.* 2014). Human populations on tropical coasts experience a high degree of dependence on local natural resources, widespread poverty, and face immediate threats from climate change including rising seas and increased storm intensity (MEA 2005; Worm *et al.* 2006; IPCC 2007). Simultaneously, ecosystems face reciprocal pressures from increasing resource exploitation, pollution, ocean acidification, and increasing sea surface temperatures (Graham *et al.* 2015; Halpern *et al.* 2015). This quagmire of interdependent relationships has shifted the paradigm through which we conceptualize sustainability in an interconnected world, to one where people and nature are coupled in social–ecological systems (SES; Ostrom 2009; Kittinger *et al.* 2012; Fischer *et al.* 2015), necessitating a cohesive response from both science and society.

Tropical marine and coastal SES are confounded by contextual complexity at multiple levels and scales (Glaser & Glaeser 2014; Leslie *et al.* 2015). In ecological subsystems, coral reefs, mangroves, seagrasses, open seas, and estuaries each contain contextually unique functional processes (McMahon *et al.* 2012; Yeakel *et al.* 2015). Biodiversity supports functional diversity and redundancy for maintaining baseline ecosystem functions (Bowen *et al.* 2013; Mouillot *et al.* 2014). The resulting ecosystem services sustain coupled social–ecological integrity (Arkema *et al.* 2015). In social subsystems, human behavior and institutions shape the provision and appropriation of goods and services (Ostrom 2009; Cinner *et al.* 2012). Institutional prescriptions or collective action typically govern society through formal and informal rules (Ostrom 2009; Horan *et al.* 2011). The coupled outcomes of coastal and marine systems thus result through an exchange of social–ecological interdependencies, with interactions occurring simultaneously within and across biophysical and socially constructed levels and scales (McGinnis & Ostrom 2014; Leslie *et al.* 2015).

Normative ambitions for tropical marine science propose that knowledge generation should collectively advance sustainability (Grorud-Colvert *et al.* 2010; Cinner *et al.* 2012; Glaser *et al.* 2012). The foundations of such a sustainability agenda need to recognize place-based challenges, but also commonalities (Ostrom 2009; Wilcox *et al.* 2015). Linkages between livelihood security, global markets, and rapid natural resource exploitation have been coined as pandemic (Berkes *et al.* 2006; Eriksson *et al.* 2015). Coastal communities and biophysical systems with low resilience thresholds can face sudden and irreversible changes from anthropogenic impacts (Graham *et al.* 2013; Troell *et al.* 2014). Such systems are often characterized by a new social–ecological condition, with rapid biodiversity loss and decreasing livelihood opportunities (Worm *et al.* 2006; Cardinale *et al.* 2012). In response, achieving sustainable development may require reconciling trade-offs between place-based needs and overarching goals (United Nations 2012), necessitating a well-informed scientific agenda with operational solutions.

Toward an agenda for sustainability science

Operationalizing a sustainability agenda for tropical marine science will require the generation and integration of diverse knowledge types (Glaser *et al.* 2012; Leslie *et al.* 2015), from both science and society. In particular, we recognize the role of nonwestern scientific knowledge in informing sustainability agendas such as local ecological and traditional knowledge (Berkes *et al.* 1995). However, this review solely focuses on the state of published scientific knowledge and how it shapes current agendas, but this nonetheless presents a challenge to comprehensively examine the diversity of literature across disciplines.

Here, we aim to inform future agendas in tropical marine science by analyzing existing literature. Furthermore, we categorize the knowledge needed to inform sustainability into three types: system, target, and transformative (Hadorn *et al.* 2006; Jerneck *et al.* 2010; Brandt *et al.* 2013). System knowledge analyzes and describes system functioning. Target knowledge understands how system knowledge passes through the interpretations, visions, goals, and normative directions of society. Transformative knowledge understands how to convey system and target knowledge into practical change mechanisms such as policy, education, and communication.

In practice, the need for science is escalated in times of increasing social and environmental change. However, the role of science in society is increasingly ambiguous. Without undermining the diversity and integrity of scientific practice, structuring an agenda for science to cumulatively advance sustainability requires reflection into how and why knowledge is generated (Spangenberg 2011). Communicating how knowledge can be oriented to real-world problems and inform practical solutions is recognized as a key step for advancing sustainability contributions within and beyond the scientific discourse (Perrings 2007). Moving toward a conscious research agenda for sustainability requires examining the agendas that are established, why they have evolved in this direction and to propose what is needed to inform a sustainable future.

In this article, we systematically examine tropical marine and coastal research from 753 peer-reviewed articles across the social and natural sciences. This review aims to provide a guidepost that can orient discussion and contribute to reflections on how and why marine and coastal research agendas can advance sustainability. To do this we examine knowledge contributions across disciplines and contexts. We outline our methods below and present our results quantitatively. Our discussion highlights key gaps and trends in the literature, and attempts to provide a starting point for critical discussion including trends in regional disparity, the role of problem orientation, multidimensional systems, the types of knowledge needed and differences between the social and natural sciences.

Methods

Our systematic literature review draws on established methods (Brandt *et al.* 2013; Luederitz *et al.* 2015). We assessed 1,995 peer-reviewed articles of potential relevance which were distilled down to 753 articles for full review within our scope. Our search string and scope related to peer-reviewed academic literature within social, ecological, or social–ecological research in the marine and coastal tropics. However, we recognize that this review cannot be considered fully exhaustive. Our step-by-step protocol is shown in Table S3. We distinguish that a case study or the relevant context of the research must fall within the Tropical latitudes of 23.5 N and 23.5 S. Articles needed to have a direct connection to the marine or coastal environment but could relate to this context through a wide variety of research ranging from land-based social research to exclusively marine natural system processes or land–sea connectivity across any scientific discipline.

Table 1 Review categories and subclasses

Category	Description of subclasses used
Year	Year article was published
Discipline/ perspective	Biology, Ecology, Political science, Economics, Sociology/ Anthropology/ Ethnography, Geography, Chemistry/ Biogeochemistry, Sustainability science, Physics, Geology, History
Location	Physical location where research was conducted or relates to was classified by World Bank subregions
Ecosystem type	Coral reef, Rocky reef, Mangrove, Soft bottoms, Open sea, Estuary/ Wetland/ Lagoon, Intertidal, Coastal, Sponges, Seagrass
Problem orientation	Subsistence/ Recreational resource use, Commercial resource use, Tourism, Conservation, Pollution/ Degradation, Aquaculture, Development, Climate change, Restoration, Mining
Level focus	Local, Regional, Global
Scale focus	Ecosystem, Jurisdictional, Knowledge, Temporal, Spatial, Institutional, Network, Management
Social processes	None, Demographic change, Distributive and procedural justice, Participation and decision making, Rules and rights transparency and implementation, Conflict resolution, Social learning, Knowledge generation and communication, Social networking, Historical societies, Community and cultural development, Socio-economics and livelihoods, Social perceptions and behavior, Rule-making and institutional change
Ecological processes	None, Habitat connectivity/ Migration/ Mobility, Recruitment, Litter processing, Carbon & nutrient cycling, Functional diversity, Functional redundancy, Biological or Ecological response to pollution, Oxygen consumption and production, Population connectivity, Sedimentation/ Erosion, Biomass prod./Transfer/ Reproduction, Sediment oxygenation/ Nutrient mixing, Calcification, Species interactions, Hydro/ Oceanographic processes, Bio./Eco. extreme events response, Ecosystem integrity and change, Climate change processes, Land–sea connectivity, Biophysical characteristics
Social–ecological processes	None, ES provision, Self-organization, Resource use and degradation, Adaptation and coping, Knowledge integration, Scale development, Values and trade-offs, Local ecological knowledge, Management, Mapping, Research
Knowledge types	System, Target, Transformative
Publication terminology	All words from each article were individually extracted, filtered for relevant terminology and associated with knowledge types

Review categories

We defined 13 review categories for data collection (Table 1). Categories follow our research focus and draw on existing frameworks, including levels and scales (Cash *et al.* 2006), research processes (Glaser *et al.* 2012), and knowledge types (Hadorn *et al.* 2006; Jerneck *et al.* 2010; Brandt *et al.* 2013). However, classes within each category were defined through a combination of framework definitions and inductive assessment during the review process through consensus among coders. If a framework was used as a starting point for a category, classes remained inductively flexible to include the full spectrum of data from articles, with an open-text "Other" option for each category. None of our review categories were mutually exclusive except year. This allowed the coding for each category to avoid forced classification. However, coding was conservative, only classifying an article if it was directly relevant to the primary research outcomes or argumentation.

The disciplinary composition of the social and natural sciences used in this article is shown in Figure 1. Regional groups are World Bank sub-regions (World Bank 2015; Figure 2). Melanesia, Micronesia, and Polynesia were grouped into the Pacific Islands. West Asia and South Asia were merged into Southwest Asia, and Hawaii as

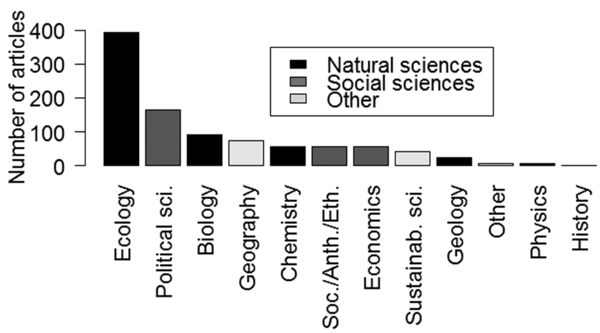

Figure 1 The total number of articles from each discipline. The disciplinary composition is shown in the Natural sciences, Social sciences, and Other. This is used to aggregate disciplinary contributions when mentioned in the text and in Figure 2, Table 2, and Figure 4(c).

its own subgroup. Levels are defined as local, regional, and global. Scales are defined from Cash *et al.* (2006) and Glaser *et al.* (2012). They are defined in short form as spatial "geographic space," temporal "time frames," institutional "hierarchies of rules," jurisdictional "organized political units," knowledge "generalized to context specific," management "hierarchy of tasks and strategies," networks "structures of [social or ecological] associations" and ecosystem "functions, services, benefits and their

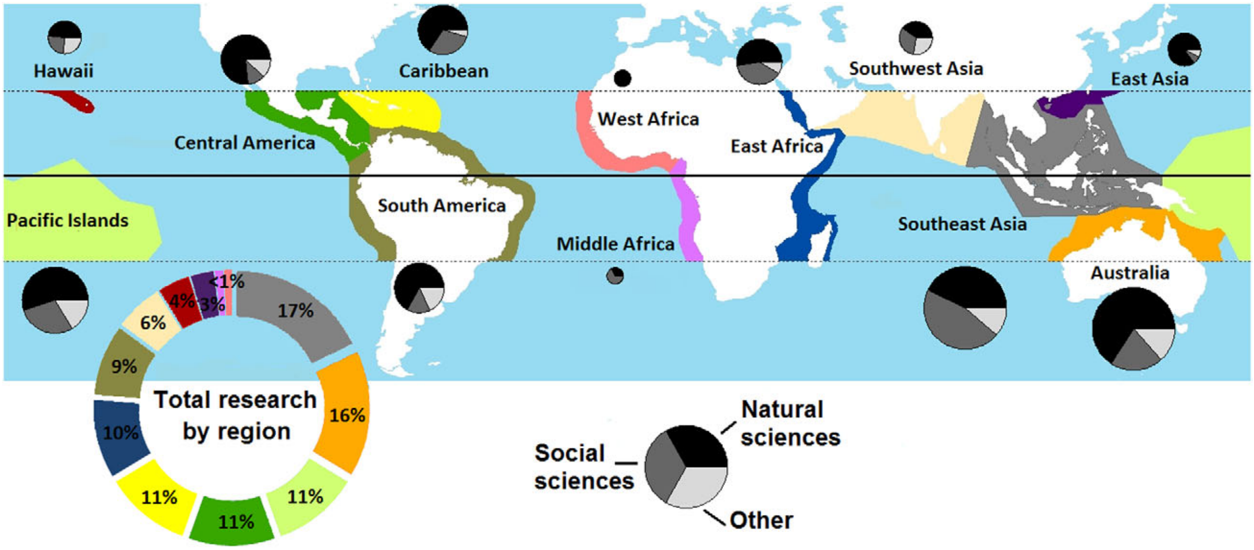

Figure 2 Total percentage of research by tropical coastal marine region. Spatial extent of region boundaries is only for visual purposes. Scientific focus by region is presented in pie charts. Pie chart size is representative of total *N*. Natural sciences include: biology, ecology, chemistry, biogeochemistry, and geology. Social sciences include: political science, economics, sociology, anthropology, and history. Other includes: geography, physics, sustainability science, and all others.

distribution." Our starting point for system processes (Table 1) to include was derived from Glaser *et al.* (2012), but additional processes were added inductively to not limit the range that exist in the literature.

Analytical procedures

Nearly all articles focus on at least one system process, and they can be classified into a domain typology of either social, ecological or social–ecological (Glaser *et al.* 2012). Each article was classified into the domain typology shown in the Venn diagram (Figure 6) based on their process focus. Articles with a focus on multiple processes from different domains (e.g., one social and one social–ecological) are colored red in Figure 6 and further analyzed in Figure 7. Articles with a focus on one or multiple processes in the same category (e.g., one or two ecological) are colored black in Figure 6 and further analyzed in Figure 8.

We analyzed two aspects of the articles that focused on multiple processes (Figures 7 and 8). First, how often two processes occur in the same article (connectivity in circle), and second, the total occurrence of each process in multiple process articles (proportion of circle edge). Multiprocess articles from different domains were analyzed as interdomain, representing a connection in Figure 7 and 8. First, the relative occurrence of each process in the literature, and second, the total connectivity between processes represented by cooccurrence in an article (for further details see Supplementary Material).

The terminology and knowledge type plot (Figure 9) was calculated by extracting all individual words (terminology) from each article into a data matrix. The presence and recurrence of words was statistically clustered based on their abundance across all articles, using an indicator species analysis to identify words that characterize groups into statistically distinct clusters (Dufrene & Legendre 1997). In order to visualize these words and the groups they characterize, we used a detrended correspondence analysis of the whole data matrix (Hill & Gauch 1980). Words (terminology) with a relevant knowledge context were manually classified as representative of system, target, or transformative knowledge based on a word typology developed by Abson *et al.* (2014). Knowledge types were plotted in direct relation to the statistically clustered terminology distribution.

Results

Our analysis presents results within five themes. (1) The spatial distribution and disciplinary composition of research across regions. (2) The current problem orientation, ecosystem focus, and time evolution of the literature. (3) The level and scale focus related to the units of analysis in each article. (4) The system process focus in the social and natural sciences. (5) The knowledge types generated and the communication of knowledge through examining terminology in the literature.

Spatial distribution and disciplinary composition of research across regions

The disciplinary composition of scientific effort is shown in Figure 1, dominated by ecology in the natural sciences. In addition, the spatial occurrence of research is not homogeneously distributed (Figure 2). Some regions receive far less research focus comparatively, including West Africa, Middle Africa, Southwest Asia, and subregions of the Pacific Islands. In contrast, a third of all research occurs in two of 12 regions, Southeast Asia and Australia. Within Australia, a large majority of the research is conducted on the Great Barrier Reef. The Pacific Islands, Central America, and the Caribbean receive relatively equal focus. However, our analysis does not consider effects of coastline length, population density, resource dependencies or differences in specific regional characteristics. It is not in the scope of the article to analyze the reasons for regional disparity. The scientific effort distribution shows a dominance of natural science across nearly all regions (Figure 2). Social sciences are more relatively abundant in Southwest Asia, East Africa, and Southeast Asia.

Problem orientation, ecosystem focus, and time-evolution

A third of all research lacks a stated problem orientation that links its purpose to a problem outside an academic discourse. The natural sciences have a very low proportion of articles with a stated problem orientation compared to the social sciences (Table 2). However, this is not a distinction between basic and applied research, only the stated purpose or motivation to conduct the research. The type of problem orientation is rather homogenous between the sciences, with the exception of pollution in the natural sciences. Conservation and tourism are emphasized in the social sciences (Table 2). Focus on conservation, commercial resource use, and pollution is homogenous across regions (Figure 3a). Specific regions exhibit a proportionally higher focus in specific areas such as development in Southwest Asia, tourism in the Caribbean, subsistence resource use in East Africa, restoration in the Pacific Islands, and aquaculture in Southeast Asia (Figure 3a).

Considering the diversity and importance of all ecosystem types, 38% of all research is conducted on or in relation to coral reefs (Figure 3b). Estuaries, wetlands and lagoons combine for the second highest focus at 10.7%, followed by mangroves at 9%. All other

Table 2 Percentage of total articles sorted by their stated problem orientation

Problem orientation category	Natural sciences (%)	Social sciences (%)	Other (%)
Aquaculture	1.4	2.3	2.0
Climate change	5.2	2.6	5.1
Commercial resource use	9.1	19.7	10.6
Development	3.9	7.2	7.6
Mining	0.6	0.5	0.5
Conservation	10.9	30.9	17.2
None[a]	37.0*	5.6*	21.7*
Other	2.2	3.5	2.0
Pollution/ degradation	23.0	9.0	15.7
Restoration	1.7	1.2	2.0
Subsistence/ rec. resource use	3.2	7.9	8.6
Tourism	1.7	9.7	7.1

[a]Indicates no stated problem orientation. Disciplinary composition is shown in Figure 1.

ecosystems account for only 6% or less of the total research, including sea grasses, open seas, rocky reefs, soft bottoms, intertidal, and all other coastal zones. Research not explicitly linked to a specific ecosystem is classified as nonspecific.

Figure 4 shows a time-series analysis of problem focus (Figure 4a), ecosystem focus (Figure 4b) and the general publication trend of included articles from 1979 to 2014, which includes the proportion of articles in the social and natural sciences (Figure 4c). The natural sciences maintain a dominant proportion of the research focus. The proportion of social science research has increased slightly over time (Figure 4c). Coral reefs, conservation, commercial resource use and pollution/ degradation have maintained a dominant focus over time. Literature on climate change has increased since 2010.

Level and scale focus

This section of the analysis examines if empirical research reflects the conceptual understanding that SES are multidimensional. We observe that the research focus at different levels and scales is uneven (Figure 5). The total level focus across all scales is 7% global, 36% regional, and 57% local. In combination, a large proportion of all research (30%) examines a unit of analysis on or related to an ecosystem or spatial scale at the local level. There is significantly less global level focus across nearly all scales. However, the proportion of regional level research is relatively similar across scales. The proportion of research examining explicit social system scales (i.e., institutional;

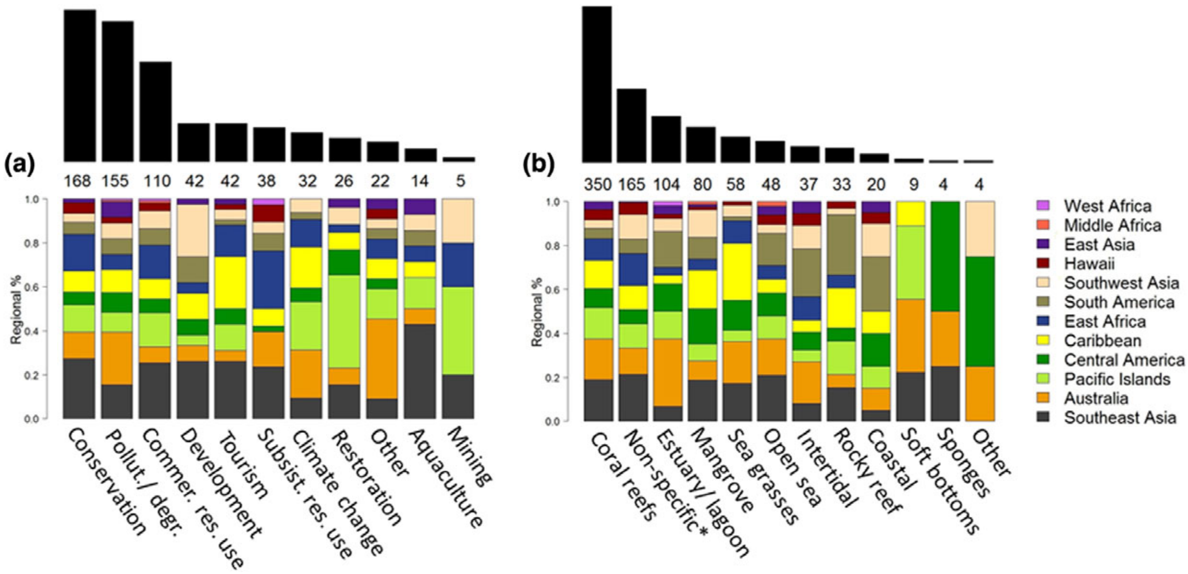

Figure 3 Percentage of problem orientation and ecosystem focus by region. Total number of problem orientation and ecosystem type across all articles. Regional colors correspond to map colors in Figure 2. (a) Conservation, pollution/ degradation, and commercial resource use dominate total-*N* problem orientation across regions. (b) Coral reefs dominate total-*N* ecosystem focus across regions. *Nonspecific ecosystem focus comes from articles that did not directly indicate relevance to a specific ecosystem type. The total-$N = 248$ for articles with no problem orientation.

jurisdictional) are comparatively even across levels, although their total N is disproportionately low. Articles focusing on knowledge, institutional, jurisdictional, or network scales cumulatively account for only 27% of all articles.

System process focus in the social and natural sciences

The number of domain processes we examined in articles include ecological ($n = 20$), social ($n = 13$), and social–ecological ($n = 11$; Table 1; Figure 7). We analyzed process focus within articles and between domains. A focus on two or more processes from different domains could be interpreted as an indicator for multi- or interdisciplinary research. Considering all interdomain processes that occur in combination, the highest total-N link occurs between the ecological and social–ecological domains (Figure 7). Similarly, research within the ecological domain is more frequent than research in the social or social–ecological domains (Figure 6). However, despite lower total-N connectivity, articles focusing on social processes have a higher proportion of connectivity to social–ecological and ecological domain processes (Figure6). We analyze the intradomain connectivity (Figure 8), and indicate the dominant empirical connections between research processes (Supplementary material). More broadly, there is a larger proportion of knowledge being generated on natural systems compared to social systems (Figures 6–8).

Knowledge types and terminology

The statistical distribution of meaningful terminology across articles indicates a wide degree of terms associated with scale (i.e., spatial) heterogeneity in the natural sciences. This is indicated on the Y-axis (Figure 9). In addition, natural science terminology indicates a wider range of disciplinary heterogeneity compared to the social sciences. This is indicated on the X-axis. Distinctly separate article groups based on common terminology are indicated by colored word clusters (Figure 9). There is a higher diversity of terminology in the natural sciences compared to the social sciences. However, the natural sciences associate almost exclusively with system knowledge generation, although with more distinct disciplinary agendas (indicated by grey dots in Figure 9). The social sciences generate a more robust profile of all three knowledge types (as indicated by grey crosses and dark diamonds). However, the social sciences use more homogenous terminology to generate this knowledge. More generally, there are few similarities in the dominant terminology used between the social and natural sciences. This analysis shows the dominant role the social sciences play in conveying system knowledge through target and transformative knowledge.

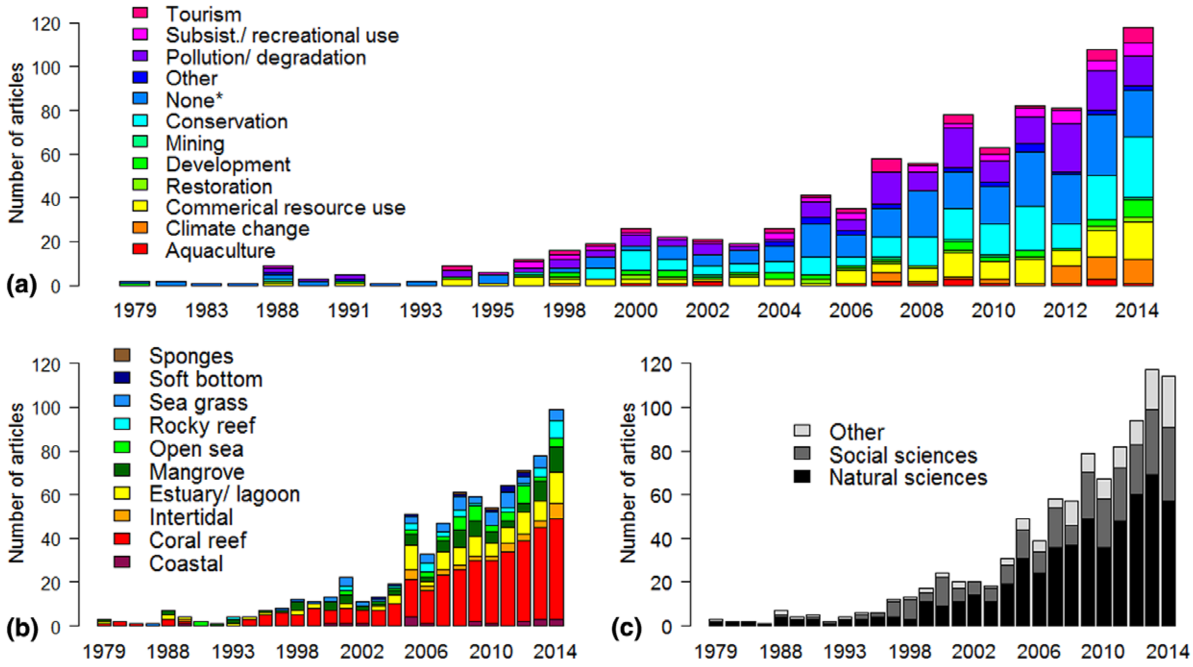

Figure 4 Publication trends over time. The number of publications in each year is divided proportionally by the number of articles in each theme. (a) Time-series of problem orientation. (b) Time-series of ecosystem focus. (c) Time-series of total publications by broad scientific effort.

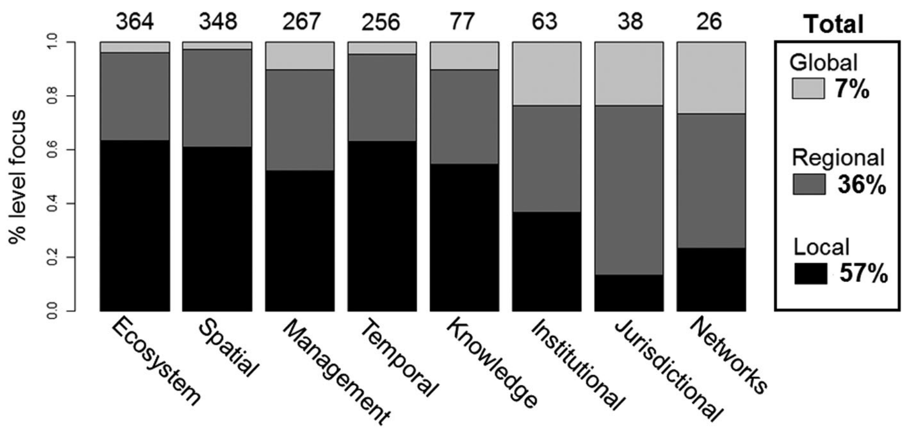

Figure 5 The total number of articles is shown on top of the stacked bar for each scale. The bar for each scale is stacked by the percentage of focus at each level. Total focus at each level is displayed as a percentage on the right.

Discussion

Distribution of research across regions

Our analysis shows that the regional focus of research is unevenly distributed. This can be partly explained by the recognition that each region contains different contexts of interest for different disciplines and research questions. There is a clear emphasis on specific ecosystem types, problems, and system processes related to regions they occur in, which we discuss in the following sections. From an organizational perspective, deciding on a location to conduct empirical research can be potentially biased by travel logistics, language barriers, historical relations, funding parameters, infrastructure availability, and relationships with partner institutions or path dependencies (Luks & Siebenhuner 2007; Pimm 2007; Fisher *et al.* 2010). Although these barriers exist, certain regions remain minimally researched despite substantial social and ecological importance. In particular, we draw attention to Western and Middle Africa. A similar pattern of regional

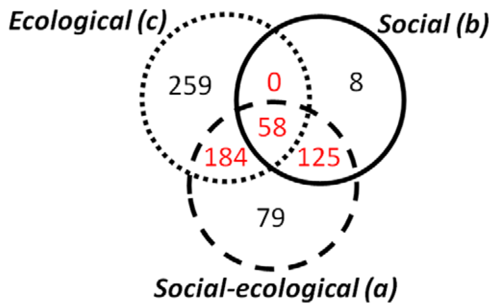

Figure 6 Total-*N* of singular articles broadly classified into domains by the singular or multiple processes focused on. Each article is only classified once, with a total-*N* = 713. The articles with multiple processes outside of a single domain are highlighted in red, and further analyzed in Figure 7. Intradomain connectivity is further analyzed in Figure 8 and matched with (a), (b), (c) labels represented by the different circular patterns of each domain in this figure.

disparity has been observed within coastal ecosystem services research (Liquete *et al.* 2013). In contrast, Australia and Southeast Asia demonstrate a large proportion of all tropical marine research and exhibit wide research agendas. In Australia, this may be explained by funding availability and the number of research-based universities and organizations compared to other tropical regions (Costello & Zumla 2000). In Southeast Asia, we observe a relatively equal balance of research in the social and natural sciences compared to other regions dominated by the natural sciences. This may in part be explained by social science interest in societal connections and dependence on local marine and coastal resource use in the region (Pomeroy 2012; Richards & Friess 2015). For the natural sciences, Southeast Asia contains vast coral reef ecosystems with high measures of biodiversity and conservation priorities (Fisher *et al.* 2010). We discuss the emphasis on coral reefs compared to other ecosystems in the following section.

Ecosystem focus

Research on coral reefs dominates the research focus. Reflection is warranted on whether the biophysical, sociocultural and economic values of coral reefs are proportional to such a dominant focus when compared to the values of, and threats to, other ecosystems demonstrated by existing research (Moberg & Rönnbäck 2003; Orth *et al.* 2006; Knowlton & Jackson 2008; Rocha *et al.* 2014). We do not suggest lessening the focus on coral reefs, but rather examining why other ecosystems have received less focus and how a future agenda would justify and improve a problem-driven ecosystem focus. Disproportionate ecosystem focus may be related to current debates on the relative emphasis of biodiversity in contrast to the societal importance such as livelihood dependence when justifying scientific effort on certain ecosystems such as coral reefs (Cinner 2014). In particular, debate continues on the trade-offs and potential synergies between ecocentric and anthropocentric justifications for research on conservation (Fisher *et al.* 2010; Mace 2014; Wolff 2015). This debate likely originates from differences in problem orientation and how research results are directed to inform potential solutions from different disciplinary or political agendas (Miller *et al.* 2011).

A stronger focus on mangroves, seagrasses, estuaries, wetlands, and lagoons seems necessary as knowledge from these habitats is proportionally lower. Knowledge gaps on ecosystems provide considerable opportunity to better understand how social–ecological relationships evolve and diversify between them. In particular, how unique ecosystem functions and biophysical conditions respond to and shape resource use patterns as well as institutions and human behavior (Pollnac *et al.* 2010; Arkema *et al.* 2015; Richards & Friess 2015). In contrast, the impacts from anthropogenic activities such as pollution and climate change vary substantially between different ecosystems and the regions they are located in (Roff & Mumby 2012; Partelow *et al.* 2015). These distinctions often relate to their resilience, which may affect how societal adaptations such as conservation can be appropriately planned in response to change (Folke *et al.* 2010; Graham *et al.* 2013; Arkema *et al.* 2015).

Problem orientation

A large proportion of all research lacks a stated problem orientation, and there are clear differences between the social and natural sciences. The natural sciences have a much lower proportion of articles with a stated problem orientation. This does not reflect on the relative importance of the social or natural sciences for a sustainability agenda. However, this may in some part reflect the differences in the need to orient scientific knowledge around particular discourses or epistemologies shaped by disciplinary-driven research agendas (Miller *et al.* 2008). Among other reasons, funding requirements and publishing norms likely play a considerable role in shaping how science is communicated and how the knowledge is conveyed in academic literature (Schoolman *et al.* 2012). While the orientation of research to disciplinary agendas is essential, building momentum toward a sustainability agenda would aim to additionally orient results and their implications to relevant problems for humanity (Jerneck *et al.* 2010). Many different disciplines can, and need to contribute to this advancement (Spangenberg 2011). We expand on this proposition below, and attempt to clarify

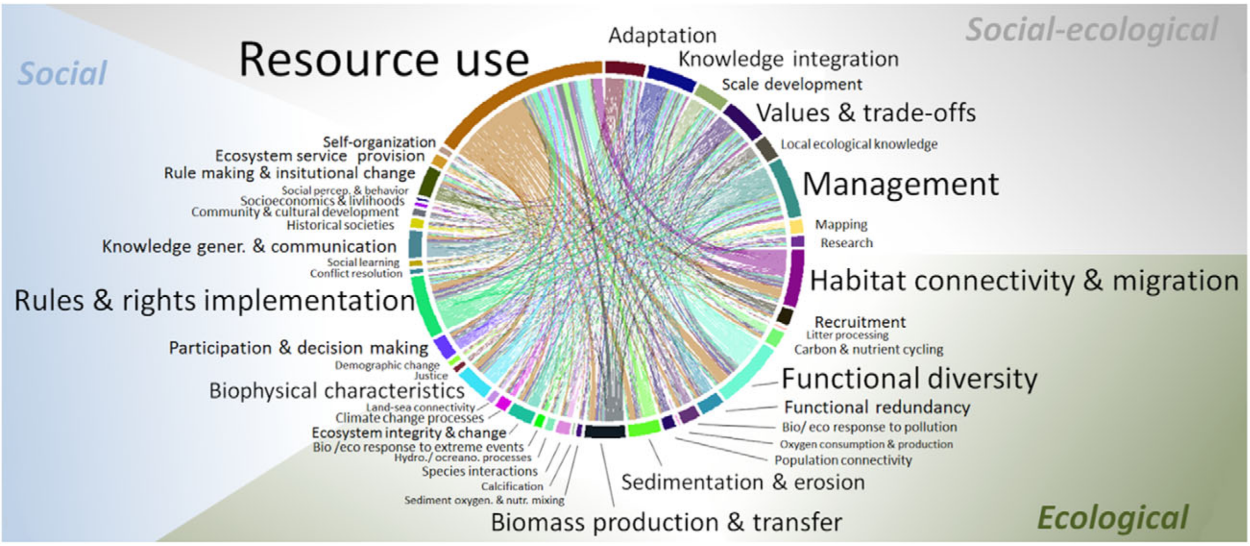

Figure 7 This figure presents a visualization of current multidisciplinary or interdisciplinary research between the domains including social, ecological and social–ecological processes. Only articles that examine at least two different tropical marine system processes in different research domains are included, which are the highlighted red articles in Figure 6. The figure is grounded on the quantitative analysis of two aspects, indicating two broad themes: (1) The proportion of the research focus that each process receives within multi- or interdisciplinary research is shown. This is visualized by the font size and the size of the colored segment of the circle. (2) Process connectivity is shown. A connection between processes in this graph means that both processes were examined in the same article. This visualization can be interpreted as a representation of how current research is examining interconnected social–ecological systems. The actual values of connectivity between specific processes are attached as a data matrix in the Supplementary Material.

how this could be done considering the diversity of disciplinary contributions. We follow by discussing how gaps and trends in the current literature reflect the perspectives on and efforts to address current challenges.

We propose that the primary purpose of a sustainability agenda be driven by understanding problems within their relevant context across all scientific domains. Statements of problem orientation should be transparently communicated within scholarly publications with clear linkages to how the research relates to or informs system, target, or transformative knowledge (Brandt *et al.* 2013; Partelow & Winkler 2016). Considering this proposition, it should be stated that not all research needs to be, or should be situated within a discourse of how results can be practically applied or what the transformative contributions may be. In addition, not all research warrants an interdisciplinary research design. However, it is envisioned that a sustainability agenda should structure otherwise unconnected or isolated knowledge to a common purpose, through linking the type of knowledge generated to a problem orientation.

Beyond the recognition that certain problems simply exist in certain regions, further examination is needed into the variation of drivers, impacts and responses related to them as they occur across diverse contexts (Schlüter *et al.* 2013). Stating a problem orientation may assist in linking all research to a common purpose and context, and attempt to make science more effective in practice by identifying such context specific variations. Conservation is the dominant problem orientation in current agendas; it provides an example for further critical discussion below.

Conservation is a dominant focus within current agendas. However, this does not indicate congruence between how different disciplinary agendas inform conservation practice. In particular, there remain contrasting perspectives on how to reconcile the support of livelihoods depending on marine and coastal resources with the need to maintain ecosystem functioning and diversity (Miller *et al.* 2011; Fox *et al.* 2012; Wolff 2015). From a sustainability perspective, the central purpose of conservation would be to benefit the continued well-being of humanity. The underlying question then becomes, who benefits from conservation (Mace 2014)? Then secondly, what are the different positions that current scientific agendas support (Chan *et al.* 2007)? It can be generally assumed that conservation practice should meet and be implemented in accordance with normative societal goals (Miller *et al.* 2011; Mace 2014). Discourses on inter- and intragenerational equity as well as distributional and procedural justice provide useful conceptual frameworks to orient such discussions (Gibson 2006; Loos *et al.* 2014). However, societal perspectives on how to implement conservation may differ substantially across contexts. They may

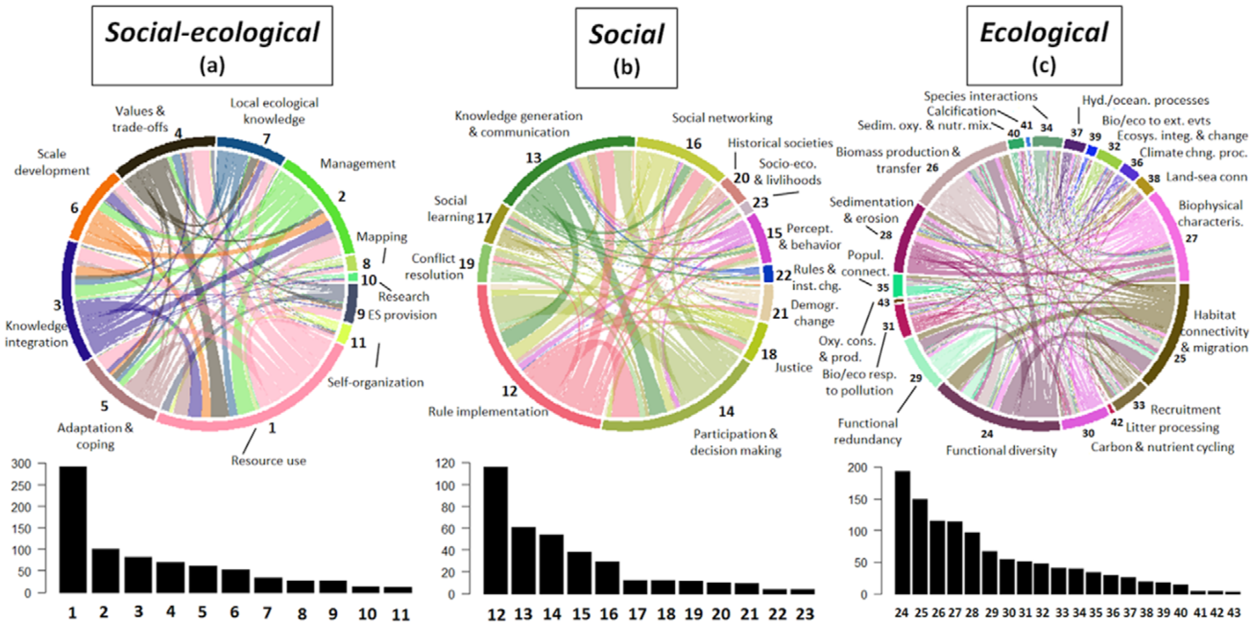

Figure 8 Intradomain connectivity of processes researched. Total-*N* of each process regardless of connectivity shown subsequently in the bar charts with number labeled references. Domains include social–ecological, social, and ecological processes. The figure is grounded on the quantitative analysis of two aspects, indicating two broad themes: (1) The proportion of the research focus that each process receives within intra-disciplinary research is shown. This is indicated by the size or proportion the process has in the circle segment. (2) Process connectivity is shown. A connection between processes in this graph means that both processes were examined in the same article.

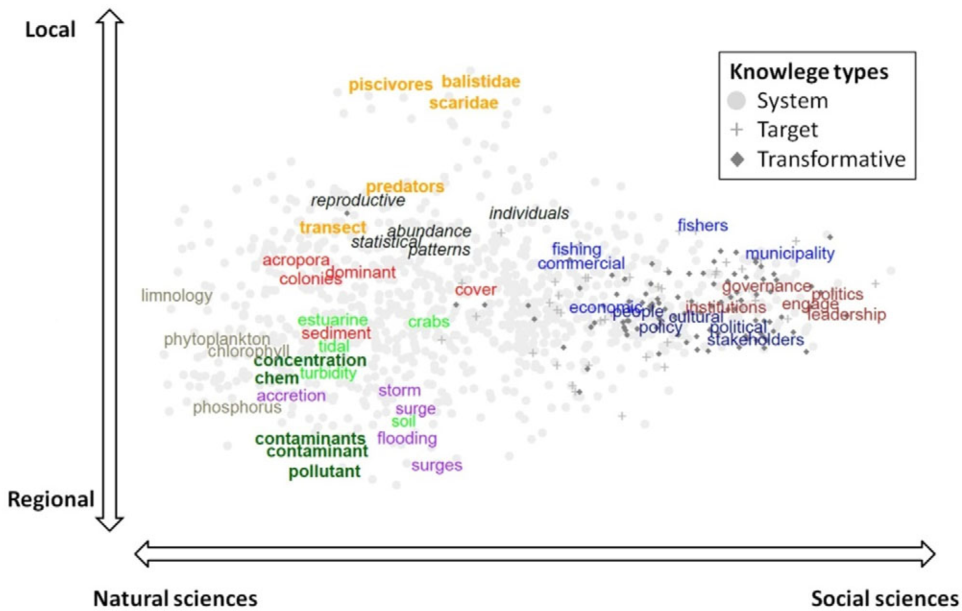

Figure 9 Statistically, clustered distribution of terminology and knowledge types in articles. Only words with the highest frequency in each cluster are shown. Colored clusters are distinguished statistically by the recurrence of common words in their articles, and interpreted as thematic groups of research articles. The distance between word clusters indicates the similarity (close together) or dissimilarity (far away) of the common terminology used in articles. The X-axis is interpreted as a gradient from the natural to the social sciences. The Y-axis is interpreted as a gradient from the local (individual) to regional (societal) level. The knowledge types generated within all articles are plotted against the clustered article groups with shaded symbols (circle = system knowledge; cross = target knowledge; diamond = transformative knowledge). The relationship between research clusters and the knowledge types they generate can be examined. Articles were corrected for length in the word usage analysis. Knowledge types were assessed by indicator words (Abson *et al.* 2014).

conflict with scientific knowledge on what influences effective conservation more generally (Pollnac *et al.* 2010; Edgar *et al.* 2014; Partelow *et al.* 2015).

Level and scales

Within each scale, research occurs at multiple levels. However, the proportion of research at each level is not equal between scales. Ecosystem and spatial scale research at the regional and global level is disproportionately low (Glaser & Glaeser 2014; Cavender-bares *et al.* 2015). This likely infers that research on the connectivity between regional and global ecosystem and spatial scales is also lacking. A ~7.5% focus on global-level processes indicates significantly less scientific effort on sustainability challenges that originate at and across multiple levels. Further research is needed to examine SES are interdependent across multiple levels and scales, and the existence of teleconnections (Scholes *et al.* 2013). In particular, further focus on institutions and governance should consider how social system scales influence or respond to change across levels (Ostrom 2005; Epstein *et al.* 2015). However, we recognize that regional and global level research often requires more capacity to conduct, including logistically intensive collaborative endeavors. We discuss the justification for level and scale focus in the Supplementary Material, and now discuss how the system process focus provides a more detailed look into gaps and trends in the research focus.

System process focus in the social and natural sciences

Our analysis shows clear distinctions in the heterogeneity of research between disciplines in the literature. The natural sciences focus on a wider variety of system processes, including how those processes are researched in combination. For comparison, the social sciences are more homogeneous in the system processes they examine. Three aspects can be discussed. First, the most evident commonality in the context of social science research is human beings, which all social sciences address some aspect of. Nearly all social settings are characterized by the same features such as culture, mental models, networks, economies, institutions, rules and decision-making processes, among many others (Ostrom 2005; Castree *et al.* 2014; Stojanovic *et al.* 2016). Second, the natural sciences analyze a wide range of different organisms, which suggests that they are characterized by a larger diversity of features. However, this does not reflect on the immense diversity in which these common features likely exist in diverse contexts and contain nested dynamic processes.

Third, the understanding of social system diversity may be less advanced than for natural systems due to less scientific effort given to them over time. As a result, social conceptual frameworks may be less developed (Binder *et al.* 2013; McGinnis & Ostrom 2014; Stojanovic *et al.* 2016). There is simply a larger amount of published literature and scientific effort from the natural sciences. Although the social sciences have slightly increased their relative contributions over time, funding availability and publishing norms seem to have favored natural science outputs in this analysis. This does not infer advancing the social sciences over the natural sciences or aim to exacerbate a competitive atmosphere. We suggest a more general shift to rethink how research programs can become more inclusive and collaborative in order to develop problem-driven research agendas that can generate the relevant knowledge needed to advance sustainability.

Knowledge types and terminology

Our analysis shows clear epistemological differences in the knowledge generation agendas in tropical marine science, reflecting what can and should be known to advance sustainability. The field has contributed most substantially to system knowledge, the objective descriptions and analysis of components and processes. Target knowledge, the understanding of more subjective preferences, values and opinions among relevant stakeholders, is less studied. A comprehensive sustainability agenda should aggregate and link together the full spectrum of knowledge around relevant problems within and between disciplines, including transformative knowledge on how to better apply scientific knowledge in decision-making, education, and policy. We reflect on a few key points. System knowledge in the natural sciences needs to improve problem orientation. Target knowledge in the social sciences needs consideration for more diverse and nonwestern perspectives on tropical coasts (Drew 2005; Hornidge 2012; Poe *et al.* 2014). Transformative knowledge is lacking and is needed to inform social–ecological change at multiple levels and scales (Richmond *et al.* 2007; Knight *et al.* 2008). In combination, the social and natural sciences need unified and urgent efforts to integrate their contributions as they currently exist across the knowledge spectrum, particularly in conservation (Chan *et al.* 2007; Gruby *et al.* 2015).

Mechanisms to bridge communication and establish collaboration will play an integral role in structuring future agendas. Progression toward common languages through conceptual frameworks will assist data comparability and communication as well as the identification of gaps (McGinnis & Ostrom 2014; Partelow 2016). However, although many conceptual frameworks exist, orientating and integrating the knowledge between them is a barrier (Binder *et al.* 2013; Partelow & Winkler 2016). Furthermore, the development of operational procedures to make conceptual frameworks useful for natural resource management or conservation practice is lacking (Leslie *et al.* 2015; Partelow 2015).

Conclusion

This analysis attempts to provide a guidepost for advancing a sustainability agenda for tropical marine science. A few key points can be mentioned. Research can better address sustainability challenges when clearly linked to a stated problem orientation in both the social and natural sciences. A comprehensive agenda would necessarily propose disciplinary diversity to address problems and knowledge gaps between ecosystems and contexts. Knowledge gaps remain at numerous levels and scales, including the interactions between them, particularly at the regional and global level. There is a distinct divide in how the social and natural sciences conduct and communicate their published research as connected to other research within and outside their own disciplines and agendas. As a result, a strong dissimilarity exists in the generation of knowledge and use of terminology across many disciplines. Common languages and conceptual frameworks can aid these challenges but need to be further developed to advance the synthesis and analysis of knowledge on interconnected SES. Moving forward, progressing a sustainability agenda will involve further discussion and critical debate between all academic and nonacademic stakeholders involved on how to integrate diverse types of knowledge to better inform societal problem solving in the appropriate contexts.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Supplementary material

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