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How the DPSIR framework can be used for structuring problems and facilitating empirical research in coastal systems

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ABSTRACT

As pressures on coastal zones mount, there is a growing need for frameworks that can be used to conceptualize complex sustainability challenges and help organize research that increases understand about interacting ecological and societal processes, predicts change, and supports the management, persistence, and resilience of coastal systems. The Driver–Pressure–State–Impact–Response (DPSIR) framework is one such approach that has been adopted in some coastal zones around the world. Although the application of the DPSIR framework has considerable potential to bridge the gap between scientific disciplines and link science to coastal policy and management, current applications of DPSIR in coastal environments have been limited and new innovations in the application of the DPSIR model are needed. We conducted a structured review of literature on the DPSIR framework as applied to the function, process and components of complex coastal systems. Our specific focus was on how the DPSIR framework has been used as a tool to organize sophisticated empirical scientific research, support transdisciplinary knowledge at a level appropriate for building understanding about coastal systems, and how adopting a DPSIR approach can help stakeholders to articulate and structure challenges in coastal systems and use the framework to support policy and management outcomes. The review revealed that DPSIR models of coastal systems have been largely used to support and develop conceptual understanding of coastal social–ecological systems and to identify drivers and pressures in the coastal realm. A limited number of studies have used DPSIR as a starting point for semi-quantitative or quantitative analyses, although our review highlights the continued need for, and potential of, transformative quantitative analyses and transdisciplinary applications of the DPSIR framework. The DPSIR models we reviewed were predominantly single sector, encompassing ecological or biophysical factors or focusing primarily on socio-cultural dimensions rather than full integration of both types of information. Only in eight of 24 shortlisted articles did researchers actively engage decision-makers or citizens in their research: given the potential opportunity for using DPSIR as a tool to successfully engage policy-makers and stakeholders, it appears that the DPSIR framework has been under-utilized in this regard.

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1. Introduction

Coastal ecosystems play essential roles in supporting human populations and biodiversity. As of 2005, 40% of the world's population lived within 100 km of the coast (Agardy and Alder, 2005), in areas that support some of the most productive and biodiverse natural communities on the planet. Human populations and development in coastal areas are projected to increase throughout the twenty-first century (Weinstein et al., 2007). Mounting pressures on coastal ecosystems, largely arising from anthropogenic drivers of environmental change (Harley et al., 2006; Syvitski et al., 2009; Mee, 2012; Cazenave and Cozannet, 2014), have prompted considerable scrutiny of the roles that conjoined ecological, social, and governance factors play in coastal management (Adger et al., 2005; Martínez et al., 2007; Duarte et al., 2008; Barbier, 2014; Nursey-Bray et al., 2014). Those pressures have intensified the need to understand how integrated upland-coastal management can ameliorate multiple stressors from both upland and marine environments and how global environmental change will affect ecological and human well-being in diverse coastal zones and across scales (Swaney et al., 2011; Rudd and Lawton, 2013; Rudd, 2014).

Coastal zone management, like a number of other large and emerging societal issues, is often described as a messy or 'wicked' (Balint et al., 2011) environmental problem. The challenges in coastal zones include defining and understanding interacting ecological and societal processes, predicting change, and managing the system toward enhanced persistence and resilience. Addressing these challenges requires a process of problem structuring, to transform unstructured problems into ones that can be effectively addressed with sound evidence about ecological and social system structure and function. This 'containment' process (Hisschemöller and Hoppe, 1995; Shaxson, 2009; Hughes, 2013) also requires information about how decision-makers, scientists, and citizens perceive and define the issues (Rudd, 2011, 2015; Wise et al., 2014). Problem structuring necessarily involves simplification of structure and function in complex coastal socio-ecological systems in exchange for increased policy salience. Predictive knowledge about environmental and human behavior must be balanced through sustained engagement between scientists, policy-makers and citizens in order to define and delineate problems, and facilitate coastal problem solving.

One approach to increase knowledge regarding complex systems has been to adopt a socio-ecological (SES) or coupled human and natural systems (CHANS) approach that aligns dynamic change, adaptation, and transformation with persistence across multiple scales and multiple dimensions (Folke et al., 2010). Coastal systems, in which reciprocal feedbacks from human and natural drivers flow across the land-sea interface, have been recognized as quintessentially coupled systems, exhibiting complex and uncertain dynamics and non-linear relationships (López-Angarita et al., 2014). Despite recent research that has identified linked feedbacks across the many different dimensions of complex coastal systems, understanding of the coupled and reciprocal drivers of coastal systems and their functioning is nascent. A central tenet of the coupled or complex systems approach is that the delineation between social and ecological systems is artificial and arbitrary, and that to study or analyze these systems requires integrated approaches. SES and CHANS approaches are related, with adopters of the different approaches often having different scientific conceptualizations of a study system. A CHANS perspective is often adopted by ecologists who believe that humans are components within an ecosystem, whereas social scientists who posit that human–environmental interactions are subsumed within a larger social system order may adopt an SES construct (Westley et al., 2002). However, this differentiation is not universally accepted (Rozzi et al., 2015). The SES approach has been linked with institutional analysis (e.g., Ostrom, 2007, 2009), governance transformations (e.g., Ayers and Kittinger, 2014) and supporting decision-making in applied coastal management and policy (e.g., Schlüter et al., 2013; Forrester et al., 2014; López-Angarita et al., 2014). While much SES research has, to date, focused on conceptual development and organizing indicator systems, efforts to develop models with real-world empirical research links are also underway (e.g., Cook et al., 2014; Vogt et al., 2015). Recognizing and acknowledging the different orientations of CHANS and SES research, we adopt a single term, SES, to represent a complex, coupled systems approach throughout the paper. However, we do so neither in opposition to the CHANS construct nor to support unnecessarily nuanced terminology distinctions (*sensu* Healy, 2015), but rather for consistent terminology and clarity.

There is a pressing need to better understand how humans benefit from as well as impact coastal environments, how coastal decision-makers perceive coast-related challenges and choose courses of action (e.g., in urban development, shipping, energy development, migration policy), and to design communication strategies for often complex and context-dependent SES science. Repeated calls for transdisciplinary approaches in the study of SESs (e.g., Walker et al., 2002; Weaver et al., 2014) have not yet, however, stimulated the level of support and enthusiasm needed for broad engagement and participation in transformative coastal science (e.g., Campbell, 2005; Lebel, 2012; Glavovic, 2013). That is, research that crosses academic disciplines and also engages scientists, policy-makers, and societal actors in the knowledge creation process are the exception, rather than the rule, in current coastal research efforts globally.

One approach that holds promise to help structure complex environmental problems and unify and connect conceptual exploration across social and natural sciences is the Driver–Pressure–State–Impact–Response (DPSIR) framework (Ness et al., 2009; Bell, 2012; Gregory et al., 2013). Originally developed in the 1970s as a stress-response model, it evolved over time and the Organization for Economic and Cooperation Development (OECD) adapted it as the Pressures–State–Response (PSR) model (OECD, 1994). DPSIR, as it is known today, resulted from the European Environment Agency (EEA, 1995) adding two new components, Driving Forces and Impact, to help policy makers identify cause–effect relationships between human and natural systems, and assist in assessing progress toward sustainable development (Smeets and Weterings, 1999; de Stefano, 2010). The UNEP adopted a version of the framework to help organize their series of Global Environment Outlook reports (Ajero et al., 2012). Because of its ability to integrate knowledge across different disciplines and help formalize different decision alternatives, the application of the DPSIR framework has considerable potential for bridging the gap between scientific disciplines as well as linking science to policy and management (Svarstad et al., 2008; Tscherning et al., 2012). Specifically, DPSIR may offer an approach to articulate problem structure and serve as a template to help organize sophisticated SES research and help identify viable options for managing and protecting coastal systems, and increasing social adaptive capacity and resilience to exogenous drivers.

The aim of this paper is to assess the potential for the DPSIR framework to be used as a tool to simultaneously organize sophisticated scientific research at a level appropriate for building understanding about coastal SESs and, simultaneously, to help stakeholders and policy-makers to articulate and manage coastal sustainability challenges. Other recent DPSIR reviews have examined the role of the framework in supporting environmental decision-making in a mix of terrestrial and aquatic contexts

(Tscherning et al., 2012) and reviewed the application and evolution of DPSIRs in coastal SESs (Gari et al., 2014). In this review, we expand the discussion to explore (1) how to use the DPSIR framework as a tool to simultaneously organize sophisticated empirical scientific research and transdisciplinary knowledge at a level appropriate for building understanding about coastal SESs; and (2) how adopting a DPSIR approach can help stakeholders to articulate and structure challenges in coastal systems and use the framework to support policy and management outcomes. In doing so, we search for the processes or components of DPSIR, or methods used in conjunction with DPSIR that can advance coastal SES science and support protection of coastal systems and communities.

2. Methods

We conducted a structured review of literature on the DPSIR framework as it has been applied to study the function, processes, and components of complex coastal systems and ocean and coastal management. The articles represent both natural and social science perspectives, and were taken from a broad array of journals representing these different disciplines. Our focus was on the potential for the employment of rigorous coastal science within the DPSIR framework. As such, our focus was on the international journal literature. Ours was not a full systematic review per se, as the scope of the exploratory analysis did not include assessing the directional effects of specific inputs or interventions on scientific or social outcomes (for a broader systematic review of ecosystem service indicators and their function within coastal zones, see Liquete et al., 2013).

2.1. Search strategy

We used the following terms for our search: ''Driver–Pressure–State–Impact–Response'' OR ''DPSIR'' OR ''Pressure–State–Response'' OR ''Driver–State–Response''. We conducted primary searches using Web of Science (all databases), Scopus, OvidSP, and ScienceDirect. After combining titles from those primary databases, we supplemented the results from searches using the economic literature database IDEAS and Google Scholar. The Google Scholar search was conducted using Publish or Perish (Harzing, 2010), from which we sorted the top 1000 hits by year of publication. The search was not date restricted. Journal articles, books, book chapters, and Ph.D. dissertations were accepted but we screened out non-reviewed reports and manuscripts. Our initial search included ecologically, economic- and social science-oriented studies; our aim was to identify all DPSIR related academic literature and narrow from there in order to ensure full coverage of all potentially relevant coastal studies.

We restricted our source documents to those that were published in English. While this may have limited the scope of our search results somewhat, English is the primary language for scientific publication, often even in regional journals. In our preliminary investigations, we saw numerous English language abstracts from Chinese journals but the full articles were in Mandarin, so inclusion was beyond our capacity to translate. Even among Chinese authors, the number of English language publications on DPSIR (and environmental management in general) are rising quickly, so at least some of the literature was captured in English language search. While it is possible that relevant DPSIR findings have been published in the grey literature, in many cases there are at least one or two academic articles that draw extensively on the same cases as do technical reports.

2.2. Document screening

In our initial search ($n = 1483$ documents potentially related to DPSIR in all fields), we found 1315 that had possible relevance to the area of SES research (i.e., not transport, agriculture production, food processing, energy, air pollution or emissions, business-management, or narrow ecotoxicology studies). Our first keyword-based screening (Fig. 1) reduced that to 810 that were broadly relevant to socio-ecological systems; a second screening narrowed those to 231 titles potentially relevant for coastal and marine research.

A third screening was conducted independently by the two lead authors. Our criteria for exclusion of articles at this point was based on the abstract text. Articles were excluded if DPSIR/PSR relationships were not explicitly mentioned, if papers referred to the DPSIR framework as a point of reference but did not directly utilize the framework in their analyses, or if the abstract indicated that the article was: a general discourse on coastal systems, resilience, and SESs; a general discourse on coastal indicator systems; or a specialized technical assessment (e.g., toxicity, marine biota, fisheries). We retained documents when the abstract indicated that the article: used coastal or marine modeling approaches based on empirically computed data; assessed the resilience of coastal systems with a PSR or DPSIR component; was theoretical in orientation but with DPSIR-related coastal examples; or had an upland watershed DPSIR orientation but with possible links to coastal systems. After independent screening, the two lead authors discussed any differences of opinions regarding the screening results and came to consensus on whether a document should be included in the final stage of full text screening. That led to a final full text screening of 50 candidate documents in order to ensure that they did indeed address coastal issues, used a DPSIR-related framework, were academically rigorous, and included at least one case study. After our final screening, we also conducted a supplemental literature search prior to final coding to identify additional articles that had been published after our main literature search (note that only journal articles in international journals fulfilled all our criteria; book chapters were typically screened due to their general discourse or simple descriptive analyses). The sequential screening process reduced the sample of documents from 1315 possible DPSIR-relevant documents to 24 articles that met all study criteria (Table 1). They were published over the last 10 years and applied the DPSIR framework at various spatial and temporal scales from around the globe (note that Gari et al., 2014, provide brief overviews for several of those documents).

2.3. Document coding

Each document retained after the screening process was examined in detail and key a priori and emergent themes regarding the DPSIR's use in empirical coastal research were identified and coded using NVivo 10 (QSR International Pty Ltd, 2012). We coded each document to consider the purpose for which the DPSIR framework was being applied: building science-policy collaborations; developing conceptual understanding; exploring relationships; as a framework for quantitative analysis; identifying drivers and pressures; indicator development (i.e., using DPSIR to organize or justify indicator choice); and providing management information. We also examined the structure of the DPSIR framework adopted (with a particular focus on how different studies conceptualized pressures and impacts) and whether cross-disciplinary or science-policy cooperation was used for problem structuring (information source classifications included data assembly, expert input, focus groups, interviews, models, own expert knowledge, surveys, and workshops; multiple classifications were allowed in the coding).

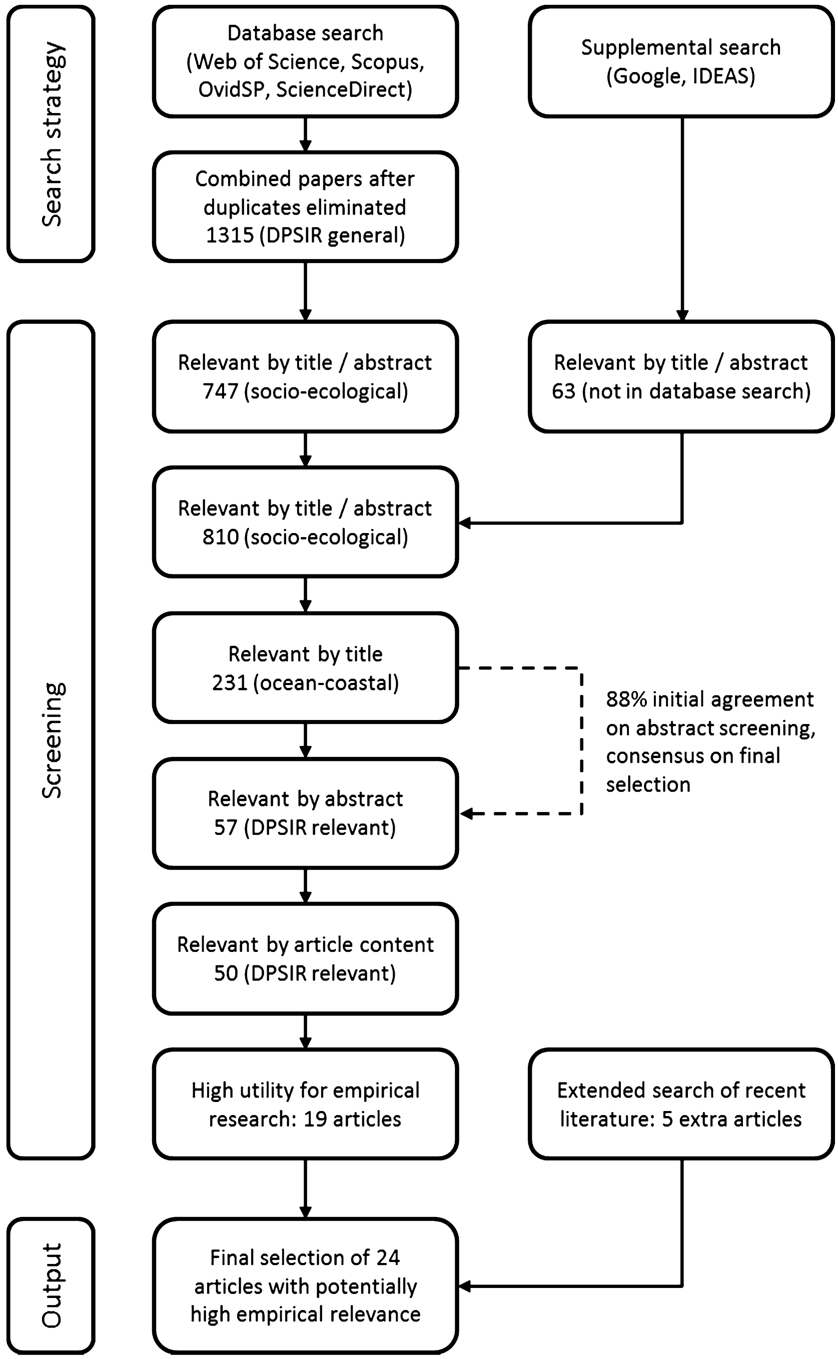

Fig. 1. Document sources and screening of the structured review process.

3. Results and discussion

3.1. Current applications and structure of DPSIR models for coastal research

3.1.1. Geographic distribution

Although the DPSIR framework has been widely used across many systems and contexts, our review revealed that the number of DPSIR journal articles that focused specifically on coastal zones was limited (recall Fig. 1). We found that the use of the DPSIR framework for coastal zones research was international in scope, with a somewhat stronger user base in Europe (see also Gari et al., 2014). Eleven studies were conducted in Europe, six in North America, four in Asia, one in Africa, and two were global in nature. The DPSIR framework has been used to explore dynamics at single locations such as Milne Bay, Papua New Guinea (Butler et al., 2014) and Venice Lagoon (Pastres and Solidoro, 2012). The DPSIR framework has also been used to organize regional research in south Florida (Cook et al., 2014) and the Baltic Sea (Lowe et al., 2014). The somewhat heavier European focus is not surprising given the adoption of the DPSIR framework as an indicators development and communications tool by the OECD.

3.1.2. Temporal scale of studies

Nine articles examined systems using a time frame of >20 yr, four using a time frame of 10–20 yr, and the remaining 11 articles

Table 1
Final list of articles identified in a structured review of literature on the DPSIR framework as applied in coastal management.

	Article
1	Atkins et al., 2011. Management of the marine environment: integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. *Mar. Pollut. Bull.* 62, 215–226.
2	Borja et al., 2006. The European Water Framework Directive and the DPSIR, a methodological approach to assess the risk of failing to achieve good ecological status. *Estuarine Coast. Shelf Sci.* 66, 84–96.
3	Butler et al., 2014. Stakeholder perceptions of ecosystem service declines in Milne Bay, Papua New Guinea: is human population a more critical driver than climate change? *Mar. Policy* 46, 1–13.
4	Cook et al., 2014. Towards marine ecosystem based management in South Florida: investigating the connections among ecosystem pressures, states, and services in a complex coastal system. *Ecol. Indic.* 44, 26–39.
5	Espinoza-Tenorio et al., 2010. Ecosystem-based analysis of a Marine Protected Area where fisheries and protected species coexist. *Environ. Manage.* 45, 739–750.
6	Fletcher et al., 2014. Using the integrated ecosystem assessment framework to build consensus and transfer information to managers. *Ecol. Indic.* 44, 11–25.
7	Gregory et al., 2013. A problem structuring method for ecosystem-based management: the DPSIR modelling process. *Eur. J. Oper. Res.* 227, 558–569.
8	Hossain et al., 2015. Integrating ecosystem services and climate change responses in coastal wetlands development plans for Bangladesh. *Mitigation Adapt. Strategies Global Change* 20, 241–261.
9	Karageorgis et al., 2006. Impact of 100-year human interventions on the deltaic coastal zone of the Inner Thermaikos Gulf (Greece): a DPSIR framework analysis. *Environ. Manage.* 38, 304–315.
10	Karageorgis et al., 2005. An integrated approach to watershed management within the DPSIR framework: Axios River catchment and Thermaikos Gulf. *Reg. Environ. Change* 5, 138–160.
11	Kelble et al., 2013. The EBM-DPSER conceptual model: integrating ecosystem services into the DPSIR framework. *PLoS ONE* 8, e70766.
12	Lowe et al., 2014. Human–environment interaction in the Baltic Sea. *Mar. Policy* 43, 46–54.
13	Mangi et al., 2007. Reef fisheries management in Kenya: preliminary approach using the driver–pressure–state–impacts–response (DPSIR) scheme of indicators. *Ocean Coast. Manage.* 50, 463–480.
14	Newton and Weichselgartner, 2014. Hotspots of coastal vulnerability: a DPSIR analysis to find societal pathways and responses. *Estuarine Coast. Shelf Sci.* 140, 123–133.
15	Nobre, 2009. An ecological and economic assessment methodology for coastal ecosystem management. *Environ. Manage.* 44, 185–204.
16	Nobre et al., 2011. Integrated environmental modeling and assessment of coastal ecosystems: application for aquaculture management. *Coast. Manage.* 39, 536–555.
17	Pastres and Solidoro, 2012. Monitoring and modeling for investigating driver/pressure–state/impact relationships in coastal ecosystems: examples from the Lagoon of Venice. *Estuarine Coast. Shelf Sci.* 96, 22–30.
18	Perry and Masson, 2013. An integrated analysis of the marine social–ecological system of the Strait of Georgia, Canada, over the past four decades, and development of a regime shift index. *Prog. Oceanogr.* 115, 14–27.
19	Pinto et al., 2013. Towards a DPSIR driven integration of ecological value, water uses and ecosystem services for estuarine systems. *Ocean Coast. Manage.* 72, 64–79.
20	Pirrone et al., 2005. The Driver–Pressure–State–Impact–Response (DPSIR) approach for integrated catchment-coastal zone management: preliminary application to the Po catchment–Adriatic Sea coastal zone system. *Reg. Environ. Change* 5, 111–137.
21	Sekovski et al., 2012. Megacities in the coastal zone: using a driver–pressure–state–impact–response framework to address complex environmental problems. *Estuarine Coast. Shelf Sci.* 96, 48–59.
22	Sundblad et al., 2014. Structuring social data for the Marine Strategy Framework Directive. *Mar. Policy* 45, 1–8.
23	Yee et al., 2015. Developing scientific information to support decisions for sustainable coral reef ecosystem services. *Ecol. Econ.* 115, 39–50.
24	Zhang and Xue, 2013. Analysis of marine environmental problems in a rapidly urbanising coastal area using the DPSIR framework: a case study in Xiamen, China. *J. Environ. Plann. Manage.* 56, 720–742.

did not specify time frames, largely due to their primary focus on modeling, conceptual development, or scenario development. This ability to be used across geographic and temporal scales demonstrated the potential utility and applicability of the DPSIR framework to support research on coastal systems and communities for a wide variety of applications.

3.1.3. Information sources and use

A common theme across the selected studies was that the information organized with the DPSIR framework largely came from two sources, either from empirical data from published or available literature (11 studies) or stakeholder workshops which solicited expert knowledge, often in combination with syntheses of existing data (9 studies). Other studies utilized a combination of published information and author's expert knowledge of specific systems or processes (4 studies). Given one advantage of the DPSIR is usually deemed to be its suitability for facilitating engagement of scientists, stakeholders and policy-makers (Tscherning et al., 2012), the lack of it being used to take full advantage of its transdisciplinary potential in coastal research was notable.

3.1.4. DPSIR components–clarifying Pressure, States, and Impacts

While there was generally a degree of consistency among the studies with regards to what comprised a driver in the DPSIR model, there was little consensus on the definitions of pressure and impact. Driving forces were almost exclusively anthropogenic factors such as population growth, demographic change (e.g., coastal urbanization), economic and industrial development, and climate change (although there were alternative perspectives on whether this should be considered an environmental driver given society's limited options to reverse its current trajectory). Coastal hazards and species invasions were also sometimes referred to as environmental drivers (Newton and Weichselgartner, 2014; Pinto et al., 2013). There were different opinions regarding the dividing line between driving forces and pressures arising from those drivers (Gari et al., 2014). There was relatively broad agreement across more recent studies, however, that pressures are changes in environmental parameters resulting from human activities (e.g., increasing levels of contaminants as a result of an increased volume of wastewater discharge as population grew). Those pressures contribute to changes in the state of the environment, such as the abundance and health of fish or eutrophication of coastal waters.

The largest discrepancies in how various DPSIR researchers applied the framework were apparent in definitions of what constituted impacts. Ten studies (including three focusing on ecosystem services) took a largely human-focused perspective on impacts in the DPSIR framework, while six focused on environmental impacts, three used a mix of human and environmental factors, and four did not specify (or only examined the DPS portion of the DPSIR). Much of the European DPSIR research has been focused on human impacts (see Newton et al., 2013; Gari et al., 2014) but some recent USA (Kelble et al., 2013) and European research (Elliott, 2014) have increasingly emphasized that environmental impacts occur via changes in ecosystem services. That is, the ecosystem service-oriented studies emphasized the need for clear differentiation between environmental endpoints and the subsequent benefits that humans gain from final ecosystem services further down the impact pathway.

These different interpretations support the assertion that the conceptual understanding or operationalization of the DPSIR framework is not yet uniform (Gari et al., 2014). Given the relatively recent coalescence of how ecosystem services are conceptualized (i.e., landscape and seascapes → supporting or intermediate ecosystem services → final ecosystem services → benefits to humans → economic valuation of those benefits amenable to valuation; see Fisher et al., 2009; Liquete et al., 2013) and their application in complex and information-sparse coastal environments (O'Higgins and Gilbert, 2014; Raheem et al., 2012; Wilson et al., 2005), the debate regarding the role of coastal ecosystem services within the DPSIR framework is understandable. Kelble et al. (2013) advocated for replacing impacts in the DPSIR with ecosystem services in a modified DPSER-EBM framework, while Nassl and Löffler (inpress) argued for merging DPSIR and ecosystem service frameworks. Our view is that further clarity is still needed regarding how DPSIR components can be better integrated with the ecosystem services paradigm. Even though different research groups may have contested views on the rationale for defining pressures, states, and impacts, efforts to merge DPSIR with the ecosystem services framework in order to broaden its appeal to policy-makers may be beneficial.

3.1.5. DPSIR components—Responses

With regards to responses considered within DPSIR research, the focus of the 24 articles was on: changes in policy, legislation and enforcement; behavioral change; institutional strengthening; investment (both for coastal infrastructure and institutional capacity); new pricing strategies; and conducting further research. Given the focus of most of the articles in our review was on developing conceptual understanding of SES processes and potential indicators of drivers and pressures, the level of sophistication regarding policy and intervention options was modest. This was reflected somewhat by the choice of publication outlets for the articles (Table 1): eight articles were published in ecology-oriented journals and the balance in a variety of geography, environmental management, and coastal/marine policy journals with varying levels of policy emphasis and sophistication.

Our review, like others (Gari et al., 2014; Tscherning et al., 2012), points to some important limitations of the DPSIR framework. From a policy response perspective, these include a lack of explicit hierarchy or scales, typically unidirectional relationships, and the potential for developing biased knowledge (Kelble et al., 2013; Maxim et al., 2009; Svarstad et al., 2008). While much coastal research could be framed within DPSIR, there have been relatively low levels of uptake of DPSIR compared to other frameworks such as the Institutional Analysis and Development (IAD) framework (Ostrom, 2009) and the Sustainable Livelihoods framework (Ashley and Carney, 1999). Rudd (2004), for instance, suggested DPSIR models can be fully subsumed within the IAD framework, which provides a platform for explicitly classifying and organizing rules and social norms in multi-level policy systems. Ostrom and Ostrom (2004) argued that the IAD framework is a universal framework for policy analysis in that it can be used to structure theories, suggest hypotheses, and test empirical evidence. As a result, it is more amenable to technical policy analysis compared to the more general DPSIR model. Despite DPSIR's high level of buy-in in the European policy arena, where its primary role appears to be for organizing indicator systems and communicating broad information regarding potential environmental threats, DPSIR is a crude tool for technical policy analyses. This may help explain both the relatively light attention on the response component among the 24 articles in this review (and beyond in the DPSIR literature more generally) and DPSIR's virtual invisibility in the policy research literature. For example, of the 810 documents identified as being possibly DPSIR-relevant and with a socio-ecological focus, limited numbers appeared in journals typically regarded as having a policy research focus (i.e., 26 in *Environmental Science & Policy*; 2 in *Environmental Policy and Governance*; and no articles from either *Research Policy* or *Research Evaluation*).

3.1.6. DPSIR as a basis for scientific modeling

To date, DPSIR models of coastal systems have been largely used to support and develop conceptual understanding of coastal SESs and to identify drivers and pressures in the coastal realm (15 articles in this review, but with some overlap in study goals). We found a smaller number of studies have used DPSIR as a starting point for semi-quantitative or quantitative analyses (7 out of 24). Those studies adopted a range of methodological and modeling approaches, including: expert-derived impact scores in a matrix-based approach (Cook et al., 2014); scaled vulnerability indices (Hossain et al., 2015); impact and indicator indices (Nobre et al., 2011); Bayesian Belief Networks (BBNs) (Lowe et al., 2014); steady-state biogeochemical models combined with empirical monitoring data (Pastres and Solidoro, 2012); and multivariate statistical approaches (Perry and Masson, 2013).

The limited uptake of DPSIR from quantitative scientists may stem from the DPSIR framework itself. The typically linear, deterministic and unidirectional causal relations may not capture the complexity of bidirectional, non-linear and synergistic pathways of both natural systems and human communities (Gobin et al., 2004; Smeets and Weterings, 1999; Spangenberg et al., 2002). The incorporation of numerical representations of relationships between DPSIR components could, however, represent a new approach toward information and data integration. Bayesian belief models, for example, can be used to combine quantitative data and qualitative input (e.g., expert opinion, solicited local ecological knowledge) and define conditional probabilities between links in the activity-output-impact chain. They can also be adapted to capture dynamic feedback loops (Lowe et al., 2014), explicitly addressing the cross-sectoral challenge of how one integrates qualitative and quantitative data sources. This demonstrates how the DPSIR framework can inform the organization of quantitative and innovative mixed-method analyses of coastal SESs. Scientists internationally continue to develop different synergistic approaches to SES research, for example by integrating the DPSIR framework within the context of ecosystem services (e.g., Loomis and Paterson, 2014; Nassl and Löffler, in press; O'Higgins and Gilbert, 2014; Rounsevell et al., 2010). New quantitative and synergistic efforts point to both the ability and the need to build on the strong foundation of conceptual DPSIR research through application.

3.1.7. DPSIR as a basis for problem structuring

With regards to problem structuring, only in eight of our shortlisted 24 articles did researchers actually actively engage decision-makers or citizens in their research, although some articles did draw on academics' own extensive participatory experience to present stakeholder-oriented perspectives in their articles. Given the potential opportunity for using DPSIR as a tool to successfully engage stakeholders, it appears that the DPSIR framework has been under-utilized in this regard.

3.2. Future directions for DPSIR in coastal zones

3.2.1. DPSIR strengths

Although the DPSIR framework has been criticized as being too simplistic or not being able to serve as a basis for organizing causally complex environmental research (Maxim et al., 2009), the framework has been used successfully to structure environmental problems and to serve as a tool for research in coastal zones. Our review revealed strengths of the DPSIR framework, such as the capacity to potentially describe linkages between human activity and environmental issues, encourage transdisciplinary research, or act as a heuristic tool for complex systems analysis.

Recent research using the DPSIR framework demonstrated how the DPSIR can help advance our understanding of SESs. We found that the DPSIR framework was used to cross numerous boundaries: between disciplines by linking natural and social scientists (e.g., Lowe et al., 2014); between the scientific and non-scientific community (e.g., Butler et al., 2014; Espinoza-Tenorio et al., 2010); and between science, management, and policy (e.g., Fletcher et al., 2014). The DPSIR models we reviewed, however, were predominantly single sector, encompassing ecological or biophysical factors or focusing primarily on socio-cultural dimensions rather than full integration of both types of information: this highlights the continued need for, and potential of, integrative work in the future.

3.2.2. DPSIR opportunities

Decision-making happens "within a context of a social system that includes differing levels of capacity, commitment, economics, political mandates and pressures, and cultural and traditional frameworks" (Loomis and Paterson, 2014: 63). By helping to structure the analysis of complex systems, DPSIR can act as a powerful communication tool that can promote discourse regarding the causes and consequences of human activities and policy responses. That discourse can include issues of power balances and the contributions of different kinds of knowledge to sustainable coastal management solutions (Carr et al., 2007; Svarstad et al., 2008), thus opening opportunities for inclusion in DPSIR research of issues such as equity and social justice, which are typically not addressed in empirical studies.

As our review also demonstrated, DPSIR frameworks in coastal systems have been used as a platform or point of departure for empirical analyses. The limited number of quantitative efforts to date, however, likely stems from the continuing challenges of integrating ecological, socio-cultural, and economic data as well as the complexity of coastal systems and communities (a challenge not unique to DPSIR). Given the increasing pace of ecological and social change, there is a clear need for DPSIR frameworks to account for non-stationarity and system dynamics, and it is clear that such complex relationships can be analyzed and quantified within the DPSIR framework. In one such approach, Perry and Masson (2013) demonstrated the ability of a DPSIR-based quantitative analysis to identify phase or regimes shifts.

In addition to the approaches that already have been integrated with the DPSIR framework (e.g., BBNs, indicator or indices-based approaches, multivariate statistics, loop analysis), other types of complex systems approaches can integrate disparate data and uncertainty, especially in participatory and transdisciplinary research. Agent-based models and BBNs are possible approaches for integrated and participatory modeling of SESs (e.g., Haapasaari et al., 2007; Van Berkel and Verburg, 2012; Schmitt and Brugere, 2013; Forrester et al., 2014; Schoon et al., 2014). Other methodologies based on influence-diagrams (e.g., Peyronnin et al., 2013) may also provide an analytical avenue to model the probabilities of various coastal policy scenarios leading to desirable and robust socio-ecological outcomes within a DPSIR framework. One advantage of such approaches based on influence diagrams is that they can be updated as information is gathered about the causal mechanisms or conditional probabilities along the chain: that provides opportunities for participants to debate and discuss what constitutes 'reasonable' modeling assumptions in processes that assess risks of particular policy options (Lempert et al., 2004).

There is also an opportunity to pair DPSIR frameworks with new methods of geographical visualization that can display and link complex and disparate qualitative and quantitative data in space (e.g., Cartwright et al., 2004; MacEachren et al., 2004). Grant et al. (2015) and Lieske et al. (2015), for example, recently used visual methods coupled with scenario planning to facilitate the communication of context-dependent scientific information that was easily understood by the public, yet scientifically rigorous enough to be endorsed by experts and respected by policy-makers. Methods like parallel coordinates plots, which capture high-dimensional geometry, multivariate data, and the development of simulated virtual environments may provide insight into the complexity of coastal phenomena and processes, and into the structures and relationships envisioned within coastal DPSIR frameworks. The continued development and integration of quantitative analyses could continue to contribute to the importance of DPSIR frameworks as part of complex system analyses.

3.2.3. DPSIR needs

Some critical factors have still received fairly limited inclusion in the DPSIR framework in a coastal system context. One factor that will require a more focused integration is economics. To date, this has been addressed to some extent in DPSIR by the incorporation of ecosystem services as state, pressures or impacts (Kelble et al., 2013; Loomis and Paterson, 2014; Nassl and Löffler, in press). Still, major challenges remain in quantifying seascape- and habitat-oriented spatial ecosystem valuation efforts because of major valuation data gaps, and differing geographic and temporal scales for those bearing the costs of coastal conservation and reaping the benefits from coastal ecosystem services (Raheem et al., 2012). A modified framework, DPSWR (Driver–Pressure–State–Welfare–Response), may facilitate further integration of economic factors and analyses (Cooper, 2013), although a more comprehensive integration of a wide range of economic values requires potentially challenging survey research to support future efforts to transfer benefits estimates from one region to another (e.g., Brander et al., 2012; Liu et al., 2011). In addition to final ecosystem services amenable to economic valuation, there are also a variety of other 'cultural ecosystem services' that are not amenable to economic valuation (see Chan et al., 2012; Liquete et al., 2013) but that need to be considered in future DPSIR-based analyses.

Another key area for development focuses on the R in DPSIR: responses. Although most of the papers reviewed here discussed the desire to use DPSIR to develop relevant management or policy responses, we found that the responses included in DPSIR frameworks were limited and focused largely on traditional governance and legislative approaches. It would be useful for future DPSIR research to consider a wide range of potential responses, ranging from those that alter rules and payoffs thereby shaping behavior, to direct investments in state variables (e.g., ecological restoration), to initiatives that might alter human values and preferences that influence consumption and production choices underlying drivers and pressures in the DPSIR framework. Expanding DPSIR models to account for both operational level actors (e.g. businesses, community groups), who would serve as the focus for efforts to affect change in the systems, as well as higher level policy and regulatory actions (e.g. incentives) may be an important step for the DPSIR framework. An integration of more actor or agent-centered approaches (e.g., Stone-Jovicich, 2015) may also support the development of responses that include and extend beyond the traditional policy realm.

4. Summary

Our review demonstrates the potential utility of the DPSIR approach for analyses and management of complex coastal SESs. The existing literature demonstrated a range of empirically-oriented DPSIR applications. The body of DPSIR research in coastal zones demonstrates comparable applicability and relevance of the DPSIR framework to research with an ecological, social science or economic perspective, suggesting that DPSIR has utility that extends across disciplinary or other research boundaries, e.g. CHANS and SES research.

While the recent studies illustrate the flexibility and malleability of the DPSIR framework, our review also points to an ongoing disconnect in how separate disciplines engage the DPSIR framework. While diverse practices can invigorate research, the limited ability to connect and integrate social and natural science data and knowledge remains a barrier to our understanding of the processes that govern coastal systems and the associated actions and responses needed to manage them. Given the mounting pressures on coastal systems, enhancing capacity to work across disciplines and, more specifically, to merge data from different research paradigms is critical. The DPSIR framework should, for example, be able to integrate across disciplines and across different organizations (i.e. community, government, non-governmental, academic). The relatively limited use of quantitative approaches within DPSIR research arises, in part, from the challenges of merging disparate data types. Innovative quantitative and analytical efforts are needed as pressures to coastal systems mount. Considerable work remains for the DPSIR framework to reach its full potential as a tool to help span multiple boundaries, engage stakeholders, and serve as a foundation for comprehensive investigations of the linked socio-ecological processes that affect coastal zones and the people that live there.

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