Science of the Total Environment 705 (2020) 135838

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Socio-ecological vulnerability to tipping points: A review of empirical approaches and their use for marine management

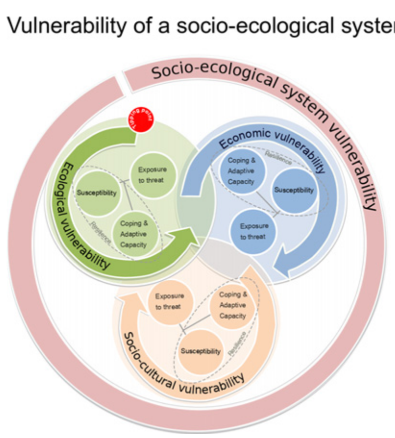
R.A.M. Lauerburg [a,e,*], R. Diekmann [b], B. Blanz [d], K. Gee [c], H. Held [d], A. Kannen [c], C. Möllmann [e], W.N. Probst [a], H. Rambo [a], R. Cormier [c], V. Stelzenmüller [a]

[a] Thünen-Institute of Sea Fisheries, Herwigstraße 31, 27572 Bremerhaven, Germany
[b] Thünen-Institute of Fisheries Ecology, Herwigstraße 31, 27572 Bremerhaven, Germany
[c] Helmholtz-Zentrum Geesthacht, Centre for Materials and Coastal Research, Max-Planck-Straße 1, 21502 Geesthacht, Germany
[d] University of Hamburg, Research Unit Sustainability and Global Change, Grindelberg 5, 20144 Hamburg, Germany
[e] University of Hamburg, Institute for Marine Ecosystem and Fisheries Science, Olbersweg 24, 22767 Hamburg, Germany

HIGHLIGHTS

- Socio-cultural aspects are underrepresented in socio-ecological system (SES) vulnerability assessments
- A common understanding of tipping points (TPs) in SES is crucial as basis for ecosystem based management
- Societal and consequently scientific interest in the influence of TPs on SES has grown exponentially during recent decades
- Heterogeneous terminologies and definitions lead to a complication of practical operationalisation of TPs concepts in SES
- Transdisciplinary research approaches involving stakeholders strengthen the link between SES research and management processes

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 9 October 2019
Received in revised form 27 November 2019
Accepted 27 November 2019
Available online 4 December 2019

Editor: Damia Barcelo

Keywords:
Ecosystem-based management

ABSTRACT

Sustainability in the provision of ecosystem services requires understanding of the vulnerability of social-ecological systems (SES) to tipping points (TPs). Assessing SES vulnerability to abrupt ecosystem state changes remains challenging, however, because frameworks do not operationally link ecological, socio-economic and cultural elements of the SES. We conducted a targeted literature review on empirical assessments of SES and TPs in the marine realm and their use in ecosystem-based management. Our results revealed a plurality of terminologies, definitions and concepts that hampers practical operationalisation of these concepts. Furthermore, we found a striking lack of socio-cultural aspects in SES vulnerability assessments, possibly because of a lack of involvement of stakeholders and interest groups. We propose guiding principles for assessing vulnerability to

* Corresponding author at: University of Hamburg, Institute for Marine Ecosystem and Fisheries Science, Olbersweg 24, 22767 Hamburg, Germany.
E-mail address: Rebecca.lauerburg@uni-hamburg.de (R.A.M. Lauerburg).

https://doi.org/10.1016/j.scitotenv.2019.135838

Socio-ecological systems
Tipping points
Stakeholders
Transdisciplinary research
Vulnerability assessments

TPs that build on participative approaches and prioritise the connectivity between SES components by accounting for component linkages, cascading effects and feedback processes.

Contents

1. Introduction

Abrupt and unexpected ecosystem state changes are increasingly likely to occur under the cumulative anthropogenic pressures and the expected effects of climate change (Conversi et al., 2015; Möllmann et al., 2015). These so-called regime shifts have been documented globally for different marine ecosystems (e.g. Reid et al., 2001; Möllmann and Diekmann, 2012; Beaugrand et al., 2015) and might be associated with thresholds, which are commonly defined as regions in which a small changes in pressures cause disproportionately large, abrupt changes in system properties, whether in single species or populations, entire ecosystems, climate or human society (Scheffer et al., 2001; Beisner et al., 2003; Samhouri et al., 2010). These thresholds are also often referred to as tipping points (TPs) (e.g. McClanahan et al., 2011). Acceleration is caused by positive feedbacks driving the system to a new state (van Nes et al., 2016; see glossary in Box 1).

The term 'tipping point' was originally introduced by social scientists describing a phenomenon in the context of racial segregation (Wolf, 1963). Regime shift research in the early 2000s defined TP as a point in time or an ecosystem state that is marked by a sudden turn to a different state (Box 1).

Since then the term gained further popularity in many disciplines, with a variety of synonyms and definitions being used that, nevertheless lack a unified taxonomy (Milkoreit et al., 2018). Abrupt changes in ecosystem state result in changes of ecosystem functioning and the provision of ecosystem services (van Nes et al., 2016), implying that in the event of an ecological regime shift, economic and societal impacts are also likely. Such cascading effects thus represent a change in the functioning of the socio-ecological system (SES) which depends on the provision of ecosystem services.

Ecosystem-based management (EBM) should acknowledge the complexity of socio-ecological systems and account for the ecological, economic and social effects of management measures (Katsanevakis et al., 2011; Piet et al., 2019). Therefore, management processes should prepare for regime shifts not only from an ecological perspective, but need to be adapted and redefined holistically in the context of associated social and economic interdependencies (Redman et al., 2004; Folke et al., 2004; Ingeman et al., 2019). The influence of ecological TP on SES and the practical implications for ecosystem-based management are yet to be understood (Collins et al., 2011; Link and Browman, 2017; Link et al., 2018; Milkoreit et al., 2018). Thus a key question is how SES respond to endogenous and exogenous drivers of change (Walker et al., 2002; Berrouet et al., 2018). For instance, the risk that ecological collapse is followed by social-economic collapse has been documented for fisheries dependent communities (Serrao-Neumann et al., 2016). Such cascading events underline the importance of understanding the linkages and dynamics of SES to develop risk mitigation strategies for the sustainable use of resources. A prerequisite for the development of such risk mitigation strategies is sound understanding of the vulnerability (Berrouet et al., 2018) of SES to ecological TP. Although the value of vulnerability concepts for decision-making has been recognised, key principles or good practice guidance for their actual use in marine resource management are currently lacking (Foley et al., 2015). Here we provide results of a comprehensive review of marine case studies on the actual use of SES frameworks in combination with TP theory in marine EBM. We review the available literature based on standardised assessment criteria addressing key questions such as (i) how are SES defined and assessed?; (ii) what is 'tipping' in the SES and are there potential cascading effects within the SES?; (iii) is the vulnerability of the SES addressed and if yes, how?; and (iv) have the results been used for decision making? Finally, we synthesise the implications of our results and suggest guiding principles as basis for the operationalisation of SES frameworks and their adoption in management processes.

2. Defining socio-ecological systems and their vulnerability to tipping points

A standardised review process requires an a priori definition of concepts and terminology around TPs in SES. A SES comprises numerous components that are related to the provision of ecosystem services and is composed of three sub-systems (spheres) (Fig. 1). These subsystems are in turn determined by the resources that contribute to the flux of ecosystem services. In fisheries, the resource (target species) of a fishing fleet determines the state and dynamics of the components of the socio-economic subsystems. The *ecological sub-system* refers to the exploited population and its interaction with the environment.

Box 1
Glossary.

Tipping points can be described as thresholds of localised effects, including ecological, socio-cultural or economic system properties. They occur when small changes in pressures induce large, abrupt changes in system properties, whether in single species or populations, entire ecosystems, climate or human society. Acceleration is caused by positive feedback driving the system to a new state (van Nes et al., 2016).

Social-ecological systems (SES) are coupled systems of nature and humans, acknowledging people as part of and not apart from nature (Berkes and Folke, 1998).

SES research aims to integrate both ecological research, focusing on the cross-scale dynamics of ecosystems, and social research, targeting organizations, institutions, and social practices.

Vulnerability: The affinity of a system to changes, determined by both, the exposure to external stresses and shocks and the intrinsic factors that determine the systems' resilience (Birkmann, 2007; Chapin et al., 2010; Resilience Alliance, 2010; Halpern et al., 2012; Cormier et al., 2017; Stelzenmüller et al., 2015).

Resilience: The susceptibility and overall (adaptive and coping) capacity of a system, determined by intrinsic factors to absorb perturbations from disturbances and reorganise by retaining essentially the same function and structure without crossing a tipping point (Bohle, 2001; Carpenter et al., 2001; Folke et al., 2004; Walker and Meyers, 2004; Resilience Alliance, 2010).

Susceptibility: Defines the predisposition and likelihood of a system to suffer harm from a specified disturbance when exposed to it (Birkmann, 2007).

Coping Capacity: The ability of a SES to manage and overcome adverse effects of a given threat or disturbance by using available skills and resources on a short-term basis (Birkmann, 2007; IPCC, 2012).

Adaptive Capacity: The properties of a SES, including available attributes and resources that enable the SES to respond and adapt to disturbances on a medium term basis (Birkmann, 2007; IPCC, 2012).

The *cultural sub-system* represents e.g. the fishing communities and the traditions that have evolved in relation to the fished resource and how they influence the behaviour of fishers. The *economic sub-system* represents e.g. the choices made by fishers and consumers, determining the market prices of the fished commodity depending on production costs such as fishing material or the fuel price for ships involved in harvesting the resource. All three spheres of the SES are connected to each other via linkages that depend on individual system properties. In the fisheries example the ecological sub-system might be connected to the socio-cultural sphere via the installation of marine protected areas in response to societal demands for nature conservation. The economic sphere might be connected to the ecological sphere via the number of people that are employed in the fishing sector, which in turn is controlled by the availability of the fished resource.

The vulnerability of SES to TPs results from an interaction of the vulnerability of three spheres of the economic, the ecological and the socio-cultural sub-system. Vulnerability is a function of the exposure to a specified threat, the susceptibility of the sub-system to a specified TP and the system's overall capacity (including coping and adaptive capacity) to respond to it. In this context the systems' resilience is determined by the internal systems' susceptibility to specified disturbances and its coping and adaptive capacity towards the given pressure (Bohle, 2001; Birkmann, 2007; Resilience Alliance, 2010; Johnson et al., 2016; Berrouet et al., 2018). Thus, the vulnerability of a SES reflects its general affinity to changes caused by the occurrence of TPs and is determined by both external threats and the intrinsic factors that determine the systems' resilience (Resilience Alliance, 2010; Cormier et al., 2017; Stelzenmüller et al., 2015) (Fig. 1, Box 1).

Depending on the assumed linkages between the SES' sub-systems and the potential point of action of a TP, two settings are plausible. The first is that a TP might be present in only one sphere, which is the setting typically described in papers dealing with ecological regime shifts (e.g. Folke et al., 2004). In our fishing example a TP in the ecological sphere might result in the loss of the fishing resource which might lead to knock-on or cascading effects in the other spheres. The loss of a resource might translate into the socio-cultural sub-system by causing the collapse of local fishing communities that were targeting that resource, which then potentially cascades into the economic sphere via

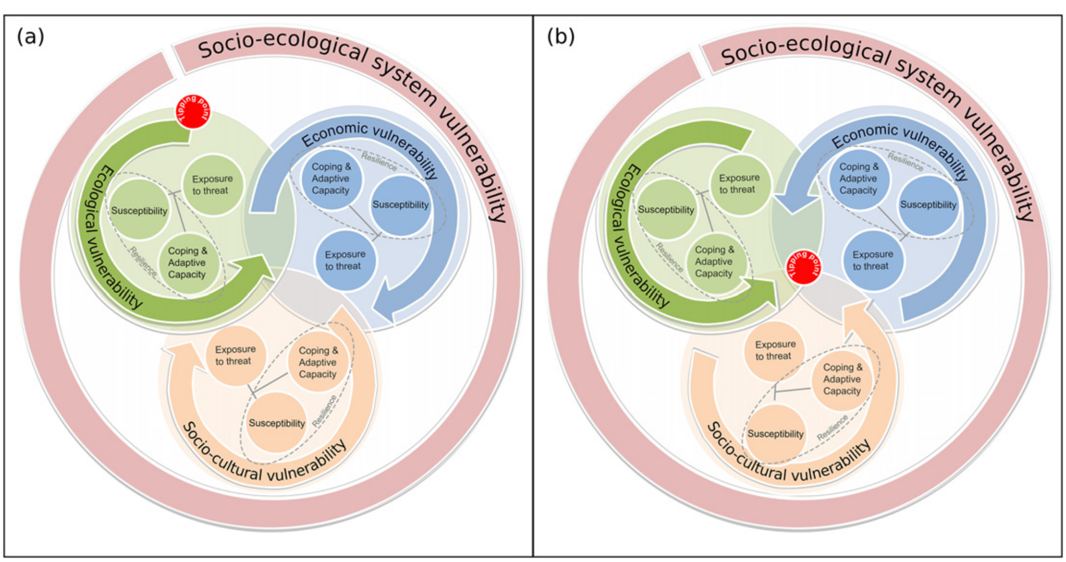


Fig. 1. Conceptual framework of the vulnerability of a socio-ecological system (SES), the assumed connectivity of its sub-systems and the potential point of action of a tipping point (TP). Depending of the internal setting of the SES and the point of action of the TP, different scenarios are conceivable. Scenario I ('chain reaction'; panel a): The sub-systems of the SES are linearly interlinked and connected in series. The TP occurs in one sub-system, e.g. the ecological system, and affects its vulnerability to a specified disturbance. Changes in vulnerability in the directly affected ecological sub-system then reproduce in the adjacent economic sub-system due to interlinked feedback mechanisms, which in turn affects the socio-cultural sub-system. Scenario II ('chaos reaction'; panel b): All three components of the SES are interlinked in a more or less unknown way. The TP simultaneously occurs in multiple sub-systems of the SES and affects the vulnerability of the respective sub-system(s) towards a given threat in an unpredictable way. Please note that potential feedback mechanisms are not shown here.

Table 1
Synonyms used for SES and TP in the peer reviewed literature extracted from the Scopus data base (https://www.scopus.com).

	Socio-ecological system	Tipping point
Synonyms	Social-ecological system	Abrupt change
	Bioeconomic model	Threshold
	Socio-ecological system	Regime shift
	Socioeconomic-ecological system	Regime change
	CHANS	
	Coupled human and natural system	

the collapse of associated port logistics. Thus, the consequences of having reached a TP can result in a cascade of tipping elements across social, economic, legal and political systems (Cooper, 2013; Cormier et al., 2019; Elliott et al., 2017). The second setting is that in theory a TP might co-occur in multiple sub systems simultaneously, which would be the case if e.g. the local fishing community switches to another resource due to for instance an ecological change which led to decreasing availability of the resource with a simultaneous increase in fuel prices which in turn causes that the harvest of the original resource becomes uneconomical.

3. Systematic review

We identified a non-exhaustive list of six synonyms for SES and five for TP (Table 1) that are commonly used in the peer-reviewed literature and by experts from social, economic and ecological sciences. Using the Scopus database (www.scopus.com) we then conducted a systematic search of scientific articles published before the 16th of October 2017 with no limit back in time that made use of the concepts of SES and TP. The database itself contains publication records from 1788 onwards (Scopus Content Coverage Guide, 2017). For this, we applied all possible combinations of the keywords in the title, abstract and keywords of scientific articles in the English language, excluding articles from medical, arts and physics research journals (for search string see Table A1). We followed the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)' approach (Moher et al., 2009) to retrieve an initial set of 211 articles for further evaluation (Fig. A1). Next, we screened the 211 papers in relation to their actual contents and relevance to the research questions based on titles, abstracts and keywords. 173 studies were excluded for being freshwater or terrestrial studies ($N = 161$) or exclusively theoretical ($N = 12$) (Fig. A1). For the final review we selected only empirical marine case studies describing SES and a TP, resulting in 38 case studies for the detailed review (Table A2). Depending on the nature of the study, some publications did not explicitly use words like "coastal" or "marine" in their title, abstract or key-words (e.g. Banos-González et al., 2016; Lade and Niiranen, 2017). Therefore, it was necessary to refine the selection after the initial search which does not include key-words like "coastal" or "marine" in the search string. We assessed the retained studies with the help of 27 standardised assessment criteria (Table A3) derived from both the theoretical concepts of SES and TP and the research questions addressed here. They comprised not only contextual aspects such as case study location or scale, but also a description of the nature and complexity of the SES, assessment of SES vulnerability, relevant data sources, methods used or the nature of tipping points. A key aspect was whether the results of a study gave recommendations or formed the basis for management.

4. Results

4.1. Variability in terminology between marine cases studies

Publication dates of the 38 studies range from 1990 to 2017 with the majority of studies published after 2010. We distinguished between case studies (63%), reviews (21%) and theoretical studies (16%) (Fig. 2). Within these publications the use of the term 'SES' is most prevalent. Other terms include 'bioeconomic model' or 'human-environment system' (Renaud et al., 2010). 74% of the studies provided no further definition of the concept of SES, while definitions varied greatly among the remaining publications. Hansen (2014) defined SES as a 'complex adaptive system in which people rely on ecosystem services and are key drivers of ecosystems', whereas Renaud et al. (2010),

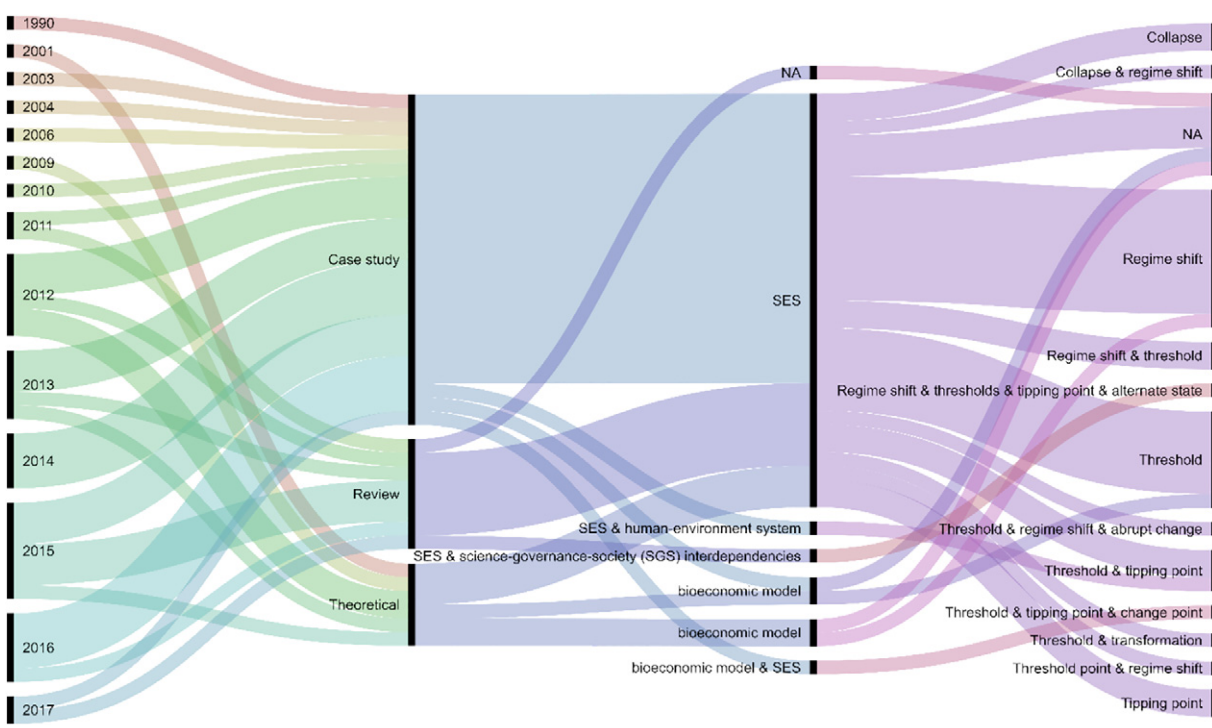


Fig. 2. Alluvial diagram of publication dates, article type and terminology used for socio-ecological system (SES) and tipping point (TP) of 38 articles retained after screening using RAWGraphs Visualisation Platform (Mauri et al., 2017). The height of the back bars (nodes) and coloured lines is proportionally to the flow quantity and shows the number of publications represented.

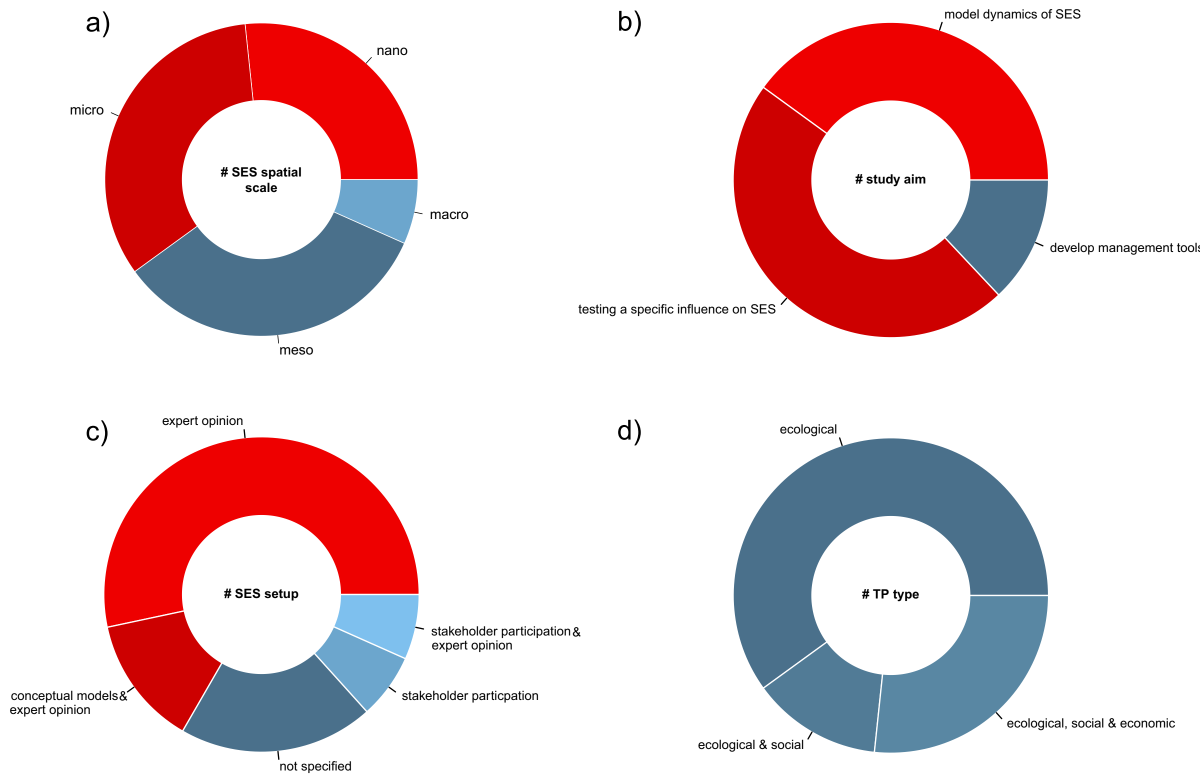


Fig. 3. Percentage share of a) spatial scale to which the study relates, b) objectives the study are aiming for, c) different approaches that define which SES components to include in an empirical assessment and their frequency of application and d) sub-system of the SES in which the described TP occurs in the 15 empirical case studies describing tipping points (TP) in socio-ecological system (SES).

adopting the definition by Gallopín (1991), stated that 'an SES is defined as a system that includes societal (human) and ecological (biophysical) subsystems in mutual interaction'.

Compared to SES, we observed an even greater variation in the terminology used for TPs. Frequently multiple terms are used synonymously in the same article (Fig. 2).

The most frequently used term for TP was 'threshold' (45%), followed by 'regime shift' (42%). The actual word 'tipping point' was only used in 21% of the cases. Additionally, terms such as 'transition' (Joseph et al., 2013) or 'transformation' (Andrachuk and Armitage, 2015) were used as synonyms (Fig. 3b). Similar to terminology, definitions of TPs varied between the studies; TPs were not defined in 39% of

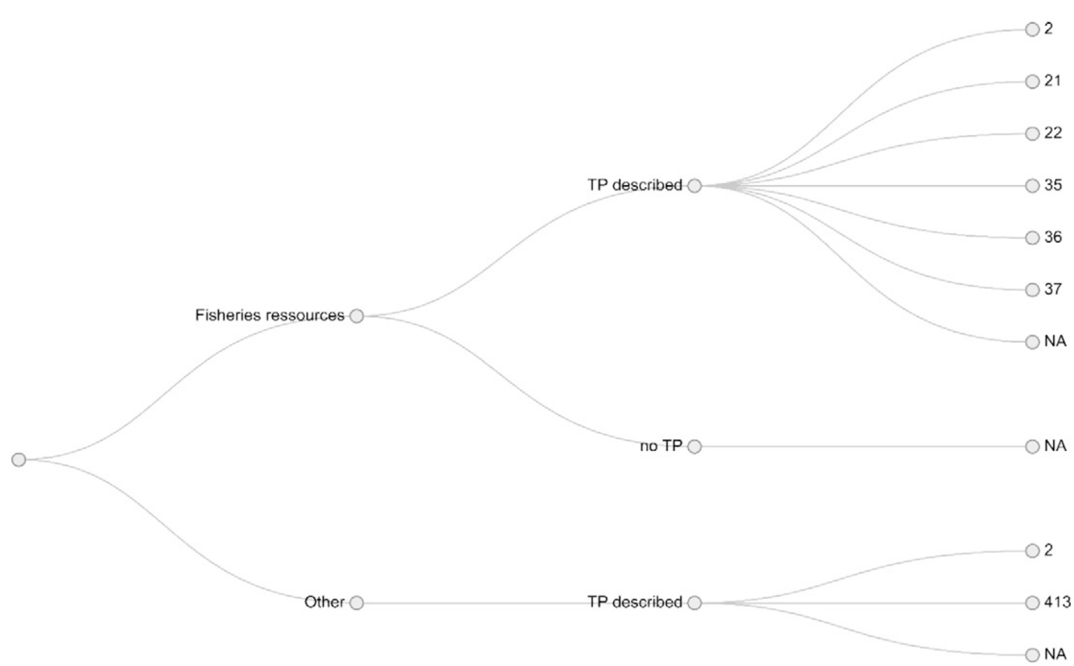


Fig. 4. Cluster dendrogram representing the spread of case studies addressing fisheries resources (80% out of 15 case studies), describing tipping points and the related number of SES components included (RAWGraphs Visualisation Platform; Mauri et al., 2017).

Table 2
Eight different methods used to analyse spatio-temporal aspects of SES and their application in key studies. In total, 8 studies focused on temporal (t) assessments, while 6 studies considered spatio-temporal (st) aspects.

Study	Spatio-temporal aspects considered?	Generalised socio-ecological model	Ecological model (growth, population, etc)	Ecosystem services indicators	DPSIR/conceptual framework	Multivariate statistics	Descriptive	Decision support tool (e.g. VENSIM simulation software)	Stakeholder consultation
Lade and Niiranen (2017)	t	1							
Lade et al. (2015)	t	1							
McClanahan et al. (2011)	t		1						
Burkhard and Gee (2012)	st		1	1					
Dearing et al. (2015)	t			1					
Perry and Masson (2013)	t				1	1			
Broderstad and Eythórsson (2014)	t						1		
Banos-González et al. (2016)	t							1	
Serrao-Neumann et al. (2016)	st				1				
Conrad and Rondeau (2015)	st		1						
Andrachuk and Armitage (2015)	t								1
Eriksson et al. (2015)									1
Renaud et al. (2010)	st						1		
Hansen (2014)	st						1		
Joseph et al. (2013)	st								1
Sum		2	3	2	2	1	3	1	3

the cases. A few studies gave very brief definitions such as 'a fundamental shift in system characteristics that result in a qualitatively different system identity' (Andrachuk and Armitage, 2015) or 'ecosystems rapidly change to a contrasting state' (Nyström et al., 2012), while other cases presented a very detailed description of criteria that must be met to define a TP (e.g. Cumming and Peterson, 2017). We also observed that the definition of TP depends on the sub-system in which it occurred (economic, ecological, social or a combination of those) (Fig. 3d).

4.2. SES complexity and diversity of assessment approaches

One aim of this study was to identify whether TPs and SES are being used to inform management (e.g. management to avoid cascading effects in SES), hence we selected only empirical case studies for further analysis. In total, only 15 of the 38 studies qualify as empirical studies (for details see Supplementary material Fig. A1). In terms of the geographical scale we found that practical SES and TP research is predominately applied on a small geographical scale (e.g. "The German Bight of the North Sea"; Burkhard and Gee, 2012), in most cases describing the state, regulation and use of a single biological resource (Fig. 3a). All but three case studies focused on a single fisheries resource and the connectivity and interdependencies of the corresponding SES (Fig. 4). The temporal aspect is addressed by 14 out of 15 (93%) studies.

The aims of the case studies analysed can be summarised as descriptions of an SES by applying different modelling approaches (40%), testing for the influence of specific agents on the respective SES (47%), and concrete problem phrasing and development of management tools for a practical issue (13%) (Fig. 3b). Examples of the latter are Perry and Masson (2013) who established an index of large scale changes in the Strait of Georgia and Canada, and McClanahan et al. (2011) who developed critical reference points for the sustainable management of coral reefs of the western Indian Ocean.

Scientific approaches to SES set-up (Fig. 3c) and assessment approaches (Table 2) vary widely among the studies. In most cases expert opinions, sometimes in combination with conceptual models, are used to identify SES components for subsequent analyses. Surprisingly, we only found three cases where stakeholders were involved to conceptualise the SES (Fig. 3c). The number of SES components and therefore the level of complexity varied considerably between studies, ranging from two (McClanahan et al., 2011; Renaud et al., 2010) to 413 in a modelling study which simulated all SES status indicators and processes (Banos-González et al., 2016). Although the studies qualified as empirical, in six cases no further specification of the number of SES components was given. Five studies aggregated 20 to 40 SES components for their respective analyses and all but one study were based on empirical data (Fig. 4).

4.3. Cascading effects in marine SES

The majority of the empirical studies reviewed (60%) located the TP solely in the ecological sub-system, four studies (27%) in all three sub-systems. One exception described two simultaneous TPs in the ecological and the social sub system (Burkhard and Gee, 2012). The number of TPs identified ranged from one in 33% of the case studies to seven in one case study (Broderstad and Eythórsson, 2014). The majority studies described one or multiple TPs in the ecological resource of the SES (Fig. 3d). Others put emphasis on physical changes that affect the SES (Dearing et al., 2015), or a TP in the relationship between the amount of ecological resource and other parameters within the SES (Perry and Masson, 2013).

With regard to cascading or knock-on effects, just about half of the studies (47%) identified a translation of the effect of the TP from one sub-system to one or more components. Serrao-Neumann et al. (2016) described three respective case studies of TP in SES. In all three cases TPs were crossed in the ecological as well as the social and economic spheres. In one case anthropogenic impacts in combination with natural pressures induced TP(s) in the SES: a change in the coral species composition and a loss of seagrass was caused by decreasing water quality due to increasing nutrients and turbidity by land run-off in combination with flood events. Most likely substantial development in the region led to increasing anthropogenic pressures (increased nutrient loads and suspended solids leading to deteriorating water quality). The authors described cascading effect to the socio-cultural subsystem which resulted in a decline in tourism, amenity and fishing. The two other case studies described natural pressure induced TPs in the ecological sphere cascading into the socio-cultural and economic sub-systems. Hence, climatic events caused an undesired increase or decrease in a species which altered the ecosystem in an unwanted way leading to a decline or loss in the fished resource. This in turn led to fisheries demise, tourism decline and loss of livelihoods. Perry and Masson (2013) identified a combination of natural (indicated by temperature, wind speed and the North Pacific Gyre Oscillation index) and human (reflected by human population number, fishing effort and fry release number) pressures inducing TP in the SES. Likewise, Dearing et al. (2015) found that human pressures in combination with climate caused TP. Here, authors described an interesting feedback mechanism where the degrees of human modification strongly interact with the resilience of natural ecosystems to climate change.

Regarding cascading or knock-on effects, about the other half of the studies (53%) did not describe an effect of the TPs on other SES components or spheres, although a change in the ecological resource presumably has an impact on the other sub-systems of an SES (Ostrom, 2007). One study described the impact of one external shock on all three spheres of an SES in parallel, but cascading effects of a TP in the ecological system on the social sub-system have been avoided by feedback mechanisms (Renaud et al., 2010). A cascading effect through all three subsystems (ecological, economic and social) was only described by Joseph et al. (2013). In this case study the cascade moved down from ecological change resulting in destruction of resources, leading to economic impacts and affected livelihood which then resulted in occupational change in the related communities. We found that this description of a feedback loop within the socio-cultural sphere of the SES is rarely described across the reviewed studies. Most papers focused on the ecological changes and feedback loops, describing e.g. predator-to-prey loops (Lade and Niiranen, 2017) or feedbacks within the food web (McClanahan et al., 2011) or the economic linkages (Conrad and Rondeau, 2015).

4.4. SES vulnerability and advice for management

A further aspect of our review was to evaluate whether and how vulnerability and resilience of SES were defined and addressed and whether findings have been used to advise management processes (see assessment criteria Table A3). The majority (>70%) of studies neither addressed the topics of vulnerability or resilience nor gave practical advice for EBM. About 20% of the studies acknowledged the resilience of the respective SES or discussed associated implications but did not analyse it quantitatively or qualitatively. Likewise, only 13% of the papers recognised SES vulnerability. Resilience and vulnerability of the SES were qualitatively analysed by 26% and 20% of the studies, respectively.

Only one study conducted a mixture of quantitative and qualitative assessments of ecosystem resilience by combining ecological modelling with a more qualitative approach concerning the socio-economic system components (Burkhard and Gee, 2012) (see also Table 2). A further study described a detailed quantitative vulnerability assessment by applying a sustainability model of the entire SES that allowed analysis of the impact of different climate change scenarios in combination with the effects of certain policy measures (Banos-González et al., 2016).

Although about half of the reviewed studies (53%) addressed management questions for the respective SES, most of the advice was very generic and lacked concrete recommendations for management actions. Broderstad and Eythórsson (2014), for instance, recommended stronger political support for local communities, and Serrao-Neumann et al. (2016) advised greater inter-agency collaboration.

4.5. Guiding principles for the operationalisation of SES frameworks

One main conclusion from our review is that studies need to become more transparent in how they are defining SES and what exactly they are analysing. A more focused approach would strengthen the analytical use of the SES and TP concepts, not least by making studies more easily comparable. The use of decision support tools such as the VENSIM software (Ventana Systems, 2011), classically used for the analysis of management systems, are promising approaches to master the high level of complexity inherent to SES and to come to a better understanding of marine SES.

In order to facilitate the uptake of SES and TP-related concepts in marine resource or spatial management, we propose practical guidelines to aid defining explicit links between SES, TPs and management decisions with special emphasis on who needs to participate in that process (Box 2). Our 3-step procedure includes phrasing (1), localisation (2) and analysis (3). In the first step (phrasing) the issue, which can be e.g. a TP in the ecological system, an undesired economic subsystem state or a societal demand, has to be identified. This issue has to be put into relation of the SES state and the use and regulation of the marine resource. For the second step (localisation) a transparent identification of SES components, components' connectivity and feedback mechanisms needs to be operated in relation to the in step (1) identified issue. In the third step (analysis) a precise and clear specification of the data available, the resources and information that is used to represent the SES is required to perform an analysis of the SES, the component connectivity and the defined issue. Although it has been stated by the Resilience Alliance (2010) that stakeholders should be included in the process of resilience assessments, our findings show that already at the level of defining an SES, stakeholders are more or less not consulted (Fig. 3c). Additionally, it still seems unclear who should participate when it comes to the operationalisation of SES frameworks (Table 2; Fig. 3c). We suggest that in the first (phrasing) and second (localisation) step of our guideline stakeholders knowledge, that only primary users in first line have, should be part of the process. In the present review, we found that with the sub-system considered, definitions and terminology of SES and TP is varying. Likewise, it can be assumed that scientific focus will vary with the background of the researcher. Thus, we propose an interdisciplinary research approach that requires in all three steps the involvement of scientists from the fields of ecology, economy and social sciences. Otherwise aspects from single fields might be underrepresented or overseen.

5. Discussion

Our results show that empirical application of the concept of socio ecological systems (SES) and their vulnerability to tipping points (TPs) in the marine realm is still in its infancy. There is a striking lack of harmonised terminology and stakeholder engagement, and a high diversity in assessment approaches. Many studies focus on small geographical scales, mostly addressing consequences of changes in fisheries resources. All empirical studies addressing TPs in SES show a distinct lack of transparency with regard to the data resources used and assumptions made. Furthermore, the majority of the reviewed studies on marine SES are only conceptual in nature, describing frameworks of SES, assuming how an SES or a selected group of components might behave or considering how an SES could be quantitatively modelled.

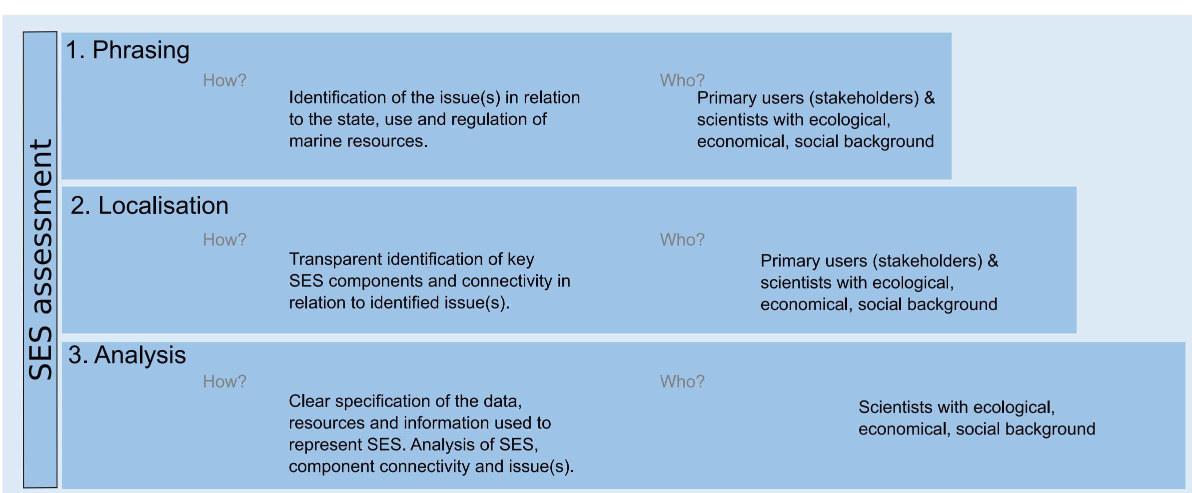
In more detail, locations of TPs within the SES, most studies reviewed here describe the 'tipping' of an ecological resource or a component within the ecological sub-system and knock-on effects resulting from that TP. Generally, the analysis of TPs and resulting cascading effects within SES is not trivial as the detection of both depends largely on the SES setup (Steffen et al., 2018). A prerequesite for the identification of a TP and subsequent knock-on effects is detailed knowledge about the connections and interlinkages between the sub-systems within the SES. In the context of EBM, the consequences of a TP are of concern from a policy perspective. In contrast to governance processes involved in setting goals and priorities, the aim of a management processes is to identify, in consultation with stakeholders, the root causes of a TP to avoid the consequences and the repercussions that it could have on policy (Cormier et al., 2017). However, the consequences of having reached an ecosystem TP can also result in a cascade of TPs across, economic and social (including legal and political) systems (Cooper, 2013; Cormier et al., 2019; Elliott et al., 2017). In an SES context, assessment of TPs would have to integrate the causal pathways of the consequences across the SES to inform managers and stakeholders as to the socio-cultural and economic or even the legal and political consequences. Importantly, these would likely need different mitigation strategies than the management measures needed to prevent the root causes of the TP (Serrao-Neumann et al., 2016). Such an approach requires transdisciplinary research to operationalise SES considerations in management in addition to current monitoring approaches (Leenhardt et al., 2015).

Our results show that the social sphere of the SES investigated is often underrepresented and does not feature as a starting point for investigation. In the reviewed cases, the researchers tended to focus on the biological resource in their analyses, while inter- or transdisciplinary approaches that incorporate social sciences are still rather rare (Leslie et al., 2015).

This may partially be caused by the fact that we cannot claim the review to be comprehensive, and that potential synonyms for TP or SES may have been missed in the initial Scopus key word search (e.g. critical transition, transformation or coupled human–environment systems). However, the homogeneous picture observed is most likely resulting from the general conceptualisation of the SES without the involvement of stakeholders, in addition to the composition of the team of researchers. In most of the cases we found that the authors' opinion was the foundation for setting up an SES. In other words, the decision as to which components to include in the SES was solely that of the researcher or team of researchers. This subjective perception can be problematic and may lead to certain (preventable) risks when assessing an SES. As we have shown, the scientific background of the authors determines the definition, terms and use of the concepts of TP and SES, which is likely to colour the setup and also the outcomes of any subsequent assessment. We contend that the intrinsic nature of an SES requires both transdisciplinary approaches and a high degree of interdisciplinarity. Social elements were neglected across the board, meaning the understanding of the SES in question is likely to be incomplete. We postulate that a participatory approach, including many stakeholders with different societal backgrounds will substantially reduce the risk of ending up with a biased view of the SES or missing important aspects of the system. This is all the more important when addressing human needs in relation to the use of marine resources. Only three reviewed studies are based on stakeholder participation. Social, ethical and political values may be missed when stakeholder knowledge is ignored and only scientific perception is included (Middendorf and Busch, 1997); incorporation of a variety of perspectives will also result in a more representative rationale and reduction of uncertainties (Olsson et al., 2004). Despite evidence that competing interests of stakeholders can make participation processes difficult, especially for adaptive management approaches (Brody, 2003), incorporation of insights from stakeholders when defining an SES and its constituent processes is therefore crucial as a starting point for management (Walker et al., 2002; Stringer et al., 2006; Leslie et al., 2015). Thus, if the dynamics and specifically SES vulnerability to tipping points are to be investigated, a clear link between problem definition and key stakeholders should be established (see Box 2).

Box 2
Guiding principles for the operationalisation of SES frameworks.

To address the shortcomings identified here in marine applications of SES frameworks, we propose a simple 3-step procedure for empirically analysing SES in the context of marine resource management:



The first step is *problem phrasing*, in which the issues in relation to marine resources and the boundaries of the SES in question are defined by stakeholders in particular primary users and a multidisciplinary team of scientists. In the second step of *problem localisation* potential TPs and the key SES components are defined together with the degree of connectivity between these components. Consideration is also needed of spatio-temporal aspects at this stage, requiring a collaborative effort of stakeholders and scientists. In the last step of *problem analysis* the vulnerability of the SES to the occurrence of TPs is established, differentiating between pressures leading to a TP which can readily be regulated through the implementation of management measures and those that require a different approach. Analysis should firstly aim to identify the root causes of a TP, so that management can be designed to prevent it from being reached. For this purpose, it is important to understand in which spheres and components of the SES tipping points are located, how resilient and vulnerable these components are to which agents of change and what measures could mitigate the potential risks of their tipping.

6. Conclusion

Societal and consequently the scientific interest in the influence of TPs on SES has grown exponentially over the last two decades. A variety of terminologies, definitions and concepts have emerged as a result, leading to a certain opacity. Practical operationalisation of these concepts has so far remained difficult, especially in the marine environment where SES and TP-related studies are still scarce (Walker and Meyers, 2004; Carpenter and Brock, 2006; this review). One reason may be the added complexity of marine SES in that they transcend land-sea boundaries. Thus the ecological sub-system (related to the resource use or provision of ecosystem service) is often geographically distant from the social-economic sub-systems that make use of the resource, and it can be difficult to delineate the boundaries and interconnections in these systems, especially where the marine environment is still not fully understood. As yet empirical research is mainly limited to small scale case studies, which is probably due to the high level of complexity of SES. This calls for new approaches that reduce the complexity of SES and prioritise connectivity within an SES, which would enable the concept to be applied in larger and likely more complex settings such as coastal-marine systems. With the principles presented here the link between SES research and management processes can be strengthened through comprehensive participative approaches that involve stakeholders from the start. This calls for transdisciplinary research approaches which should be promoted in future SES research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This article is based on work carried out under the SeaUseTip project (Spatial and temporal analysis of tipping points of the socio-ecological system of the North Sea (German EEZ) under different management scenarios) funded by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) (grant number: 01LC1720A) under the Tipping Points, Dynamics and Interactions Between Social and Ecological Systems (BioTip) call. We thank three anonymous reviewers for their helpful feedback on the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.135838.

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