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Marine ecosystem regime shifts: challenges and opportunities for ecosystem-based management

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Regime shifts have been observed in marine ecosystems around the globe. These phenomena can result in dramatic changes in the provision of ecosystem services to coastal communities. Accounting for regime shifts in management clearly requires integrative, ecosystem-based management (EBM) approaches. EBM has emerged as an accepted paradigm for ocean management worldwide, yet, despite the rapid and intense development of EBM theory, implementation has languished, and many implemented or proposed EBM schemes largely ignore the special characteristics of regime shifts. Here, we first explore key aspects of regime shifts that are of critical importance to EBM, and then suggest how regime shifts can be better incorporated into EBM using the concept of integrated ecosystem assessment (IEA). An IEA uses approaches that determine the likelihood that ecological or socio-economic properties of systems will move beyond or return to acceptable bounds as defined by resource managers and policy makers. We suggest an approach for implementing IEAs for cases of regime shifts where the objectives are either avoiding an undesired state or returning to a desired condition. We discuss the suitability and short-comings of methods summarizing the status of ecosystem components, screening and prioritizing potential risks, and evaluating alternative management strategies. IEAs are evolving as an EBM approach that can address regime shifts; however, advances in statistical, analytical and simulation modelling are needed before IEAs can robustly inform tactical management in systems characterized by regime shifts.

1. Introduction

An increasing number of examples of regime shifts have been observed in marine ecosystems around the globe [1]. We consider regime shifts in marine ecosystems to be changes that are abrupt, high-amplitude and low-frequency events that occur over large spatial scales and that are evident in multiple bio-physical attributes over a range of trophic levels [2]. These phenomena can result in dramatic changes in the provision of ecosystem services. Understanding regime shifts is thus critical for marine natural resource management because they change the rules of the game. Regime shifts are of particular importance for management as they involve abrupt changes that often come without warning [3,4]; they are often caused by multiple interacting external drivers that can erode system resilience (the ability to tolerate disturbances without transforming to a qualitatively different state) [5]; and perhaps most worrying for managers, they may be irreversible [6].

While the scientific community has recently made great strides in understanding the causes and consequences of regime shifts (e.g. [6]), there is still a dearth of practical tools available to managers to anticipate and respond to rapid ecosystem shifts. Accounting for marine regime shifts in management clearly requires integrative, cross-sectoral ecosystem-based management (EBM) approaches. EBM has emerged as an accepted paradigm for ocean management worldwide and is well suited for dealing with regime shifts, as it considers the multiple interacting stressors and ecosystem linkages that generate ecosystem shifts. Ecosystem

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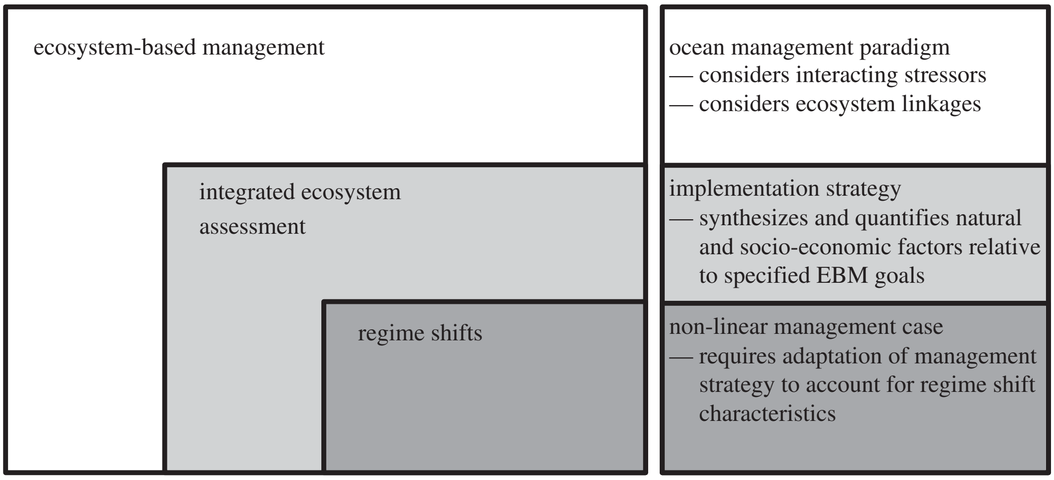

Figure 1. Hierarchy between and characteristics of the management paradigm of EBM, the EBM implementation strategy of IEA and the special nonlinear management case of regime shifts.

linkages occur within food webs, between associated ecological and social systems, as well as between several use and impact sectors. Yet, despite the rapid and intense development of EBM theory, implementation of EBM has languished [7,8], and many implemented or proposed EBM schemes largely ignore the special characteristics of regime shifts.

In this paper, we first explore key aspects of regime shifts that are of critical importance to EBM, and next suggest how regime shifts can be better incorporated into EBM. We make use of Integrated Ecosystem Assessment (IEA), an EBM framework developed by a number of management agencies around the world (e.g. [9–11]). We chose IEAs for this exploration because they are becoming globally ubiquitous, but are still undergoing a great deal of intellectual development [12]; thus, providing an important opportunity for the inclusion of regime shift theory in an emerging EBM framework ([10,13], figure 1). Following Levin *et al*. [14], we define an IEA as a formal synthesis and quantitative analysis of information on relevant natural and socio-economic factors in relation to specified ecosystem management goals. Ideally, an IEA uses approaches that determine the likelihood that ecological or socio-economic properties of systems will move beyond or return to acceptable bounds as defined by resource managers and policy makers [11]. IEAs provide a transparent means of summarizing the status of ecosystem components, screening and prioritizing potential risks and evaluating alternative management strategies against a backdrop of environmental conditions. To this end, IEAs must (i) identify ecosystem attributes and human activities of concern; (ii) develop and test indicators and reference levels that reflect key ecosystem attributes and human activities; (iii) explore the susceptibility of an indicator to natural or human threats as well as the ability of the indicator to return to its previous state after being perturbed and (iv) evaluate the potential different management strategies to influence the status of key ecosystem components and the pressures that affect these ecosystem components [11,14].

2. Key aspects of regime shifts of importance to ecosystem-based management

Scheffer & Carpenter [6] identify a number of key attributes of regime shifts, three of which are particularly important for EBM: (i) multiple causality is the rule, (ii) patterns depend on scale and (iii) different initial states can lead to different final states. We briefly discuss each of these, in turn, below.

(a) Multiple causality is the rule

EBM must confront a world of increasingly prevalent human pressures. This is, of course, a challenge for managers [15], but the task is made even more difficult because regime shifts are frequently triggered by a combination of factors, both internal and external to the system (e.g. [16]). Phase shifts on Jamaican coral reefs described by Hughes [17] have become a classic and sombre example of the outcome of multiple impacts on an ecosystem. In this case, two major hurricanes led to the degradation of reefs that had already suffered the ill effects of decades of overfishing [17]. Nonetheless, available evidence suggests the reefs were on the road to recovery [18], but an epizootic decimated populations of urchins—reef-dwelling grazers. The cumulative impacts of natural catastrophes (hurricanes and disease) in combination with human pressures (overfishing herbivorous fishes) led to a shift from a highly productive coral habitat to a less productive algal-dominated habitat. Similarly, in the Baltic Sea, climate effects and overfishing caused a regime shift in the pelagic ecosystem [19]. Climate-related changes in salinity and temperature initiated changes in ecosystem structure and function that were exacerbated by overfishing, resulting in a trophic cascade that spanned several trophic levels [20,21].

These examples highlight the importance and challenge of incorporating cumulative and interacting impacts into IEAs. In order for science to inform management, these examples point out that we need knowledge of how environmental drivers interact with human pressures to affect the probability that an ecosystem will shift states [6]. Additionally, these examples underscore the need to focus attention on chronic pressures such as fishing and pollution that may slowly diminish resilience.

(b) Patterns depend on scale

EBM is place-based [22], thereby making heterogenous landscapes a particular challenge for the implementation of EBM. Humans interface with the ocean at multiple spatial scales and interactions within the socio-ecological system operate across scales [23]. Thus, how regime shifts are manifested

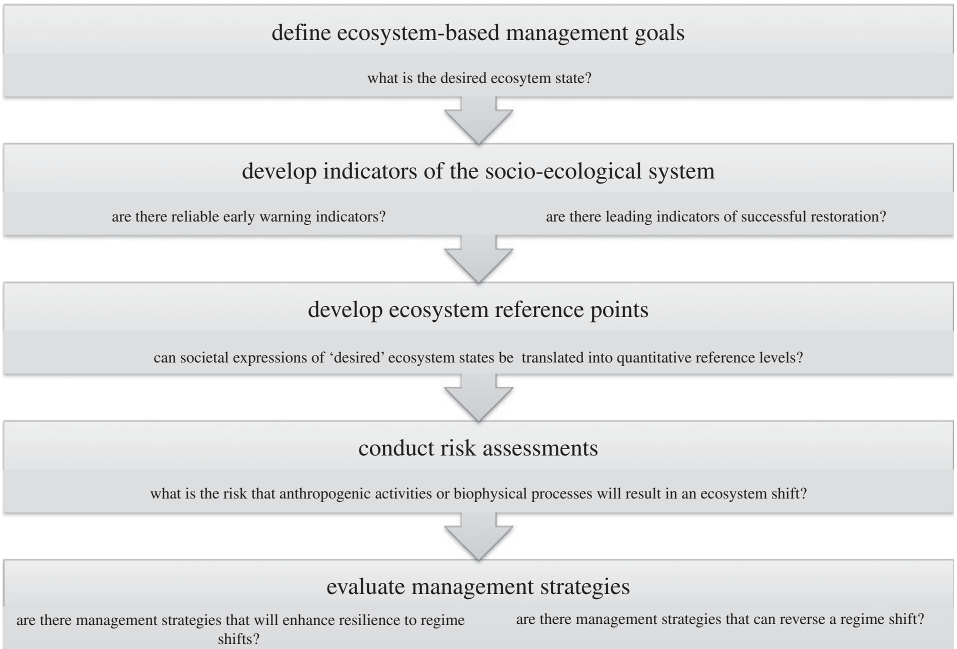

Figure 2. IEA steps adapted to the special management case of regime shifts.

across time and space are critical to effective management. Kelp forests in the Haida Gwaii archipelago, approximately 100 km off the northern British Columbia coast, provide an instructive example. In this location, the archetypal relationship among sea otters, urchins and kelp forests [24] exists such that the extirpation of sea otters led to an expansion of herbivorous urchins and a large-scale shift from highly productive kelp forests to relatively unproductive urchin-dominated communities [25]. Nonetheless, maps of Haida Gwaii reveal a spatial mosaic of urchin 'barrens' and kelp forests [25]. These alternative stable states thus exist side-by-side, meaning that the ecosystem state which an individual ocean-user experiences depends on the scale and location of observation.

In pelagic systems distant from shore, a regime shift in one location may lead to ecological impacts in adjacent near-shore regions. For example, Casini *et al.* [26] revealed that a regime shift in the pelagic, main basin of the Baltic Sea led to trophic cascades in the neighbouring coastal ecosystem of the Gulf of Riga. In this case, the ecological impacts and associated management concerns of the regime shift were spatially distinct thereby complicating appropriate management responses. Consequently, this and the previous example illustrate that as we consider how to implement EBM in the face of spatially variable ecosystem structures, it will be important to consider how the scale of ecological patterns interacts with the scale of resource management institutions [27].

(c) Different initial states can lead to different 'final' states

A number of studies reveal that ecosystems can converge to different states depending on the initial state [6]. For example, using elegant experiments, Almany [28] showed that the composition of the resident fish community on coral reefs has a large influence on the development of the community. Prior residency by piscivores and adult damselfishes reduced the success of damselfish and surgeonfish recruitment, but enhanced recruitment of wrasses. Similarly, in the California Current overfishing led to the demise of a number of large, long-lived, late-maturing rockfishes (*Sebastes* spp.) [29]. As appears to occur on coral reefs, successful rockfish recruitment may be inhibited by the composition of the resident community. In this case, smaller bodied, 'weedy' rockfish may be a significant source of predation or may be superior competitors than juveniles of larger species [30]. Thus, a key finding is that different orders of colonization can lead to alternative, but stable communities. A critically important question from a management perspective is if the objective of management is to return to a specific endpoint, can we go back the same way we came?

3. Regime shifts and integrated ecosystem assessments

Given the ubiquity of regime shifts in marine ecosystems, both scientists and resource managers must confront the challenges of nonlinear shifts in ecosystem structure and function. Below, we use the IEA process to organize a framework for incorporating regime shift theory and observations into management practice (figure 2).

(a) Defining ecosystem-based management goals

IEAs are driven by clearly defined management objectives, and this requires that scientists, managers and stakeholders work together to define the broad vision and objectives of EBM, the spatial scale or scales of interest, and the ecosystem components and ecosystem threats that will be included in the effort [11]. This is typically thought of as a fairly straightforward exercise in which experts in stakeholder engagement, management and science work together to define a common vision (e.g. [31]).

Regime shifts (especially those resulting from human activities), however, can complicate this process immensely. A critical step in defining EBM goals is articulating a vision of a 'desired' ecosystem state (figure 3). In some cases, such as the Jamaican coral reef example described above, the

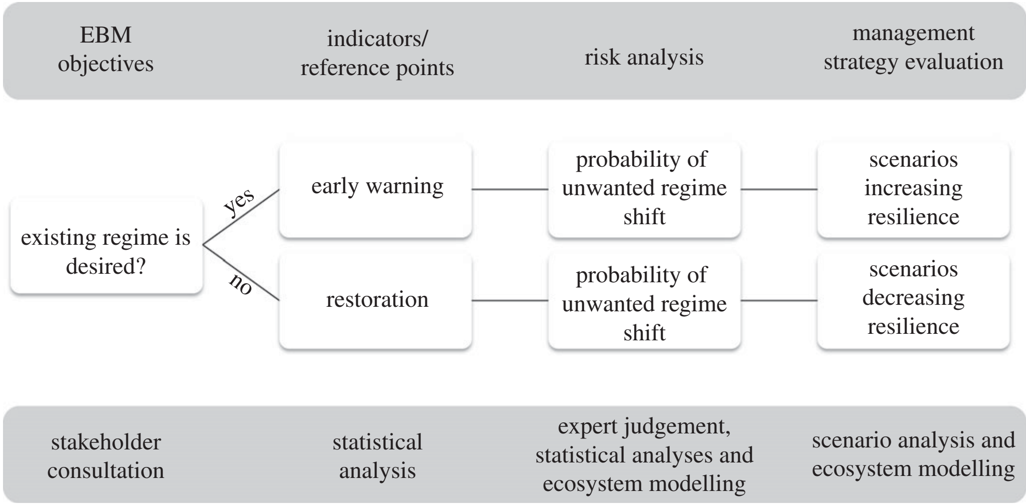

Figure 3. Outline linking the two pathways of regime-shift management to IEA steps (top grey field) and methodological approaches (bottom grey field).

desired state is seemingly obvious—a healthy, functioning coral reef ecosystem. This state ostensibly benefits most if not all marine resource users and enhances the well-being of most of the island's residents (e.g. [32]). Other cases are less clear. The ecosystem of the Northwest Atlantic Ocean provides an informative example. In this system, Atlantic cod (*Gadus morhua*) was the fisheries mainstay for centuries [33]. In the 1990s, cod stocks collapsed and fisheries were closed [34]. Stocks were expected to rebound within 10 years, but after two decades, cod populations remain depleted (http://www.nefsc.noaa.gov/sos/spsyn/pg/cod/). In Newfoundland, the cod collapse directly affected 40 000 people (*ca* 7% of the population), leading to substantial economic disruption [35]. However, with the demise of cod, fisheries for the former prey of cod, especially shrimp, crab and lobster greatly expanded [36]. Combined, these new invertebrate fisheries now exceed the maximum value ever achieved from cod [35]. Clearly, the human system adapted to this regime shift, and now the desired state of the ecosystem is less obvious. Different ecosystem states and associated management options will have costs and benefits that vary among sectors. Thus, the ultimate objectives of EBM may be as much about politics as they are about science. Nonetheless, despite the complexities and uncertainty that regime shifts bring to goal-setting processes, clearly articulating the desired state of the ecosystem is paramount.

A related complication in goal-setting emerges when the goal of management is to avoid crossing a tipping point from one ecosystem state to another. In this case, management may require substantial initial expenditures in exchange for future benefits associated with not crossing the tipping point. Communities often have difficulty incurring costs to avoid future problems, no matter how dire they may be. Thus, understanding the drivers and pressures underlying regime shifts is critical to informing early scoping processes.

(b) Develop indicators of regime shifts

Ecosystem-based management requires a means to track progress in achieving ecological, social-culture and economic objectives. Consequently, indicators—quantitative measures that serve as proxies for key attributes of ecosystems—have gained prominence in EBM (e.g. [37–41]) and form a foundation for IEAs (figure 2). A carefully assembled portfolio of indicators can provide managers with the knowledge necessary for assessing current ecosystem states as well as providing the information necessary for planning.

A profound challenge facing both ecosystem scientists and managers is that we are often unaware of regime shifts until well after the system crosses a tipping point (e.g. [42,43]). However, recent advances suggest that some indicators can be used to anticipate system-state changes (figure 3, upper pathway). These have been referred to as leading or early warning indicators. Increased variability, decreased responsiveness to management intervention and other factors have recently been identified as general indicators that a system is losing resilience and is approaching a regime shift (e.g. [4,44]). Related potential leading indicators include wider swings in dynamics of key ecosystem variables, spatial correlation, slower return rates after perturbation and shift of variance towards lower frequencies [45–48]. A variety of parametric and non-parametric statistical methods have been developed to measure and test these indicators, though most of this work has focused on modelled data or lake systems.

However, empirical applications of early detection of abrupt shifts in real ecosystems are still limited [49–51]. The basic rationale behind early warning indicators is based on the fact that the recovery of a system to equilibrium after a perturbation becomes slower close to a transition. This phenomenon is known as 'critical slowing down' [52] and causes the variance and autocorrelation in the fluctuations of a system to increase prior to a regime shift. These indicators can be used to detect abrupt shifts across an array of ecosystems and types of transitions [48], but they require long time series of high resolution. However, ecological monitoring datasets are typically short and lack detailed information on spatial distribution patterns of key organisms; and, therefore, the practical use of any of the proposed early warning indicators for risk analysis may be problematic.

By providing early warning of approaching thresholds, these indicators may enable managers to avoid crossing ecosystem thresholds and experiencing undesired conditions. However, given the degraded state of the oceans [53], a common challenge facing ecosystem managers is restoring ecosystems, their components and the services they deliver [54]. Thus, in many instances, the objective is not to avoid thresholds; rather, the aim is to push the ecosystem over a tipping point from an objectionable to desirable state (figure 3, lower pathway). Because changes in the state of an ecosystem can be path dependent [5], the indicators that foretell a shift away from a desirable ecosystem state may be different from the metrics that can serve as early indicators of recovery. Indeed, theoretical work suggests that early warning indicators are asymmetrical such that those metrics used to signal a shift from one state to another cannot be used in the reverse direction. Leading indicators of restoration are extremely useful as many of the species and ecological interactions that characterize a desired ecosystem may take decades to re-establish following their decline [55]. Rigorously tested marine examples of early recovery indicators appear rare. However, polychaete assemblage structure has emerged as a potential leading indicator for recovery in some near shore systems. For example, following degradation of a Portuguese estuary as a result of nutrient loading, polychaete assemblages signalled the remediation of nutrient enrichment and appear to be leading indicators of the establishment of a fully functioning estuary [56].

(c) Risk analyses in a world of shifting regimes

The indicator selection step within the IEA framework results in a set of indicators suitable to support the management goals of avoiding abrupt change to an 'unwanted' state or recovering to a 'wanted' state. Additionally, thresholds have been defined for these indicators that show critical levels of the indicators to be avoided or to be reached. The next step in the IEA framework would now be a risk analysis that anticipates the probability that an abrupt shift in the selected indicators occurs (in either of the two directions; figures 2 and 3). Probability of regime shifts needs to be evaluated as a response to the multiple and interacting drivers identified in the respective ecosystem to cause the abrupt shift.

Approaches to risk assessment are well developed and can be readily applied in an IEA framework [57,58]. Depending on available data and modelling tools, risk analyses can be conducted in a hierarchical approach that subsequently applies qualitative, semi-quantitative and fully quantitative analyses [11]. In the context of regime shifts, risk assessments must estimate the risk of human activities or natural perturbations to ecosystem structure and function, given that the functional relationship between ecosystem state and ecosystem pressures is nonlinear.

A qualitative risk assessment is often based on expert judgement. For example, Hobday *et al*. [57] describe an approach in which stakeholders evaluate the scale, intensity and consequence of potential stressors facing ecosystem components. Such an approach could be applicable to regime shifts if stakeholders characterize the consequence of stressors as nonlinear. However, because human perceptions are influenced by a number of psychological, social or contextual processes [59], qualitative assessments may be particularly problematic in systems in which thresholds are prevalent. Consequently, rigorous risk assessments for regime-shift management requires quantitative approaches that are able to reproduce (i) the effect of multiple, interacting drivers (i.e. external pressures and internal food web dynamics), (ii) abrupt and nonlinear changes of the indicator (ecosystem component), as well as (iii) feedbacks to cause resilience and hence changes in thresholds between 'forward' and 'backward' changes.

Predicting regime shifts and hence quantitative risk assessments is still difficult and often impossible since available modelling approaches are usually incapable of representing the typical regime shift characteristics. However, progress has been made using mass balance approaches (such as Ecopath with Ecosim) that account for multiple external drivers (usually climate, fisheries and eutrophication) affecting internal processes of the system (i.e. trophic interactions) [60]. Other modelling approaches can simulate the multi-sector impacts on an ecosystem and additionally resolve it in space allowing spatially explicit management approaches (such as Atlantis [61]). If these modelling approaches are able to simulate abrupt shifts in its state variables remains to be tested, but is at least doubtful. An alternative approach is nonlinear statistical time-series modelling as conducted for the Black and Baltic Seas [62,63]. Here, single statistical models of food web components (representing external and internal drivers) are combined to form a simulation model that theoretically can forecast abrupt changes. Furthermore, these models can map stabilizing or destabilizing feedbacks within food webs, and hence allow investigating changes in resilience. However, statistical models are generally restricted to conditions in their observation period and will likely fail to project ecosystem responses to environmental conditions not encountered before such as those expected with future climate change.

Owing to the limited ability of modelling approaches, analysing risk in a manner that incorporates regime shifts may be best accomplished using semi-quantitative means (cf. [64]). In this case, risk would be defined as the Euclidean distance of an ecosystem component from the origin in a space defined by exposure and sensitivity to stressors (e.g. [57,58]). Unlike a fully quantitative risk assessment, the axes in this analysis are categorical (i.e. high, medium or low exposure or sensitivity). In the case of regime shifts, sensitivity to threats would be nonlinear. Thus, the qualitative bins used in this analysis would need to be developed in such a way to account for the threshold behaviour that characterizes such systems.

(d) Management strategy evaluation

The final step of the IEA process uses conceptual, analytical and simulation modelling to evaluate the bio-physical and socio-economic consequences of different management strategies (figure 2). As we have highlighted above, most modelling approaches used in marine resource management are currently unable to handle the characteristics of regime shifts in a manner sufficient for decision-making. This problem is compounded when one considers linking bio-physical models to socio-economic models. For instance, regional economic impact models such as Impact Analysis for Planning (http://www.implan.com), make a number of assumptions such as (i) the supply of outputs is not constraining, (ii) prices of factors of production such as fuel are fixed and (iii) there is no substitution in production and consumption. Consequently, such models cannot forecast the consequences of extreme, nonlinear changes in the economic or ecological system [65].

What, then, is the solution to this problem? In the short-term, a reasonable approach may be to conduct systematic scenario analyses (figure 3). Scenario analysis generates multiple alternative descriptions of potential outcomes, including attributes of particular importance in regime shifts such as processes of change, thresholds and uncertainties [66]. Using scenario analysis, it is possible to explore alternative perspectives about thresholds, hysteresis and system resilience, and thus identify key issues by using a carefully considered set of assumptions about the system state [67,68]. IEA scenarios typically would include assessments of ecosystem states (arising from the indicator step of the IEA), driving forces of ecosystem change (emerging from the risk assessment), as well as descriptions of critical uncertainties [69]. History has taught us that ecosystems characterized by regime shifts will certainly surprise scientists and managers, and thus 'what-if' scenarios offer a useful approach for analysing consequences of abrupt changes in the system [69]. Scenarios can be qualitative, in which 'storylines' are developed, or quantitative, in which the outcomes of numerical models are explored [68]. As a result, narrative scenarios can be used to capture the qualitative shifts in the system, and these can be combined with quantitative models to provide geographical and numerical specificity to the concepts provided by qualitative scenarios [70].

The rigorous evaluation of management strategies would surely be improved by food web or 'end-to-end' ecosystem models that explicitly incorporate regime shifts. Certainly, population models that incorporate stochastic or autocorrelated environmental change are widely used [71]. In this approach, discrete-state Markov chains or first-order autogressive models can be used to simulate environmental processes. A function then links environmental states to demographic rates, and then it is straightforward to simulate population dynamics. An ecosystem analogue of such an approach would parametrize different models with interaction strengths that vary with regime states (e.g. [72]). No matter what precise advances are made, it is clear that modelling improvements are needed before they can adequately capture regime shifts in a manner that is useful for robustly evaluating management options with sufficient rigour to inform tactical decision-making.

4. Conclusion

Sustainable ocean management is predicated on the aim of meeting the 'needs of the present [generation] without compromising the ability of future generations to meet their own needs' [73, p. 43]. As such, sustainability in social–ecological systems has been an elusive goal that is value-laden [74], and difficult to define in systems where thresholds and feedbacks among ecosystem components are uncertain. Nevertheless, successful management of oceans requires that we confront this challenge. Understanding societal preferences, developing ecosystem indicators, conducting risk analyses and evaluating management scenarios are fundamental for successful management in any system (figure 3). They may be even more important in systems that are characterized by tipping points. In such systems, IEAs may benefit from resilience thinking where there is a focus on critical thresholds for system performance [75]. Identifying, anticipating and reacting to emerging ecosystem changes will be critical to maintain the delivery of ecosystem services. IEAs are evolving as an EBM approach that can do this; however, as we have highlighted here, advances in statistical, analytical and simulation modelling are needed before IEAs can robustly inform tactical management in systems characterized by regime shifts. Until then, IEAs can be a critical component in the strategic management of marine ecosystems and play an important role in considering how to maintain or restore the structure and function of the peopled seascape.

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