SPECIAL ISSUE

CSIRO PUBLISHING

Marine and Freshwater Research
https://doi.org/10.1071/MF17248

Perspective

Progress in integrating natural and social science in marine ecosystem-based management research

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Abstract. Climate change, in combination with population growth, is placing increasing pressure on the world's oceans and their resources. This is threatening sustainability and societal wellbeing. Responding to these complex and synergistic challenges requires holistic management arrangements. To this end, ecosystem-based management (EBM) promises much by recognising the need to manage the ecosystem in its entirety, including the human dimensions. However, operationalisation of EBM in the marine environment has been slow. One reason may be a lack of the inter-disciplinary science required to address complex social–ecological marine systems. In the present paper, we synthesise the collective experience of the authors to explore progress in integrating natural and social sciences in marine EBM research, illustrating actual and potential contributions. We identify informal barriers to and incentives for this type of research. We find that the integration of natural and social science has progressed at most stages of the marine EBM cycle; however, practitioners do not yet have the capacity to address all of the problems that have led to the call for inter-disciplinary research. In addition, we assess how we can support the next generation of researchers to undertake the effective inter-disciplinary research required to assist with operationalising marine EBM, particularly in a changing climate.

Received 21 August 2017, accepted 9 April 2018, published online 6 August 2018

Introduction

Our oceans provide goods and services critical to human welfare. However, factors such as climate change and human population growth are increasingly threatening the long-term sustainability of these goods and services. For instance, warming sea temperatures and changing ocean currents have resulted in shifts in species composition, abundance and distribution (Poloczanska *et al.* 2007; Doney *et al.* 2012; Cheung *et al.* 2013; Pecl *et al.* 2017), which have affected the stability of supply, access to, and the utilisation of these resources. At the same time, the degradation of coastal ecosystems as a result of urbanisation has become increasingly apparent (Wang *et al.* 2007; Diaz and Rosenberg 2008; Nellemann and Hain 2008; Borja *et al.* 2013). Such pressures are projected to increase (Merrie *et al.* 2014). Single-sector (a distinct part of the economy, e.g. fisheries) approaches to managing changing marine environments cannot address these increasing pressures.

In recognition of the need to manage complex marine systems, approaches to management are being developed, such as ecosystem-based management (EBM; Christie *et al.* 2007). There is little consensus regarding the definition of EBM because it is considered an evolving concept, and its interpretation varies (Cortner *et al.* 1998; Barnes and McFadden 2008; Smith *et al.* 2017). Yet, there is consensus regarding several EBM aspects. It aims to cover the entire ecosystem, including humans; its goal is to sustain ecosystem health, integrity and resilience to disturbances, and it requires the integration of social, economic and ecological considerations (Grumbine 1994; Arkema *et al.* 2006; Crowder and Norse 2008; Arbo and Thy 2016), suggesting the need for a strong grounding in inter-disciplinary research. However, anecdotally EBM has not delivered the promised benefits. For instance, in fisheries, EBM has manifested in the breadth of ecological issues considered by management (e.g. by-catch species, protected species, habitats and communities), rather than embracing an inter-disciplinary approach *per se*.

The case for an inter-disciplinary approach to EBM research

Operationalisation of EBM in the marine environment has been slow. Many management organisations have adopted the approach in principle, but there are few examples that are comprehensive and well executed. It has been suggested that a key barrier to marine EBM is the lack of inter-disciplinary science (e.g. Rosenberg and McLeod 2005; Christie *et al.* 2007; Leslie and McLeod 2007; Dell'Apa *et al.* 2015; Röckmann *et al.* 2015). It has also been suggested that integrated science, particularly between natural and social sciences, is problematic because of the challenges combining potentially opposing worldviews. (Barnes and McFadden 2008; Berkes 2012). However, it is difficult to understand what we mean by 'integrated natural and social science in marine EBM research' without discussing a suite of linked topics such as where EBM research is going, social–ecological systems, inter-disciplinarity, and collaboration for the co-production of knowledge.

Successful EBM of marine resources is inherently challenging, given the complex socio-ecological systems in which they are embedded (Berkes *et al.* 2008). For example, a resource system (e.g. a coastal fishery), resource unit (e.g. abalone), resource users (such as, e.g. commercial fishers, recreational fishers) and governance units (e.g. various levels of decision-making bodies responsible for managing the resource) are intrinsically interlinked and decisions made on one aspect inherently affect other subunits within the system (Ostrom 2009). Accordingly, conventional approaches to management that focus on a single aspect or discipline within the system, without accounting for the broader challenges, will be insufficient for responding to the complex, unpredictable and uncertain challenges posed by threats such as climate change and human population growth. Rather, responding to these challenges to ensure the long-term sustainability and provision of marine goods and services for human wellbeing and prosperity necessitates a social–ecological system approach to management and governance (Virapongse *et al.* 2016). This is an aim of EBM and an increasing focus for EBM research.

In its broadest sense, we interpret inter-disciplinary research as those investigations linking epistemologies, theories, methods and skills from different disciplines to produce new synthesised approaches to problems (Pickett *et al.* 1999; Christie 2011; Cheng *et al.* 2014). Nevertheless, the term 'inter-disciplinary' has often been confusing (Stember 1991). The literature on inter-disciplinary research covers a range of approaches, several of which are often used interchangeably (such as multi-disciplinary and inter-disciplinary). For this reason, we define several disciplinary terms (taken from Stember 1991) to clarify our use in the present paper, including the following:

- *intra-disciplinary* – working within a single discipline.
- *cross-disciplinary* – viewing one discipline from the perspective of another.
- *multi-disciplinary* – people from different disciplines working together, each drawing on their disciplinary knowledge.
- *inter-disciplinary* – integrating knowledge and methods from different disciplines, using a real synthesis of approaches.
- *trans-disciplinary* – creating a unity of intellectual frameworks beyond the disciplinary perspectives (we would further argue that trans-disciplinary research also integrates stakeholders, i.e. a person or group that has an investment, share or interest in the outcome of the research; Frusher *et al.* 2014).

We view integration as a scale from cross-disciplinary (least integrated) through to trans-disciplinary (most fully integrated). In the present paper, we use the term 'integrated' to collectively cover all these disciplinary terms, except for intra-disciplinary (no integration).

Although there are several arguments for intra-disciplinary work more generally, both intellectual and practical (Stember 1991), inter-disciplinarity has become synonymous with progressive research (Rhoten and Parker 2004). Intellectually, we can enrich ideas in any field by using theories, concepts and methods from other fields, particularly in terms of providing context to problems and generating new insights, or concepts. Inter-disciplinarity can provide us with a broader understanding of any system as well as providing triangulation of research and knowledge. Indeed, inter-disciplinary research has become the 'mantra of science policy' (Metzger and Zare 1999; Feller 2016). Practically, the problems that we face in marine systems are not organised according to academic disciplines, despite trends towards greater depth of disciplinary expertise in academic researchers. This is, in part, due to perverse incentives (Bromham *et al.* 2016). Examples of this perversion include the Research Excellence Framework (UK) or Excellence in Research for Australia, which allocate University funding on the basis of quality of research within disciplinary groupings.

In fact, the current focus of marine EBM research is moving further towards our definition of trans-disciplinary research. However, the production of knowledge concerning marine social–ecological systems is as complex as are the systems themselves. Co-production of knowledge is a concept that recognises that science is a social practice, among other varying practices used by a range of actors to produce different types of knowledge (Jasanoff 2004). Designing research to directly include participatory processes to facilitate collaboration among resource users, other stakeholders and science-knowledge producers is argued to enable more effective mobilisation (Puente-Rodríguez *et al.* 2016). Integrated marine EBM research is no longer only about combining different disciplines, but, increasingly, about combining different types of knowledge.

Aims and structure

In the present paper, we ask what progress has been made in integrating natural and social sciences in the context of EBM, and why? To do this, we address the following three subquestions: (1) are we making progress in inter-disciplinary research in EBM; (2) what are the barriers and incentives affecting progress; and (3) how can we support the next generation of researchers to undertake the effective inter-disciplinary research required to assist with operationalising marine EBM in a changing climate? To answer these question we draw exclusively on the perspectives and experiences of the authors, who, collectively, have over 235 years of experience undertaking inter-disciplinary research in relation to the world's oceans across Australia, Europe, North America, the Pacific and Africa.

To collate the perspectives and experiences of the authors, a short survey was undertaken asking all participants to answer the following two questions:

(1) How does your area of research focus contribute towards operationalising marine EBM?
(2) What do you view as the positives and negatives of interdisciplinarity?

We then drew on these responses over a range of meetings and discussions to shape our collective view, as described here. As such, this manuscript does not represent a comprehensive review of the EBM literature, instead it uses specific case studies to illustrate our perspectives.

The progress of integrated research in marine EBM

We illustrate the actual and potential contribution of interdisciplinary research to operationalising marine EBM at each of nine steps commonly used in adaptive management (Walters 1986). These steps include defining goals and targets, developing indicators, assessing the ecosystem, analysing uncertainty and risk, evaluating strategy, implementing the action, monitoring the indicators, evaluating and assessing outcomes and adapting the plan as required (Fig. 1). In this study, we used the National Oceanic and Atmospheric Administration (NOAA) Integrated Ecosystem Assessment Programme process cycle, but with the additional stage of 'adapt'. This was to enable the feedbacks in the NOAA process to be accounted for as a standalone step for the purposes of analysis. A range of alternative frameworks existed, with the steps being combined in several ways (e.g. Levin *et al.* 2009; Tallis *et al.* 2010). However, we used this nine-step model because it provided additional resolution over representations with fewer steps. This adaptive-management approach is also particularly suitable when environmental

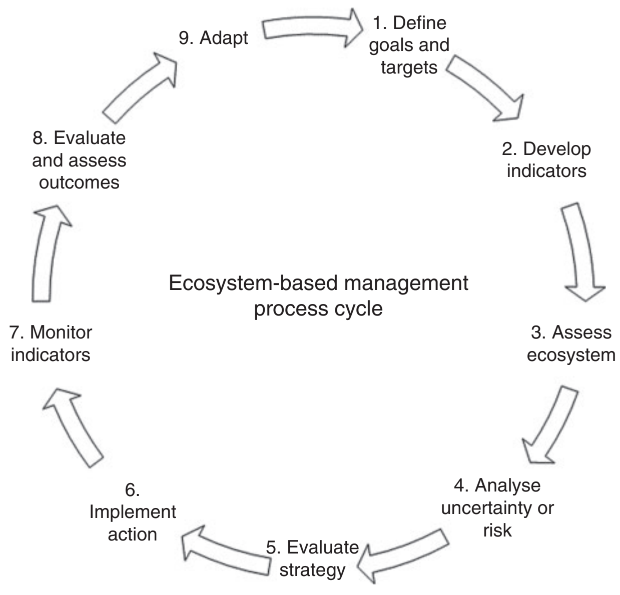

Fig. 1. Steps involved in the operationalisation of ecosystem-based management. Adapted from NOAA (http://www.noaa.gov/iea/next-gen-tool.html, accessed 30 November 2016).

conditions are changing and the future is uncertain, as noted by Hodgkinson *et al.* (2014).

At each step, we asked the following questions: what is the research focus and why; who is working together (with a starting assumption that all disciplines may have a role to play); what are the examples of research collaboration among disciplines; and whether we are progressing towards interdisciplinarity?

Step 1. Define goals and targets

Goals and targets should be based on societal values of marine ecosystem functions and services (e.g. requirements for jobs or for environmental protection). However, frequently, little is known or understood about societal values relating to our seas and coasts (Martin *et al.* 2016). Furthermore, difficulties in establishing agreed-on goals may arise as a result of conflicts and tensions among different actors (those who exercise agency) involved in the EBM process (Dankel 2009; Jennings *et al.* 2016). Research on conflicts in the oceans and coasts has often been spatial in nature and research has found that they can arise as a result of competition among multiple uses of the same marine space (Hoagland *et al.* 2003; Gray *et al.* 2005; Alexander *et al.* 2012, 2013). Conflict may also arise among the agencies that manage the marine environment, as a result of overlapping jurisdictions and competing objectives (Ekstrom *et al.* 2009).

Research activity has begun to focus on eliciting the values that society places on the oceans and coasts (Ruiz-Frau *et al.* 2011; Ressurreição *et al.* 2012; Ogier and MacLeod 2013). Some research has shown ways of understanding and communicating environmental issues, such as climate-change impacts and adaptations (e.g. Cvitanovic *et al.* 2014*a*; Fleming *et al.* 2014). Questions have been raised regarding whether, and how, private and public values inform public policy-formulation and decision-making processes (Kaiser and Stead 2002; McDaniels *et al.* 2006; Gilliland and Laffoley 2008; Klain and Chan 2012; Cvitanovic *et al.* 2014*b*). Indeed, some studies have highlighted a lack of alignment of contemporary public values with those formalised in public policy and in ecosystem research, assessment and monitoring programs for marine systems (Leith *et al.* 2014*b*; Dentoni and Klerkx 2015).

With regard to research on goals and targets, we believe that there has been a demonstrated shift from intra- to multidisciplinarity (mostly among various social sciences) described in the literature; however, additional benefit would be likely to result from the inclusion of further disciplines. For example, environmental psychology could enrich our understanding of how a changing environment affects its inhabitants, to assist in goal and target development. Environmental law could contribute to the development of legal and institutional frameworks that foster equitable and sustainable environmental management goals.

Step 2. Develop indicators

Indicators represent the key elements for monitoring and measuring changes to a social–ecological system. Developing indicators provides the basis from which to assess the status and trends in the condition of the ecosystem or an element within the ecosystem (Link *et al.* 2002; Link 2005), and is particularly important when a system is changing.

Our experience suggests that the majority of this research has been intra-disciplinary. As an example, a broad suite of ecological indicators in data-poor, multispecies, coral-reef fisheries has been developed, which may be incorporated into pressure–state–response frameworks to inform management decisions (e.g. Jennings *et al.* 1995; Mangi *et al.* 2007; Vallès and Oxenford 2015). We can also find examples of intra-disciplinary social science research to develop socio-economic indicators, such as those developed by Bowen and Riley (2003). We acknowledge that efforts have been made by ecologists to develop socio-economic indicators (e.g. Kim and Zhang 2011), suggesting some cross-disciplinary attempts in this area. However, more recently, we are seeing a move towards trans-disciplinary research. This research has involved working with stakeholders to identify ecological, economic and social objectives for management of the marine environment and then matching these to indicators identified from the literature (Trenkel *et al.* 2015) or system models (Hayes *et al.* 2015), as well as soliciting preferences for the types of indicators used (Marre *et al.* 2016). The involvement of stakeholders in the co-production of holistic assessment frameworks and suites of management objectives has entailed a form of boundary work between the domains of science, public policy and non-science interests, as well as between natural and social sciences. Because indicators must provide the feedback valued by different actors, therefore, an inclusive, trans-disciplinary process is imperative to generate indicators that each group of actors value.

Step 3. Assess ecosystem

From an EBM perspective, assessing the ecosystem should be an inherently inter-disciplinary endeavour. This means not just the various species within the ecosystem and the physical properties that govern the movements of those species, but also considering the linkages between marine ecosystems and human societies, economies and institutional systems (McLeod and Leslie 2009).

Multi-disciplinarity in this step is starting to be reflected in the content of global initiatives, such as INDISEAS (www.indiseas.org) and the EU requirement for Good Environmental Status as part of the Marine Strategy Framework Directive (Borja *et al.* 2013). Such initiatives have expanded from an ecological indicator base to include indices for the human dimensions (see also Borja *et al.* 2009). Multi-disciplinary approaches are also emerging in ecosystems assessment as a result of the rise of 'citizen science' (Dickinson *et al.* 2012; Bonney *et al.* 2014; McKinley *et al.* 2017). Citizen science is one of a suite of collaborative and potentially inter-disciplinary approaches (between social and natural scientists and between scientists and communities) that can lead to increased engagement on important marine issues and improved knowledge that has been 'co-produced'. An example is the Range Extension Database and Mapping project, Redmap (www.redmap.org.au). The project has contributed to a strong understanding of species and ecosystem changes (Johnson *et al.* 2011; Last *et al.* 2011; Robinson *et al.* 2015) occurring in one of the fastest-warming regions of the southern hemisphere (Hobday and Pecl 2014), and has helped build community and industry awareness of climate-related changes at the same time. Further analysis has determined the social learning model and outcomes arising from marine-user participation in this citizen-science application (Nursey-Bray *et al.* 2018).

Inter-disciplinary research is also moving forward in this arena; modelling has brought together the natural and social sciences to investigate linkages in social–ecological systems. Examples include modelling the effects of fishing damage to habitats (Watson *et al.* 2006; Pitcher *et al.* 2010), livelihood strategies of professional fishers and dependent businesses in coastal communities (van Putten *et al.* 2014) and linking the wild capture and aquaculture of marine and freshwater species to trade commodities and their consumption (Watson *et al.* 2016).

Step 4. Analyse uncertainty and risk

Analysing uncertainty and risk to the ecosystem posed by human activities and natural processes is key to enabling management strategies. Understanding potential future risk facilitates proactive and anticipatory decision-making, in contrast to management that is only reactive (Hodgkinson *et al.* 2014; Pecl *et al.* 2017).

Risks to ecosystem health, and, thus, ecosystem services, tend to be considered individually in the biological, physical, economic and social realms. Collaboration and integration across the disciplines is still fairly nascent in all cases. Risk-based methods have been important in developing options to support EBM, because they use best available information, involve stakeholders and elicit expert judgement (Astles *et al.* 2009; Gaichas *et al.* 2014; Micheli *et al.* 2014). For example, the development of the risk-based ecological risk assessment for the effects of fishing (ERAEF; Hobday *et al.* 2011) (1) recognised the importance of all aspects of the environment, namely, target, by-catch, protected species, habitats and ecological communities, and (2) allowed decisions to be made even if information was deficient for some of these aspects. The ERAEF approach has now been implemented in Australian Commonwealth and other fisheries worldwide (Leadbitter 2013; Gaichas *et al.* 2014; Gilman *et al.* 2014) as has an alternative risk-based approach in Australian State fisheries (Fletcher 2015). Research relating to this step is moving towards integration in terms of the inclusion of stakeholders and different types of knowledge. Non-technical stakeholders have been involved in data provision, assessment workshops, review and development of management options (Hobday *et al.* 2011). Risk-based assessment methods have recently been developed to assess climate risk for fished species (Hare *et al.* 2016).

We believe that research in this area is moving in the right direction in terms of the inclusion of stakeholders into the process, usually to inform the perspective of a single discipline (e.g. biological risk from climate change). However, this research arena could benefit from collaboration with social scientists to identify varying levels of perceived risk and uncertainty relating to a wide variety of human activities on the state of marine ecosystems as well as the risks to society arising from decisions taken in any single sector (e.g. Brander 2010).

Step 5. Evaluate strategy

Evaluating the effectiveness of potential management strategies is important in determining how management actions may affect ecosystem indicators. Strategy evaluation can also be useful for helping resource managers to consider the system trade-offs and the potential for success in reaching a required goal (Sainsbury *et al.* 2000).

Intra-disciplinary research in marine systems has focused on modelling human behaviour in fishery settings (e.g. the Great Barrier Reef; Little and McDonald 2007) to capture possible responses to management reactions. This allows for prior prediction of some of the pitfalls that management might encounter should a management action be implemented in reality. In terms of inter-disciplinary research, management-strategy evaluation tools based on a systems approach are an area where input from a variety of disciplines has come together to create a 'whole' (e.g. Fulton *et al.* 2014). Examples include modelling information-sharing in a social network and capturing the fishing behaviour (Little *et al.* 2008, 2009*a*, 2009*b*) and identifying what strategies the stakeholders themselves would use to achieve objectives under a changing climate (Pascoe *et al.* 2009; Jennings *et al.* 2016). Such models can then show the results of implementing candidate management strategies with the intention of showing potential trade-offs between contested objectives (e.g. conservation *v.* economic objectives; Mapstone *et al.* 2008; Thébaud *et al.* 2014) or under different climate-management strategies (Fulton and Gorton 2014).

The development of MSE tools (Fulton *et al.* 2014) has involved contributions from many disciplines, including geography, oceanography, ecology, economics and social science (in terms of understanding perceptions and behavioural drivers of fleet dynamics, for example). These tools are increasingly used to test different solutions to complex fishery problems (Plagányi *et al.* 2013). Although these approaches were initially developed for Australian fisheries, both risk-based (e.g. Pecl *et al.* 2014) and MSE approaches have since been modified for use in climate assessments, marine park planning (e.g. Savina *et al.* 2013), and, more generally, in the contested coastal space (Fulton *et al.* 2015). We would argue that inter-disciplinary research, as exemplified in these examples, is progressing strongly, particularly in MSE, which requires synthesising knowledge from different disciplines.

Steps 6 (implement action), 7 (monitor indicators), 8 (evaluate and assess outcomes)

We discuss steps six to eight in an adaptive management cycle because they collectively involve the 'doing' of actions developed in the preceding steps.

Although being predominantly single-sector in focus, fishery management has increasingly focussed on constraining catch. This is not only to ensure biological sustainability of targeted species but also to preserve ecosystem integrity through monitoring and managing levels of by-catch and discarding (Fletcher 2006, 2015; McLoughlin *et al.* 2008). Collection of fishery-dependent or -independent indicator data proceeds under the guidance of the management agency (e.g. logbooks, observers), or may be outsourced to a third-party provider (Grafton *et al.* 2007; Little *et al.* 2016). In either case, these indicators are rarely reported in real time, unless the management levers are in place to allow rapid responses, such as in-season closure when a quota or by-catch limit is reached, or when high profile species are captured (Tracey *et al.* 2013; Smith *et al.* 2014). More typically, indicators are assessed at the next formal decision-making event, such as the annual meeting for setting the fishing quota for the following year. Likewise, evaluation is limited to occasional reviews of the approach, with business as usual being the *modus operandi*.

Social-science approaches, such as interviews, surveys and case-study approaches, are often used to consider how well these three (and earlier) steps have worked (Cvitanovic *et al.* 2016), with little evaluation of the implementation or monitoring method *per se*. In contrast, deep engagement throughout these steps could support triple-loop learning (Armitage *et al.* 2008), which involves 'learning how to learn'. This form of learning helps stakeholders understand a great deal more about the complexity and linked nature of the system and subsystems under management, and the beliefs and perceptions of the various actors (Berkes 2012). Evaluation is often an external process, and so the opportunity for learning and insight come at the end of the assessment through a review of material generated by evaluators not involved in previous stages. Although this single loop learning provides an opportunity not to repeat the mistakes next time, it is slow and inefficient (Pahl-Wostl 2009). By embedding evaluation as part of the preceding steps, more value will be created for those involved. Moreover, using co-production or co-design processes could allow research, action, evaluation and adaptation to be combined throughout the process.

We suggest that these steps (6–8) are generally not integrated across disciplines. They may occur as part of the regular processes of an implementing body (as in fisheries) and are generally assumed to be 'non-research areas', with little funding allocated to support innovation. As a result, any inter-disciplinary research occurring in these steps would be likely to follow from the degree of inter-disciplinarity in earlier steps.

Step 9. Adapt

This final, reflective step involves taking the lessons from the evaluation step (which is sometimes grouped together with this step), and planning improvements for the next cycle of EBM. If there has been system failure, then additional research for the other steps may be planned. However, direct research on the process of Step 9 is limited to case studies around success and failure of the system as a whole (Cvitanovic *et al.* 2016). Again, social sciences tend to dominate in this generally qualitative endeavour.

Larger environmental and marine management agencies, such as the Great Barrier Reef Marine Park Authority (GBRMPA) and the Australian Fisheries Management Authority (AFMA), have the scale (e.g. budget, reach, scope) to bring together different disciplines to consider changes to their operating mode around EBM. Although they may be able to bring other coastal decision and policy makers to the table, these endeavours have not tended to produce new agreements for shared resource use outside the sector. AFMA has a process of developing ecological-risk assessments for key fisheries (Hobday *et al.* 2011), and, following an evaluation review, recently revisited development of the methods employed (Zhou *et al.* 2016). The assessment framework has been redesigned, as indicators showed that some methods for assessing ecological sustainability were not sensitive to the changes that might be occurring. This 'adapt' portion of the process results in changes to the research supporting the EBM approach, as well as the implementation. However, through our collective experience, we have not witnessed inter-disciplinary approaches to adapting management strategies.

Steps 1–9. The complete cycle

Progress is apparent at all 'research-relevant' steps of the marine EBM cycle; however, the pace is not even. Is this because inter-disciplinary research is needed at some steps more than others? Alternatively, is interdisciplinary research easier at some steps and not others? Or perhaps heterogeneity between steps is due to barriers, or, conversely, a lack of incentives, to inter-disciplinary research? We explore these questions in the following section.

Barriers and incentives to inter-disciplinary research

We believe that formal institutional barriers to inter-disciplinary research have received considerable attention in the academic literature, but that there has been less focus on practitioners' experience of informal barriers, or incentives to address these barriers. Here, we explore these forms of barriers and incentives on the basis of our collective experience of undertaking research relating to marine ecosystem-based management, and, where possible, we assess whether climate change is likely to exacerbate or reduce these barriers.

Barriers

It has been suggested that a *language barrier* exists between disciplines (Anon. 2015*a*; Essington *et al.* 2017). The modes of language and style of thinking standard to the biophysical sciences are often an anathema to the social sciences, and *vice versa*. Operating in an inter- or trans-disciplinary space requires the development of a common (and plain) language. This requires investing time in understanding different traditions, literatures and methods, learning ourselves, and, perhaps more importantly, listening, across a range of disciplines, which builds trust for when compromise is needed. There is limited appreciation for the initial transaction costs in learning to work together across the biophysical and human systems and understand discipline-specific nomenclature, approaches and methodologies (Frusher *et al.* 2014). The emergence of climate change as an issue for EBM may reduce this barrier, because climate change is a problem confronting multiple disciplines with a clear time-for-action imperative. As a result, these disciplines may share the same problem framing and adopt a common language, such as around 'adaptation' (e.g. Adger *et al.* 2005), perhaps because there has been less time to develop independent disciplinary cultures.

We suggest that one key difficulty for inter-disciplinary research is the *lack of guidance on how to undertake inter-disciplinary research*. It can be difficult to integrate social data with biophysical data because of differences in scale, dynamics, spatial scope, structure, as well as varying levels of abstraction or theorisation and quantification (K. McDonald, pers. comm.). Currently, there is a dearth of empirically grounded guidance for researchers from different disciplines about the key principles underpinning successful collaboration and the core capacities needed to support them (van Kerkhoff and Lebel 2015).

An inter-disciplinary approach may require borrowing of existing ideas, repackaging and practical application. This is often *not viewed as 'cutting-edge' science*, and the system of academic rewards (recognition of achievements) may dissuade some researchers from engagement. This can be addressed by thinking early on about the 'academic outputs' that can emanate from such research projects, and involving the full project team in the preparation of outputs (e.g. Hobday *et al.* 2016). Unfortunately, some cutting-edge approaches that deliver academic benefits (high-profile publications) may not be available or suited to end users, which becomes a barrier to uptake (Curtice *et al.* 2012).

Perhaps the most often-cited barrier to inter-disciplinary scholarship, in an academic context where 'publish or perish' prevails, are the *significant on-going transaction costs* associated with inter-disciplinary collaborations (e.g. Bromham *et al.* 2016). The time required to maintain links and to see products through to a state acceptable to all participating disciplines can be challenging, particularly when dealing with complex problems relating to rapidly changing environments. Our experience suggests that agreeing on problem structuring and definitions can manifest as extra workshop activities in any research exercise. This would suggest that we could deal with this particular barrier during the timeframe of one meeting. However, we also note that renegotiation can, and often does, occur throughout the program of work, particularly during the process of writing, thus, constantly extending time and effort. The costs of this research may be higher with more researchers involved (Ling and Hobday 2018) and substantially higher for a trans-disciplinary researcher, where the needs of non-academic partners must also be met. Furthermore, these costs are often unfairly borne on the early career researchers or next generation of researchers who are trying to navigate these inter- and trans-disciplinary spaces.

Finally, the products of inter-disciplinary and trans-disciplinary work are also often more problematic to categorise in terms of 'standard' university *productivity and impact accounting*, although this is changing in countries such as Australia. It is often less valued by established disciplinary-oriented review boards (meaning it can be less likely to be financially supported), and may be more difficult to publish, despite being a 'requirement' of many new approaches (Ledford 2015) and the stated aim of some major funding agencies. At the global level, international University rankings can sometimes dis-incentivise pursuit of inter-disciplinary research. For example, 20% of the metric that constitutes the academic ranking of world universities (ARWU) comes from a highly cited (HiCi) indicator produced by Thomson Reuters (highlycited.com). The methodology favours authors who consistently publish in single fields and those with equivalent HiCi articles, but not those who publish across disciplines. Overall, it seems that research that transcends conventional academic boundaries is still harder to fund, conduct, review and publish, and those who pursue it may struggle for recognition and advancement (Anon. 2015*b*).

Incentives

A key incentive for working in inter-disciplinary (and trans-disciplinary) teams is the *opportunity to tackle larger questions about marine socio-ecological systems facing society* (Anon. 2015*b*) and in a way that is realistic, regardless of scale. As

Schwartz (2008) argued 'focusing on important questions puts us in the awkward position of being ignorant' (p. 6). An important incentive for inter-disciplinary research is that in a world faced with increasingly large-scale, interconnected environmental and social issues, such as climate change, the most interesting and challenging research questions are those that can be addressed only by using inter-disciplinary approaches. The alternative perspectives and knowledge brought to bear by collaborating across disciplines means that complex questions can be more directly tackled. This occurs by a broadening of the understanding, but also by a ratcheting of insight and intellectual stimulus. It is all too easy for single disciplines to see each issue as either one best suited to being solved by the tools they are already familiar with or as simply outside their purview. In the case of inter-disciplinary research to support marine ecosystem-based management, the interweaving of disciplines allows for the realisation that the complex issue is in scope, but that novel (co-created) or alternative analytical tools are more appropriate (e.g. the combination of multi-criteria analysis, geographical information systems and facilitated stakeholder workshops as used in Alexander *et al.* 2012). The potential for novel tool development and the associated research impact generated can, in turn, incentivise inter-disciplinary research.

Academic opportunities to seek *new knowledge and methods* from colleagues who approach academic questions from different perspectives (e.g. qualitative and quantitative research perspectives) provide a rich environment of advanced learning. For example, in quantitative studies, explanations expressible in terms of quantities are often the focus, with hard to characterise aspects being ignored or down-weighted in subsequent analyses. Alternatively, a more even-handed consideration of all components is possible in qualitative studies, with some of the most difficult-to-characterise aspects being considered as the most informative.

Similarly, many of the larger international *funding agencies* (such as e.g. Belmont Forum and G8 Research Councils Initiative on Multilateral Research Funding – International Opportunities Fund, Future Earth), which have been established to address major societal challenges, recognise the need for this type of research, meaning that it is beginning to be funded. For example, some of the authors have received funding through the Belmont scheme (http://www.marinehotspots.org/index.php/featured-projects/gulls, accessed 31 July 2018) because of their ability to bring inter-disciplinary teams together across global marine hotspot regions (Hobday *et al.* 2016; Popova *et al.* 2016).

Inter-disciplinarity for the next generation of researchers

As we have shown, ecosystem-based management requires the integration of the social, economic and ecological (as suggested by Grumbine 1994; Arkema *et al.* 2006; Crowder and Norse 2008; Arbo and Thy 2016). Given the potential research incentives, how can we address the barriers while training the next generation of researchers working in this arena? Although experience can accrue from working in inter-disciplinary teams, as for our 'older' co-authors, this is a risky and time-consuming approach; can we design a better way?

First, we need to work with students and experienced researchers to address potential language barriers, navigate disciplinary boundaries and incorporate different types of knowledge. Where students have supervisors from different disciplines, key strategies to support breadth include creating opportunities for frequent and proactive communication, as well as supporting recognition of differences and ways to address them (Morse *et al.* 2007; Record *et al.* 2016; Essington *et al.* 2017). Accounting for additional project time and establishing shared languages within inter-disciplinary teams are practical solutions to facilitate effective relationships (Bridle *et al.* 2013; Record *et al.* 2016). Investing additional effort towards fostering research relationships across disciplines is also necessary (Bridle *et al.* 2013). Networking for students in support of inter-disciplinary research is emerging, through, for example, the Inter-disciplinary Graduate Student Network (iGSN) at the University of British Columbia, and a growing number of cross-disciplinary teams such as the Centre for Marine Socioecology at the University of Tasmania, the Stockholm Resilience Centre, and the Centre for Ocean Solutions at Stanford University. Such collaborative effort requires researchers to identify and develop common understanding across disciplines, revisit basic methods, assumptions and strategies, and adopt professional respect for the differing ontologies and epistemologies at play (Lach 2014; Siedlok and Hibbert 2014).

As well as training disciplinary experts to work together in teams, we should also be creating inter-disciplinary people. Inter-disciplinary researchers are often viewed as a 'jack of all trades, master of none' and like single-discipline researchers, inter-disciplinary researchers do need disciplinary strengths. We would call for interdisciplinary researchers to be 'T' shaped researchers similar to Hansen and von Otinger's (2001) 'T' shaped managers. These 'T' researchers would have their academic rigor (vertical part of 'T') in their disciplines, but have the breadth of understanding (horizontal part of 'T') from other disciplines. This would allow researchers to transfer ideas and methodologies across disciplines (e.g. qualitative and quantitative approaches). It would allow them to obtain broader input into decision-making, and to capitalise on shared expertise. It would enable researchers to develop new projects through cross-pollination of ideas. Finally, it would contribute to progressive research impacts by delivering impacts that demonstrate the trade-offs in biological terms, social terms and economic terms, and strengthen the connection between research and policy.

As noted earlier, there is a lack of guidance on how to undertake inter-disciplinary research, perhaps because research entities have been slow to support transitions towards inter-disciplinary research (Rhoten 2004). There has been a growing institutional trend for expanding educational curricula, faculty training and recruitment to cover cross-discipline foci and to reduce real and psychological boundaries to inter-disciplinarity (Holley 2009). Yet, the scope and focus of such programs remain widely debated (Newing 2010). For students and supervisors across multiple disciplines, shared training programs have the potential to minimise future academic conflicts that may arise during research planning (Armsworth *et al.* 2009). They can also provide a platform to facilitate cooperation (Collins 2002).

Finally, we need to incentivise inter- and trans-disciplinary research, across scholarly and other relevant institutions. Early career researchers are excited and motivated to solve complex world problems; indeed, one study showed graduate students with higher rates of inter-disciplinarity than any for other researcher group (Rhoten and Parker 2004); however, they need to know that it will not inhibit their careers. As noted by Sibbald *et al.* (2015), we need to address why we shape inter-disciplinary researchers into 'round pegs' that are flexible, transferable and adaptable, and then expect them to fit into existing 'square holes'. If we do not alter the overarching research, funding and merit system, particularly in terms of productivity and impact accounting, then this is precisely what we are doing. Similarly, we need to address the lack of institutional demand for inter-disciplinarity in the evaluation and management of the marine environment by highlighting contributions of inter-disciplinary research to operationalising marine EBM through adaptive management.

Conclusions

A recognition of the social–ecological complexity involved in marine environmental governance, in addition to several notable failures in ocean and coastal resource management, has led to a call for inter-disciplinary research in this field. We have found that the integration of natural and social science has progressed at most stages of the marine EBM cycle (used here as one example of a research area in which inter- and trans-disciplinary research is important). Yet, we must emphasise that this progress has been, on occasion, difficult to identify. For example, in the first two EBM stages, boundary spanning (by bringing together scientists and managers with varying approaches to knowledge production to consider a wider array of stakes and ways to frame the problems to be investigated (Cvitanovic *et al.* 2015)) is taking place, but is often unrecognised. Several boundary spanning-design elements are already standard practices of integrated research, in comparison to disciplinary research. These may include science communication (as a minimum, between disciplines), informal linkages and relational networks (constituted by research teams), brokering and intermediary roles with actors (undertaken by leaders of inter-disciplinary teams) and temporary organisations (such as science advisory committees; Leith *et al.* 2014*a*). These contributions to the production of actionable and policy-useful knowledge are not easily detected in any assessment of progress towards integration of natural and social sciences to support marine EBM (Frusher *et al.* 2014). Greater recognition and fostering of these contributions may provide a basis for future assessment of progress at these stages.

The area in which we seem to be making least progress in integrating natural and social science relates to 'understanding the ecosystem', despite this being a dominant research activity. Improved understanding of complex social–ecological systems is seen by many as one of the major challenges facing management of our oceans and coasts. To meet this challenge requires understanding components such as system dynamics, system boundaries, spatial and temporal distributions of resources, economic values, histories of resource use, property-rights systems and collective-choice rules, among many other properties (Ostrom 2009). With climate change, understanding a rapidly changing system is further complicated. Research is expanding our knowledge of these different components individually, but gaining that elusive understanding of the whole system still appears to be problematic. As noted by Walker *et al.* (2006), the structures and functions of social–ecological systems can change as a result of internal dynamics and external influences and suffer from both top-down and bottom-up interactions that can interact across scales. Understanding the feedbacks between these processes across an entire social–ecological system is mindboggling, particularly when these systems are changing. From a management perspective, we want to understand 'enough' of the relevant aspects of the social–ecological system to make good management decisions. Co-production of knowledge focuses on enough to act, evaluate, act again and learn. Perhaps the question to be asked here is 'without integrating natural and social research, do we understand enough?'

We have highlighted several barriers to inter-disciplinary research that must be addressed. In addition to recognised formal institutional barriers, there may be further informal capacity-related barriers, such as finding the 'right' combination of skills, exposure to these skills and identifying those researchers who are willing to engage with the 'other'. One example of this may be in ERA where managers, scientists and fishers all participate in the screening of draft results. Although these 'champions of practice' can emerge naturally, we are hopeful that these barriers, at least, can be overcome in formally training the next generation of inter-disciplinary researchers. Ultimately, we do not yet have the capacity to address the problems that led to the call for inter-disciplinary research, but we appear to be making progress.

Progress in all steps we discussed has been the most substantive where multi-disciplinary research has been used to understand the various natural and social components and subcomponents of the marine social–ecological systems under governance. Progress is most required in understanding the interactions and feedbacks between the behaviours of natural subsystems and social subsystems under climatic or adaptive management-driven change. However, to enhance production of effective science to meet this need, boundary-spanning work in combination with discipline-spanning research is required (Cash *et al.* 2003; Jasanoff 2004). The integration of stakeholders into research (rather than into management) has been uneven and largely driven by access to stakeholder knowledge. Progress in co-design and production of research through greater integration of stakeholders and their stakes and interests is likely to further challenge disciplinary boundaries and lead to greater uptake and impact of, and eventual demand for, inter-disciplinary marine research.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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