2018-05-01

A new wave of marine evidence-based management: emerging challenges and solutions to transform monitoring, evaluating, and reporting

Addison, PFE

http://hdl.handle.net/10026.1/12268

10.1093/icesjms/fsx216
ICES Journal of Marine Science
Oxford University Press (OUP)

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Authors: Addison, P. F. E.[1,2], Collins, D.J [3,4], Trebilco, R.[5], Howe, S.[6], Bax, N. [7,8], Hedge, P. [7], Jones, G.[9,10], Miloslavich, P.[7,11], Roelfsema, C.[12], Sams, M.[13], Stuart-Smith, R.D.[7], Scanes, P.[14], von Baumgarten, P.[15], McQuatters-Gollop, A.[16]

[1] Department of Zoology, University of Oxford, Oxford, United Kingdom

[2] Australian Institute of Marine Science, Townsville, Queensland, Australia

[3] Environment Protection Authority Victoria, Macleod, Victoria, Australia

[4] Environment Southland, Invercargill, New Zealand

[5] Antarctic Climate & Ecosystems CRC, University of Tasmania, Hobart, Tasmania, Australia

[6] Parks Victoria, Melbourne, Victoria, Australia

[7] Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania, Australia

[8] CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia

[9] Tasmania Parks and Wildlife Service, Tasmania, Australia

[10] Geography and Spatial Sciences, School of Land and Food, University of Tasmania, Hobart, Tasmania

[11] Departamento de Estudios Ambientales, Universidad Simón Bolívar, Caracas, Venezuela

[12] Remote Sensing Research Centre, School of Earth and Environmental Sciences
The University of Queensland, Queensland, Australia

[13] Environment Protection Authority Victoria, Macleod, Victoria, Australia

[14] Water Wetland and Coastal Science, Office of Environment and Heritage, NSW

[15] Department of Environment, Water and Natural Resources, Adelaide, South Australia, Australia

[16] Centre for Marine and Conservation Policy Research, Plymouth University, Plymouth, United Kingdom

Keywords: adaptive management, biodiversity, fisheries, environmental impact assessment, environment, socio-economic, monitoring, modelling, collaboration.

Abstract:

Sustainable management and conservation of the world's oceans requires effective monitoring, evaluation and reporting. Despite the growing political and social imperative for these activities, there are some persistent and emerging challenges that marine practitioners face in undertaking these activities. In 2015, a diverse group of marine practitioners came together to discuss the emerging challenges associated with marine monitoring, evaluation and reporting, and potential solutions to address these challenges. Three emerging challenges were identified: (1) the need to incorporate environmental, social and economic dimensions in evaluation and reporting; (2) the implications of big data, creating challenges in data management and interpretation; and, (3) dealing with uncertainty throughout monitoring, evaluation and reporting activities. We point to key solutions to address these challenges across monitoring, evaluation and reporting activities: 1) integrating models into marine management systems to help understand, interpret, and manage the environmental and socio-economic dimensions of uncertain and complex marine systems; 2) utilising big data sources and new technologies to collect, process, store, and analyse data; and 3) applying approaches to evaluate, account for, and report on the multiple sources and types of uncertainty. These solutions point towards a potential for a new wave of evidence-based marine management, through more innovative monitoring, rigorous evaluation and transparent reporting. Effective collaboration and institutional support across the science–management–policy interface will be crucial to deal with emerging challenges, and implement the tools and approaches embedded within these solutions.

1 Introduction

In order to more sustainably manage and conserve biodiversity and marine resources in the world's oceans, there has been a push from marine practitioners to implement evidence-based management, where scientific evidence from monitoring and research is used to inform more robust and transparent management decisions. Monitoring, evaluation and reporting (hereafter collectively referred to as MER) are critical stages of evidence-based management, which focus on assessing environmental state and pressures, evaluating management effectiveness, publicly reporting findings, demonstrating public accountability, and delivering the evidence-base to inform adaptive management (Pomeroy et al., 2005; Ferraro and Pattanayak, 2006; Levin et al., 2009; Jones, 2015). The decision-making processes that MER activities are commonly packaged within include: ecosystem-based fisheries management (Long et al., 2015), state-dependent conservation management (Nichols and Williams, 2006), and adaptive management of natural resources (Holling, 1978).

Marine environmental monitoring has a relatively long history in the environment sector, with some monitoring programs now running for almost 90 years (e.g., the Continuous Plankton Recorder surveys; McQuatters-Gollop et al., 2015). Whilst some of these early monitoring programs commenced as surveillance exercises to discover and explore the marine environment, more recently there has been a push to ensure the monitoring programs are fit-for-purpose to inform management needs (i.e., through evaluation and reporting activities to address evidence-based management; Pomeroy et al., 2005; Ferraro and Pattanayak, 2006; Nichols and Williams, 2006). The imperative for MER and evidence-based management is now reflected in international conventions (e.g., Convention for Biological Diversity (CBD, 2011) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR, 1992)); which, has flowed through to national and regional policy drivers for marine MER (e.g., the European Marine Strategy Framework Directive (European Commission, 2008) and the United States Federal Water Pollution Control Act (USC, 2002)). MER activities will be increasingly required as countries report their progress against the United Nations Sustainable Development Goals, and will be critical in the future management of biodiversity beyond national jurisdiction currently being negotiated at the UN (Druel and Gjerde, 2014).

Marine MER activities can be integrated within a single program, but in many cases these activities are undertaken completely separately (e.g., undertaken and funded by different organisations). For example, many monitoring programs in the Great Barrier Reef are undertaken by scientists from research institutions for a variety of reasons (e.g., scientific research through to citizen science engagement), and results from these programs are drawn upon by responsible marine decision-makers in evaluation and reporting programs like the Great Barrier Reef Outlook assessment (GBRMPA, 2014). The spatial extent of MER activities ranges from local through to global, and their temporal extent can be short-term through to on-going; these activities vary in extent depending on whether they are designed to address discrete management issues or support on-going management of the marine environment.

There are now many notable examples of marine MER activities around the world, that are compiled in outputs such as the recent global assessment of ocean health (OHI, 2017), the State of Europe's

Seas (EEA, 2017), and the Great Barrier Reef Outlook assessment (GBRMPA, 2014). In parallel, there has been increasing focus and co-ordination at both national and international levels to develop standardised methods for monitoring ecosystem variables, in order to quantify ecosystem status and trends to inform evaluation and reporting and ultimately feed into evidence-based management. Notable examples include the Reef Life Survey (Stuart-Smith et al., 2017), Integrated Marine Observing System (IMOS, 2016), the Integrated Framework for Sustained Ocean Observing (IFSOO, 2012), Essential Ocean Variables (Lindstrom et al., 2012) and ecosystem Essential Ocean Variables (Constable et al., 2016), and Essential Biodiversity Variables (Pereira et al., 2013).

Drawing on elements of the notable examples outlined above and research into best-practice MER and evidence-based management (Nichols and Williams, 2006; Kemp et al., 2012; Hallett et al., 2016; Hedge et al., 2017), there are at least seven important characteristics that define effective marine MER: (1) Having clear management objectives (e.g., related to conservation of biodiversity, sustainable harvest of natural resources, or threat reduction) and monitoring objectives (i.e., to measure key indicators related to management objectives); (2) Having robust monitoring program design, with targeted monitoring data to assess progress towards objectives and evaluate management effectiveness; (3) Having the capacity to incorporate various data sources (e.g., quantitative and qualitative monitoring data, traditional ecological knowledge and expert judgement); (4) Undertaking routine evaluation and reporting of monitoring results; (5) Producing accessible reporting for public outreach (e.g., report cards), which demonstrates progress towards achieving objectives and provides access to more detailed monitoring and evaluation reports; (6) Allowing for adaptation in response to changing environmental conditions and management needs (i.e., adaptive management); and, (7) Securing long-term funding for MER activities that extend beyond political cycles.

Despite the growing political and social imperative for MER, and the rise in MER approaches employed around the globe, there are some persistent challenges to implementing and undertaking successful marine MER activities. There are institutional challenges, such as: a lack of stability in resources to fund MER activities through time, which means that the time-frame of many important ecological changes will not be detected by MER activities (Duarte et al., 1992; Ferraro and Pattanayak, 2006); a continued failure to set clear management, monitoring and evaluation objectives (Kemp et al., 2012; Fox et al., 2014); and, persistent difficulties in accessing fit-for-purpose environmental monitoring data, successfully evaluating different types of monitoring data, and “closing the loop” to ensure the results of monitoring and evaluation informs evidence-based management (Fox et al., 2014; Addison et al., 2015). Scientific challenges also exist that limit the ability of marine MER activities to inform evidence-based management, which include the challenge of monitoring extensive, remote environments, poor scientific understanding of large-scale ecological processes and interactions, uncertainty in the attribution of cumulative impacts of threats, and in understanding the effectiveness of management interventions (Cvitanovic et al., 2015; Addison et al., 2017). Some of these persistent challenges represent the reality of organisational constraints that MER practitioners must work within, whereas other challenges are being addressed by scientific advancements and sharing best-practice lessons (Ferraro and Pattanayak, 2006; Cvitanovic et al., 2015; Addison et al., 2017). However, there are emerging challenges in the field of evidence-based marine management that are yet to be comprehensively addressed in the peerreviewed literature, and require inter-disciplinary solutions to help progress marine monitoring, evaluation and reporting activities.

Today's practitioners involved in marine MER work across the science–management–policy interface, and include scientists, decision-makers (i.e., managers and policy-makers), and knowledge brokers from government agencies, non-governmental organisations (NGOs), academic institutions, and consultancies. This diversity in practitioners means that historically some marine MER challenges have been slow to overcome, as communication and collaboration has been limited across the science–management–policy interface. However, this diversity in practitioners means that a range of technical, managerial, and political skills can be used to advance MER in the face of emerging challenges in this evolving area of evidence-based marine management (Thébaud et al., 2017).

A diverse group of marine MER practitioners from universities, government agencies, and consultancies, came together at the 2015 Australian Marine Sciences Association conference to discuss the emerging challenges and novel solutions for marine MER. This group of practitioners shared common ground in wanting to share experience and expertise to improve the management and protection of the marine environment. Here we synthesise the discussions, identifying three critical and emerging challenges facing today's marine practitioners. We then propose solutions to these challenges and in doing so offer a vision for a new wave of marine MER within evidence-based management.

2 Emerging challenges facing marine MER

Emerging challenge 1: Integrating environmental, social, and economic MER

Traditionally, marine MER activities have focussed on assessing the environmental variables in the marine environment across the water quality, fisheries and biodiversity management sectors (e.g., FAO, 2003; Hering et al., 2010; Tett et al., 2013; USEPA, 2015). Monitoring and evaluating environmental variables, such as water quality, habitat quality, ecosystem condition, and species abundance have come with a range of challenges, which include understanding and assigning causality of complex interactions in marine ecosystems, and developing suitable indicators to cut through the complexity and deliver simplified measures of environmental change (McQuatters-Gollop, 2012; Constable et al., 2016; Stuart-Smith et al., 2017). However, social and economic aspects of marine systems are increasingly being considered in the management of the marine environment, with the recognition that true sustainability needs to balance these aspects with the often opposing needs for ecological sustainability (Thébaud et al., 2017).

The social and economic dimensions of marine systems are vitally important to consider as humans have a range of connections, dependencies, and conflicts with the environmental dimension of marine systems (Marshall et al., 2016). For example, people can be financially and culturally dependent on the marine environment, which means that society and economy can draw direct benefits from oceans (e.g., community wellbeing, and livelihoods dependent on natural resources), but this dependence can also impact marine ecosystems (e.g., through unsustainable resource use; Marshall et al., 2016). Consideration of socio-economic and environmental dimensions is critical for evidence-based management, as these dimensions are often competing, thus trade-offs between dimensions will be made – whether decision-makers deal with trade-offs transparently or not. Integration in evaluation (e.g., through modelling) or reporting (e.g., through dashboards or integrated reporting) allows for interdependencies, interactions, and feedbacks between critical environmental, social and economic indicators to be explicitly considered. For example, integrated modelling of Essential Ocean Variables in the Southern Ocean is helping scientists and decision-makers explore and understand ecosystem dynamics in light of human pressures and physico-chemical properties, to help attribute drivers of change and make predictions about future changes that may require management (Constable et al., 2016).

Integrating the environmental, social, and economic dimensions within marine MER activities requires a great breadth of technical skills and knowledge, and the data generated from these different spheres do not necessarily lend themselves to integration. To date, the best efforts that have been made to incorporate environmental, social, and economic assessments within reporting programs have involved a silo approach. This is where environmental, social, and economic monitoring data are evaluated and reported separately, with some attempt to synthesize these during the reporting phase – often just verbally. Examples of these evaluation and reporting approaches include the Great Barrier Reef Outlook Report (GBRMPA, 2014), marine assessments by the Intergovernmental Panel on Climate Change (Pörtner et al., 2014), and the World Oceans Assessment (United Nations, 2016), and the French marine protected areas dashboard (Agence des aires marines protégées, 2014).

There are very few examples of integrated assessments of environmental and socio-economic factors, such as where evaluations enable trade-offs between environmental, social, and economic variables (but see: Weijerman et al., 2015 for a coral reef example). Beyond the challenges of integrating the evaluation of these different components, reporting this variety of information presents further challenges such as ensuring integrated reporting is factually reliable, aligned with management objectives, and communicates key messages clearly and simply to a broad range of audiences including the general public, marine managers, and politicians.

Emerging challenge 2: MER and the world of big data

The collection, analysis, storage, and visualisation of data are fundamental to marine MER. Early marine monitoring programs faced the challenges associated with intensive data collection and analysis, which due to resource constraints, often focused on a limited number of metrics over a small number of sites. Since then, an increased focus on marine management has fuelled the need for a greater diversity of information about marine systems (Ducrotoy and Elliott, 1997). Subsequently, marine monitoring programs have become more complex, looking at additional physical, chemical, and biological factors, often with an increased volume of data collected through monitoring and generated from modelling (De Jonge et al., 2006).

Increases in data volume and complexity have also originated from advances in monitoring technology (Vitolo et al., 2015). Modern in-situ, continuous, and remote sensing technologies (e.g., long-term deployed probes, autonomous systems, and higher resolution satellite imagery) offer increasingly larger volumes of information for scientists and environmental decision-makers (Kogan et al., 2011). Improvements in technology also extend to loggers, autonomous vehicles, telemetry networks, and databases, and this is revolutionising the way data is collected, transmitted, and stored. Rapid data availability brings a range of advantages to managers, and can enable dynamic ocean management where responses to changes in monitored social and environmental variables can be made in near real-time (e.g., in fisheries management in Australia and the U.S.A, and marine conservation management in the USA; Maxwell et al., 2015).

Despite the benefits of big data, this new world also presents a number of challenges for marine management organisations. Additional human capacity and expertise is required to ensure data quality can be assured for decision making purposes (e.g., daily checking of data plots, regular cleaning and maintenance and validation against samples to achieve the required data quality). Many organisations have also found that their systems, designed to process and store relatively simple and discrete monitoring data, have proven unsuitable in the face of institutional changes and rapidly evolving technologies. These systems lack the required architecture, complexity and processing speed for handling the volumes and variety of new data. For example, datasets may now include images, audio, video, and spatial data, along with the traditional environmental variables stored as numbers and text characters, and qualitative data in the form of expert judgement and traditional knowledge. The outputs of modelled data add another challenge as they can easily take up terabytes of storage and are not always recognised as valuable datasets requiring appropriate metadata and management in their own right.

There are a range of technologies now emerging for processing large datasets, such as more flexible web-based and geo-spatial databases that can facilitate large volumes of heterogeneous environmental data (Vitolo et al., 2015). However, the increasing scope of data collected and the potential future purposes for which it will be used, means that established tools and processes for collecting, storing and analysing datasets may become increasingly bespoke, particularly if the trend for repurposing data continues (e.g., the use of artificial intelligence and machine learning to extract new information from existing databases). The need for ever more sophisticated data processing makes it even harder to meet the open data standards, which are needed going forward to make data accessible and synoptic analyses possible.

Emerging challenge 3: The challenge of uncertainty throughout MER activities

Uncertainty is a pervasive challenge for marine practitioners across all stages of marine MER. Uncertainty is the incompleteness of knowledge, or lack of certainty in understanding and managing marine systems. Drawing on uncertainty research (Regan et al., 2002; Kujala et al., 2013), we classify three (non-mutually exclusive) types of uncertainty relevant to marine MER activities: 1) epistemic uncertainty - the gaps in knowledge or lack of certainty in socio-ecological system understanding (both current state and future regime shifts), uncertainty in the measurement of ecosystems, and uncertainty in model representation; 2) linguistic uncertainty - vagueness or ambiguity in terms, expressions or concepts used to develop objectives, select indicators and interpret monitoring results; and, 3) decision-making uncertainty – subjective judgment and human preferences that can influence or bias indicator or model parameter selection, choice of normalization of monitoring data, and model interpretation (Table 1).

Uncertainty is present across all stages of marine MER, and can influence activities such as: setting management objectives (e.g., influenced by linguistic uncertainty, where a vagueness of terms used in management objectives can have very different meanings to different people); monitoring program design (e.g., influenced by epistemic uncertainty, where information gaps, lack of certainty about ecosystem processes, and natural variation will influence monitoring program design); model design and parameterisation (e.g., influenced by epistemic and decision-making uncertainty, where subjective human judgement can influence the type of model and parameters included in models; Table 1).

Models and the modelling process are themselves important sources of uncertainty, but, if used appropriately, they offer opportunities to explicitly consider and account for uncertainty by exploring and clarifying epistemic uncertainty in system understanding, monitoring program design, and decision-making rules. Another key opportunity for better dealing with uncertainty is improving decision-making processes using participatory methods and approaches to elicit expert judgement to reduce subjective bias, linguistic uncertainty and decision-making uncertainty (see further discussion in Solution 1 and 3). Despite opportunities and methods to robustly consider and account for uncertainty, scientists and managers alike commonly fail to account for uncertainty. Common traps evident in environmental science and management include: completely ignoring the influence of uncertainty in monitoring data and in decision-making, addressing an incomplete set of more trivial uncertainties in models, believing that models represent the truth, and failure to set unambiguous objectives (Milner-Gulland and Shea, 2017).

An emerging issue for marine MER activities is how to address uncertainty in reporting of monitoring results, as this is subject to epistemic, linguistic and decision-making uncertainty (Table 1). Report cards are a common output of MER activities, which often include ratings of condition of environmental or socio-economic indicators to reflect the status and trends in environmental and socio-economic attributes (e.g., GBRMPA, 2014; Carey et al., 2017). Report cards help simplify complex monitoring information for public reporting to a broad audience ranging from scientists, to policy-makers and the general public. They commonly present colour coded condition assessments of environmental or socio-economic indicators. Whilst these reporting formats provide clear and simple messages, this perceived simplicity can be misleading as uncertainty associated with environmental or socio-economic attributes can be completely hidden, and ecosystem complexities (e.g., multi-state systems) can be over-simplified. The failure to explicitly communicate uncertainty in report cards can arise from: i) the motivation to present simple results in report cards (i.e., hiding error bars), and ii) the incorrect treatment of uncertainty in underlying models used in evaluations that are presented in report cards (i.e., epistemic uncertainty not incorporated into model parameters). Either way, the outcome of failing to deal with uncertainty can mean that readers, including managers, policy-makers, and the general public may be misled by interpreting results with false certainty (e.g., with a water quality report card: Queensland Audit Office, 2015).

Table 1. A taxonomy of uncertainty affecting marine monitoring, evaluation and reporting.

Type of uncertainty	Issue	Various stages of MER that can be influenced by uncertainty						
		Setting management objectives	Indicator selection	Monitoring program design	Model design & parametrisation	Interpretation of monitoring data and model outputs	Reporting monitoring results	Evidence-based management
Epistemic uncertainty	*Gaps and lack of socio-ecological system understanding* e.g., information gaps and lack of certainty about ecosystem processes, such as ecosystem interdependencies, interactions, and feedbacks between variables.	•	•	•	•	•	•	•
	Natural variation, measurement or systematic error e.g. the natural variability of socio-ecological systems, and the uncertainty that arises from monitoring (i.e., measurement error) and modelling these systems (i.e., systematic error).			•	•	•	•	•
	Model structure uncertainty e.g., representation (or lack of representation) of socio-ecological variables in models.				•	•	•	•
Linguistic uncertainty	*Vagueness or ambiguity in terms, expressions or concepts* e.g., vagueness and ambiguity in the description of management objectives; ambiguity in indicator selection (based on different interpretation of objectives); and ambiguity of ecosystem concepts in reporting of monitoring results.	•	•	•	•	•	•	•
Decision-making uncertainty	*Subjective judgement and uncertain preferences* e.g., the human values and subjective judgment that can influence or bias decision-making (i.e., in indicator or model parameter selection, choice of normalization of monitoring data, approach to weighting or aggregating indicators (e.g., in composite indicators or multi-objective models), and in the interpretation of model outputs).	•	•	•	•	•	•	•

3 Solutions for a new wave of marine MER to support evidence-based management

The field of MER has evolved considerably over the last decade, but addressing the challenges we have outlined above requires innovative solutions. We believe the solutions proposed here will assist with developing and sustaining MER activities so that they meaningfully inform the development of policy and implementation of evidence-based management of the marine environment. Marine practitioners with a diverse range of expertise will need to effectively collaborate across the science–management–policy interface to implement the recommended solutions. Thus, we cannot stress enough the human dimension of our solutions, in the form of effective collaboration and enabling political conditions, and their critical role in the implementation of these solutions to support a new wave of marine MER and evidence-based management.

Solution 1: Integrating modelling and monitoring to maximise MER activities in evidence-based management

An integration of data and models should be at the core of MER activities. Data-integrated modelling applications have been extensively used in this context in some marine sectors, like fisheries management (Link et al., 2002; Collie et al., 2014), and are a core component of adaptive management (Addison et al., 2013), but uptake has been less widespread in other marine sectors. In some cases this may be because marine monitoring data have not been available or adequately targeted to address marine management needs (Fox et al., 2014; Hedge et al., 2017), but in other cases it may be because marine practitioners have not been aware of, or have not had access to, the full suite of models that could support management decisions, and may not have considered modelling as complementary to monitoring.

Models are abstractions of real world phenomena that can help make environmental and socio-economic processes easier to understand. One model will never suit all applications; rather a toolbox of models of different types, complexity and scope are often required to support environmental management (Table 2). Models can span a range of complexity from simple conceptual models that help formalise and clarify our understanding of how systems work (e.g., used in the scoping and monitoring phases), to statistical models that help interpret monitoring data and quantify patterns and associations in systems (e.g., used in the evaluation and reporting phases), through to mechanistic models that can mathematically represent real-world processes (e.g., used to inform the management response phase). A toolbox of models can assist with integrating multiple lines of evidence (e.g., expert judgement, traditional knowledge, and monitoring or research outputs), reducing or highlighting epistemic or linguistic uncertainty, evaluating alternative decision scenarios, and clarifying cause-and-effect relationships for marine practitioners to better understand and manage marine systems. Furthermore, spatially explicit and dynamic mechanistic models (e.g., oceanographic / hydrodynamic models, and species distribution models) can allow us to evaluate processes and environmental condition on scales that are much larger than can generally be achieved though monitoring alone.

Models are not a panacea, and on their own cannot drive marine MER activities towards more robust evidence-based management. If not well understood, model outputs can easily be misinterpreted and used incorrectly to inform decision-making. For example, a recent study of papers reporting marine socio-ecological model forecasts found that the majority (90%) failed to account for uncertainty in the interpretation of model outputs, which can have profound effects on decisions based on model outputs (Gregr and Chan, 2014). For models to be useful in evidence-based management, they require effective collaboration between marine practitioners to ensure that models are developed within existing management frameworks, and that models of appropriate scope and complexity are used to address management questions (Addison et al., 2013; Cartwright et al., 2016). Examples where models have been integrated into management frameworks, include: the use of fisheries models to set catch limits worldwide (Tittensor et al., 2017); the use of statistical models within an adaptive management process for protected areas in Australia (Carey et al., 2017); and the Atlantis model, which is a representation of the management strategy evaluation cycle (including a full end-to-end ecosystem model) and is used operationally to inform marine ecosystem management decisions in both Australia and the U.S.A. (Fulton et al., 2011).

Developing "toolboxes" of models will help marine practitioners explore how to better understand the system they are managing, use existing monitoring evidence to test their understanding, and subsequently in management, potentially identify where more or different monitoring and evaluation techniques are required. Model toolbox (or ensemble) approaches are also essential for overcoming the emerging challenge associated with integrating environmental, social and economic aspects of MER (Emerging challenge 1; e.g., previously called for in marine natural resource and conservation management (Melbourne-Thomas et al., 2011; Long et al., 2015; Marshall et al., 2016)). There are currently relatively few examples where models have simultaneously incorporated environmental and socio-economic variables in evaluation and reporting stages of MER. However, some notable examples that are emerging include: conceptual models to define complex socio-ecological systems (e.g,. conceptual models developed by stakeholders for Australian marine park management, to explore and document perceptions of critical ecological and socio-economic values and pressures in marine systems; Bryars et al., 2016); through to more complex, dynamic whole-of-ecosystem models to test and predict ecological and socio-economic dynamics (e.g., ecosystem models used to inform ecosystem-based management, such as Atlantis (Fulton et al., 2011), Ecopath with Ecosim (Heymans et al., 2016), and CORSET (Melbourne-Thomas et al., 2011)).

Integration of environmental and socio-economic variables in evaluation and reporting stages of MER does not solely rely on a one-way process of feeding data into models. There are also exciting developments in platforms (models with user-friendly, visual displays) that can process and display environmental and socio-economic data in an interactive dashboard. Such models are important to support interpretation and uptake for more rapid and effective evidence-based management. For example, the dynamic ocean management applications outlined in Maxwell et al. (2015), such as the Turtle Watch program in Hawaii that displays information on temperature fronts and satellite tracking of loggerhead sea turtles to help guide reduced turtle bycatch in local fisheries.

The toolbox of models approach we propose to support MER activities will also help address the emerging challenge of big data, as statistical models become critical for dealing with increasing volumes of data and modelling complex natural system patterns (Spiegelhalter, 2014; addressing Challenge 2). For example, Markov, Bayesian and dynamic modelling are being used to help predict (and not just observe) species distributions, population dynamics, and inform biodiversity management, by drawing on increasingly larger datasets (Gimenez et al., 2014).

The use of multiple modelling approaches can also help support marine managers in clarifying uncertainties in interpreting monitoring data (helping overcome Challenge 3; Table 2)). For example, a diverse set of qualitative models was used to explore and test sources of epistemic and linguistic uncertainty associated with the system dynamics of Australia's commonwealth waters, where the level of system knowledge varied greatly between environmental assets. This allowed the selection of asset-specific indicators to inform monitoring program designs (Hayes et al., 2015).

Finally, using a toolbox of models is also a good way to explore model structure (epistemic) uncertainty (Challenge 3), by considering variability of outcomes from different modelling approaches. Importantly, this requires that there is actually structural diversity among the models, and the same assumptions and flaws are not present in all models and simply being represented in different ways (Gregr and Chan, 2014).

Table 2. Types of models and their application through the different stages of marine monitoring, evaluation and reporting activities.

MER phase	Qualitative and conceptual models	Statistical models	Dynamic and mechanistic models
Monitoring	• Assist with indicator selection (e.g., conceptual and systems models)	• Understand patterns and interactions when selecting indicators (e.g., statistical analysis of historic data, or meta-analysis of published results) • Inform monitoring program design (e.g., power analysis using baseline monitoring data or published results)	• Inform indicator and target selection (e.g., ecosystem models) • Inform monitoring strategy (e.g., observation models) • Inform monitoring program design (e.g., model evaluation of monitoring strategies)
Evaluation	• Understanding surprises (e.g., conceptual models) • Distinguishing mechanisms of change	• Understand patterns of monitored indicators (e.g., statistical analysis of monitoring data) • Support model choice where alternative models exist	• Extrapolating monitoring data over larger scales (with accompanying estimates of uncertainty)
Reporting	• Displaying ecosystem interactions between threats, ecosystem status and management responses (e.g., conceptual models)	• Display temporal or spatial patterns in monitored indicators (e.g., statistical model outputs)	• Display modelled results

Solution 2: Working effectively in the world of big data

Some of the most prevalent opportunities that have arisen for marine monitoring programs over the last decade have come through improvements across the data life-cycle. Of particular note are advances in the technology and systems for data collection, transmission, management, processing, and analysis. These advances have opened doors for novel and more cost-effective monitoring techniques, which are seen in regional and global collaborative projects dedicated to observing and measuring ocean attributes (IFSOO, 2012; Meredith et al., 2013; Constable et al., 2016; IMOS, 2016). Combining some of these technologies offers a previously unheard-of range of options available to MER practitioners to collect high-quality data, that capture daily, seasonal, annual and event-based environmental variability, and in some cases, inform real-time marine management (Maxwell et al., 2015; Edgar et al., 2016). It is not just technology that is contributing to the big data era – people are too. The management of big data requires new collaborations between marine practitioners and data scientists with expertise in programming languages and packages like R and Python. These new collaborations are making it possible to manage and analyse extremely large, complex data sets to inform marine evidence-based management.

Citizen science offers another area of growth for marine data collection and analysis (Gimenez et al., 2014). Citizen science uses volunteers to collect and/or analyse data, and cost-effectively increase research capacity and potentially fill data gaps (e.g., in scientific monitoring programs) over large geographic areas (Bird et al., 2014; Vann-Sander et al., 2016; Stuart-Smith et al., 2017). Many citizen science programs are beginning to supplement traditional modes of field data collection with mobile phone apps, which are a versatile data collection tool supported by mobile capabilities like GPS, camera, clock, and data storage (e.g., Marine Debris Tracker, 2017; Project Seagrass, 2017; Secchi Disk, 2017). There have sometimes been concerns over the quality of citizen science datasets (Vann-Sander et al., 2016). Data quality is not an issue confined to citizen science, however, and there is growing recognition of effective ways to tackle issues of data quality, which include adequate training of data collectors, quality control mechanisms for collected data, and statistical consideration of data quality or observer error during analysis and interpretation (e.g., as addressed in the Reef Life Survey citizen science program; Edgar and Stuart-Smith, 2009; Bird et al., 2014). Collaboration between marine practitioners and new partners, like citizen scientists, are opening up new opportunities to bring additional information into marine MER activities.

Improved modes of data collection form only part of the digital age innovations for marine MER, and in response to the rise in big data, non-relational databases are now emerging to help deal with the ever-increasing volume of complex and varied data (Vitolo et al., 2015). A crucial aspect of these databases is metadata, which allow data to be more confidently used in the future, potentially in ways not envisaged by the original collector, and as more powerful and innovative analytical techniques are developed (e.g., Seeley et al., 2009). A vast array of modelling techniques matched with online technologies now exist to support the processing of large and multidimensional datasets (Maxwell et al., 2015; Vitolo et al., 2015).

It is impossible for MER practitioners to be experts in the varied fields required to be able to effectively interpret and most effectively apply data from varied sources to management processes. Thus, collaboration is key to fully utilise the increasing volume and variety of data available to inform marine MER. Many bespoke data management solutions are emerging (Vitolo et al., 2015), but the next step for marine MER practitioners will be to share and create best-practice data management and sharing standards in the world of big data.

Digital datasets, especially those available online, now offer marine practitioners access to a wealth of information that would have been previously inaccessible. Examples include the Ocean Biogeographic Information System, the Australian Ocean Data Network and a variety of government data portals. This increased accessibility becomes even more valuable when we consider MER practitioners looking to work across environmental, social, and economic spheres. While this sort of data sharing and accessibility is yet to be uniformly adopted by individuals or organisations (Huang et al., 2012), it is at least recognised that there is a growing trend for MER practitioners willing to share their data (Wallis et al., 2013). Furthermore, governments are embracing open access data and requiring publicly-funded institutes to make their data accessible to the public. The next challenge to be tackled is how to encourage and facilitate the sharing of environmental data collected by industry, such as commercial fisheries and proponents undertaking environmental impact assessment, where access to these data is commonly restricted by commercial-in-confidence clauses. Responsible and effective use of shared monitoring data will require: strict data quality assurance/quality control (QA/QC) procedures to ensure the quality of data prior to sharing (Addison, 2010), standardised metadata specifying essential details of the data to minimise potential for mis-use (Vitolo et al., 2015), approaches to protect commercial-in-confidence elements, and a robust data sharing policy that benefits both the user and data provider by supporting the ongoing funding of the monitoring (Juffe-Bignoli et al., 2016).

Solution 3: Approaches to evaluate, account for, and report on uncertainty in MER

Environmental management is subject to diverse sources of uncertainty (e.g., epistemic, linguistic and decision-making uncertainty), which affects all stages of marine MER (Challenge 3; Table 1). During the evaluation phase, a range of models can be used to help interpret patterns in environmental condition (Table 2), and statistical models have the functionality to robustly explore and account for epistemic uncertainty. As mentioned in Solution 1, model simulations, sensitivity analysis or Bayesian methods can help account for epistemic uncertainty and in the interpretation of environmental patterns detected in statistical models (e.g., Spiegelhalter, 2014; Milner-Gulland and Shea, 2017). Similarly, statistical power analysis can help practitioners understand and account for epistemic uncertainty associated with natural variation, measurement error, and modelling approaches (Gimenez et al., 2014; Milner-Gulland and Shea, 2017).

Mechanistic models can be used to make predictions about environmental responses to a range of management interventions, and test the effect of epistemic uncertainty associated with model parameters (e.g., using Monte Carlo simulation) – helping identify parameters that may need additional data and testing to help understand natural system dynamics (Fulton et al., 2011; Heymans et al., 2016). Finally, model inter-comparisons and ensemble approaches (e.g., using statistical models to combine outputs from multiple mechanistic models) can account for structural uncertainty associated with individual models, by considering whether structurally distinct models give consistent or divergent results, and thus can help resolve epistemic uncertainty in system understanding and model representation.

Models cannot, however, directly address linguistic and decision-making uncertainty. Instead, this is where the human dimension of decision-making dominates, and where structured decision-making processes and expert elicitation methods can be used to reduce the influence of linguistic and decision-making uncertainty in objective setting, indicator development and monitoring design. For example, structured decision-making in addition to objectives hierarchies can be used to ensure management objectives and indicators are carefully defined prior to monitoring (Addison et al., 2013). When expert judgement is used (e.g., to inform quantitative model parameters), more structured methods of elicitation can be used to minimise subjective bias and linguistic uncertainty (e.g., the four-step elicitation and Delphi procedure used to elicit judgements from groups of experts; Hemming et al., 2017).

When it comes to reporting uncertainty in socio-ecological assessments, lessons can be learnt from climate reporting. In response to great public and political interest and interrogation of climate change the Intergovernmental Panel on Climate Change provides guidance on reporting uncertainty (Mastrandrea et al., 2010), which includes articulating confidence in the datasets used in assessments as well as in the final interpretation made in the assessment. Confidence is already communicated by some notable marine report cards from Australia, Europe and the USA (PIFSC, 2016; EEA, 2017; Karnauskas et al., 2017). Drawing on lessons from these report cards, we recommend: 1) use of categorical estimates of confidence to support condition and trend assessments made by experts or estimated from monitoring data (e.g., Victorian MPA assessments include confidence categories 0-25%, 26-50%, 51-75%, 76-100%; Carey et al. (2017), and State of Europe's Seas assessments include high, medium and low confidence in ecological assessments made (EEA, 2017)); 2) include a measure of comparability with the previous report card assessments (e.g., the Australian State of Environment Report demonstrates the level of comparability between 2011 and 2016 assessments as comparable, somewhat comparable, not comparable and not previously assessed; Evans et al. (2017)); and, 3) allow the evidence (e.g., reports and papers) used in assessments to be accessed and considered independently (e.g., the online Gladstone Harbour report card allows full interrogation of supporting monitoring data (GHHP (2016)), and the Ocean Health Index online platform allows users to drill down to evidence used for all assessments (OHI (2017)).

4 Conclusion: the new wave of MER

Monitoring, evaluation, and reporting activities help us understand environmental state and pressures, evaluate management effectiveness, and provide the evidence-base to inform management decisions and policy. The growing political and social imperative for MER reflected through international conventions and national policy drivers means that marine MER is no longer an optional activity, but a necessity.

As the number of marine MER approaches employed around the globe has risen, we have witnessed the emergence of challenges associated with MER activities, including: 1) the need to incorporate environmental, social and economic dimensions of the marine environment in evaluation and reporting programs; 2) the implications of big and open data creating challenges in the collection, analysis, storage, visualisation and accessibility of data; and, 3) uncertainty throughout monitoring, evaluation and reporting activities that is not transparently acknowledged or accounted for. These new challenges require innovative solutions to help support a new wave of MER. We have pointed to key solutions that offer a vision for a new wave of more robust and transparent marine MER within evidence-based management: 1) integrating models into marine management systems to help understand, interpret and manage the environmental, social, and economic dimensions of uncertain and complex marine systems; 2) utilising big data sources and new technologies to collect, process, store, and analyse data; and, 3) applying approaches to evaluate, account for, and report on the multiple sources and types of uncertainty in MER (Figure 1).

The successful implementation and application of these solutions requires a diverse range of expertise, thus collaboration is key. Marine MER will increasingly require extensive and effective collaboration across the science–management–policy interface. To facilitate the transfer of technical expertise and information, newer modes of interdisciplinary collaboration and knowledge exchange are required. These will help break the old model of academic scientists working in isolation, employing idiosyncratic techniques that cannot be compared with other studies, with little appreciation of the context and limitations of marine management, and marine managers not having access to or an awareness of new scientific techniques and innovative solutions to progress evidence-based management. New modes of collaboration can occur through: the establishment of boundary organisations or consulting arms of universities to undertake applied research; by embedding research scientists in marine management agencies to work with decision-makers or vice versa; and, by employing knowledge exchange practitioners to help facilitate the multi-directional transfer of knowledge and co-development of fit-for-purpose MER approaches (Michaels, 2009; Cvitanovic et al., 2015). Effective institutional structures within policy (Brooks and Fairfull, 2016) and academia (Keeler et al., 2017) will be critical in supporting and enabling this type of inter-disciplinary collaboration.

While the diversity of MER activities means that there is no single successful approach to address the multitude of challenges, the solutions, illustrative examples and synthesis of tools provided here offer a pathway towards innovative monitoring, rigorous evaluation and transparent reporting (Figure 1). It will be up to marine practitioners to consider and implement these solutions and make their scientific results increasingly relevant and enduring, thus improving our collective ability to more sustainably manage marine resources and conserve biodiversity in the world’s oceans amidst complex management challenges.

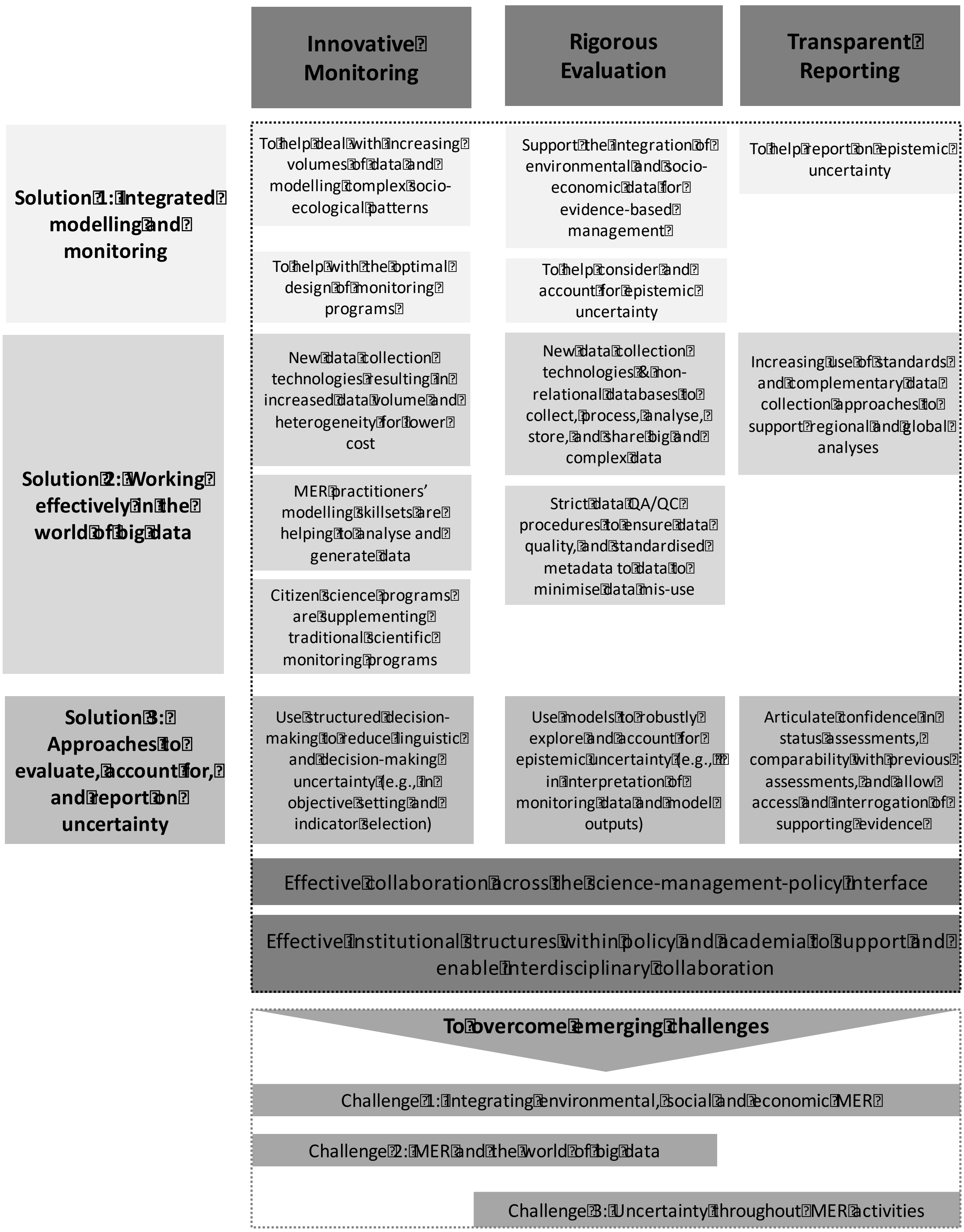

Figure 1. Solutions to support a new wave of MER – towards innovative monitoring, rigorous evaluation and transparent reporting. A conceptual diagram synthesizing the key recommendations made within each of the three solutions.

5 Acknowledgements

We wish to acknowledge all of the marine scientists and managers who presented their research and shared their ideas at the Marine Monitoring Evaluation and Reporting symposium at the Australian Marine Sciences Association conference in July 2015. Initial discussions with symposium participants helped shape this paper, and we thank all of those involved in the symposium for their contributions. PFEA and AMG thank the UK Natural Environmental Research Council for support through the NERC Knowledge Exchange fellowship scheme (NE/N005457/1 & NE/L002663/1). NB, PH and RDSS were supported by the Marine Biodiversity Hub, a collaborative partnership supported through the Australian Government's National Environmental Science Programme (NESP). RT was supported by the RJL Hawke Postdoctoral fellowship.

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