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Lessons learned from developing integrated ecosystem assessments to inform marine ecosystem-based management in the USA

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Borne out of a collective movement towards ecosystem-based management (EBM), multispecies and multi-sector scientific assessments of the ocean are emerging around the world. In the USA, integrated ecosystem assessments (IEAs) were formally defined 5 years ago to serve as a scientific foundation for marine EBM. As outlined by the US National Oceanic Atmospheric Administration in 2008, an IEA is a cyclical process consisting of setting goals and targets, defining indicators, analysing status, trends, and risk, and evaluating alternative potential future management and environmental scenarios to enhance information needed for effective EBM. These steps should be hierarchical, iterative, non-prescriptive about technical implementation, and adaptable to existing information for any ecosystem. Despite these strengths and some initial successes, IEAs and EBM have yet to be fully realized in the USA. We propose eight tenets that can be adopted by scientists, policy-makers, and managers to enhance the use of IEAs in implementing EBM. These tenets include (i) engage with stakeholders, managers, and policy-makers early, often, and continually; (ii) conduct rigorous human dimensions research; (iii) recognize the importance of transparently selecting indicators; (iv) set ecosystem targets to create a system of EBM accountability; (v) establish a formal mechanism(s) for the review of IEA science; (vi) serve current management needs, but not at the expense of more integrative ocean management; (vii) provide a venue for EBM decision-making that takes full advantage of IEA products; and (viii) embrace realistic expectations about IEA science and its implementation. These tenets are framed in a way that builds on domestic and international experiences with ocean management. With patience, persistence, political will, funding, and augmented capacity, IEAs will provide a general approach for allowing progressive science to lead conventional ocean management to new waters.

Keywords: ecosystem-based management, indicator, integrated ecosystem assessment, marine policy, risk, sustainable marine management and conservation.

Introduction

People are unquestionably dependent upon the services that marine ecosystems provide (Guerry *et al.*, 2012). In turn, ocean conditions are affected by people's actions and influences (Halpern *et al.*, 2012). Marine resources face a well known and growing list of pressures and demands—from long-standing activities like fisheries and extraction of fossil fuels, to newer uses such as wind and wave energy (Halpern *et al.*, 2008). Because of existing governance structures, ocean managers have historically tackled the most pressing activities, and addressed them one-by-one (Kareiva and Marvier, 2011).

However, in the face of emerging uses and increasing demands from existing activities, this reactive, sectoralized approach to ocean management has been called into question (Levin and Lubchenco, 2008). Protected areas, for instance, may achieve some conservation objectives within their boundaries, but without coordinated management outside of their boundaries, displaced fishing effort may result in the degradation of an ecosystem as a whole (Hilborn *et al.*, 2006; Jennings, 2009). Similarly, reductions in chemical pollution and improvements in water quality have facilitated the recovery of endangered coastal species such as the bald eagle, but recovery of eagles has led to the decline of some other seabird species and overall diversity (Hipfner *et al.*, 2012). As these examples illustrate, well intentioned but segmented management has the potential to interfere with other ecosystem goals and perhaps even degrade the overall state of marine environments.

A potential solution is a more systematic, integrated approach known as ecosystem-based management (EBM; McLeod and Leslie, 2009). The transition to EBM will not be easy, fast, or simple. It is likely to be gradual and iterative, building on existing single species and single-sector governance where possible and characterized by trial-and-error learning where such building is not possible. The evolution of comprehensive management is likely to benefit from integrated science—a rarity in many regions. In the USA, the National Oceanic and Atmospheric Administration (NOAA) has been developing the integrated ecosystem assessment (IEA) as a means to conduct and deliver integrated, cross-sectoral science to support EBM (Levin *et al.*, 2009). IEAs transparently identify socio-economic and biophysical attributes that maintain ecosystem structure and function, assess human activities and their interdependence with the natural ecosystem, and evaluate management alternatives that will maintain or improve the coupled social-ecological system (Figure 1).

While IEAs are a major step forward for developing the science to support EBM (Foley *et al.*, 2013), both in the USA and around the world (Smith *et al.*, 2007; European Commission, 2008; Katsanevakis *et al.*, 2011; ICES, 2011, 2013a, b, c, Möllmann, in press), widespread confusion exists about what, exactly, defines an IEA, and how to use an IEA so that it informs on-the-water actions. A companion paper by Levin *et al.* (this volume) and previous descriptions (Levin *et al.*, 2008, 2009) delineate one perspective of what an IEA is. In this article, we explore the question of how such IEAs can be used in US ocean management now (through several proposed tenets), discuss reasonable expectations of IEAs in the context of implementation of EBM, and offer some suggestions about what needs to happen next to make better use of them. Our perspective on these topics is based on our collective experience attempting to inform EBM via IEAs in the USA, largely learning by trial and error, while doing our best as scientists to create a solid technical basis from which to conduct EBM. We hope this mini-review of what has worked well, what has not worked well, and what may work well in the USA will be of interest to those developing integrated scientific assessments, and trying to avoid potential impediments to their use, for ocean management around the world.

Brief history of IEAs in the USA

High-profile reports by the US Oceans Commission (USCOP, 2004) and the Pew Oceans Commission (POC, 2003) stressed the importance of incorporating ecosystem principles into US ocean and coastal resource management. Indeed, the premise of EBM is now codified in the US National Ocean Policy (Obama, 2010; USNOC, 2013). In response to recommendations of these reports suggesting the need for technical information to support EBM decisions, NOAA's Science Advisory Board commissioned an external review of NOAA's ecosystem research. The resulting report (Fluharty *et al.*, 2006) recommended that NOAA prioritize the production of IEAs, although the report did not precisely define an IEA. As a result, NOAA developed the US IEA framework (Levin *et al.*,

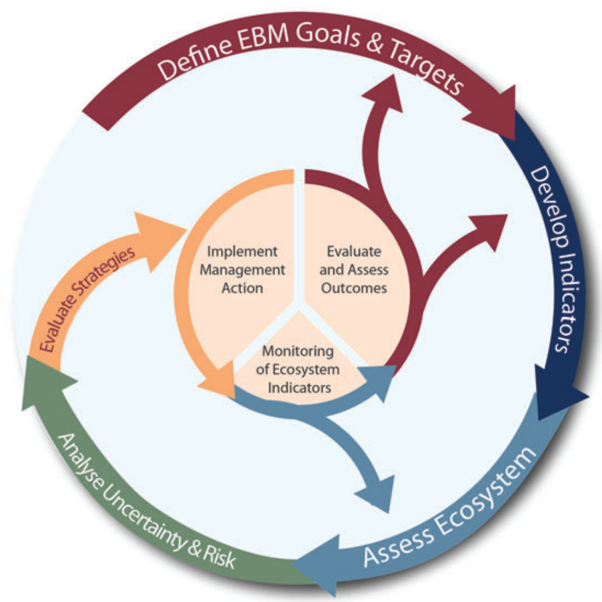

Figure 1. Conceptual schematic describing the cyclical, iterative nature of IEAs at the US NOAA. This figure is an update of the characterization of the approach depicted in Levin *et al.* (2009). *Define EBM goals and targets:* the IEA process involves manager engagement to identify critical ecosystem management goals and targets to be addressed through and informed by the IEA approach. The rest of the process is driven by these defined objectives, which can be informed by available scientific syntheses during the development of the first IEA in any region. Engagement is continual throughout the entire IEA process. *Develop indicators:* indicators represent key components in an ecosystem and allow change to be measured. They provide the basis to assess the status and trends in the condition of the ecosystem or of an element within the system. Indicators are essential to all subsequent steps in the IEA approach. *Assess ecosystem:* ecosystem indicator data are assessed together to evaluate overall ecosystem status and trends relative to ecosystem management goals and targets. Individual indicators are assessed to determine the underlying cause for the observed ecosystem status and trends. *Analyse uncertainty and risk*: ecosystem analyses and models evaluate risk to the indicators (and thus the ecosystem) posed by human activities and natural processes. These methods incorporate the degree of uncertainty in each indicator's response to pressures. This determines incremental improvements or declines in ecosystem indicators in response to changes in drivers and pressures and to predict the potential that an indicator will reach or remain in an undesirable state. *Evaluate strategies:* management strategy evaluation (MSE) is useful to help resource managers consider trade-offs and potential for success in reaching targets. It relies on ecosystem modelling and empirical analysis to evaluate the potential for different management strategies to influence the status of natural and human system indicators and to achieve stated ecosystem objectives. *Taking, monitoring, and assessing action:* Based on the MSE, an action is selected and implemented. Monitoring of indicators is important to determine if the action is successful; if yes, the status, trends, and risk to the indicators continue to be analysed for incremental change. Otherwise as part of adaptive management, the outcomes need to be assessed and evaluated to refine goals, targets, and/or indicators.

2009) as a cyclical process consisting of setting goals and targets, defining indicators, analysing status, trends, and risk, and evaluating alternative potential future management and environmental scenarios (Figure 1). The NOAA approach is a direct descendant of approaches advocated by Caddy (1999), Sainsbury *et al.* (2000), and Smith *et al.* (2007), but it is related to decades of EBM thinking around the globe (reviewed by Rosenberg *et al.*, 2009; also see European Commission, 2008; Katsanevakis *et al.*, 2011; ICES, 2011, 2013a, b, c; Möllmann, in press).

Underpinning the distinct IEA steps (Figure 1) are four integrative ideas. First, an IEA is hierarchical: all indicators, status assessments, risk analyses, and scenario evaluations must map back to the established ecosystem management goals. Second, IEAs must be considered an iterative process. This idea complicates an otherwise hierarchical structure during the development of the first IEA for a region. The process of setting ecosystem management goals for the first time can definitely benefit from synthesis of scientific information that allows a description of what is possible from a multi-sector perspective. For example, in what has emerged as a national example of EBM implementation, a synthetic scientific report was produced in Puget Sound, WA (Ruckelshaus and McClure, 2007), before the delineation of ecosystem goals by the regional management agency. Indeed, the first IEA for any region, and any major changes to ecosystem management goals, requires an iterative dialogue between scientists and those charged with setting goals. Third, the IEA is not prescriptive about analytical approaches. There are a variety of qualitative and quantitative tools that can be used to conduct an IEA, and the appropriate tool depends on the particulars of data availability, scientific capacity, and ecosystem goals. Thus, because it is not prescriptive, an IEA can be implemented now, over a range of spatial and temporal scales, for a variety of ecosystem objectives (Tallis *et al.*, 2010). Fourth, an IEA is fundamentally cross-sectoral. That is, IEAs address drivers, pressures, and impacts on ecosystem services that cross ecosystems, habitats, species, and human activities and institutions. Thus, ecosystem assessments that address a single sector (e.g. fisheries) cannot be considered truly integrated (Levin *et al.*, 2009).

IEAs are currently under development throughout the USA in a phased implementation strategy (Table 1). NOAA selected the California Current for the first full IEA development, and work began in 2009. There is also formal IEA work being conducted in the Gulf of Mexico, the US Northeast Shelf, Alaska, and the Pacific Islands. Although IEAs were introduced only 5 years ago as an approach to enable marine EBM (Levin *et al.*, 2008), there are already examples that illustrate how they can and will be used.

A key success of the US IEA programme has been the adoption of a standard conceptual framework that facilitates customized implementation. While IEA products are best tailored to regional goals and institutions, the existence of a common, cyclical approach (Figure 1) has provided for national consistency while enabling and encouraging regional flexibility. It is already clear that this programme design eases internal and external communication and enhances the potential for regional comparisons.

Perhaps as a result of national consistency and regional flexibility, the "clientele" for IEAs is substantial and growing. The primary IEA clients include (i) new decision-making entities that have emerged to address increasingly diverse ocean uses in a comprehensive fashion (e.g. regional planning bodies and regional ocean partnerships); and (ii) marine resource managers who are required by law to incorporate ecosystem considerations into their decisions but need tools to do so in a useful way.

As an example, in 2008, the West Coast Governors Alliance (WCGA) created the WCGA IEA Action Coordination Team to address the following issue (their Action 3.2): *Assess physical, biological, chemical, and socio-economic factors in ecosystem health across the West Coast to establish standards and indicators for ocean health.* The WCGA IEA team created a plan to divide the dynamic and heterogeneous California Current Large Marine Ecosystem into six subregions to allow for local customization. For example, the Oregon Coast sub-IEA may focus on interactions of fisheries and renewable ocean energy projects, whereas the Southern California sub-IEA may be more concerned with water quality issues that can lead to frequent beach closures in popular recreation areas.

Although IEAs are a nascent enterprise in the USA, there has been ample opportunity for growth and progress. While no region in the USA can yet boast a fully mature IEA, the IEA approach must nonetheless look forward to ensure that it is actually used to facilitate EBM. Below we identify eight key tenets (Table 2) that we have extracted from the US experience, with the objective of improving the implementation and practice of IEAs. These tenets are by no means unique to the USA. Indeed, they build on best practices proposed elsewhere (e.g. UNEP and IOC-UNESCO, 2009) but are focused on areas in which emphasis is needed to see IEAs implemented in the USA: transparency, accountability, assurance of scientific rigor, and forging effective links between IEA science and ocean policy. It is our hope that clear articulation of these tenets will help scientists, managers, and policy-makers avoid potential pitfalls as ocean management transitions from its historical focus on single species and single sectors to the one that is ecosystem-based.

Key tenets of IEA implementation and practice

1. Engage with stakeholders, managers, and policy-makers early, often, and continually

Good communication underlies almost all successful applications of science to management and policy (Olson, 2009; Baron, 2010). The success of IEAs depends fundamentally on the scientist–manager–stakeholder dialogue in which scoping sessions serve to support the policy-making process that leads to the establishment of a shared vision of the current and future desired states of their ecosystem. This dialogue provides an opportunity for scientists to evaluate realistic alternative approaches for management to achieve desired states. Interactions between scientists, managers, and stakeholders must not be limited to a one-time event, but should be maintained to adapt scientific products, management strategies, and ecosystem goals over time (Watson, 2005; Fletcher, 2007; UNEP and IOC-UNESCO, 2009; deReynier *et al.*, 2010).

There are a number of means that IEA teams can use to engage the larger EBM community. In countries like the USA, these include presenting IEA science in person or via webinars, developing web content, engaging in social media, producing web-based videos (http://www.noaa.gov/iea/multimedia/index.html), and convening workshops, among others. Critically, effective communication must consider the technical and scientific knowledge of each user. Sophisticated data analyses and mathematical models that are a large part of IEAs may not be accessible to all users (cf. Gleason *et al.*, 2010). Such hesitancy can be assuaged by communicating in a way that is tailored to specific interests and the knowledge base of each audience. For some groups, using marine spatial planning as an entre to the utility of IEAs may be useful, while for others, it may be better to explain an IEA as an extension of standard stock assessments that includes such considerations as multispecies and

Table 1. Snapshot examples of regional implementation of IEAs in the USA, as described on regional IEA websites accessible at http://www.noaa.gov/iea/.

Region	Select examples of implementation progress	Key management topics	Current clientele
Alaska Complex	• Annual ecosystem considerations chapter provided to NPFMC • Ecosystem indicator selection process through multistakeholder workshops • Use of multiple ecosystem models to develop and test indicators • Development of metrics to represent condition of ecosystems; help establish reference points and comparisons across ecosystems (part of Risk Assessment)	• Fisheries • Climate • Energy	• North Pacific Fisheries Management Council • Arctic Research Commission • North Pacific Marine Science Organization (PICES) • Bureau of Ocean Energy Management
California Current	• Two IEA reports, including all steps within IEA process (2011, 2013) • Ecosystem considerations report delivered to PFMC (2011) • Integration of IEA science into management discussions (e.g. Sanctuaries, Puget Sound, Sacramento River) • IEA "toolkit" for CC • Next steps: habitats, highly migratory species	• Climate • Fisheries • Energy	• Pacific Fisheries Management Council • West Coast National Marine Sanctuaries • West Coast Governors Alliance • North Pacific Marine Science Organization (PICES)
Gulf of Mexico	• Demonstration project with GMFMC SEDAR process to provide ecosystem considerations • Development of ensemble set of ecosystem models • Ecosystem Assessment Management Report for 4 estuarine ecosystems • Development of digital trophic database and Data Atlas • Next: Ecosystem Status report for 2013	• Commercial and Recreational Fishing • Energy • Population • Recreation and Tourism • Shipping	• Gulf of Mexico Fisheries Management Council • Gulf of Mexico Alliance • National Marine Sanctuaries
Northeast US Shelf	• Development of multispecies and ecosystem models • Indicator development using DPSIR • Development of spatial tools for EBFM • Semi-annual production of Ecosystem Advisory report • Biannual Ecosystem Status report	• Fisheries • Wind energy • Protected species • Climate • Recreation and Tourism • Shipping	• New England and Mid-Atlantic Fisheries Management Councils • Northeast Regional Ocean Council • Mid-Atlantic Regional Council on the Ocean • North Atlantic Fisheries Organization • International Council for Exploration of the Seas
Pacific Islands	• Studies on effects of ocean circulation on larval retention • Development of "reef" and "coastal" ecosystem model to understand energy flows and interactions • Studies on human dimensions in ecosystem functions in Kona Coast (incl. indicator development, identification of drivers and pressures, communication and networking with managers) • Hawaiian Islands Humpback Whale National Marine Sanctuary plan review • Cetacean habitat modelling • Kona IEA research cruises	• Shared use resources • Aquaculture • Climate change and Kona Sentinel Site • Fisheries and aquarium fish collection	• Western Pacific Regional Fisheries Management Council • The Kohala Center • Hawaii Division of Aquatic Resources • Pacific Islands and Hawaii Ocean Observing Systems • National Marine Sanctuaries

Over time, examples of progress, key management topics, and current clientele will expand and there are aspirations to add Caribbean, Southeast, and Great Lakes regions for IEA implementation.

trophic relationships as well as environmental conditions. The bottom line is that one size will not fit all, and that meeting audiences where they are will be crucial in engaging the diverse constituents of IEAs.

The Puget Sound Partnership (PSP) provides one model of engagement for IEAs. The PSP was established by the Governor of Washington state, USA, in 2005 to protect and restore the Puget Sound ecosystem. The PSP worked with the general public, diverse

Table 2. Tenets for IEA implementation and practice.

1. Engage with stakeholders, managers, and policy-makers early, often, and continually
2. Conduct rigorous human dimensions research
3. Recognize the importance of transparently selecting indicators
4. Set ecosystem targets to create a system of EBM accountability
5. Establish a formal mechanism(s) for the review of IEA science
6. Serve current management needs, but not at the expense of more integrative ocean management
7. Provide a venue for EBM decision-making that takes full advantage of IEA products
8. Embrace realistic expectations about IEA science and its implementation

stakeholders, a science working group, and regional managers and policy-makers to craft an "Action Agenda" to achieve this goal. The Action Agenda was developed using a community-based approach that made use of a number of public forums and that promoted extensive public and scientific input. These included workshops, expert topic meetings, and local meetings with the general public. In all, 1600 people attended workshops, 75 presentations were given to community and business groups, and some 12 300 public comments were received (PSP, 2009). This level of engagement has been central to the success of the PSP in obtaining funding to support restoration efforts$—$230 million has been spent annually on Puget Sound Restoration since the creation of the Action Agenda (http://www.kitsapsun.com/news/2012/oct/27/little-progress-reported-in-puget-sound-health/#axzz2RtAGFF1l).

2. Conduct rigorous human dimensions research

The notion that humans are integral to marine ecosystems is now commonplace (McLeod and Leslie, 2009). However, there remains a surprising asymmetry in the attention researchers devote to natural vs. human systems when it comes to marine EBM (cf. Kittinger *et al.*, 2012). We contend that for EBM, an absence of rigorous investigations on the human dimensions of ecosystems is akin to ignoring basic elements of ecosystems such as upwelling, plankton productivity, and fish population dynamics.

Beyond simple definitions of EBM (McLeod *et al.*, 2005), there are a number of reasons why social science is fundamental. First, EBM is predicated on managing the actions of people based on their needs, and understanding people and their motivations is fundamental to the achievement of ecosystem goals (Pollnac *et al.*, 2010; Gutierrez *et al.*, 2011). Second, understanding and addressing trade-offs is a central EBM pursuit; consequently, identifying how and why cultures value different ecosystem services derived from marine systems is a basic necessity of EBM. Additionally, including human dimensions of ecosystems can enhance the implementation of EBM by quantifying impacts on livelihoods and communities, increasing buy-in, reducing conflict (Evans and Klinger, 2008), and helping to develop alternatives that address concerns of those affected by ecosystem changes (Turner *et al.*, 2008).

The ways in which human dimensions research could be incorporated into IEAs are as varied as the academic disciplines that study humans in marine ecosystems (e.g. history, political science, geography, anthropology, sociology, economics, psychology, etc.). We offer three illustrative examples below that underscore the importance of including such work in IEAs.

Cultural keystone species

Clearly, in evaluating trade-offs among management options, it is critical to know if a particular species holds importance beyond its monetary value or ecological role. For example, the red alga *Porphyra abbottiae* has been dubbed a "cultural keystone species" for the role it plays in indigenous cultures in the Northern California Current (Turner, 2003). *Porphyra* is highly valued for its nutritional content, as a gift and trade item, and for its medicinal properties (Garibaldi and Turner, 2004). As the term cultural keystone species suggests, small changes in the availability of *Porphyra* can have disproportionate impacts on the cultures that depend on it. Elders believe declines in gathering this alga will lead to a substantial loss of knowledge and tradition (Garibaldi and Turner, 2004). Thus, ignoring the cultural role species like *Porphyra* play in human communities will miss fundamental attributes of the social-ecological system.

Ecosystem service modelling

Marine ecosystems produce goods and services that sustain human life, and increasingly, modern conservation science is focused on protecting ecosystems for the benefit of humanity (Kareiva and Marvier, 2011). Process-based ecosystem service models that quantitatively link change in marine ecosystems to change in human well-being will substantially enhance our ability to analyse the status and forecast the future of coupled social-ecological systems (Guerry *et al.*, 2012). They offer a productive avenue for quantifying impacts of EBM strategies on livelihoods and communities. These models cannot be developed, refined, and put to use for management planning without deep interdisciplinary collaboration between economists, social scientists, and natural scientists.

Many examples of fruitful ecosystem service modelling efforts exist around the USA (Barbier *et al.*, 2011; Tallis *et al.*, 2013; White *et al.*, 2012b). Perhaps the area ripest for further development is related to services provided by coastal habitats (e.g. saltmarshes, coral reefs, mangroves, oyster beds, barrier islands, etc.). The value of coastal habitats can be enormous—in many areas, they provide a large variety of benefits to people, including coastal defence from storms, aesthetic value, climate change mitigation via carbon storage and sequestration, and more. For instance, a recent analysis examined how natural habitats across the entire USA modify hazards due to sea-level rise, suggesting that the number of people, poor families, elderly, and total value of residential property most exposed to hazards can be reduced by half if existing coastal habitats remain fully intact (Arkema *et al.*, 2013). This study underscored just one of the important functions natural habitats play in the coupled social-ecological system. The development of models that adequately capture the layered complexity of ecosystem services provided by coastal habitats will require significant intellectual consideration and resources, but are central to the development of socially resonant IEAs.

Behavioural science as a source of insight

A deficiency of standard economic models is that they assume people make decisions rationally (Amir *et al.*, 2005). The evidence across a wide range of examples suggests, however, that humans act in predictably irrational ways (Ariely, 2009). For example, Johnson and Goldstein (2003) showed that organ donation rates across several European countries were highly predictable based on default options: participation rates were much higher in countries where citizens "opted in" to donor programmes by default than in countries where the default option was to "opt out".

People may be motivated to action based on similarly subtle differences in choices about how to report and deliver IEA science. For instance, Levin *et al.* (2010) showed that in some cases, indicators with equivalent ecological information content have widely varying social resonance. Similarly, Beaudreau *et al.* (2011) demonstrated that alternative views of biodiversity can lead to radically different perceptions of risk to ecosystem components. Moreover, recognition of boundaries of acceptable ecosystem conditions for different ocean users and stakeholders can help define the "safe" operating space for EBM decisions (Rockström *et al.*, 2009). Successful implementation of EBM will require people to support management actions, and in some cases, to take actions as individuals (e.g. voting, clean up efforts, compliance with regulations, etc.). Social science can facilitate an understanding of people's motivations for supporting or opposing such actions. Insights from behavioural science can help guide the development of socially meaningful IEA products most likely to garner public support for, and participation in, EBM implementation (cf. Thaler and Sunstein, 2003).

3. Recognize the importance of transparently selecting indicators

The development of a performance evaluation system is basic to good management of businesses, environmental issues, human health, and more (Otley, 1999; Link, 2005; Rice and Rochet, 2005; Manski, 2013). Indicators are the basic building block for a performance management system: they provide a means to track progress towards management goals. At first glance, indicator selection may seem like a straightforward process. IEAs require indicators that capture key ecosystem and socio-economic states and processes (Levin *et al.*, 2009), and a number of frameworks exist to rigorously determine an indicator set (e.g. Methratta and Link, 2006; Shin *et al.*, 2010a, b; Kershner *et al.*, 2011; James *et al.*, 2012).

In practice, deriving a set of indicators is more challenging than simply determining proxies for key ecosystem components or processes. This difficulty emerges from the truism that IEAs require some indicators, but not too many (cf. Lægreid *et al.*, 2006). IEAs require that the performance characteristics of the indicators are understood and that the status and trends and current values relative to EBM targets can be interpreted correctly (Rice and Rochet, 2005). Using too few indicators limits the scope for adequately assessing the ecosystem, but too many indicators reveal a lack of prioritization of goals and objectives (Aucoin and Jarvis, 2005; Fulton *et al.*, 2005; Methratta and Link, 2006). The fact that there is a limit on the number of indicators means that choices must be made, and not all potential indicators can be used.

The key to whittling down a potentially infinite list of candidate indicators is a transparent selection process. Transparency can avoid, or at least reveal, institutional and personal biases, helping to create an indicator portfolio that meets the needs of EBM by being scientifically, politically, and socially meaningful. Formal evaluation of indicators following one of many indicator-screening frameworks (see references above) ensures the transparency of indicator selection. Final selections can be made based on additional input from complementary public engagement efforts and conventional political processes. Indicators that are reported regularly can represent a subset of those that are tracked for the purposes of ecosystem status assessment, providing a hedge in the event of ecological surprises and evolving management goals. This recipe, if executed properly, will generate a transparent and inclusive indicator set that truly allows for monitoring and measuring of progress towards ecosystem goals. Further, it can be used to generate a subset of standard indicators that will facilitate comparisons among IEA regions.

An example of culling these indicators, as developed in an IEA context, comes from the Northeast US shelf ecosystem where over 300 indicators have been documented (Link and Brodziak, 2002). After an iterative selection process conducted to winnow this number down (Link, 2005; Methratta and Link, 2006), many consultations among scientists, and several stakeholder workshops, the number of indicators routinely reported (http://www.nefsc.noaa.gov/publications/crd/crd1207/crd1207.pdf) is ∼30–50 (EcoAP, 2009, 2012). These ecological, economic, and social indicators are intended to represent aspects of the marine social-ecological environment that affect and are affected by human use of the ecosystem. This much more concise list allows for multiple uses of the information in many contexts, regular updates (every 2–3 years), and the examination of novel hypotheses and processes related to observed patterns. An even smaller subset of indicators is reported more frequently to track trends in ecosystem dynamics and provide alerts in the event of major shifts (http://www.nefsc.noaa.gov/ecosys/advisory/current/advisory.html).

4. Set ecosystem targets to create a system of EBM accountability

Alone, a transparently selected, ecologically defensible, politically acceptable set of ecosystem indicators is of limited value for EBM. To guide effective management, indicators must be associated with targets, or values of the indicators equated with successful achievement of management goals (Samhouri *et al.*, 2011, 2012). We distinguish between targets and other reference points such as ecosystem thresholds, in that targets need not be defined objectively through analysis of biophysical or socio-economic data. Rather, targets should reflect desired ecosystem states, as articulated through people's stated or revealed preferences for alternative ecosystem conditions. Active monitoring of indicators in relation to such targets can be used to instigate, cease, or adapt EBM actions.

However, generating consensus on target values for indicators at the ecosystem level is no small task, for at least two reasons. First, perceptions of ecosystem status are just that: a personal, subjective assessment that is very likely to differ from stakeholder to stakeholder depending on how s/he uses and values marine ecosystems (e.g. Loring, 2013). Thus, it is realistic to expect target setting to be a political activity, informed by scientific information. Such is the case in many familiar single-sector management examples (e.g. targets for protected areas, fisheries harvest guidelines, water quality, etc.). Yet means of objectively determining ecosystem thresholds in relation to environmental and anthropogenic pressures show some promise of at least identifying regions where target levels are apt to be most effective (Samhouri *et al.*, 2010; McClanahan *et al.*, 2011; Large *et al.*, 2013). The actual control rules used will still need to be specified, but many other disciplines (e.g. ecotoxicology, water quality, species-focused fisheries management) have used similar non-linearities to support the establishment of these target levels. A related idea advocated by Rockström *et al.* (2009), among others, is to define nature's safe operating space, or boundaries, via objective analysis. Policy-makers can use this information to delineate targets within or outside of the natural system boundaries.

The second challenge in defining target values at the ecosystem level is that they force trade-offs to the fore. It is relatively easy to develop ambitious targets for individual indicators. However, achievement of individual targets is complicated by interrelationships among ecosystem components. Improvements towards one target may impede or enhance progress towards another (Samhouri *et al.*, 2011; Fay *et al.*, 2013). Thus, it is critical for IEA science to outline how establishment of alternative targets for individual indicators influences the full suite of indicators related to

EBM goals (for a related discussion on an ecosystem approach to fisheries, see Rice, 2005).

There are many, non-mutually exclusive ways for IEA teams to illustrate the inter-relations of different target sets. For example, simulation models can describe what is ecologically and socio-economically feasible for the full ecosystem, given a set of targets for a particular subset of indicators (e.g. Kaplan and Leonard, 2012; Fay *et al.*, 2013). For example, Kaplan and Leonard (2012) illustrated the direct, indirect, and induced effects of management strategies with alternative groundfish targets for the broader ecological communities of which groundfish are a part and for fishery sectors, industry suppliers, and household spending patterns. Scenarios such as these can be developed into survey instruments, designed to solicit thresholds of acceptability for different ecosystem states. Similar approaches are commonly used to evaluate normative beliefs associated with wildlife management actions (Zinn *et al.*, 1998) and outdoor recreational activities (Vaske *et al.*, 1993). With an understanding of what is acceptable across the full ecosystem, targets for individual indicators can be deduced. Just as important, these approaches can identify ecosystem states that are categorically non-desirable by all stakeholders or those that are technically infeasible to achieve.

By specifying indicator targets, IEAs have the potential to create a system of EBM accountability. Given such a system, it is up to policy-makers to decide on a course of management action that most appropriately reflects stakeholder desires for the ecosystem.

5. Establish a formal mechanism(s) for the review of IEA science

A basic step in seeing IEA science used to inform EBM implementation is likely to involve the development and institutionalization of a mechanism(s) for peer review. Ideally, managers, stakeholders, and scientists will work with policy-makers to develop a template for the review of IEA science. Key elements of a review process may include committees tasked with external, independent review of IEA scientific products, opportunity for public comment, and a clear commitment to ensure the best available science is used to inform management decisions. In the USA, federal fisheries management practices provide a useful analogue, as they are conducted in a highly reviewed context. National Standard 2 of the Magnuson-Stevens Sustainable Fisheries Act requires documentation that a stock assessment has used best available science. A significant process to review information relied upon and produced by stock assessments has thus developed.

The success of the precedent set by US species-focused fisheries management is encouraging, although from our perspective, the precise format of an IEA review process is less important than ensuring that it occurs. The expectations from an IEA, whatever they may be, should be specified in a formal terms of reference to clarify scientific deliverables and their intended uses. The review process could lead to standardized outputs tailored for use by EBM decision makers. For example, the terms of reference may state that IEAs must include a minimum of five management strategy evaluations associated with corresponding risk levels for stakeholder-designated ecosystem goals. We urge caution with any type of standardization, however, as it should not be applied in a way that impedes innovation and adaptability. While we do not intend to be prescriptive regarding what standardized products or the review mechanism(s) should look like, we do feel that the development of these processes is essential to guaranteeing rigor in IEAs and for more effective use of IEA science in EBM implementation.

6. Serve current management needs, but not at the expense of more integrative ocean management

IEAs were borne out of the need to provide integrative science to inform comprehensive, ecosystem-based ocean management. While genuine EBM must operate across different ocean use sectors, in the USA, it is clear that this vision is constrained by existing governance structures and is more of an aspiration than the current reality (Rosenberg and Sandifer, 2009). The current reality bears more of a resemblance to many individual actors operating in a common space and using common pool resources (Crowder *et al.*, 2006), without much accommodation for the joint social value of their decisions (White *et al.*, 2012a). There are some examples available, however, suggesting that accounting for the joint social value of single-sector management decisions can lead to improved outcomes (Hannesson *et al.*, 2009; Allnutt *et al.*, 2012; Levi *et al.*, 2012). The contrast between aspiration and reality creates a tension between meeting single-sector ocean management needs today and making directed progress towards true, cross-sectoral EBM.

In the near-term, as EBM and IEAs gain trust, traction, and momentum, it is imperative that IEA products support current national ocean resource mandates as they are prescribed now. If IEA products do not provide information relevant to single sector and single species marine management decisions (e.g. fisheries, protected species, marine sanctuaries, etc.), then the IEA enterprise will not be viewed (by some) as useful. However, this existential risk need not be a major concern. Because they are synthetic "scientific warehouses", IEAs can be leveraged to augment single-sector management. For instance, IEAs summarize information about climatic conditions, species abundance, and human activities in the ocean, and these data can be packaged to inform the emerging needs of ecosystem-based fisheries management. In fact, "ecosystem considerations" reports and fisheries ecosystems reports that place individual stocks at the centre of the ecosystem, and describe climate, prey availability, predator abundance, and non-fisheries stressors, have already been requested and delivered to several Regional Fisheries Management Councils across the USA (e.g. Levin and Wells, 2011; EcoAP, 2012; Zador, 2012). Similarly, within National Marine Sanctuaries, habitat risk assessments can be used to inform spatial planning decisions regarding species of concern such as corals and sponges (Samhouri *et al.*, 2012).

The easier path forward is to repackage existing scientific products and market them as IEAs. However, in the longer term, if IEAs focus exclusively on the scientific needs of individual ocean use sectors, they will fail to fulfil the goals of EBM. While potentially useful, a report describing ecosystem considerations for an individual species or an individual sector is not an IEA. Such reports will help to justify the existence of an IEA programme in today's ocean management spheres, but will not help to realize EBM. Individual sectors aim to maximize utility based on their independent goals for marine ecosystems (White *et al.*, 2012a), yet at some point, a comprehensive evaluation of resulting trade-offs is needed. To truly blaze a new trail for a sustainable ocean future, IEA science is better served by striving for the anticipatory development of tools that can assist in actualizing better, more efficient marine EBM. Only by integrating biophysical and socio-economic information across an ecosystem can an IEA—and by extension EBM—help to shape a new reality characterized by coordinated and sustainable ocean uses.

7. Provide a venue for EBM decision-making that takes full advantage of IEA products

An IEA is in many ways widely marketable; it is designed to provide scientific information that can inform more sustainable, efficient, and compatible ocean uses across multiple sectors. Perhaps most importantly, an IEA strives to clarify the varied outcomes of alternative management scenarios, by drawing connections between land and sea, nearshore and offshore, fisheries and water quality, energy extraction and coastal recreation, and whale watching and shipping, just to note a few possible contrasts. However, although IEAs create a broader perspective for decision makers, more integrative ocean management will not just happen.

As is true on the international stage (Gjerde *et al*., 2008), challenges to coherent management and regulation in the USA represent both a policy implementation gap and a governance gap (Hildreth, 2008). Governance processes have been exploring ways for effective coordination of cross-sector decision-making ever since the Law of the Sea came into force, and many hurdles remain (Rice, 2011). Nonetheless, in the long term, we believe that EBM will require the creation of a venue for making decisions about ecosystems, in contrast to decisions about individual species, individual issues, or individual sectors.

Getting there will not be easy. In the USA, IEAs do not yet fold neatly into any one existing governance structure, and the creation of a new one is an enormously complex undertaking. Such a decision-making body would need to be charged with maintaining a cross-sectoral focus, possibly by way of an inter-sectoral set of constituent members. The US National Ocean Policy recognizes the importance of Regional Ocean Partnerships (ROPs) that have identified priorities relevant to their specific regions, and could provide a preliminary venue for the delivery of IEA science. The ROPs may serve as an initial template, and could work to leverage existing legal mandates and apply them within existing single-sector management frameworks, while remaining cognizant of the cross-sectoral trade-offs that deserve consideration.

The formation of such a venue is a step that will facilitate dialogue, the adjudication of compatible vs. incompatible ocean uses, and the coordination of management decisions. Ideally, it could serve a facilitative role by tracking actions taken within individual sectors and providing a forum to negotiate trade-offs that influence the joint social value of an ecosystem with respect to stakeholder-determined goals (White *et al*., 2012a). Even with due diligence by scientists to see IEAs used in management, EBM is unlikely to become a reality without the creation of a group charged with maintaining a broad perspective to coordinate trade-offs across individual ocean-use sectors.

8. Embrace realistic expectations about IEA science and its implementation

Historically, there is a time-lag between the development of the science for a new environmental management approach and the adoption of this information into policy and management. For instance, in the USA, extinction risk is one of the main criteria evaluated in determining whether a species should be listed under the Endangered Species Act (ESA) of 1973. Population viability analysis is considered one of the best quantitative methods for evaluating extinction risk, yet it remains infrequently used in endangered species recovery planning (Morris *et al*., 2002). This reality is natural, expected, and to a limited extent even desirable—unfamiliar scientific products require time for vetting and shaping to practical applications. However, lack of familiarity should not be an excuse for a lack of reliance on best available science in guiding management decisions.

Given the lag time often associated with new management strategies, EBM and IEAs could take a generation or more to establish a strong foothold across all sectors of US ocean management. The application of stock assessment science in US fisheries management provides a useful corollary. In his book, Smith (1994) elegantly tracked the development of the theory and associated scientific underpinnings of fish stock recruitment and production dynamics, largely in the middle of last century. He noted that it was at least a decade, or more, before such information was used as the basis for setting reference points and harvest control rules to manage living marine resources. It has taken even longer for the full suite of governance structures and review venues to evolve into something even remotely familiar to what we now observe in the USA with National Standards, Regional Fisheries Management Councils, and related machinery to conduct fishery management. A similar evolution is to be expected for IEAs as they begin to support EBM.

IEA science is young and necessary, but not sufficient for making EBM happen. The National Ocean Policy, the National Environmental Policy Act, the National Coastal Zone Management Act, and other statutes do provide inroads for implementing facets of EBM (Keiter, 1998; Abbott and Marchant, 2010; Fox *et al*., 2013). However, it could be argued that the readiness of IEA products precedes the preparedness of legal and management structures to use the information. Happily, there are several examples from across the world, suggesting that even complex, international policy-making organizations are capable of adapting quickly to new scientific developments and including them in their processes (e.g. IUCN extinction risk assessments have used "quantitative population models" since 1994; in 1992, Rio Agenda 21 created a policy framework for precautionary fisheries management based on stock–recruitment productivity dynamics, etc.). Our observation is that these efforts tend to be particularly effective when top-down actions to implement policy and management are coupled to bottom-up efforts to develop the relevant science.

The future of IEAs for ocean management in the USA and beyond

To date, IEAs are most useful as syntheses of information and for influencing the way scientists, managers, and policy-makers think about ocean issues. IEAs take the conceptually appealing idea of EBM, and provide some structure around which to consider the otherwise overwhelming task of identifying, evaluating, and developing management strategies for multiple ecosystem components and sectors. These characteristics make them a next-generation tool for ocean and coastal management. Those involved with developing IEAs in the USA are learning by doing, improvising as they go, and subsequently trying to improve the implementation of EBM. The eight tenets introduced in this article (Table 2) represent lessons we have learned along the way that may enhance the uptake of integrated scientific assessments in the USA and beyond.

IEAs face the tall order of meeting managers where they are today, while at the same time remaining sufficiently visionary that they can show managers where they could be tomorrow. IEA scientists will be challenged to remain nimble and responsive to sectoral needs, and at the same time steadfast and persistent in the pursuit of the larger goal of EBM. In the short term, we expect that the most efficient way forward is to tailor IEAs, so that they are clear where and how cross-sectoral, coordinated management can increase the probability of attaining ecosystem goals relative to single-sector, siloed decision-making (White *et al.*, 2012a). If successful, IEAs will lead managers and policy-makers to create the infrastructure capable of ingesting and applying principles of ecosystem science to foster sustainable ocean uses in the future.

The full utility of IEAs in ocean management will not be apparent overnight. We have spent centuries studying the parts and only recent decades in more formally developing the science to inform management of the whole (Jackson, 2011). IEAs are science for tomorrow's oceans, and we urge patience as it matures, and with it, the readiness of ocean managers to use it. The eight tenets outlined above summarize our perspective on how to carry IEAs from the realm of interesting scientific products to the realm of useful EBM tools. Common to all of them is a need for patience, persistence, political will, funding, and augmented scientific capacity (especially human dimensions capacity). It will also take innovation, engagement, and open dialogue to see ecosystem science implemented into effective, ecosystem-based ocean management, but we assert that it can be done using IEAs.

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