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Dynamic Ocean Management: Identifying the Critical Ingredients of Dynamic Approaches to Ocean Resource Management

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Dynamic ocean management, or management that uses near real-time data to guide the spatial distribution of commercial activities, is an emerging approach to balance ocean resource use and conservation. Employing a wide range of data types, dynamic ocean management can be used to meet multiple objectives—for example, managing target quota, bycatch reduction, and reducing interactions with species of conservation concern. Here, we present several prominent examples of dynamic ocean management that highlight the utility, achievements, challenges, and potential of this approach. Regulatory frameworks and incentive structures, stakeholder participation, and technological applications that align with user capabilities are identified as key ingredients to support successful implementation. By addressing the variability inherent in ocean systems, dynamic ocean management represents a new approach to tackle the pressing challenges of managing a fluid and complex environment.

Keywords: bycatch, sustainable fisheries, stakeholder involvement, remotely sensed data, data integration

The world's oceans are under an unprecedented level of pressure from resource use and commercial activities—for example, fisheries, shipping, aquaculture, and mineral, natural gas, and oil extraction. The impacts from these activities are compounded by climate change, pollution, and invasive species (Halpern et al. 2008, Merrie et al. 2014). In the face of these chronic influences from human activities, ecosystem functions and the services they provide are being eroded (MEA 2005). Ocean management approaches that can address these growing pressures have been the focus of considerable research and agency action (Foley et al. 2010, Ban et al. 2014).

Management of ocean seascapes is complicated by their dynamic spatial and temporal nature. Ocean currents create filaments and eddies that persist for weeks to months (Waugh et al. 2006). Mesoscale variability in ocean structure and processes lead to spatial and temporal patchiness in primary productivity (Hazen et al. 2013). In turn, zooplankton, fish, and other pelagic species in the food chain are mobile and patchily distributed as they seek areas of food to support growth and reproduction (Haury et al. 1978). As a result, the ocean is considered highly dynamic in space and time, albeit with persistent physicobiological patterns across a range of scales (e.g., Sheldon et al. 1972, Steele 1980). These dynamic ocean systems are changing—and are predicted to continue to change—in the face of climate change (Polovina et al. 2008, Hazen et al. 2012, Pinsky et al. 2013).

Over the ages, people have often exhibited dynamic behavior in response to changing ocean conditions and have modified or altered their use of ocean resources, particularly fish (Berkes et al. 2000). In this context, dynamic ocean management (DOM) has long been an integral part of human cultures. In the 1400s, fishers in the northwest Atlantic (e.g., Norway, Spain) followed fish populations as local climates changed, resulting in the rise and fall of settlements along the coast (Jackson et al. 2011). Whalers in the early 1900s followed the dynamic ice edge to locate desired species throughout the Arctic (de la Mare et al. 1997). Johannes (1998) describes fishers in modern-day Palau who alter fishing effort on grouper in response to spatial and temporal shifts in spawning aggregation sizes. Several studies have explored shifts in fishing effort in response to changing

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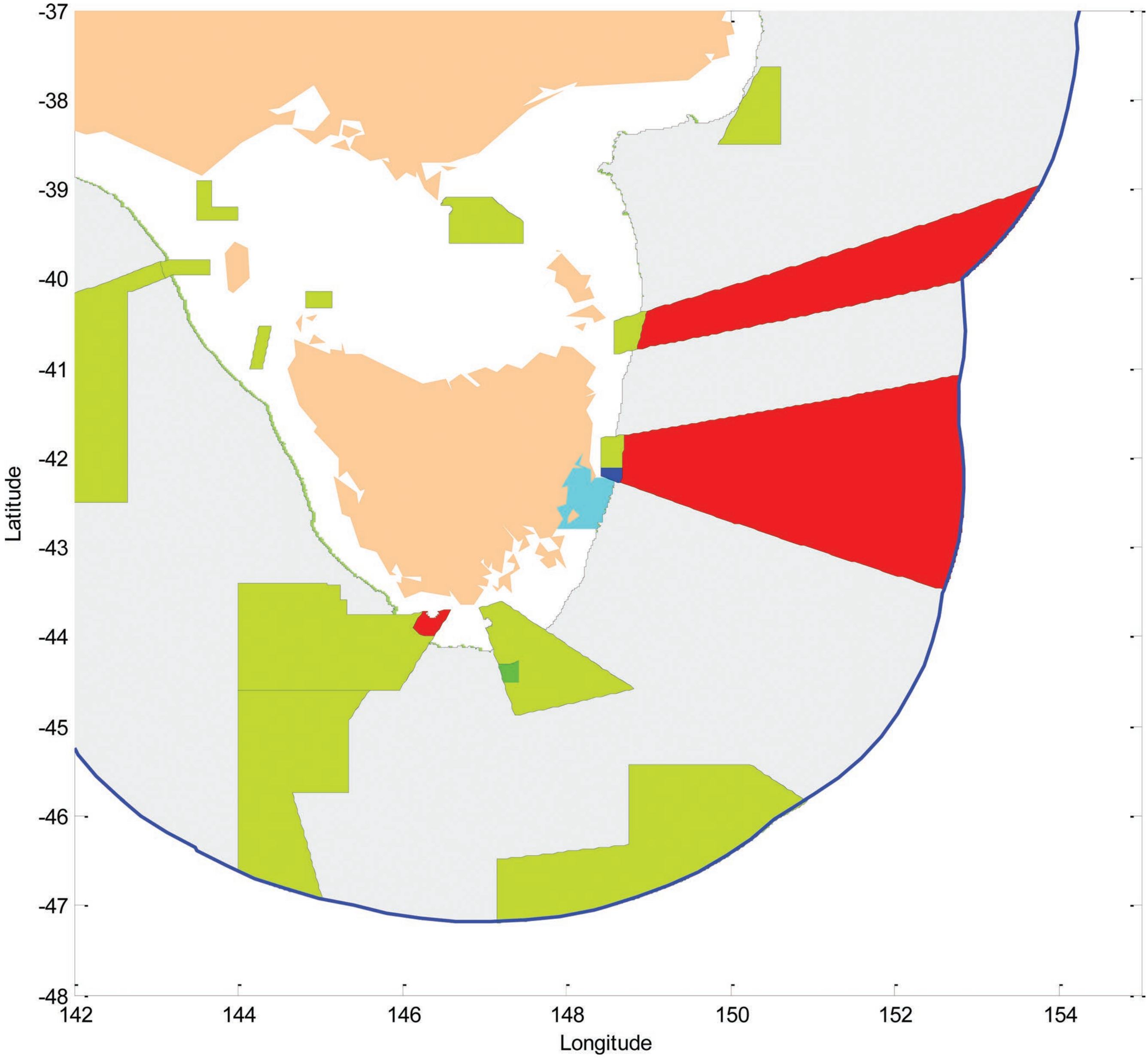

Figure 1. Examples of some typical static ocean management structures found worldwide, shown here for Tasmania, Australia: exclusive economic zone (outer blue line), marine protected areas (colored by International Union for Conservation of Nature protection categories—red, IA; blue, II; green, IV; lime, VI), time area closure to protect an inshore squid spawning region (light blue), and a fisheries management zone (grey—trawling closure in waters deeper than 600 meters within the Australian exclusive economic zone).

ocean conditions across many countries, including Solomon Islands, Papua New Guinea, Indonesia, and Hawaii (Aswani 1998, Cinner and McClanahan 2006), and have documented the tactical and strategic decisions fishers make to account for seasonality, changing weather conditions, and levels of bycatch (Christensen and Raakjaer 2006). More recently, ocean use patterns have been shown to change in response to shifting economic conditions. In an analysis of fisher behavior in the French Guyana shrimp fishery, Bene (1996) found that changes in the spatial distribution of fishing effort over time were more closely associated with market constraints and fluctuating economic incentives than with changes in the spatial distribution of the resource. Scheld and Anderson (2014) describe dynamic landing patterns in which fishers alter concurrent landings of other stocks to avoid flooding markets and dropping market value, a pattern observed in other fisheries (Christensen and Raakjar 2006, Guillen and Maymou 2014).

In contrast to the dynamic nature of ocean organisms, conditions, and users, many ocean management approaches are static (figure 1). Nations have declared exclusive economic zones (EEZs) to delineate sovereign waters. Ocean management agencies have established fixed marine protected areas (MPAs) and employed time area closures to restrict access and use of areas with sensitive resources. Fisheries managers have set harvest allocations, often at yearly intervals based on synoptic surveys and historical catch information. In many regions these static management constructs have supported resource management, reduced pressure on critical habitats or threatened marine species (Gormley et al. 2012; Pichegru et al. 2010), and in some cases, have resolved conflict among ocean activities or users (Agardy 1994, Gaines et al. 2010). Static management approaches can support management of resource use at fixed locations—for example, offshore energy platforms, or to protect fixed ocean features—for example, coral reefs, but static approaches may be less effective in managing highly mobile organisms, which respond to shifting ocean dynamics and intensifying mobile human pressures (Hyrenbach et al. 2000). Static approaches have failed to prevent fishery closures that are triggered when catch of nontarget species, often referred to as choke species, or protected species exceeds established thresholds (O'Keefe and Decelles 2013). Dynamic ocean management (DOM) is an emerging tool that can support or supplement traditional management approaches for marine ecosystems. However, DOM does not replace management frameworks. Rather, like static approaches, DOM can serve as an instrument to allocate ocean uses and resource extraction within designated thresholds and limits. What differentiates DOM from static management approaches is the use of real-time or near real-time data on the shifting physical, biological, socioeconomic, and other characteristics of the ocean and ocean resource users to generate responsive spatial management measures or strategies (Maxwell et al. 2012, Hobday et al. 2014).

Here, we explore several prominent examples of this emerging management approach to better explain its utility and significance and demonstrate its potential to generate feasible and flexible management actions that can support resources and users. Dynamically managing resource use and commercial activity in marine systems is still fairly uncommon, despite the increasing technical capability to do so (Game et al. 2009, Hobday et al. 2014). We introduce emerging examples of DOM, focus on common threads and critical differences, and evaluate the successes achieved and obstacles faced by DOM approaches. In essence, our review identifies lessons learned in the emerging DOM applications that provide a roadmap to effective DOM development and implementation. Our evaluation summarizes the current state of the science of DOM, articulates the future direction for this promising management tool, and identifies the critical ingredients for DOM success.

Defining and contextualizing dynamic ocean management

Maxwell and colleagues (2012) and Hobday and colleagues (2014) described DOM as management that changes in space and time in response to the shifting nature of the ocean and its users based on the integration of new biological, oceanographic, social, or economic data. Although DOM is a more recent development in marine resource management, the concepts and potential applications are based on established fields of technical and social scientific endeavor. Information on the dynamic movements of a range of species have been collected with a novel array of biologging devices (Bograd et al. 2010, Block et al. 2011, Hazen et al. 2012), and information on ocean conditions is available from in situ measurements, satellites, and ocean models. There is a wide range of literature describing the creation of habitat models from empirical data sources (Zydelis et al. 2011), to inform the design of MPAs (Bailey and Thompson 2009, McGowan et al. 2013). Similarly, information-sharing networks have been documented for commercial shipping and fishing industries and social science has explored incentives for cooperation amongst ocean resource users (Hardin 1982, Ostrom et al. 1990). Although several types of data and models have been explored, the transfer of these information sources to support management decisions has generally focused on static advice rather than dynamic management approaches (but see Hobday et al. 2010).

Recent advances in the availability, compatibility, and dissemination of long-term biological and remotely sensed environmental data now support the development of dynamic approaches. Likewise, other data types, including social and economic, and genetic information are increasingly accessible and available. Importantly, the ability to disseminate data has rapidly expanded in the last decade with advances in Internet, smart devices, and tablet technologies (Teacher et al. 2013). This rapid paired technology and data expansion supports the defining feature of DOM, which is building management strategies on a range of data layers available in near or real-time. With these data, management products that can support multiobjective or multicriteria management decisions can be developed (Hobday et al. 2014).

Current applications of DOM: Addressing ocean management challenges

DOM approaches are emerging in several places globally, replacing static management approaches to support the management of various mobile ocean activities, including fishing and shipping (table 1). These initiatives have been implemented to maintain target catch within quota limits, reduce bycatch of species of conservation concern, or resolve conflicts among ocean users and uses. Here, we review several examples to illustrate the diversity of applications and the benefits that result from a DOM approach. As the examples demonstrate, the success of these examples derives from innovative combinations and syntheses of complementary environmental, biological, technological, and socioeconomic data.

Maintaining target catch within quota limits. Modern fisheries management is moving towards a system of property rights

Table 1. Key qualitative characteristics and features of the emerging dynamic ocean management (DOM) applications based on literature and expert opinion.

		Yellowtail flounder bycatch avoidance[a]	Turtle Watch[b]	Scottish conservation credits[c]	Pacific Groundfish fishery[d]	British Columbia salmon fisheries[e]	Eastern Australian longline fishery[f]	Bering Sea Pollock trawl fishery[g]	Whale ALERT[h]	River herring bycatch avoidance[i]
Program characteristics	Target quota mgmt			X	X	X				
	Bycatch mgmt	X	X				X			X
	Avoid protected spp.							X	X	
	Development stage	Oper	Exper	Oper	Oper	Oper	Oper	Oper	Oper	Oper
	Compliance	Vol	Vol	Comp	Vol	Comp	Comp	Vol	Vol	Vol
	Data used	Emp	Mod	Emp	Emp	Emp	Mod	Emp	Emp	Emp
	Type I, II, III, IV	I	III	II	I	I	IV	II	I	I
	Time from data received to product release	Within 24 hours	Hourly	1–2 days	Hours	Hours or days	Hours	Hours	Hours	Daily or weekly
	Frequency of product update	Daily	Daily	Every 20 days	Within hours	2–3 times per week	Every 2 weeks	4 times per day	Within hours	Daily-weekly
Data used	Environmental variables		X				X			X
	Fisheries dependent	X	X	X	X	X		X		X
	tags, telemetry, acoustics		X				X		X	
	Survey	X								
	Genetic					X				
	Socio-cultural									
	Economic									
Stakeholder involvement	Industry participation (L/M/H)	H	M	H	H	L	L	H	M	H
	Incentives for industry (W/M/S)	S	M	S	M	S	S	S	W	S
	Incentive description	Reduce bycatch, avoid closure	Reduce bycatch, avoid closure	Increased effort allocation	Manage target catch	Manage target catch	Reduce bycatch, avoid closure	Participation linked to higher overall bycatch cap	Avoid collisions	Reduce bycatch, avoid closure
	Partners	Industry University	Government	Industry Government NGO	Industry NGO	Government[s] University	Government[s]	Industry	Government	Industry Government University
Costs	Cost of program initiation (L/M/H)	L	M	L	M	M	H	M	H	M
	Cost of program maintenance (L/M/H)	L	L	L	M	M	L	M	H	M

Note: The type numbers (Type I-IV) correspond to those in figure 2. The stage of program development was described as operational (Oper) or experimental (Exper). Compliance was described as compulsory (Comp) or voluntary (Vol). Data for programs is either empirical (Emp) or modeled (Mod). Industry participation was described as low (L), moderate (M), or high (H). Incentives for industry were described as weak (W), moderate (M), or strong (S). Relative costs of starting and maintaining DOM programs were categorized as low (L), less than $100,000; moderate (M), $100,000 to $1 million; and high (H), more than $1 million. Government[S] denotes a governmental scientific agency. The references for the programs are the following: [a]O'Keefe and DeCelles 2013. [b]Howell et al. 2008. [c]Holmes et al. 2011, Needle and Catarino 2011. [d]Molteni et al. 2013, *www.ecatch.org*. [e]Beacham et al. 2004, 2008. [f]Hobday et al. 2011. [g]Haflinger and Gruver 2009. [h]Wiley et al. 2013, Sibler et al. 2012, *http://stellwagen.noaa.gov/protect/whalealert.html*. [i]Bethoney et al. 2013.

and output controls, often vested in annual quotas that seek to ensure sustainable harvest or promote stock recovery (Hilborn et al. 2003, Gutiérrez et al. 2011). In fisheries operating under quotas, DOM can be used to maintain target catch within allocation limits. Near real-time data can be used to dynamically inform fisheries managers throughout the fishing season allowing them to monitor and manage quota allocations of the target species. For example, British Columbia salmon fisheries are being dynamically managed in order to limit overexploitation of populations of conservation concern, while at the same time supporting the harvest of abundant populations (Beacham et al. 2004, Beacham et al. 2008). The management strategy is based on rapid and highly accurate estimates of stock composition and identification via in-season genetic analyses to allow population-specific exploitation targets to be reached and, generally, quota use to be increased. Similarly, in the New England multispecies groundfish fishery, catch of juveniles from low-quota and unmarketable species (i.e., discards) are counted against the overall fishery quota because juvenile catches degrade stock size and catch of unmarketable species (discards) leads to negative population effects. Dunn and colleagues (2013) provide a theoretical example of DOM that generates rules to guide when a fishing vessel should leave an area, termed a move-on rule. The move-on rules are derived from spatiotemporal autocorrelation analyses that use near real-time data on spatially explicit catch information to reduce unwanted catch of quota-limited and discard species while supporting the harvest of high-quota target species.

Reducing bycatch. Fisheries typically aim to catch one or more target species, but at the same time, can also catch unwanted species, which is termed *bycatch*. Bycatch is a serious issue in many regions, with seabirds, sea turtles, marine mammals, vulnerable sharks, and other fish species impacted (Cullis-Suzuki and Pauly 2010, Croxall et al. 2012, Worm et al. 2013, Lewison et al. 2014). Traditional static management approaches for reducing bycatch include large time–area closures, which can result in serious economic impacts on ocean resource users (Sibert et al. 2012, O'Keefe and Decelles 2013). There are a number of current applications of DOM to reduce bycatch, while still maintaining—and even enhancing—economic efficiency.

One of the best-known DOM examples occurs in the Eastern Australian longline fishery (Hobday and Hartmann 2006; Hobday et al. 2011). Since 2003, a dynamic spatial management approach has been used to limit unwanted capture of southern bluefin tuna (SBT). The approach combines a habitat model conditioned with temperature preference data from pop-up satellite archival tags deployed on SBT, and an ocean model to produce near real-time habitat predictions used by fishery managers during the fishing season. The estimated tuna distribution is used to assist managers in locating management zones that restrict entry by fishers without quota. Three management zones are delineated based on expected SBT distribution and then regulated through observer coverage and vessel monitoring. The three zones combine the likelihood of tuna presence and the quota status of a fisher. In Zone 1 (OK zone), SBT are not expected to occur and fishers without SBT quota can fish. In Zone 2 (the buffer zone), where there is a limited distribution of SBT predicted, fishers with a limited SBT quota are permitted. In Zone 3 (the core zone), SBT abundance is likely to be highest and only fishers holding sufficient SBT quota may fish and are required to have 100% observer coverage (Hobday et al. 2011).

Another example of the use of DOM to reduce bycatch is TurtleWatch, a tool developed to minimize loggerhead sea turtle (*Caretta caretta*) bycatch in the Hawaii longline swordfish fishery (Howell et al. 2008). Loggerheads are US federally protected species that can be accidentally caught by longline gear. To manage bycatch, an annual loggerhead limit was implemented which, if reached, leads to a fishery-wide closure. Using thermal habitat preferences derived from turtle satellite telemetry data and bycatch occurrences, developers of TurtleWatch found that more than 50% of bycatch interactions occurred between the 17.5 and 18.5 degrees Celsius isotherms. Weekly maps showing the location of both isotherms, areas where loggerhead bycatch is more likely, are computed based on the most recent available sea surface temperature data and distributed online to fishers through the TurtleWatch tool, allowing for voluntary fishing responses. This product has been modified to also include recommended exclusion zones for leatherback turtles (Howell et al. 2015).

On the East Coast of the United States, a yellowtail flounder bycatch avoidance program demonstrates how DOM can be used to reduce bycatch in a scallop fishery. Bycatch levels in relatively small spatial grids (approximately 50 km^2) are communicated through vessel monitoring system ship to shore email technology daily or weekly by participating fishing vessels. Researchers summarize the information and provide daily (or weekly) grid-cell specific bycatch advisories to the vessels on the fishing grounds. The program has been used successfully in the Atlantic sea scallop fishery in rotational harvest areas, as well as large regions on Georges Bank and in southern New England to limit yellowtail flounder (*Pleuronectes ferruginea*) bycatch (O'Keefe and DeCelles 2013). Since adopting this bycatch avoidance approach, the fishery has remained open for the designated duration because yellowtail bycatch quota has not been exceeded. This general approach was adapted for the River herring bycatch avoidance program (*Alosa pseudoharengus* and *Alosa aestivalis)* in the US northwest Atlantic midwater and bottom trawl fisheries (Bethoney et al. 2013) with similar success.

The Scottish conservation credits scheme incorporates real-time closures to reduce cod discards and mortality in Scottish and foreign multispecies demersal fisheries. These fisheries target a number of demersal species, including cod (*Gadus morhua*), haddock (*Melanogrammus aelgefinus*) and whiting (*Merluccius merlangus*), but the quotas are set for each species independently, which leads to significant discards of otherwise marketable fish because they cannot be landed once the quota for that species has been reached. In this DOM application, vessel monitoring systems data and landings are analyzed in gridded fishing areas. On the basis of this analysis, grids with the highest landings per effort are closed to fishing for 21 days if the catch rate of cod exceeds a trigger level. Although evidence of compliance and the direct effects of the closure are difficult to measure, initial analyses of catch savings indicate benefits from the dynamic management regime (Holmes et al. 2011). Grid size and the number of grid closures have been increased to support the goal of limiting discards (Needle and Catarino 2011).

To reduce chinook salmon bycatch, fishers in the Bering Sea pollock fishery are given the opportunity to join bycatch reduction incentive plans which accommodate different processing modes. Participants in the plans are allowed to fish with a higher overall bycatch cap, and all vessels in the fishery have elected to participate. The plans use a rapid response to high bycatch encounters: upon receipt of either an observer report or landing report indicating high salmon bycatch, a short message is sent by email to the entire fleet that contains the coordinates of the encounter and a link to map of the vessel's vessel monitoring system track. The same link allows the user to inspect all high-encounter vessel monitoring system tracks for the week, or for any user-defined period for which data exists on the site. All systems that receive data and generate alerts are fully automated and operate around the clock, so there is almost no delay between receipt of data and the generation of bycatch alerts. On weekly intervals, an analysis of all data received is conducted and fishing areas where bycatch exceeds specified thresholds are closed (Haflinger and Gruver 2009).

Fishers in the Pacific groundfish fishery have also used a DOM approach to reduce bycatch (Molteni 2013). Here, fishers have established risk pools where they share individual transferable fishing quotas for a number of species with low quota, which includes bycatch or traditionally overfished target species. High catch of these species can lead to fishery closures. To avoid capture of overfished target species and the potential of a fishery closure, fishers share data on catch and catch location of these species using a smart-device application called eCatch. Created in partnership with The Nature Conservancy, eCatch collects and shares catch locations of overfished target species in near real-time. Fishers input data on the location and quantity of their overfished target species catch, and a Web-based application serves the data back to fishers in near real-time so they know how much quota of these species have been caught, and what areas to avoid to minimize additional capture of these species.

Resolving direct conflicts. Conflicting management objectives occur in marine sectors other than fisheries, such as shipping, where in some cases species protection goals may be compromised due to deleterious interactions. A smartphone or tablet application called WhaleALERT (*http: //stellwagen.noaa.gov/protect/whalealert.html*) has been developed by resource managers and partners in the Stellwagen Bank National Marine Sanctuary to reduce ship strikes of North Atlantic right whales (*Eubalaena glacialis*), a highly endangered marine mammal with a total population of approximately 522 animals (Pettis and Hamilton 2014). Ships using WhaleALERT receive real-time information on digital nautical charts that includes the location and movement of their ship relative to right whales in the area. The presence of whales is detected by near real-time acoustic buoys that detect right whale calls in the shipping lanes that cross the sanctuary. This information is fed directly into WhaleALERT. Users are alerted when they approach management areas where mandatory or voluntary speed limits are imposed, and compliance is enhanced by pop-up notices that appear on electronic navigation charts when a management boundary is crossed (Wiley et al. 2013). Tools that inform and engage stakeholders may help to improve compliance with mandatory and voluntary measures that are implemented to protect vulnerable species and populations (Silber et al. 2012). Other products developed from whale tracking data, such as seasonal model-based habitat distributions, may also help inform DOM and reduce conflicts between human uses and protected species (Irvine et al. 2014).

Learning from application: Identifying the critical ingredients for DOM success

The emerging applications of DOM provide compelling evidence of the feasibility, efficacy, and utility of the DOM approach. These examples also provide insight into the factors that contribute to DOM success. From a review of the current DOM literature and practice, we identify four key interrelated factors that have influenced the efficacy of DOM approaches: the existing regulatory framework, incentive structure, technological and analytical requirements, and stakeholder participation. More information on the review process can be found in the supplemental material.

Existing regulatory framework and incentive structure. Strong incentives are necessary in order to create successful fisheries management structures (Hilborn et al. 2005, Gutiérrez et al. 2011), a conclusion that also emerges from review of existing DOM approaches (table 1). Existing regulatory frameworks can influence the incentive structure and have been a prominent factor in the establishment of DOM applications. Such regulatory frameworks can include legislation protecting threatened or endangered species (e.g., the US Endangered Species Act or Marine Mammal Protection Act, Australia's Environment Protection and Biodiversity Conservation Act), governing fisheries (e.g., the US Magnuson–Stevens Fishery Conservation and Management Act, the EU Common Fisheries Policy, Australia's Fisheries Management Act), and management directives, such as those through industry management bodies (e.g., US Fishery Management Councils and Commissions). In many of the DOM examples presented here, the approaches were incentivized or catalyzed directly by the existing regulatory framework, often preceding a large-scale closure or injunction on a particular activity. For example, TurtleWatch was developed to help fishermen avoid reaching a bycatch limit on loggerhead sea turtle bycatch, which if reached can result in a full fishery closure. The yellowtail flounder bycatch avoidance and the Bering Sea pollock trawl fishery programs were developed to help fishers avoid catching nontarget species that had led to complete or partial closures of the fishery with resulting economic loss. Similarly in the Eastern Australian longline fishery, the need to reduce unwanted catch of southern bluefin tuna led to the development of a DOM approach to meet international quota obligations (Hobday et al. 2009). In all three cases, the existing regulatory framework provided the guidelines for the management objectives to be met to maintain fishing activity, and a dynamic approach allowed for an effective means of staying below bycatch quota thresholds, reducing the risk of fishery closures and supporting harvest of target species. Impending regulations can also catalyze the creation of DOM strategies. The development of the River Herring Bycatch Avoidance Program in the US Atlantic herring and mackerel fisheries, was spurred by the proposed creation of river herring protection areas, which would have seasonally closed large portions of the fisheries. Although there may be costs from DOM strategies for ocean resource users, there are also direct and indirect economic and ecological benefits from many of the DOM examples presented here, including increased access to resources, reduced waste and unwanted catch, fewer depleted populations, and more resilient marine assemblages.

Unlike the fisheries examples, the use of dynamic management areas to protect whales from ship collisions with WhaleALERT has a less direct incentive structure for the shipping industry. Vessel collisions are often fatal to the whale and can cause damage to the ship with consequent economic costs. However, these events are rare in comparison to the number of ships at sea and the miles they travel with an average of 11 confirmed or possible ship strikes to large whales per year off the United States based on 292 records between 1975 and 2002 (Jensen and Silber 2004), although this is a minimum as many may go undetected or unreported. To address the threat to whales, vessel speed restrictions have been used as a mitigation measure to reduce the risk of ship strikes for North Atlantic right whales. Compliance with these measures incurs costs by delaying port arrival times, increasing the route length to avoid the management areas or slow down through them. Compliance with the regulations was initially low, but improved with each notification program (Silber et al. 2014). Enforcement activities (citations and fines) appear to be strong motivators and had the greatest influence on improving compliance. Voluntary dynamic measures have been less successful in modifying vessel behavior in this application (Silber et al. 2012). Achieving a balance between economic costs to shipping and benefits to whales, in consultation with the industry, may allow more effective dynamic management strategies to be developed.

DOM applications have been used primarily in fisheries with a large or established management structure. However, DOM can be relevant for fisheries that do not have robust regulatory structures (i.e., as seen in small-scale fisheries), and industry members have formed partnerships with managers to reduce impacts, even in the absence of regulatory triggers. DOM approaches may help an industry maximize economic gains either by increasing income (e.g., increasing target catch) or minimizing loss (e.g., decreasing bycatch of nuisance species). For example, in small-scale fisheries in Peru, fishers and fisheries observers trade information on unwanted sea turtle bycatch, as well as on ocean and market conditions in real-time using high-frequency two-way radios (Alfaro-Shigueto et al. 2012). The radio program directly benefits the fishers by supplying data on sea turtle bycatch, oceanographic features, and warnings about dangerous conditions. It serves as a vessel safety device, supports economic yield by giving fishers more information on when and where to land their catch, and helps fishers avoid areas of high sea turtle bycatch. Such proactive DOM applications, represent an alternative to reactive approaches to a looming regulatory change, and may support long-term sustainability of a fishery before a crisis develops.

Technological and analytical requirements. Although all DOM approaches require some level of technological and analytical capacity, DOM approaches range from relatively simple approaches that require basic arithmetic to analytical approaches using multiple data streams or complex modeling techniques. Using these examples, it is possible to categorize DOM approaches into four types based on the level of analytical complexity (figure 2). A type I approach involves a single data type and requires minimal data processing. For example, the Yellowtail flounder bycatch avoidance program relies on emailed catch data and creates an easy to follow map as output (type 1). Fishermen send emails to scientists at SMAST with amounts of yellowtail flounder bycatch and target scallop catch by location within grid cell reporting maps that are overlaid on scallop fishing grounds. Scientists then compile data by location and return summarized advisories the next day to highlight areas to avoid in order to minimize yellowtail flounder bycatch. A type II example requires some statistical analysis to integrate near real-time data into a dynamic model. For example, in the theoretical work on the New England multispecies groundfish fishery, the distance a fisher should move from an area to stay below quota limits is determined based on patterns of spatial clustering. A type III approach uses multiple data types to create a dynamic product based on the relationship among input data (e.g., habitat use and environmental data). TurtleWatch relies on more complex data analyses and processing, using location (satellite-tracking or geolocation from archival tags) data and remotely sensed ocean data to model temperature-dependent habitat preferences for loggerhead sea turtles.

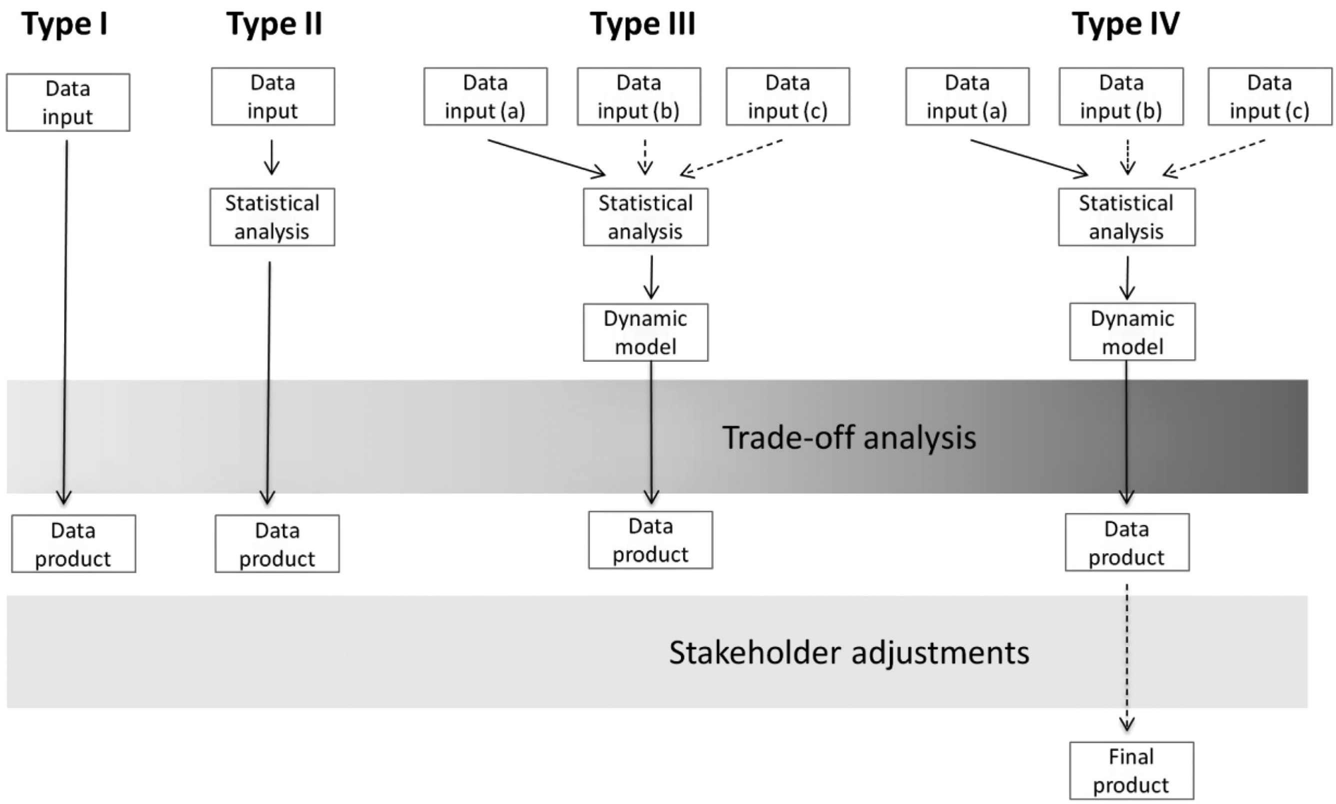

Figure 2. The range of complexity of dynamic ocean management (DOM) approaches. In type 1, a data stream is processed into a data product for distribution with minimal data processing. In type II, input data are analyzed statistically to produce a dynamic data product. In type III, multiple data types are used to infer statistical relationships, which are then used to build a predictive dynamic model, merged with real-time environmental input, generating data products. In type IV, the output from the dynamic model can be modified by stakeholder adjustments (e.g., manager preferences, additional information on fleet dynamics, compliance considerations) to produce a final data product. Individual data types may be static or can be updated for each run of the model. To date, trade-off analysis has occurred on an informal basis by the stakeholders but could be formally included in future DOM analyses, probably at the type IV end of the spectrum. The dashed lines indicate possible multiple sources of data.

Finally, type IV uses multiple data types and accounts for ocean user behavior. For example, real-time and forecasting habitat models are used in the Eastern Australian longline fishery to regulate fisher access to ocean regions expected to have high numbers of southern bluefin tuna (Hobday and Hartmann 2006, Hobday et al. 2011). In response to these models, fishery managers designate fishing zones that can be accessed depending on fishermen's available tuna quota. To date, trade-off analysis has occurred on an informal basis by the stakeholders but could be formally included in future DOM analyses (e.g., Abbott 2010).

Although DOM applications can vary in their level of complexity, the technological and analytical tools should align with both the capacity of users to apply the program on the water and the resources available to develop and—critically—maintain the DOM approach. Applying the least labor intensive and most efficient technological and analytical approach will support long-term sustainability of programs by decreasing costs of continued maintenance. Once developed, some analytically complex approaches may be no more labor intensive than simpler approaches, as computer programing allows for automation of methods (Hobday et al. 2014). For example, the Eastern Australian longline fishery uses a series of automated Matlab scripts to download and integrate remotely sensed data into predefined habitat modeling algorithms (Hartog et al. 2011).

The temporal lag between data capture and management implementation may constrain the types of DOM approaches available to managers. Although WhaleALERT functions in near real-time using acoustic and other data sources, the yellowtail flounder bycatch avoidance program functions on daily time scales, and TurtleWatch uses approximately weekly data. The application of near real-time or time-lagged datasets will further dictate the need for different analytical and technological capacity, both in collecting either remotely sensed or *in situ* type data, and serving it back to users. Shorter time lags may require Internet access on the part of users in remote situations, such as at sea, whereas longer time lags allow for the download of data before departing areas of cell phone or wireless

Internet access. The rapid expansion of smart devices and device-based applications is expanding the options of data sources—for example, crowdsourcing or citizen science, and data delivery (Newman et al. 2012).

Stakeholder participation. Stakeholder collaboration and cooperation have been identified as key components of management success, both in terms of facilitating initial participation and long-term compliance (Österblom et al. 2011). For many of the examples presented here, the development of a DOM application served as a platform to build collaborative networks between scientists, management bodies, industry, and stakeholders (Costanza et al. 1998, Scarlett 2013). Though the parties involved vary among the examples, sometimes including government and nongovernment agencies, the private sector, and academic institutions, all case studies involve some form of partnership with industry and stakeholder participation has been an essential common thread to successful outcomes (see table 1). In the British Columbia salmon fisheries, where a DOM approach has been successful in increasing target species quota use (Beacham et al. 2008), industry was involved from the onset of the program and fishers crowd-sourced information and collected samples for genetic testing. In the yellowtail flounder bycatch avoidance program, which relies on data provided by fishers to successfully meet its management objectives, industry has been involved since the early stages of program development and helped to define the initial program objectives and methods. Extensive collaboration with industry has been similarly fruitful in the Scottish conservation credits cod fishery, and River herring bycatch avoidance program. WhaleALERT was developed with substantial input from shipping companies whose vessels operated in areas subject to regulations protecting right whales, including the development of a test fleet prior to release of the product. In contrast, for TurtleWatch and the Eastern Australian longline fishery, industry were involved primarily as an end user of the products.

Current applications of DOM suggest that building sustained cooperative partnerships among stakeholders, industry, and end users in general in the development of program goals and design may increase the credibility, relevance, legitimacy, and ultimately, the success of DOM. Compliance and participation—whether the program is compulsory or voluntary—can be supported by the establishment of stakeholder networks that work collaboratively to develop and implement the DOM application (O'Keefe and Decelles 2013, Little et al. 2014). Voluntary programs offer an attractive alternative to compulsory ones in many cases because they can be implemented quickly, do not require costly monitoring and penalty regimes, and can promote industry and management innovation (Anton et al. 2004, Silber et al. 2012). However, end-user participation is considered essential in order for voluntary programs to be successful, particularly when monitoring capacity is weak (Bodin et al. 2006, Segerson 2013). In our review, we similarly found strong evidence to suggest that participation varies depending on the initial level of collaboration with end users, despite the existence of strong incentives (table 1). Even in cases where enforcement capacity is strong, increasing stakeholder collaboration in DOM would likely be advantageous because it can spur self-regulation and curb potential free-riding, thereby reducing enforcement costs (Ostrom 1990, Raakjaer and Mathiesen 2003).

Next steps in dynamic ocean management

DOM approaches are nascent and, as a result, no formal assessment of DOM relative to static management approaches has been conducted. However, our review of existing applications of DOM demonstrates that a suite of management tools have been adopted in multiple sectors across ocean regions, successfully supporting ocean management where competing priorities of economic and ecological outcomes pose challenges. By allowing for explicit incorporation of real-time or near real-time data, these examples show how DOM approaches have the potential to rapidly respond to potential conflicts around ocean resources and support effective management decisionmaking.

One appealing feature of DOM approaches is the ability to provide flexible and fine-scale approaches that balance competing management objectives (figure 3). Traditional static management measures, or those that are updated on seasonal or yearly time scales, encompass comparatively large spatial extents to ensure resource protection. DOM provides an opportunity to create more focused or tailored management structures that can reflect the underlying spatiotemporal relationships between the ocean and the organisms as well as the human activities and the resources being managed. By using real-time or near real-time data, DOM approaches can help to reduce the spatial extent of management actions, fine tuning the management structures and reducing the need for coarse-scale management tactics, even for highly mobile, vagile species.

The current examples of DOM illustrate the utility and relevance of a dynamic management approach and highlight how DOM applications can be coupled with adaptive management in ocean systems as well as the broad goals of ecosystem-based management and marine spatial planning. By directly linking management actions to current conditions, DOM approaches follow the familiar framework of adaptive management—a management structure that supports an iterative decisionmaking and learning process designed to reduce uncertainty in natural system dynamics while concurrently meeting specified management goals and objectives (Walters and Holling 1990, Armitage et al. 2009). DOM approaches align well with the goals of ecosystem-based management as DOM represents place-based management that integrates and recognizes the interdependence across organisms, the environment, and associated processes (biological, oceanographic, social, or economic, *sensu* McLeod et al. 2005). DOM can also support marine spatial planning and zoning efforts. One tool often implemented within the marine spatial planning context is the designation

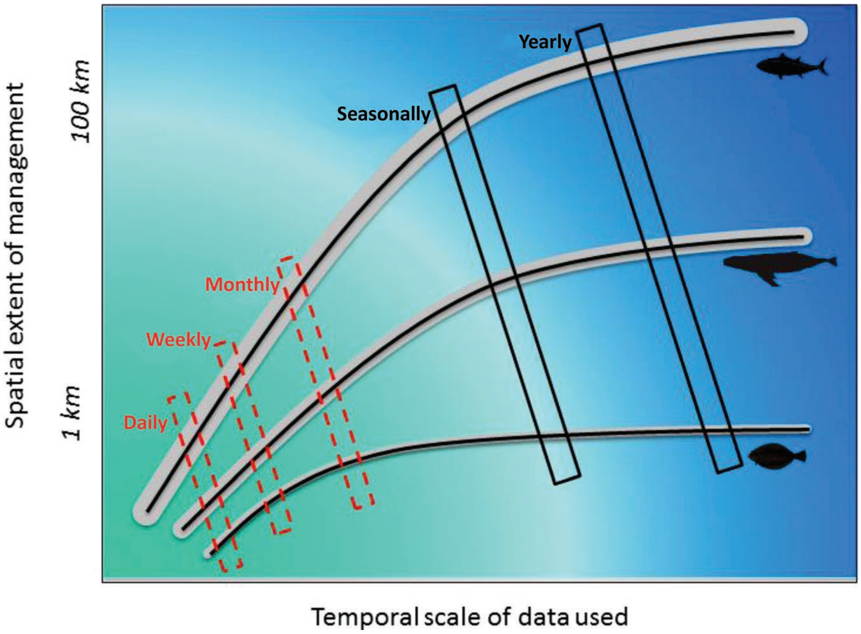

Figure 3. The relationship between the temporal scale of input data and the spatial extent of management required across a range of species (with variance represented in grey). The species range from a mobile species with a relatively limited distribution (flounder) to a highly vagile species (tuna). Static management measures that are based on data updated on a seasonal or yearly timeframe, shown in black, require comparatively large management areas to ensure resource protection is captured. By using near real-time data on daily, weekly, or monthly time scales, dynamic management, shown in red, allows for the delineation of comparatively smaller areas even for highly vagile species. Abbreviation: km, kilometers.

of marine protected areas (MPAs). In more recent years, calls for dynamic, rather than static, MPAs have intensified to increase MPA effectiveness for highly mobile marine species with variable distributions and in response to projected climate-change induced range shifts (Hyrenbach et al. 2006, Game et al. 2011). Although dynamic MPAs are one potential DOM application, DOM extends far beyond protected areas designation, as the case studies we discuss demonstrate.

The level of complexity with which DOM approaches can be applied is driven by the technological and analytical capacity of both the developers and end users. However, adopting a DOM approach does not necessitate highly complex data input or output as DOM applications have been shown to be successful across a range of complexities (i.e., type I–type IV), as long as the level of complexity of models and the time lags on which data is served to users reflect the ecological and socioeconomic realities of the system being managed. The flexibility and adaptability of this approach presents an appealing feature of DOM; effective DOM approaches can be tailored to meet the needs of the stakeholders. This suggests that DOM can be relevant in both developed and developing country or sector contexts.

Most of the existing DOM examples presented were developed in response to legislative or management action that threatened to impede or completely curtail ocean uses. Although DOM provided workable solutions in response to these crises, proactive DOM measures are also feasible in balancing the needs of resource users and resources. DOM approaches have also been effective in settings with both voluntary and compulsory compliance regimes. Successful DOM approaches, particularly voluntary or preemptive initiatives, can be facilitated by maintaining active communication channels between resource users, scientists, and managers. This type of ongoing interaction over time also helps to build trust between these different groups, thereby facilitating greater collaboration and cooperation in developing, implementing, and maintaining successful DOM programs. Successful DOM programs that draw from and build on the extensive literature base on stakeholder involvement will likely be most successful in leading to long-term and sustainable change (Gleason et al. 2010, Gopnik et al. 2012).

DOM is an emerging management approach with clear potential, as well as room for improvement and growth. Many of the current DOM examples were designed with a narrow focus on a single species of management concern. As DOM approaches continue to evolve and develop, future DOM applications will likely need to address more complex, multispecies management and include structured trade-off or economic analyses, structured decisionmaking, and multicriteria decision analysis (White et al. 2012, Klein et al. 2013). There is also a need for future DOM applications to include more social and economic data. In general, stakeholder community structure and diversity (Barnes-Mauthe et al. 2013), attitudes, beliefs, and motivations concerning ocean uses (e.g., Suman et al. 1999), and economic productivity (e.g., Sharma and Leung 1998), have not been explicitly integrated into working applications of DOM. Because communities are often dependent on marine resources to support their livelihoods and humans represent the primary force driving change in marine and coastal systems, lack of integration of these data can directly limit the success of effective management strategies through need for costly enforcement and lack of compliance (see Levin and Lubchenco 2008).

DOM represents an innovative paradigm to tackle the challenges to ocean management and resolve conflicts among multiple objectives by providing an effective alternative to traditional static management. Despite evidence for success in the examples discussed here, there remains a need for formal evaluations of DOM programs to demonstrate the utility of DOM to industry, management, and other stakeholders. Although no one management approach will resolve the increasing challenge to balance resource use and resource protection, more widespread adoption and implementation of dynamic approaches can play an role in supporting effective ocean management in the twenty-first century.

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Supplemental material

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