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Review

Data requirements and tools to operationalize marine spatial planning in the United States

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ABSTRACT

The U.S. is adopting a Marine Spatial Planning (MSP) approach to address conflicting objectives of conservation and resource development and usage in marine spaces. At this time MSP remains primarily as a concept rather than a well-defined framework, however expanding anthropogenic impacts on coastal and marine areas reinforce the need to adopt an MSP approach to manage societal demands while preserving the marine environment. The development of theory and methods to implement MSP are on the rise across the nation to address coastal and marine environmental challenges. Critical components of marine spatial planning are (1) spatial data collection, (2) data management, (3) data analysis, and (4) decision support systems. Advances in geotechnology have increased access to spatial data enabling the development of decision support tools to organize, analyze, and inform the MSP process by projecting future scenarios. A review of the current literature reveals the available technological and methodological tools that are best suited for marine spatial planning, as well as suggests areas for further research in order to better inform this process in the U.S.

1. Introduction

Marine spatial planning is a concept that has rapidly gained momentum. Regional MSP projects are currently underway in the United States and abroad (Allnutt et al., 2012a; Collie et al., 2013). According to the United Nations Educational, Scientific, and Cultural Organization, "marine spatial planning is a public process of analyzing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process" (Ehler and Douvere, 2009). In June of 2009 the Obama administration created a Task Force to develop a framework for coastal and marine spatial planning. In December of that year, the U.S. Interagency Ocean Policy Task Force released an Interim Framework for Effective Coastal and Marine Spatial Planning. They summarize Coastal and Marine Spatial planning (CMSP) as "a public policy process for society to better determine how the oceans, coasts, and great lakes are sustainably used and protected now and for future generations." CMSP encompasses nearly identical concepts as MSP and may be more accurate given that coastal and marine space and processes are inextricably linked and should not be considered as distinct in a planning process. For the purpose of simplicity however, the more widely used term of MSP will be used in this paper.

The practice of marine spatial planning is made possible by the increasing availability of high quality spatial data (Collie et al., 2013). Various software and other tools allow for the management and analysis of this data and give practitioners the ability to create alternate management scenarios upon which planning decisions are made (Guerry et al., 2012; Melbourne-Thomas et al., 2010; Weijerman et al., 2013). It is important to remember that MSP is not a simple linear progression but rather a dynamic process with many feedback loops. Analyses of existing and future conditions will evolve as new information is identified and incorporated into the planning process (Yee et al., 2015). Understanding and

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utilization of the proper tools is essential for successful MSP endeavors (Halpern et al., 2012). The purpose of this review is to present and describe the kinds of tools that are available for MSP and provide examples from the current literature. Much discussion has occurred regarding MSP policy, frameworks, and best practices. As existing federal and state agencies prepare to shift their practices towards an MSP approach, a comprehensive review of data requirements and available tools is timely.

A primary goal of MSP is to support current and future uses of ocean ecosystems and maintain the availability of valuable ecosystem services for future generations (Douvere, 2008). An MSP process also addresses the legal, social, and economic aspects of governance, including the designation of authority, stakeholder participation, financial support, enforcement, monitoring, and adaptive management (UNEP, 2011). Key steps include (Ehler and Douvere, 2009) (Fig. 1):

1. Defining existing conditions through data collection;
2. Analyzing existing conditions using spatial ecological modeling, human dimension research methods, and cumulative impact assessments; and
3. Projecting future conditions using decision support tools.

Information generated throughout this process informs the preparation of a spatial management plan (Ehler and Douvere, 2009). These critical steps are facilitated by the use of data, software tools, and other well-defined spatially explicit methodologies (Papathanasiou and Kenward, 2014; Shucksmith and Kelly, 2014), which we will collectively refer to as "tools". They fall into four major categories as relevant to MSP and will be the basis upon which this review is organized. The categories are: 1) data collection; 2) data management; 3) data analysis; and 4) decision support systems.

2. Data collection

The collection of pertinent spatial data is critical to the MSP process (Ehler and Douvere, 2009). For the purpose of this review we will make a distinction between the tools and technologies used for collecting primary data and the tools utilized by MSP practitioners to define, manage, and analyze this information. Ehler and Douvere (2009) identify five primary sources of data relevant to MSP, which include scientific literature; expert scientific opinion or advice; government sources; local knowledge; and direct field measurement. Most spatial planning efforts rely heavily on the first three sources (Ehler and Douvere, 2009). However local knowledge is increasingly recognized as an important source of information (Thornton and Scheer, 2012) and methods are in development to collect and incorporate this knowledge in the planning process (St. Martin and Hall-Arber, 2008). Direct-field measurements are typically outside the scope of MSP practitioners, though are sometimes necessary if significant knowledge gaps are identified. However, given that many MSP projects are large in scope, it can be difficult to obtain datasets that are consistent across the area of interest. This issue is particularly pronounced for ecological and human use data.

Current technology and methods have made available a great deal of spatially explicit data for use in MSP, especially in terms of ecological and environmental information. Palumbi et al. (2003) describe the application of some of the tools currently used in oceanography and marine ecology to inform the design of ocean reserves, which have implications for all aspects of MSP. Remote sensing data is a major source of ecological and environmental information. Human dimensions, including (spatial) information about human activities, have been less studied and often represent a knowledge gap in MSP (St. Martin and Hall-Arber, 2008). With the current proliferation of MSP initiatives this "missing layer" is

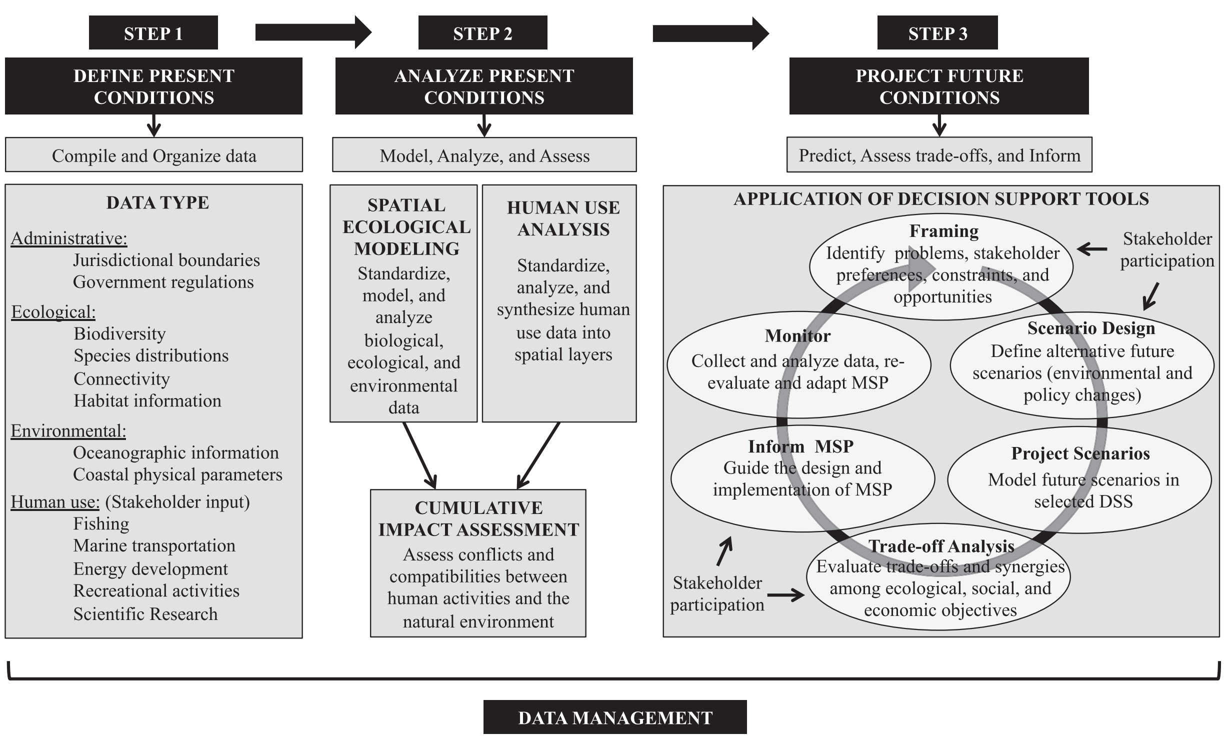

Fig. 1. Key steps within the MSP process related to data and information, adapted from Ehler and Douvere (2009): Step 1: Define present conditions through data collection; Step 2: Analyze existing conditions using spatial ecological modeling methods, human use analysis, and cumulative impact assessments; and Step 3: Project future conditions using decision support systems (DSS) and scenario modeling.

increasingly becoming addressed through various techniques (Collie et al., 2013).

A critical consideration for the collection of data for MSP is the issue of scale (Hughes et al., 2005; Kendall and Miller, 2010; Kendall et al., 2011), similarly to natural ecosystems and social processes; MSP should address multiple scales (Cumming et al., 2006; Hughes et al., 2005). According to sustainability theory and recent experiences, MSP should adopt a hierarchical approach to define its planning units (Kay et al., 1999; McCay and Jones, 2011; Spalding et al., 2007) so issues and information are considered at multiple levels and each level provides context to the lower one. This enables more coordinated management (Gilliland and Laffoley, 2008) and a more effective institutional arrangement (Ostrom, 1990).

In the U.S., these planning levels have been defined as: Federal, Regional (nine Regional Planning Bodies have been tasked with implementing MSP), and State (Halpern et al., 2012). In addition to the challenges of defining the scale of planning units, how to define coastal and offshore boundaries is also subject to discussion (Gilliland and Laffoley, 2008). According to an ecosystem-based approach and for planning purposes, those boundaries should be established based on natural ecosystem borders and their delineation should incorporate biogeography, oceanography, connectivity, and habitat (Crowder and Norse, 2008; Foley et al., 2012; Spalding et al., 2007; Toonen et al., 2011); while also reflecting socio-cultural (Olson, 2010), socio-political, and administrative conditions (Crowder and Norse, 2008; Gilliland and Laffoley, 2008). Identifying areas where ecosystem and governance boundaries converge and diverge is also necessary to establish measures that maintain planning coherence (Gilliland and Laffoley, 2008).

This transition to a more holistic and coordinated management of ocean spaces and marine resources generates two key planning challenges: (1) Maintaining coherence across the nested hierarchy in terms of linking policy goals, objectives, management tools, and actions without gaps; and (2) ensuring coordination across planning unit boundaries (Halpern et al., 2012). Identifying and agreeing on the scales of the hierarchical nested planning units and the allocation of those boundaries will be necessary to inform the scale of the data collection process (Gilliland and Laffoley, 2008; Halpern et al., 2012). It is often unproductive to collect fine-scale data sets for small parts of the planning unit area, because when put together they are frequently not compatible (Ehler and Douvere, 2009). Types of spatial data that are necessary for marine spatial planning include administrative, ecological, environmental, and human use (Shucksmith and Kelly, 2014). Each of these main data types will be discussed in turn along with key sources and tools utilized for their collection.

2.1. Administrative

Administrative data includes jurisdictional boundaries and government regulations. Maritime boundaries and limits delineate the extent of a nation's exclusive rights and control over the maritime areas off its coast. In the U.S., these boundaries include a 12 nautical mile territorial sea, a 24 nautical mile contiguous zone, a 200 mile exclusive economic zone, and the continental shelf. Government regulations regarding coastal and marine areas apply to specific legislative and jurisdictional zones and can be represented as spatial footprints. The combination of jurisdictional boundaries and the regulations that apply to the areas they delineate are essential to understanding existing legislative frameworks and place the MSP process in the current management context (Sanchirico et al., 2010; UNEP, 2011).

The Marine Cadastre is an online spatial database provided by the NOAA Coastal Services Center (CSC) and the US Department of the Interior's Bureau of Ocean Energy Management (BOEM) (NOAA CSC a). It is a useful tool for the retrieval of administrative layers needed for MSP efforts including jurisdictional boundaries, restricted areas, laws, and marine infrastructure. This tool is accessible via the internet and features an online GIS, in which a user zooms into and selects their area of interest to identify available data resources, which they then have the option to download. A GIS application is necessary to view and analyze the downloaded spatial data.

2.2. Ecological

Ecological data necessary for MSP include biodiversity, species distributions, connectivity, and habitat information (Crowder and Norse, 2008; Foley et al., 2012). In most cases, these types of data are collected by scientific and/or government organizations. Various field methods are used to generate ecological distribution and biodiversity data as part of inventory and monitoring projects (Murphy and Jenkins, 2010). The scale and extent of these datasets however, are often small and patchy (Hughes et al., 2005; Knudby et al., 2013), making them unsuitable for large scale MSP endeavors (Collie et al., 2013). Seascape properties, such as benthic cover and structural complexity can be used as proxies or surrogates of important ecosystem properties, including biodiversity, species distributions, ecological processes, and ecosystem goods and services (Mellin et al., 2011; Mumby et al., 2008; Pittman et al., 2010). This information is increasingly obtained through remote sensing methods, allowing data collection on large scales (see Diaz et al. (2004) for a review of methods). This has important implications for MSP as it represents large scale, low cost means of collecting information useful for spatial ecological modeling (Knudby et al., 2010a) (further discussed in Section 4.1) and essential for identifying sensitive or ecologically important areas (Bostrom et al., 2011; Schmiing et al., 2013).

2.3. Environmental

The marine environment is dynamic and complex (Hughes et al., 2005), and patterns and trends exist on different time and spatial scales (Bostrom et al., 2011). An understanding of ocean and near shore physical parameters is important for MSP (Ehler and Douvere, 2009). Oceanographic information can include mean sea level change, temperature, ocean winds, circulation, currents, waves, and water chemistry (Mellin et al., 2010). While historically much of this data was collected directly by ships and oceanographic buoys, today remote sensing from satellites records the same data on the scale of whole ocean basins. On a much smaller scale, land-based remote sensing techniques, such as Coastal Ocean Dynamics Application Radar, allow precise measurements of surface currents within a few kilometers of shore (Palumbi et al., 2003). Marine environmental and circulation patterns are important for determining different uses for marine spaces (Ban, 2009). In addition, knowledge of ocean currents can allow us to infer dispersal patterns for marine larvae (Anadón et al., 2013; Hogan et al., 2012), which is particularly important for the design of marine reserves (McLeod et al., 2009). Oceanographic maps for different parameters at appropriate scales are useful for spatial ecological modeling and informing MSP (McArthur et al., 2010). These are obtainable through U.S. government agencies such as the NOAA National Ocean Service (NOS), the U.S. Integrated Ocean Observing System (IOOS), and the NASA Physical Oceanography Distributed Data Archive Center (PO.DAAC).

2.4. Human use

Data regarding human activities in marine spaces is instrumental for marine spatial planning (Ban et al., 2012; Dalton et al., 2010). The social seascape however, is largely undocumented and often represents a "missing layer" in decision making (St. Martin and Hall-Arber, 2008). Human uses of ocean and coastal areas encompass a broad range of activities which can include: fishing (commercial and recreational), aquaculture, marine transportation and shipping, oil and gas development and exploration, sand and gravel mining, offshore renewable energy, military operations, scientific research, as well as a range of recreational activities (Katsanevakis et al., 2011). At this stage, no convenient proxy exists for the delineation of human activities in marine spaces. Some of these activities are site specific and can be mapped fairly easily, others such as fishing and recreational uses, can be variable in time and space (Cummins et al., 2008; Tallis et al., 2012). Due to the proliferation of ecosystem-based management and marine spatial planning, researchers have begun to focus on quantifying and mapping these activities (Selkoe et al., 2009; White et al., 2012), and various initiatives are underway at the federal level to collect this information through stakeholder analysis and participatory mapping (National Ocean Service, 2015).

Data collection on human uses of the marine environment occurs by identifying the relevant stakeholders in all sectors and providing them with opportunities to contribute (Gilliland and Laffoley, 2008), using a 'stakeholder analysis approach' (refer to Pomeroy and Douvere (2008) for a more comprehensive discussion and methodology for the identification of stakeholders). Participatory mapping draws on stakeholder and local knowledge to locate fishing communities at sea (St. Martin and Hall-Arber, 2008) as well as collect other MSP relevant information (Scholz et al., 2004). Questionnaire surveys and/or interviews (Cummins et al., 2008) and shipboard surveys (Dalton et al., 2010) have been used to collect information about marine recreational activities. Vessel Monitoring Systems (VMS) are used to define principle areas for fisheries (Fock, 2008; Lee et al., 2010; Mills et al., 2007). Similar to natural seascapes, social and cultural seascapes are often equally complex, heterogeneous, and dynamic (Pungetti, 2012; St. Martin and Hall-Arber, 2008). Currently available data collection techniques often fail to adequately represent them over space and time, in spite of the recognition that marine a ecosystem-based approach should include human impacts, knowledge, and needs, which are dynamic and multi-scale (St. Martin and Hall-Arber, 2008).

3. Data management

Data management is nearly as important to successful marine spatial planning as are the data themselves (Ehler and Douvere, 2009). Information and data collected and created in the MSP process may be underutilized without careful management and documentation. Organizing and managing spatially explicit databases is typically the most time-consuming aspect of planning activities. Data models and other resources exist to assist practitioners during this phase. A well-organized inventory of available data facilitates analysis and subsequent planning steps. It should be refined during the planning process to reflect modified objectives and new sources of information.

A geodatabase or spatial database is designed to store, query, and manipulate geographic information and spatial data. This is the preferred method for managing MSP data specific to a particular area or project. Guidance on the theory and practice of designing geodatabases is provided by Arctur and Zeller (2004). A data model such as ArcMarine provides a basic template to implement a MSP geodatabase, and facilitates the process of extracting, transforming, and loading data. Users can build upon the common marine data types provided by the model to suit the needs of their project (Wright et al., 2007).

Regional and national initiatives to manage and make accessible coastal and MSP relevant data, utilize Spatial Data Infrastructures (SDI) (Rajabifard et al., 2005; Strain et al., 2006). An SDI is a system or framework that facilitates the exchange of spatial data. Benefits of developing SDIs include improved access to data, reduced duplication of effort in collecting and maintaining data, better availability of data, and interoperability between datasets (Strain et al., 2006). Examples of SDI's for the United States which are relevant for MSP include the NOAA Coastal Services Center – Digital Coast (NOAA CSC b) and Multipurpose Marine Cadastre (NOAA CSC a). These are valuable resources for obtaining MSP relevant data, which are updated on a continual basis.

4. Data analysis

Analyzing existing and future conditions represents another critical part of the MSP process (Ehler and Douvere, 2009). Various tools have been developed for this purpose, all of which fall under the realm of Geographic Information Science (GISc), which is the foundation of Geographic Information Systems (GIS). Of the four primary data types discussed previously, ecological and human use data require additional analysis to maximize their usefulness in a MSP framework. These analyses include mapping important biological and ecological areas and human uses. Second order analysis consists of cumulative impact assessment which draws on ecological, human use and environmental data to assess possible conflicts and compatibilities among human activities and the natural environment.

4.1. Spatial ecological modeling

Spatial ecological modeling is a type of analysis that compiles and summarizes all available biological, ecological and environmental information for a study area. It involves the characterization of seascapes and biological communities to identify ecologically important areas based on species–habitat associations (Kendall et al., 2004; Mellin et al., 2009; Pittman et al., 2007). Recent research focusing on the relationship between benthic habitat and marine life assemblages utilized benthic habitat and seascape variables as predictors for diversity and abundance of fish and corals (García-Charton and Pérez-Ruzafa, 2001; Gratwicke and Speight, 2005; Knudby et al., 2010a; Mellin et al., 2011; Pittman et al., 2007, 2009; Walker et al., 2009; Wedding and Friedlander, 2008).

Spatial ecologists develop methods, ranging from linear to nonlinear modeling and machine learning techniques, coupled with a Geographical Information System (GIS), to geographically extrapolate in-situ data on the distribution, diversity, and abundance of species based on seascape properties (Bostrom et al., 2011; Franklin and Miller, 2010; Pittman et al., 2007). Therefore, developing spatial ecological models begins with observations of species distributions (often summarized in terms of biodiversity, biomass, or other ecological metrics), and the identification of environmental variables thought to influence habitat suitability, and therefore the distributions of the species in question (Franklin and Miller, 2010; Mellin et al., 2006; Schmiing et al., 2013).Modeling techniques can be rule-based or quantitative, and can include multivariate ordination, generalized linear models (Guisan et al., 2002; Knudby et al., 2010a), generalized additive models (Guisan et al., 2002; Knudby et al., 2010a), classification and tree ensemble techniques (Knudby et al., 2010b; Pittman et al., 2009), and artificial neural networks (Guisan and Zimmermann, 2000; Pittman et al., 2007).

Geographical extrapolation, or predictive mapping provides cost-effective, quantitative, and spatially explicit information at multiple scales, on patterns of species distribution and abundance (Pittman and Brown, 2011). Hence, this work and its resulting map products expand upon field-based measurements that are expensive and spatially limited, and produce spatial information of the scope and scale which are necessary for MSP. Spatial ecological modeling can allow managers and ecologists to undertake large-scale ecological assessments, gain better understanding of species-habitat associations, and inform management strategies, with a focus on areas of high ecological significance (Mellin et al., 2010; Shucksmith and Kelly, 2014).

4.2. Human dimensions

Human use data that is obtained as part of a MSP process needs to be standardized into spatial layers that can then be overlaid in a GIS to identify existing or potential conflicts between human activities. These are complex processes occurring across a variety of scales and to be accurately represented should integrate a temporal as well as a spatial component. Ongoing advances in geographic information systems (GIS), geographic positioning systems (GPS), and other technologies create new alternative methods to collect data on the human ocean uses (Dalton et al., 2010). Ehler and Douvere (2009) suggest a matrix method for identifying conflicts and compatibilities among existing human activities. The Atlas Project utilized a mixed methods approach to generate GIS data layers depicting fisher behaviors, which combined spatial analytical techniques with participatory research in the form of community-based workshops and interviews (St. Martin and Hall-Arber, 2008). This method leveraged GIS advances while overcoming certain GIS limitations in terms of representing social processes and values. However, barriers remain in utilizing spatial data to represent the human dimensions of the marine environment. Incorporating social seascapes into MSP requires new methodologies and data collection efforts capable of identifying and representing places of interests and/or cultural importance, stakeholders' level of dependencies on those places and resources, and temporal and spatial use patterns at multiple scales (Dalton et al., 2010; Scholz et al., 2011; St. Martin and Hall-Arber, 2008). Until these are developed, it may well be necessary for MSP practitioners to utilize the techniques presented earlier to generate appropriate data. Spatial analysis of human activities is a critical part of MSP and a proportional amount of effort should be spent on this phase.

4.3. Cumulative impact assessments

The next step consists in integrating this information into maps of human-uses to locate conflict areas and for comparison with other spatial attributes (Halpern et al., 2012; Selkoe et al., 2009, 2008). Assessing conflicts and compatibilities between human activities and the natural environment follows, informed by previous analyses of ecological and human use data (Maxwell et al., 2013) and complemented with inputs from local experts (Teck et al., 2010). Analysis of cumulative human impacts in the marine environment is still in early stages but developing rapidly. A framework for evaluating the interactive and cumulative impacts of human activities is provided by Halpern et al. (2008a). In a related study, Halpern et al. (2008b) generated a global map of human impacts on marine ecosystems. The maps produced by this research can help to inform MSP efforts, though the scale is likely too broad for most marine planning efforts. The analytical process however, could be adapted to delineate human impacts at a finer scale by improving data and methods used to quantify, combine, and evaluate impacts from multiple stressors operating at multiple scales (Halpern and Fujita, 2013).

5. Decision support systems

Another key step in the MSP process is identification and evaluation of alternative management measures (Ehler and Douvere, 2009). It is in this capacity that interactive decision support systems (DSS) have played an increasingly important role (Collie et al., 2013; Papathanasiou and Kenward, 2014). Decision support systems constitute a class of interactive computer-based information systems that support decision-making activities. Interactive DSS can integrate, share, and contrast many people's ideas about planning options and help managers and stakeholders to visualize trade-offs between different management strategies (T. N. C. Global Marine Team, 2009). They can also be made available online to further facilitate user collaboration (Guerry et al., 2012; Villa et al., 2009). The primary benefits of using DSS in the MSP decision process are their ability to centralize, integrate, and manage a wide range of spatial data (Fulton et al., 2011), the speed of processing those data, simplicity, and outputs easily understood by the users. Governing bodies must still make decisions among alternative solutions, but these alternatives can be defined and understood more quickly and easily, and evaluated in terms of trade-offs and synergies (Yee et al., 2015).

There are a myriad of complex trade-offs that exist between the various ecological, economic, and social objectives within MSP (Fulton et al., 2011). DSS tools can be used to compare alternative scenarios to identify potential 'cost-effective' solutions (Collie et al., 2013), assess trade-offs, and identify areas of synergy (White et al., 2012). Trade-offs are analyzed with qualitative or quantitative methods coupled with expert judgment (Collie et al., 2013). Market and non-market economic components of trade-off analysis can also be useful to inform MSP (Sanchirico and Mumby, 2009; Waite et al., 2014). DSS can make explicit trade-offs, by assessing multiple ecosystem goods and services, their benefits, and values provided to different sectors (Hicks et al., 2009; White et al., 2012). Hence, the need for DSS increases with the number of planning objectives and potential trade-offs.

Initial development of DSS was primarily for the purpose of conservation and more specifically, for the siting of marine reserves. Since that time, examples from the literature that describe the use of DSS to produce and evaluate future conditions are on the rise. DSS can model exploited marine ecosystems to foster understanding of system dynamics; identify major processes, drivers, and responses; highlight major gaps in knowledge; and provide a mechanism to evaluate management strategies before implementing them (Fulton et al., 2011; Stelzenmüller et al., 2013). Most commonly used tools predict the impacts of alternative stressors (climate change) and management interventions (marine reserve placement) scenarios on future ecosystem states (Francis et al., 2011). Existing tools range from relatively simple mapping tools (Guerry et al., 2012) to more sophisticated modeling approaches capable of also characterizing uncertainty (Francis et al., 2011; Melbourne-Thomas et al., 2011a; Stelzenmüller et al., 2013; Villa et al., 2009) (refer to Table 1 for summary on pros and cons of key existing DSS). Certain tools adopt an ecosystem services approach that explore cumulative impacts and benefits and are explicit about trade-offs and win–win scenarios to inform MSP (Guerry et al., 2012). U.S. agencies at multiple levels have expressed that DSS are more useful and more likely to be adopted in a structured decision-making context when they are GIS-based, MPA related, publicly available, and participatory (Bremer et al., 2015; Pattison et al., 2004).

5.1. Marxan and Ecopath

Marxan is the most widely used conservation planning software

Table 1
Summary information of described DSS software (● – Yes; ◑ – Intermediate, ○ – No).

Model	Marxan[a]	Ecopath (Ecosim, Ecospace)[b]	Marine InVEST[c]	CORSET[d]	Atlantis[e]
Management purpose	Protected area design and monitoring	Fisheries effects & protected area design and monitoring	Ecosystem services trade-offs & policy design	Cumulative impact assessment & protected area design	Cumulative impact assessment & policy design
Ecosystems	All	All	All	Coral reefs only	All
Users expertise	Intermediate	Advanced	Minimal	Advanced	Advanced
Spatial	●	●	●	●	● (3D)
Temporal	○	●	○	●	●
Trophic interactions	○	●	○	●	●
Larval connectivity	○	●	○	●	●
Transferable & Flexible	●	●	●	●	●
Data intensive	◑	●	○	◑	●
Computational intensive	○	●	○	◑	●
Simple outputs	●	●	●	●	●
Documentation	●	●	●	●	◑
Ea se of implementation and use	●	○	●	◑	○

[a] Ball and Possingham (2000), The University of Queensland (Australia), http://www.uq.edu.au/marxan/.
[b] Polovina (1984), National Oceanographic and Atmospheric Administration (NOAA), http://www.ecopath.org.
[c] Guerry et al. (2012), The Natural Capital Project, Stanford University, World Wildlife Fund, The Nature Conservancy, and the University of Minnesota, http://www.naturalcapitalproject.org/InVEST.html.
[d] Melbourne-Thomas (2010), Institute for Marine and Antarctic Studies (IMAS), The University of Tasmania, https://ebmtoolsdatabase.org/tool/corset-coral-reef-scenario-evaluation-tool.
[e] Fulton and Scientific (2004), Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research, http://atlantis.cmar.csiro.au/.

in the world (Watts et al., 2009). It uses the simulated annealing algorithm (Kirkpatrick, 1984) to minimize the total cost of a reserve system, while achieving a set of conservation goals. Similar to other reserve siting tools it provides two zoning options for each planning unit: reserve and non-reserve. An extension called Marxan with Zones generalizes this approach by providing multiple zoning options for each planning unit. Each zone then has the option of its own actions, objectives and constraints. The purpose is to minimize total cost while ensuring a variety of (user-defined) conservation and multi-use objectives (Watts et al., 2009). Marxan provides a flexible approach capable of incorporating large amounts of data and use categories. It is computationally efficient, and lends itself well to enabling stakeholder involvement in the site selection process (Ball and Possingham, 2000). This tool has been used for the design of multiple-use marine parks in Europe (Smith et al., 2009), North America (Ban et al., 2012; Klein et al., 2009) Western Australia (Watts et al., 2009), Africa (Allnutt et al., 2012b), and Indonesia (T. N. C. Global Marine Team, 2009). One shortcoming of the Marxan approach is its inability to deal with issues of demographic connectivity. Marxan considers that including into a reserve system a site that contains a particular feature will ensure the persistence of that feature, even though surrounding sites may not have the same protection, and may therefore be ecologically compromised (Leslie et al., 2003).

Given Marxan shortcomings, the evaluation of the ecological components and trade-offs of alternate planning scenarios may be better provided by another freely available DSS, Ecopath (Polovina, 1984; Christensen and Pauly, 1992). Ecopath was designed to investigate the impacts of fisheries on ecosystems' dynamics by translating changes in biomasses and trophic interactions in time (Ecosim) (Walters et al., 1997) and space (Ecospace) (Pauly et al., 2000; Walters et al., 1999). Ecospace is an ecosystem modeling approach that has been under constant development over the last quarter of a century (Christensen and Pauly, 1992; Polovina, 1984; Walters et al., 1997). During this time the approach has grown to become the most widely applied ecosystem modeling technique (Christensen and Walters, 2004). The most recent version of Ecospace (EwE6) incorporates a new optimization module based on a seed cell selection approach, where the spatial cell selection process is influenced by geospatial information (Christensen et al., 2009). The new sampling procedure may be complementary to the Marxan approach in that Ecospace provides a robust evaluation of ecological processes, including spatial connectivity, due to its trophic modeling foundation. These topics are not fully developed in the Marxan analysis. Christensen et al. (2009) advocate that the two approaches, with their unique advantages and limitations, be applied in conjunction. Further research should reveal the efficacy of the updated Ecospace approach and how it compares with the already well-established Marxan with Zones.

5.2. Marine InVEST

Marine Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) tool was developed to map, quantify, and value changes in the delivery of multiple ecosystem goods and services generated by seascapes, including renewable energy, seafood supply, aesthetic, recreation, carbon sequestration, water quality, and habitat risk (Arkema et al., 2013; Guerry et al., 2012; Tallis et al., 2008). It estimates changes across a suite of services under different management and climate change scenarios and investigates trade-offs, in both biophysical and monetary and/or non-monetary value terms (Guerry et al., 2012). The tool is a flexible and scientifically grounded set of computer-based models with a modular, tiered approach to accommodate a range of data availability and the state of system knowledge (Tallis and Polasky, 2011), however the platform is static. Hence, InVEST is best used in an iterative and interactive fashion with stakeholders, and was applied to the west coast of Vancouver Island, British Columbia (McKenzie et al., 2014) and Belize to inform the design of their Coastal Zone Management Plans (Ruckelshaus et al., 2013). Efforts are on the way to expand and improve marine InVEST on three primary fronts (Ruckelshaus et al., 2013): (1) Further model testing and improved communication of uncertainty; (2) develop new models and improve the functionality of existing models; and (3) expand existing options for model outputs (i.e., connecting biophysical metrics to more valuation metrics) and synthesize outputs to better examine trade-offs and win–win opportunities.

5.3. CORSET

CORSET (Coral Reef Scenario Evaluation Tool) is a biophysical model suited to inform coral reef management decisions. It was specifically developed with 3 primary goals: (1) Build a generic modeling structure, transferable across biogeographic regions supporting coral reefs, while still capturing coral reef ecological dynamics of interest to management; (2) model reef dynamics at a range of spatial (sub-regional to regional) and temporal (years to decades) scales; and (3) generate outputs understandable to non-experts (Melbourne-Thomas et al., 2011a, 2010). CORSET couples larval connectivity to coral reef ecological dynamic processes (functional and trophic group interactions) and links observed conditions to terrestrial or marine-based drivers, such as sedimentation and fishing activities at the regional scale (~1000 km) in a spatially explicit manner and over simulated future projections (Melbourne-Thomas et al., 2011a, 2010). Although only applied in the Quintana Roo region (Mexico), CORSET can be coupled with a spatially explicit socioeconomic agent-based model (SimReef) (Perez et al., 2009) structured around fisheries, urbanization, and tourism drivers (Melbourne-Thomas et al., 2011b). Stochastic simulation models are of particular value in decision support, because they facilitate the projection of potential future outcomes under alternative resource management scenarios (Melbourne-Thomas et al., 2011a, 2010). However, CORSET is best applied at a regional scale due to the spatial and ecological resolution of the processes being modeled.

5.4. Atlantis

Atlantis is a dynamic modeling framework that links a biophysical system to the users of the system (industry), and socioeconomic drivers of human use and behavior (Fulton et al., 2011). It is a full ecosystem simulation model that incorporates climate, oceanography, nutrient availability, food web interactions, and other ecological factors in a spatially explicit way. Atlantis is best used as a strategic tool (long-term decision-making) to explore ecosystem dynamics (including marine habitat, nutrients, and biodiversity) and test different fisheries management approaches in terms of trade-offs between and among species, fishing gear types, management goals, and the direct and indirect effects of different management policies (Fulton et al., 2011; Kaplan et al., 2012). The Atlantis DSS has been used in these roles for a decade, primarily in Australia and North America (Kaplan et al., 2012; Link et al., 2010), and is regularly being modified and applied to new questions (e.g. it is being coupled to climate, biophysical and economic models to help consider climate change impacts, monitoring schemes and multiple use management) (Fulton et al., 2011). Like all DSS, Atlantis has weaknesses, including poor ease of use, patchy documentation, large data demands, difficult implementation, and long run and calibration times (Fulton et al., 2011).

5.5. Other software

Some marine spatial plans are using GIS-based mapping tools (e.g. SITES, Marine Atlas, Habitat Suitability Modeling) (Airamé et al., 2003; Collie et al., 2013; Pattison et al., 2004). For instance, Airamé et al. (2003) used a computer-based siting tool (DSS) called SITES to generate potential options for the no-take reserve network in the California Channel Islands. The computer used previously compiled geographic information to create a network of randomly placed reserves and then improved it slightly, searching progressively for layouts that were closer to the specified criteria. The outputs were used as a starting point for discussions about where to implement individual reserves, and what trade-offs would be necessary in different potential network configurations (Pattison et al., 2004).

Other plans use some form of quantitative index and/or decision tool, such as MarZone, MarineMap, or OceanMap (Pattison et al., 2004). For instance, OceanMap was specifically designed to allow for a participatory approach that incorporates local knowledge, collects spatially explicit-socioeconomic data, and integrates ecological, economic, and sociocultural data in the context of marine conservation planning (Pattison et al., 2004; Scholz et al., 2004). This tool was applied to inform the MSP planning process along the west coast of the U.S. (Scholz et al., 2011).

Other examples demonstrate the effectiveness of combining siting tools and GIS data in designing marine reserves in the Gulf of Mexico (Beck and Odaya, 2001) and the Florida Keys (Leslie et al., 2003). These studies make it clear that there are multiple approaches to implementing marine reserves in a particular area. Sarkar et al. (2006) provide a review of conservation planning tools that can help inform potential users about their theory and utility. Initially, almost all of the theory for spatial conservation planning was focused on identifying no-take reserves. This trend translated into tool development such that most available DSS were designed to identify one type of zone (ie. marine reserves). Marine spatial planning seeks to develop multi-use zoning schemes for which a broad range of objectives is represented. Therefore, optimization tools or frameworks that allow for multiple zones have become increasingly available in recent years.

5.6. Limitations of decision support systems

MSP needs to recognize and account for uncertainty and risk, arising from data gaps, scale mismatches, or lack of knowledge, given that DSS do not systematically include them (Fulton, 2010). Conversely, the amount of data, technical challenges, and cost of tool implementation also increase (T. N. C. Global Marine Team, 2009). Most tools do not handle a wide array of sectors or ecosystem goods and services, lack mechanisms for modeling changes in ecosystems and service delivery with changes in management or environmental stressors, and/or are not practical for MSP given the tendency to solely focus on fisheries management (Guerry et al., 2012). Remaining key challenges for implementing effective environmental DSS are now more socio-economic (data collection and data analyses) than technical, requiring also a more local- and place based-orientated attitude of researchers and government (Papathanasiou and Kenward, 2014).

6. Conclusions

Technological advances have enabled us to gather and share information about our environment and how it behaves. We use geographic information science to manage and explore this wealth of spatial data. MSP is a marriage of geographic information science, environmental management, and land use planning. It is a complex, data intensive process. Spatial analysis lies at the heart of MSP and is surpassed in importance only by stakeholder participation. To a large extent, the success of a MSP effort depends on the abundance and quality of its data, and the capacity for its analysis. Various tools can enable and facilitate different aspects of MSP. It is in the interest of all involved to make the best use of the technology available.

It is important to consider the scope and scale of the data collected for MSP which should, to the extent possible, have a consistent source, match the scope of the planning area and the scale of the planning units, and align with planning boundaries. Geographic information science has provided the tools needed to manage and analyze data for MSP. Practitioners should make full use of this capability and utilize geodatabases to maintain integrity of their spatial data in a consistent and accurate manner. Analytical methods such as spatial ecological modeling and cumulative impact assessments allow for summarization and integration of a wide range of datasets for major planning components, enabling more efficient comparisons between them and providing a holistic view of the current state of ocean spaces. Interactive decision support systems can create alternate spatial management scenarios, along with a clear evaluation of the trade-offs associated with each, making them available for the consideration of stakeholders. Proper use of these tools can greatly streamline the MSP process and support its iterative nature.

MSP represents a new global paradigm in spatial management. Though its roots lie in the familiar realm of land use planning, it presents many unique challenges and opportunities. As the practice of MSP continues, there will be continual insight into its organization, tools, and best practices. Even if MSP is a collaborative process and the organization and cooperation of stakeholders is paramount, the analytical component of the process is nearly as critical for its success. The stakes are high as we increasingly look to the development of ocean and coastal resources to support global consumption. Successful management of our marine spaces is less of a choice then a necessity.

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