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Biogeographic assessments: A framework for information synthesis in marine spatial planning

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ABSTRACT

This paper presents the Biogeographic Assessment Framework (BAF), a decision support process for marine spatial planning (MSP), developed through two decades of close collaborations between scientists and marine managers. Spatial planning is a considerable challenge for marine stewardship agencies because of the need to synthesize information on complex socio-ecological patterns across geographically broad spatial scales. This challenge is compounded by relatively short time-frames for implementation and limited financial and technological resources. To address this pragmatically, BAF provides a rapid, flexible and multi-disciplinary approach to integrate geospatial information into formats and visualization tools readily useable for spatial planning. Central to BAF is four sequential components: (1) Planning; (2) Data Evaluation; (3) Ecosystem Characterization; and (4) Management Applications. The framework has been applied to support the development of several marine spatial plans in the United States and Territories. This paper describes the structure of the BAF framework and the associated analytical techniques. Two management applications are provided to demonstrate the utility of BAF in supporting decision making in MSP.

1. Introduction

Marine spatial planning (MSP) is rapidly emerging as a viable approach for comprehensive and efficient management of coastal and marine environments around the world [14,23,16]. If built on a foundation of reliable and objective ecological and sociological information, this evolution of marine planning is expected to maintain essential ecosystem services, encourage compatible uses, minimize resource use conflicts, evaluate tradeoffs in an open and transparent manner, and include significant and meaningful stakeholder involvement [32]. Implementing MSP, however, is a considerable challenge for marine stewardship agencies, in large part because gaps exist in available data and syntheses of data on spatially heterogeneous and dynamic socio-ecological systems are extremely complex [14,20,29,79].

While it may be judicious to embrace the enormous complexity of ecosystems and work toward complete descriptions of ecological systems, pragmatism of management systems will likely necessitate a more limited focus on special areas, vulnerable resources and a subset of critical patterns and processes such as key drivers in the structure and function of the system. With this pragmatic approach, the U.S. National Ocean Policy (NOP), adopted by Executive Order 13547, advises regional planning bodies to analyze, assess and forecast information on key characteristics of coupled social–ecological systems (Box 1). These Regional Assessments are considered one of the essential elements of the spatial plan.

Even with this narrowed scope, historically, limited data coverage for both spatial and temporal dimensions, combined with issues of limited data access, has made effective information-based strategic planning in the marine environment a major technical challenge. In the past decade, however, there have been rapid technological advances in environmental sensors, considerable investments in long-term monitoring and a proliferation in remote sensing systems for acquisition of marine environmental data at a range of spatial and temporal scales [11,24,34]. In addition, advances in the spatial modeling of ecological patterns and processes, such as ocean hydrodynamics, watershed hydrology,

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Box 1–Suggested data needs for the Regional Assessment component of the U.S. Government Framework for Effective Coastal and Marine Spatial Planning (Interagency Ocean Policy Task Force, 2009).

1. Important physical and ecological patterns and processes (e.g., basic habitat distributions and critical habitat functions) that occur in the planning area, including their response to changing conditions;
2. Ecological condition and relative ecological importance or values of areas within the planning area, using regionally-developed evaluation and prioritization schemes;
3. Economic and environmental benefits and impacts of ocean, coastal, and Great Lakes uses in the region;
4. Relationships and linkages within and among regional ecosystems, including neighboring regions both within and outside the planning area and the impacts of anticipated human uses on those connections;
5. Spatial distribution of, and conflicts and compatibilities among, current and emerging ocean uses in the area;
6. Important ecosystem services in the area, and their vulnerability or resilience to the effects of human uses, natural hazards, and global climate change;
7. Contributions of existing placed-based management measures and authorities; and
8. Future requirements of existing and emerging ocean, coastal, and Great Lakes uses

biological distributions and larval connectivity, allow us to predict, visualize and better explain complex ecosystems [68,75,93,46]. Simultaneously, the diversity and geographical scope of mapped socio-economic data has also increased [6,13]. The development of reliable and cost-effective spatial models has been aided by identification of useful surrogates or proxies for complex spatial patterns that are difficult to map directly, such as species distributions, ecological function, and ecosystem service values [51,76,87]. Significant progress has also been made in data sharing through institutional contributions to open access data portals and the broadening of public participation in data collection (i.e., citizen science and crowd sourcing) [11,86,30].

Less focus, however, has been directed at the development of conceptual and analytical frameworks for prioritizing, analyzing and communicating complex, spatially explicit and non-linear socio-ecological patterns and processes [81,29,79]. This gap presents a significant challenge for the operationalization of MSP that is made more urgent as ocean uses increase and diversify globally. Typically, the MSP process involves multiple stakeholder groups with different, sometimes competing, goals for the use and management of the same geographical space. Therefore, balancing human uses to minimize conflict between users, ensure long-term environmental sustainability, and maximize the value of ecosystem services delivered is a primary challenge for MSP ([79,90]). Effective decision making in MSP, particularly where there are many stakeholder groups with highly divergent interests, requires a framework for data synthesis that provides a comprehensive, transparent and reliable science-based approach, accounts for uncertainty in the data, and provides sufficient flexibility to enable objective scenario assessment.

The Biogeographic Assessment Framework (BAF), a flexible, multi-disciplinary approach to integrate geospatial information into formats and visualization tools readily useable by coastal managers has been developed. This framework has evolved from two decades of close partnerships with natural resource managers addressing complex problems in both temperate and tropical marine and coastal environments [55]. The BAF incorporates a broad spatial ecology perspective that integrates concepts and techniques from traditional ecology, biogeography, landscape ecology, sociology and economics, remote sensing and the emerging fields of spatial eco-informatics and computational ecology [92,54,15,91]. Although the BAF approach shares some attributes with NOAA's Integrated Ecosystem Assessments (IEA), the two approaches support different, but complementary objectives. BAF provides a comprehensive spatial characterization and user conflict assessment to support spatial planning, whereas IEAs provide a structure to assess ecosystem status, risk to ecosystem indicators and the impact of management decisions within an adaptive management process [45]. The BAF is a rapid and flexible approach for responding to the relatively short time scales that are typical for implementation of management actions, such as the development of marine spatial plans, marine protected area management plans or evaluations of MPA design. The BAF usually relies on existing data sets, not all portions of the ecosystem need to be included, indicators are not required, and when compared with IEA, the BAF focuses more on spatial variation.

This paper presents an overview of the structure of the Biogeographic Assessment Framework and associated analytical techniques to demonstrate the utility of the framework in support of marine spatial planning in the United States of America (USA).

2. Methodology

2.1. Conceptual background for the Biogeographic Assessment Framework (BAF)

To understand how MSP can benefit from implementing the BAF, it is necessary to first define the subject of biogeography which provides concepts and techniques that underpin the framework. In essence, biogeography is the study of the spatial and temporal distributions of organisms, including people, and their habitats, and the historical and biological drivers of distributions [10]. Application of biogeographic concepts and analytical approaches have made major contributions to conservation planning, particularly in classifying regions with distinct characteristics and explaining patterns in species distributions and biodiversity [48,81]. Typical results from ecological biogeography range from distribution maps for species or habitats to more complex ecological analyses that integrate biological, physical and sociological variables to create maps of biodiversity and human activities within a region [59,75,56]. Biogeographic studies are usually perceived as global or continental in spatial extent and often concerned with geological time scales. However, the approach can be applied at finer scales. BAF as described here considers spatial and temporal domains that focus on more recent patterns (typically <30 years from present) than conventional studies in Biogeography and are analyzed at sub-continental spatial extents.

2.2. Operational attributes of the Biogeographic Assessment Framework (BAF)

BAF is designed to display diverse, spatially complex and multi-scale biogeographic information in a readily consumable manner via maps and spatial analyses aimed at supporting the management decision making process. At the core of the BAF analytical process are a suite of interoperable spatial technologies including Geographical Information Systems (GIS), remote sensing image analysis software, statistical data mining algorithms for predictive modeling, web-based mapping tools and database Management Applications. Although representation of ecologically realistic patterns is less problematic in data rich regions, operationally the BAF approach is flexible enough to also efficiently address situations with very sparse data, or where only specific components of the environment are being considered. This is usually achieved through spatial predictive modeling using techniques such as machine-learning algorithms and geostatistical modeling to fill data gaps [74,77]. An important focus of BAF is the quantification of uncertainty arising from data deficiencies and data processing. This focus on uncertainty throughout the data synthesis process has been an important attribute of BAF for decision-makers faced with public scrutiny in an evidence-based planning process. As such, BAF has evolved a framework to assess spatially-explicit errors using statistical model validation techniques and a range of quantitative tools for map accuracy assessment from the fields of remote sensing [58].

Finally, the framework is amenable to both question-driven science, as well as more exploratory pattern-recognition approaches such as ecological data mining to identify key environmental predictors. The approach presented here recognizes that MSP is a dynamic and adaptive process and decision makers will have diverse and changing driving forces at different stages of the process. Thus, the BAF allows for an incremental step-wise implementation from initial discussions to define the problem, through to information provisioning for a comprehensive coupled socio-ecological system, including scenario modeling for future conditions.

The BAF structure has four major components that support the marine spatial planning process: Step 1 – *Planning* involves identifying specific goals and objectives and the relevant geographical extent(s) or study area; Step 2 – *Data Evaluation* includes data collection and compilation, as well as assessment of the geographical, temporal and compositional extent of data including evaluation of gaps. Crucial at this step is understanding data and model errors, corresponding caveats, methods of visualizing BAF output uncertainty and suitability of data for the intended purpose; Step 3 – *Ecosystem Characterization* involves a synthesis of the best-available data to map and describe key ecosystem patterns and processes; and Step 4 – *Management Applications* focuses on support for operationalization of BAF products to directly address management problems (Fig. 1).

2.2.1. Step 1: Planning

Developing a direct connection with the management community tasked with making spatially-explicit marine management decisions is instrumental to the success of the BAF. Open dialog and collaborative goal setting between scientists, managers and stakeholders serves as the starting point to define the framework to meet specific needs. As such, the logical sequence of steps is adaptable and has feedback loops in the information flow. For instance, goal setting at the planning stage (Step 1) may first require exploration of available data (Step 2) resulting in a return to planning after initial data evaluation. Geographically, the planning step will define: (1) the core focal area and the spatial extent of the surroundings i.e. site context; and (2) management goals, targets, priority resources and threats, data providers, collaborators and relevant logistical and political issues. The BAF recognizes that it is necessary for local planning actions to be placed in the broader ecological context relative to regional biogeography, ecological connectivity across multiple spatial scales, threats and neighboring management activities.

2.2.1.1. Selecting spatial and temporal extents. In general, the spatial extent for a biogeographic assessment is determined by the assessment's objectives, although it is common to extend the area of interest beyond the borders of the management jurisdiction to provide broader geographical context. As such, a single study may encompass several spatial scales to understand the distances over which ecosystem components interact, or they may focus on a single scale to identify the specific details of a particular organism's distribution or other system component. This ‘ecological neighborhood’ approach to scaling environmental patterns is frequently applied in terrestrial landscape ecology [1], but is equally relevant to marine systems [73,69]. With regard to the temporal domain, biogeographic assessments include consideration of a range of time scales which may resolve changes in habitat or species distribution daily, monthly, seasonally, inter-annually or over much broader

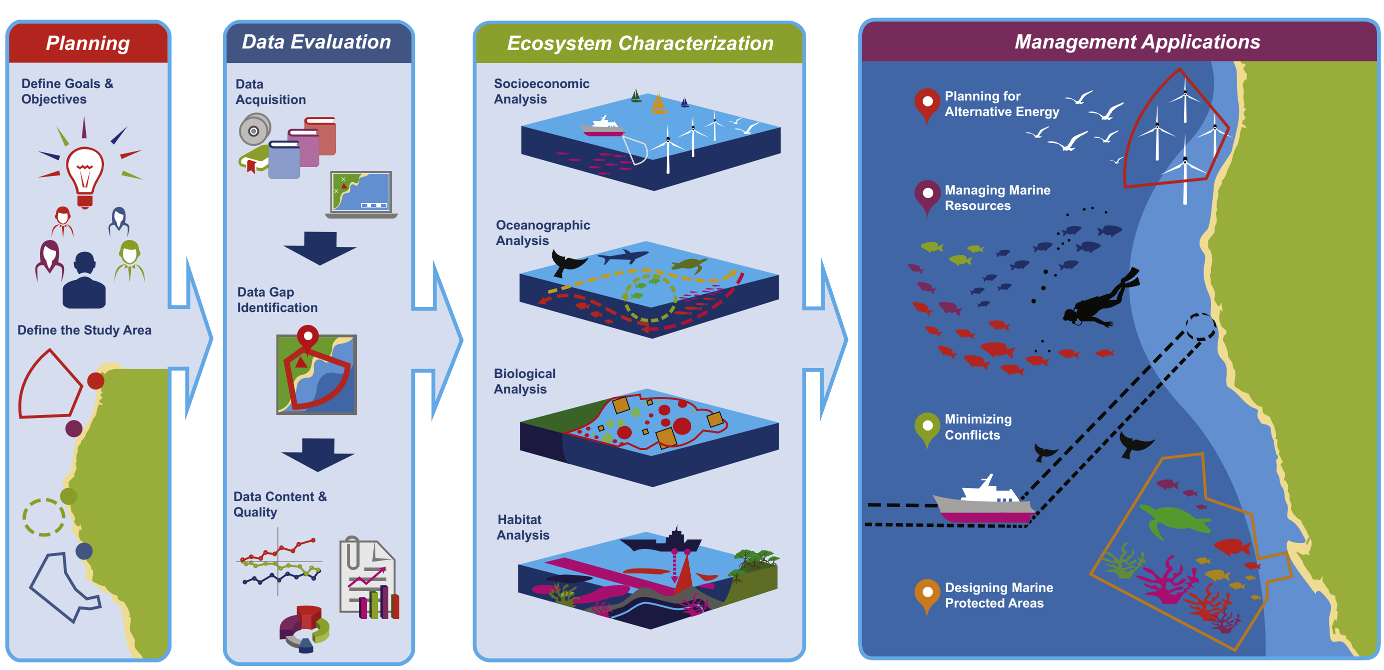

Fig. 1. NOAA's Biogeographic Assessment Framework (BAF) to support marine spatial planning. A logical sequence of steps in information synthesis: Step 1: talking with managers to determine priorities; Step 2: assessing the data and identifying data gaps; Step 3: characterizing the ecosystem patterns and processes including human activities across the area of interest; and Step 4: working with managers to support specific management applications.

temporal scales such as climate change mediated geographical shifts [70].

Addressing four key questions helps determine the spatial extent of the area for which data will be acquired and analyzed:

i.) What is the extent of jurisdictional boundaries or sub-regions of interest for MSP?
ii.) Does the MSP involve only marine areas or does it include adjacent terrestrial watersheds to account for factors such as runoff from land that can impact downstream and near-shore areas?
iii.) Are there important regulatory boundaries, human activities or anthropogenic influences in adjacent areas that will affect the focal area?
iv.) Is maintenance of key marine resources connected to and dependent on populations, patterns and processes occurring in neighboring areas?

2.2.2. Step 2: Data Evaluation

2.2.2.1. Data acquisition. Raw datasets for biogeographic assessments often originate from many different organizations, and are collected by a wide array of sensors and sampling techniques by scientists representing a range of disciplines. Direct interaction with the research community and data providers facilitates understanding of data idiosyncrasies and caveats. The past decade has experienced a rapid proliferation of online data portals and meta-portals (portals of portals) housing vast archives of easily accessible environmental information (e.g. OBIS Ocean Biogeographic Information System – http://www.iobis.org/; Marine Map http://marinemap.org/). In the USA, several nationwide portals have emerged recently specifically to support MSP related processes (e.g., Ocean.Data.Gov, Multipurpose Marine Cadastre – http://marinecadastre.gov). In some cases, data use agreements may be required to gain access to data. Once the data is obtained they are migrated into a standardized geospatial format and metadata is compiled. Questions that can be asked at this step are:

i.) Do the data contain sufficient temporal and spatial coverage?
ii.) Do the data contain sufficient number of observations?

2.2.2.2. Assessment of data gaps and gap filling techniques. Decision making in MSP often requires spatially continuous and broad scale data on the distribution of both living and non-living resources and their interactions. Geographic and compositional data gaps can adversely impact decision making. Major issues include how to appropriately generalize fine-scale data that will necessarily contain gaps and how to address decision makers' and policy makers' sensitivity to uncertainty. Direct and spatially continuous measurements of many key ecological variables, however, are usually unavailable, even for the most intensively studied regions of the earth. Gap filling techniques fall into several main categories: (1) Merging of existing datasets; (2) Acquisition of new data; or (3) Extrapolating across geographical space, even into data-less areas, using statistical relationships between existing data layers (i.e. predictive mapping). These options are not mutually exclusive and selection of an option or combination of techniques is typical, and should be considered in the context of cost-effectiveness, timeliness and data quality. New data collection can include surveying expert opinion (e.g. workshops, in-person interviews and online questionnaires) including traditional ecological knowledge, or deploying new instruments and conducting new field surveys.

A variety of statistical predictive modeling techniques ranging from geostatistical interpolation of data (kriging) to statistical models that use predictor variables (e.g., species distribution modeling, machine-learning) to dynamic ecological models, or a hybrid of these approaches, have proven to be rapid, reliable and cost-effective for filling data gaps [82,18,40,77]. In general, attempts to “scale up”, or interpolate, using simple geostatistical or other purely spatial interpolation approaches applied to relatively fine scale and sparse survey data often results in high spatial error [42]. Surrogate environmental variables, however, particularly remotely sensed satellite measurements, bathymetry and derivatives that represent primary environmental resources (e.g., heat, light, primary productivity, etc.) or quantify seafloor topographic complexity, often offer useful predictors of marine biotic distributions [52,76,8].

2.2.2.3. Data content and quality. Regardless of the approach taken to fill data gaps, errors in the source data or errors accumulated during processing can proliferate during data synthesis, generating complex spatial patterns of uncertainty. In MSP, confidence in data is important and accounting for and communicating uncertainty is critical to a successful evaluation process. To aid decision-makers and resource users in understanding data reliability, BAF quantifies and documents errors and uncertainties throughout project development.

When statistical methods are used to fill gaps, an estimate of uncertainty can be generated as part of the algorithm. It is important to retain and map these uncertainties (Fig. 2), and also when possible to distinguish and communicate the sources of uncertainty. Three major sources of uncertainty are as follows: (1) measurement or observation error (e.g. the observer miscounts the organism), (2) errors arising from assumptions and approximations made in the statistical modeling process, and (3) inherent variability in the ecological process of interest (e.g. the organism moves, aggregates, and disperses) [31,4,12].

Statistical estimates of uncertainty from models are often dependent on the assumptions of the models themselves making it necessary to assess the accuracy of a predictive model by techniques such as cross-validation, a procedure in which random subsets of data are “held out” from analysis and used to estimate model performance. A variety of statistics can be used to assess different components of model accuracy and performance [47]. When predictions are mapped, an independent map accuracy assessment should be carried out to test the predictions of the model across the entire range of possible conditions and observations. When interpolating or forecasting highly uncertain or dynamic processes, a variety of modeling approaches may be appropriate. For instance, ensemble or model-averaging approach, in which the predictions or performance of multiple models are combined or compared is useful for scenario analysis of future change when the behavior of a complex system is poorly known or poorly constrained by observations [57].

Finally, even when the methods employed do not allow for spatially explicit, quantitative assessment of uncertainty, it is still important and valuable to provide a qualitative or semi-quantitative estimate of uncertainty. Such estimates can be based, for example, on the age of information, method of collection, or expert judgment [84]. In fact, even when quantitative information on uncertainty is available it is often useful to reduce it to qualitative categories for decision-making and communication purposes (Fig. 2d; [53]).

2.2.3. Step 3: Ecosystem Characterization

The Ecosystem Characterization identifies, quantitatively describes and maps key patterns related to biological, physical and chemical processes, as well as human activities and interests that are linked to the ecology of a region. This baseline information forms the essential spatial template to support information-based decision making in an ecosystem-based management strategy for MSP [43,7,20].

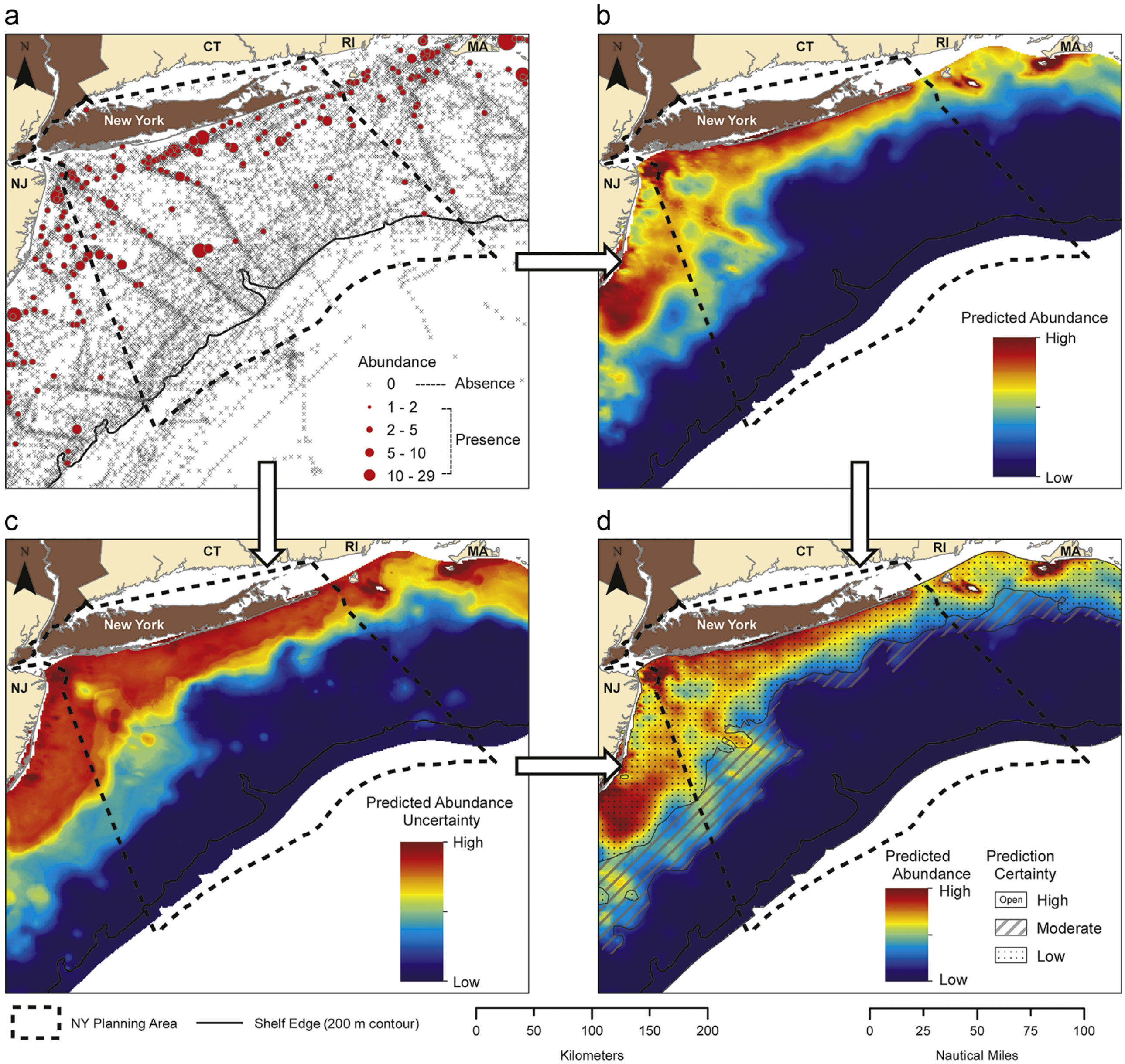

Fig. 2. Example of a spatial modeling process in BAF Step 2 (data evaluation) used to fill gaps and communicate uncertainty in ecological data. (A and B) Statistical modeling to fill spatial gaps by predicting values between original point survey data; (C) uncertainty in the predicted data is modeled and mapped quantitatively; and (D) predictions and the spatial pattern of uncertainty are combined in a final map product. Adapted from Menza et al. [53] and Kinlan et al. [40].

2.2.3.1. Defining and mapping social, cultural and economic attributes. MSP requires that the range and complexity of social connections to marine and coastal ecosystems be represented in the planning process at spatial scales that are meaningful to both decision-makers and stakeholders [9,85]. Planning for the sustainable development of some spaces can be complex because of the presence of concurrent, mixed-use patterns of human activity, as well as a diversity of ecological systems. To characterize the socioeconomic seascape, spatial and temporal data are required on a wide variety of human uses (e.g. human activities, economic and values mapping), including the intentional non-use of spaces [19,88,62,78].

Questions that can be asked to guide the process are

i.) Which ecosystem goods and services do people in the focal region value most and why?
ii.) What is the spatial and temporal distribution pattern of human activities and resource use?
iii.) What are the factors affecting these patterns?
iv.) What and where are the areas with most the competition over the use of marine resources?
v.) How and to what degree is the use of these goods and services facilitated or mitigated by social policy?

The BAF approach compiles socio-economic data to characterize the spatial and temporal patterns of human activities in coastal and marine environments (e.g., development, fishing, oil rigs, ship traffic, etc.), as well as related ecological threats from those activities (e.g., pollution from coastal run-off, over-fishing of economically important species, vessel collisions with large marine mammals, etc.). Socio-economic data can also be mapped [5,2,61] and BAF products can include a range of mapped patterns such as social values, social–ecological hotspots, and analyses that compare the density of human activities with social values. Additionally, assessments can be conducted that evaluate the trade-offs between market and non-market values of ecosystem services [83,90], to ascertain the probable opportunity costs related to different management scenarios, along with the remediation or recovery costs for the reduction or loss of valued marine uses.

2.2.3.2. Defining and mapping key ecological patterns and processes. The biophysical component of marine Ecosystem Characterization is central to the BAF as the foundation upon which all human activities occur. Integrated analyses of human use maps with maps of important ecological areas are crucial to the long term sustainability goals of MSP [27,75,26]. Important ecological areas may include sites of high productivity and biodiversity (hotspots); locations of special features, communities and key species that are critical to ecosystem function and resiliency (e.g. essential fish habitat, spawning and larval source areas); rare, endangered or functionally vulnerable marine resources, and key migratory corridors. This activity is central to the conservation of ecologically and biologically significant areas (EBSAs) as directed by the Convention on Biological Diversity. Within the BAF, identifying and mapping discrete areas with characteristics of special interest is referred to as 'hotspot mapping', yet the process can also involve mapping lower value areas too (i.e. "warm and cold spots"). A cold spot, for example, might represent an area with lower concern and could therefore be a potential candidate for human uses with low potential for conflict [41]. Thresholds for what is high or low can be driven by policy or established from exploration of the data, underlying ecological processes, and expert opinion.

A major challenge in MSP is incorporating key ecological dynamics in the planning process because conventional maps tend to represent dynamic components as static patterns and multi-dimensional structure as two-dimensional maps. Essentially this represents the planning area as a 'static flatscape'. While still useful for many applications, in reality many key patterns of interest change daily, seasonally, and over longer time-scales. It is important to capture these patterns and processes as spatial management decisions (e.g. placement of shipping lanes, wind farms, marine protected areas, etc.) typically do not shift over short (<1 year) to moderate (decades) time frames. This may be approached by integrating key statistics of temporal dynamics (e.g., variance) over an appropriate climatological time scale chosen to match the planning process, often with stratification to represent distinct period of short-term variability (e.g., seasons, El Nino vs non-El Nino years; [41,35]). Alternatively, time series approaches can be taken that map, model, and convey the full range of variation through time.

Ecological connectivity is a major factor in the resilience and sustainable management of marine ecosystems [22] and should be considered in MSP. Larval connectivity in the ocean influences population structure, resilience and the performance of management strategies and human activities operating outside a managed jurisdiction can impact what is happening inside. In all coastal areas, land and sea are intricately linked through material exchanges, such as runoff, river outflow and inflow and migratory movements of animals. Capturing this connectivity involves understanding the inputs into the system and pathways (e.g. currents, habitat corridors, migrations of organisms) through which they travel. With the application of tracking techniques (i.e. telemetry, archival tags) and spatial models for predicting hydrodynamics and predicting organism dispersal patterns, ecological connectivity can been incorporated into the BAF process [38].

2.2.4. Step 4: Management Applications

The Management Applications step of BAF provides support for operationalization of BAF information products, typically provided in the format of digital maps, to address specific management challenges and questions. In support of the rapid emergence of MSP in the United States, the four key components of the BAF (*Planning, Data Evaluation, Ecosystem Characterization, and Management Applications*) have been variously applied to support strategic planning for U.S. National Marine Sanctuaries and MSP for U.S. States including: The Commonwealth of Massachusetts Ocean Plan, New York Department of State Offshore Spatial Plan and Oregon State Territorial Sea Plan. In addition, the framework also may support information acquisition, analyses and interpretation as required for the "Regional Overview and Scope of Planning Area" and the "Regional Assessment" tasks to be carried out by the nine Regional Planning Bodies of the U.S. IOPTF, 2010 [33]. It also addresses several tasks listed under Steps 5 and 6 "Defining and Analyzing Existing and Future Conditions" of the UNESCO guidance document for marine spatial planning [17].

An important emerging challenge for the Management Applications step is the provision of alternative space use scenarios and consequences to examine options for balancing uses and evaluating trade-offs [39,90,44,79]. The development and comparison of alternative management scenarios helps decision-makers to anticipate the probable implications of competing management options, such as the ecological and/or social tradeoffs likely to result from choosing one alternative over another. In this way, the BAF is invaluable at helping decision-makers to predict potential impacts from alternate ocean planning strategies.

Finally, the Management Application step also provides forecasting of future ecosystem conditions to support longer-term strategic planning, societal adaptation plans and risk assessment relative to changes in the availability ecosystem services that are highly valued by society. Typical examples of the successful application of BAF spatial products in marine management settings include optimal siting of offshore energy installations [41], management plan revisions [63], boundary evaluations and siting of marine protected areas [64,37], and minimization of user conflict in multi-use areas [3].

3. Case studies

3.1. Case study 1: Data synthesis to support offshore renewable energy planning for New York

In 2012, a biogeographic assessment was conducted by NOAA's National Centers for Coastal and Ocean Sciences (NCCOS) to support the New York Department of State (NYDOS) in evaluating potential risks to vulnerable habitats and species of conservation concern from proposed renewable energy installations [53]. BAF products were used to inform a larger collaborative process intended to minimize conflict between siting of offshore wind farms, environmental protection and other existing ocean uses (Fig. 3).

Step 1 focused on identifying the goals and objectives of the State's offshore spatial plan, the spatial extent of the planning area and a comprehensive evaluation of existing information. This initial scoping process was informed by multiple regional and state-level natural resource assessments [71,25,21]. The biogeographic assessment was structured to focus on investigating the offshore distribution of seabirds, deep sea corals, benthic habitats and oceanography, and on providing recommendations for integrating these data and other data layers into New York's offshore spatial plan. The Data Evaluation (Step 2) compiled existing ship-based visual surveys and remote sensing data to create maps for living marine resources and physical habitat metrics (e.g., bottom types, benthic topographic metrics, surface chlorophyll, water column stratification). Oceanographic data served as proxies for predicting the habitat suitability of key living marine resources for which there were few observations (i.e., less common birds, productivity). Data were obtained from online spatial databases (e.g. OBIS-SEAMAP

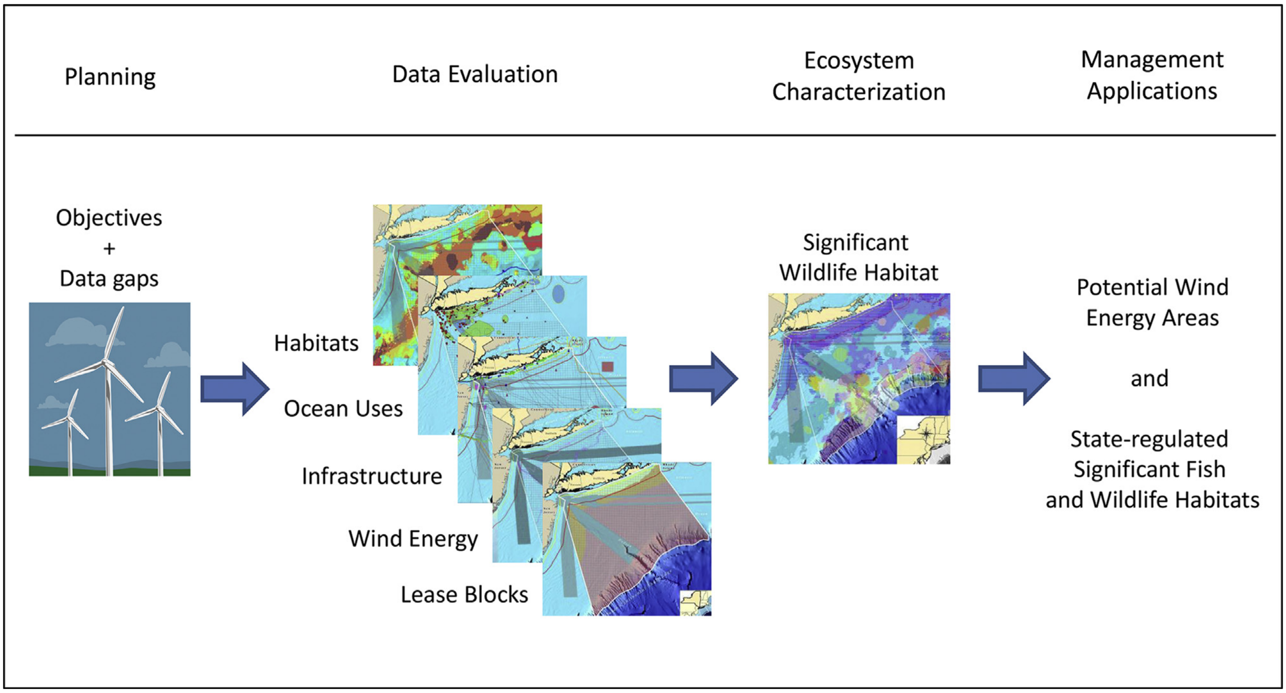

Fig. 3. A flowchart of the inputs, data layers, analyses and management products for the biogeographic assessment of the New York Bight. The biogeographic assessment was developed to support effective spatial planning for offshore renewable energy with special consideration for protection of vulnerable species and habitats. Adapted from Menza et al. [53].

http://seamap.env.duke.edu/, NOAA Environmental Research Division's Data Access Program nodes [http://coastwatch.pfeg.noaa.gov/erddap]) and federal data repositories (e.g. National Geophysical Data Center http://www.ngdc.noaa.gov/, Deep Sea Coral Research and Technology Program http://coralreef.noaa.gov/deepseacorals/). Predictive modeling was used to (1) fill spatial and temporal gaps in measurements when data were collected with irregular survey effort; (2) translate the distribution of metrics into spatial and/or temporal scales commensurate with planning decisions; and (3) obtain spatially-explicit estimates of uncertainty (Fig. 2). Synthesized model outputs from the biogeographic assessment were compiled into a common spatial framework to facilitate analysis and integration with additional ecological and human use data, and analytical methods and caveats of data use were described. The creation of standardized digital data, metadata and reports for data users were critical components of Step 2 and supported improved transparency, credibility and transferability, key elements of the National Ocean Policy [32].

An Ecosystem Characterization (Step 3) was conducted to evaluate threats to priority species and habitats [67] using existing criteria developed by the State to designate significant coastal fish and wildlife habitats, as recognized by the New York Waterfront Revitalization and Coastal Resources Act of 1981 [66]. Delineated unique and vulnerable areas formed a base layer for defining discrete managed areas and understanding connectivity between state and federal jurisdictions. Areas recommended by New York for wind energy production will likely be used to determine official wind energy areas (WEAs), and could lead to the issuance of renewable energy production leases on the outer continental shelf by the U.S. Bureau of Ocean Energy Management (BOEM).

3.2. Case study 2: Biogeographic Assessment to support MPA design within Gray's Reef National Marine Sanctuary

The stepwise BAF approach was applied to support Gray's Reef National Marine Sanctuary (GRNMS) in evaluating design alternatives for a new research area within the existing Sanctuary for the purpose of long term scientific research [36] (Fig. 4).

In partnership with the NOAA Office of National Marine Sanctuaries planning (BAF Step 1) solicited input through public meetings and also established a multidisciplinary team of experts and stakeholders to consider the need, feasibility, and general characteristics desired for the research area. The working group used consensus-based decision making to establish geographic scope, ecological criteria and the need to balance any spatial restrictions with stakeholder concerns particularly related to its use for recreational fishing. The BAF took the general criteria agreed upon during the planning phase and sought ecological and human-use datasets to represent them (BAF Step 2). Fish and habitat mapping data were acquired by working directly with scientific experts in the region to represent ecosystem variables (15 variables). On-water surveys, positions of prior research, aerial counts of boater use, and patterns of fishing related marine debris were acquired through consultation with management agencies, scientists, and monitoring programs to represent human-use (10 variables). From these datasets, using a GIS-based analysis that was custom-designed to meet the needs of the working group, the ecosystem (environmental patterns and human uses) was spatially characterized [37] (BAF Step 3). Analytical results and a geodatabase were used by the working group to identify a range of acceptable alternative boundary scenarios that balanced the conflicting scientific needs, enforcement logistics, and fishermen concerns (BAF Step 4). The alternative boundary scenarios underwent a socioeconomic impact analysis to estimate costs and benefits to the local economy. The recommendations from the working group and analytical results of the BAF were used in the Draft and Final Environmental Impact Statements used to establish the research area which was legally established in 2011 [65].

4. Discussion

MSP is an integrated, trans-disciplinary and spatially complex decision making process requiring a highly effective organizing framework for data synthesis and interpretation. In the United

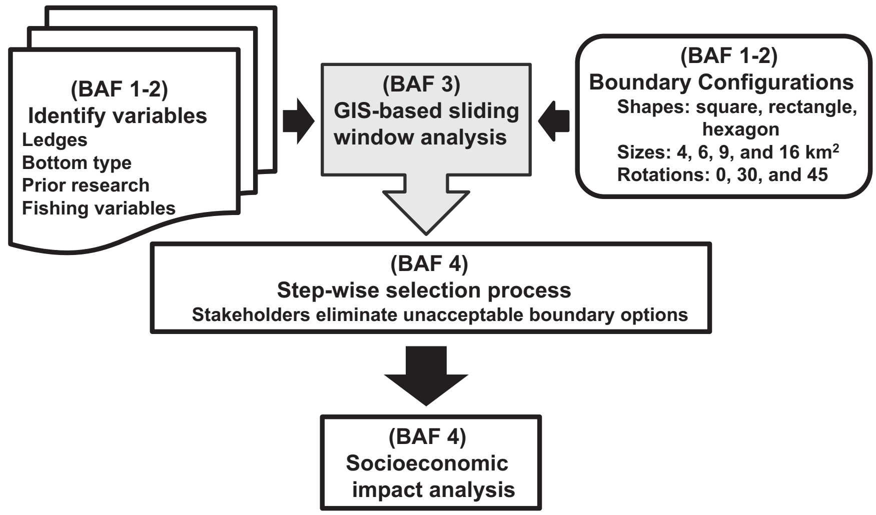

Fig. 4. Biogeographic Assessment Framework applied to the design and evaluation of a new marine protected area for long-term research within Gray's Reef National Marine Sanctuary, Georgia, USA (adapted from [37]).

States of America the importance of implementing MSP as an ecosystem-based management (EBM) approach has recently been addressed by adoption of the National Ocean Policy in 2010. When implemented as a comprehensive, adaptive, integrated spatial planning process, MSP is considered to directly support the principles of EBM by integrating social–ecological information for a specific geographical location [72,50]. The BAF provides an analytical approach to feed ecological data including human uses into the MSP process to support an EBM approach. Virtually all specifications of marine EBM share at least three common elements: (1) a commitment to establishing spatial management units based on ecological rather than political boundaries; (2) consideration of the relationships among ecosystem components, the physical environment, and human communities; and (3) the recognition that humans are an integral part of the ecosystem.

The social sciences provide great insight into the development and implementation of EBM approaches [72,80]. Anthropology, economics, legal studies, and sociology provide alternative understandings of how institutional designs affect human behavior, resource allocation, and outcomes for the economy, communities, families, and the environment [90]. It falls within the realm of social sciences to provide information on the social dimensions of EBM by addressing issues of governance, property rights, and human behavior. However, reliable spatial data documenting human activities and values is extremely sparse for coastal and marine environments. This paucity of spatially-relevant socioeconomic data is problematic for MSP.

Environmental management can be a subjective endeavor attempting to manipulate natural resources and the environment into outcomes desired by humans [90]. MSP provides an open process to balance competing uses in space and time to optimally balance protection and utilization of ecological services provided by coastal and marine ecosystems [80]. If MSP processes are carefully conducted, compromises can be found to balance competing conservation and societal uses of the coastal ocean [90,14]. Sustainable outcomes across ocean uses, users, and conservation of coastal ecosystems should be a goal of ecosystem-based management and the Biogeographic Assessment Framework has been proven to be a robust approach to facilitate planning, ecosystem characterization and evaluation of alternative management scenarios. As demonstrated in our case studies, the BAF advances EBM by coupling of science and management information needs.

A major challenge for any broad scale data synthesis for the marine and coastal realm is the great variability in the availability of data. With the use of a wide range of powerful and flexible predictive modeling algorithms BAF has been applied effectively across a gradient of data richness from sparse to relatively data dense regions. In regions where data are extremely limited, judicious assessment of uncertainty will be required. Furthermore, a major challenge in multi-disciplinary data synthesis relates to the diversity of spatial and temporal scales at which data are collected. Clearly, frameworks that are inherently multi-scale are necessary to facilitate data integration, but greater focus is needed to understand the impact of scale and the consequences of potential mismatches between ecologically meaningful scales and the operational scales that are relevant to decision making in MSP. Scale considerations and a full accounting of uncertainty will be particularly important to consider when MSP incorporates climate change forecasting into the planning process.

Another potential limitation for effective MSP is the lack of data on human use patterns in many regions, even for otherwise data rich regions. However, increasing effort is being focused on the acquisition of socio-economic data, including mapping of human use patterns and the cultural and economic values of seascapes [85,83,89]. Inclusion of local ecological knowledge is also beginning to play an important role in data synthesis for MSP [49]. This progress will dramatically improve our ability to conduct comprehensive biogeographic assessments focused on risk assessment and conflict resolution through integration of highly resolved spatial-explicit socio-economic data with environmental data [28,60]. As the availability of human geography data increases, trade-off analyses among ecosystem services will play an increasingly important role in MSP [90]. Lastly, improvements are urgently needed to ensure that information is easily accessible and effectively communicated to the public to enable an inclusive, integrated and transparent planning system.

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