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Spatio-temporal assessments of biodiversity in the high seas

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ABSTRACT: Biological diversity is one of the most important measures for marine conservation in the high seas. However, data and tools to assess and quantify biodiversity in the high seas are still not well developed. This hinders the development of the open-access tools necessary to assess biodiversity across space and time. Here, we examine prototype online mapping and visualization tools we developed within the OBIS-SEAMAP data center, a thematic node of the Ocean Biogeographic Information System (OBIS) specializing in marine mammal, seabird and sea turtle observations, to facilitate spatiotemporal assessments of biodiversity in the high seas. Our aims are to (1) summarize basic data needs for assessing biodiversity issues in the high seas; (2) discuss technical challenges to address such needs and establish a publicly accessible framework for biodiversity assessments; and (3) demonstrate how our prototype framework facilitates these assessments using a preliminary case study. We anticipate that this will serve as a model for marine researchers and managers to develop similar frameworks or improve the existing ones for ecological assessments. Of special importance is the application of these assessment tools to emerging high seas biodiversity identification processes such as the UN Convention on Biological Diversity, Ecologically or Biologically Significant Marine Areas.

KEY WORDS: Biogeographic database · Spatio-temporal ecological assessments · High seas · Marine conservation

HOW TO QUANTIFY BIODIVERSITY?

Conservation of biological diversity is one of the fundamental goals of establishing marine protected areas or planning for ecosystem-based management (Hooker & Gerber 2004). Biodiversity is also used to illustrate global patterns of taxonomic distributions or identification of hotspots (Roberts et al. 2002, Worm et al. 2005, Morato et al. 2010). At a practical level, marine spatial planning is regarded as a framework for assessing biodiversity and ecosystem services (Douvere 2008). However, as biodiversity is a complex concept and is multidimensional, it can be measured in different ways (Sala & Knowlton 2006) and there are no standardized methodologies on how to quantify it (Hamilton 2005). Many global-scale marine biodiversity studies use species richness as an indicator of biodiversity (e.g. Costello et al. 2010, Pompa et al. 2011, Tittensor et al. 2010), while ecosystem-based management tends to refer to habitat types as a proxy for biodiversity. At the scale of the local species assemblage, a variety of biodiversity indices have been proposed, assessed and criticized (Lande 1996, Rice 2003). One of the essential issues surrounding these biodiversity indices is biased sampling efforts and sample sizes, both spatially and temporally (Fautin et al. 2010, Webb et al. 2010, also see Stockwell & Peterson 2002 for effects of sample size of species distribution models).

There is growing awareness that biodiversity in the high seas, defined as all parts of the oceans that are not included in the exclusive economic zones (EEZs) (WWF/IUCN/WCPA 2001) and is used interchangeably with 'open oceans' in the present article, needs

greater protection (Ardron at al. 2008). The Convention on Biological Diversity (CBD) has defined 7 criteria for the identification of Ecologically or Biologically Significant Marine Areas (EBSAs) in the open ocean and deep seas, one of which is high biodiversity; other criteria include uniqueness or rarity, special importance for life history of species, importance for threatened species and/or habitats, fragile or slow recovery, biological productivity and naturalness (CBD 2009). However, the conservation of the high seas poses additional complications. Addressing sampling bias is particularly challenging as traditional vessel or aerial surveys are more costly in the high seas than in coastal oceans (Evans & Hammond 2004, Marques et al. 2009). Biased sample sizes also increase the difficulty of assessing temporal changes in biodiversity in the high seas. Our ability to monitor temporal changes in biodiversity as an ecosystem indicator is one of the most fundamental measures for the performance evaluation of conservation efforts (Levin et al. 2009). Large vertebrates in the high seas tend to be highly mobile and exhibit annual migration patterns, moving between various types of habitats (e.g. feeding or breeding grounds) with different importance through different life history stages (Game et al. 2009). To be effective for conservation, marine protected areas for these mobile species may require dynamic or flexible boundaries in both space and time (Hyrenbach et al. 2000). Moreover, our knowledge of the biological features in the high seas is incomplete though it is advancing with the advent of novel sampling and analysis tools (Corrigan & Kershaw 2008). Thus, a static map of biodiversity aggregating occurrence data for all species and representing a single indicator is not sufficient to examine spatial and temporal variability in biodiversity and hence may not be an optimal tool for the delineation of EBSAs or protected areas in the high seas.

WHAT IS NEEDED TO ASSESS BIODIVERSITY IN THE HIGH SEAS?

There have been numerous research studies and recommendations on the planning and establishment of ecosystem-based management strategies and pelagic marine protected areas (Hemphill & Shillinger 2006, Sumaila et al. 2007). Establishment of a framework for systematic conservation planning has been proposed (Margules & Pressey 2000, Ban et al. 2013). Further, participation of stakeholders and the general public is a crucial consideration when assessing the success of conservation efforts (Jones-Walters &

Çil 2011). Thus, a publicly accessible online framework that provides interactive tools to assess marine biodiversity from a variety of ecological perspectives would be an optimal tool for marine conservation planning. To our knowledge, however, there is no framework to facilitate such dynamic assessments of biodiversity in the high seas and incorporate the outcomes from the assessments into marine spatial planning, although there are several online biogeographic databases providing static maps of biodiversity (e.g. OBIS; Fujioka et al. 2012).

From a technical standpoint, we need to address 3 issues to establish this type of framework for biodiversity assessments. First, a framework needs to be established to share biogeographic data beyond national jurisdictions to fill taxonomic, spatial and temporal gaps. The framework also has to be flexible enough to accommodate a wide variety of data types.

Second, marine biodiversity must be assessed by taxonomically, spatially or temporally scale-dependent components (Lourie & Vincent 2004). In addition, ecosystem-based management requires spatial and temporal components to be included in the operational tools for this approach (Crowder & Norse 2008, Douvere 2008). Thus, a framework is required to provide an interactive tool set to assess different components of biodiversity at different scales.

Third, since criteria and appropriate quantitative measures of biodiversity vary depending on the project objectives and goals, no single biodiversity measurement is sufficient to cover all demands and needs. A tool set to represent and compare alternative indicators of biodiversity will greatly increase the usability of a framework for biodiversity assessments.

PROTOTYPE APPROACHES TO ASSESSMENTS OF BIODIVERSITY IN THE HIGH SEAS

Assessments of biogeographic data beyond national jurisdiction

The Ocean Biogeographic Information System Spatial Ecological Analysis of Megavertebrate Populations (OBIS-SEAMAP; http://seamap.env.duke.edu) has been accumulating data on marine mammals, seabirds and sea turtles from around the world and providing tools to interactively explore data in a spatially and temporally flexible platform (Halpin et al. 2006, 2009). All data in the OBIS-SEAMAP thematic node of the OBIS network are shared using the international OBIS portal operated under the International Oceanographic Data and Information Exchange

(IODE) of UNESCO-IOC. To broaden spatial, temporal and taxonomic coverage at a global scale, OBIS-SEAMAP incorporates different types of data including traditional visual line-transect sightings, telemetry of tagged animals, detections from passive acoustic monitoring (PAM) and sighting histories from photo-identification catalogs (Fujioka et al. 2014b). Whereas most of the vessel or aerial line-transect surveys focus on regions within jurisdictional boundaries, telemetry data trace animal movements across multiple jurisdictions and hence serve as an essential data source for ecological assessments in the high seas (e.g. Block et al. 2005, Hooker et al. 2007).

OBIS-SEAMAP provides spatial query features that allow researchers to extract data from one or more regions within a jurisdictional or biogeographic classification (e.g. EEZs or large marine ecosystems; Sherman & Hempel 2008) and to assess the extracted data from various ecological perspectives using spatially and temporally interactive tools. The ability to assess marine biodiversity data records within national EEZ boundaries can assist countries in meeting reporting requirements for the CBD Aichi 2020 biodiversity targets (CBD 2010). For biodiversity assessments in the high seas, we further refined these tools so that they are capable of extracting all data beyond the boundaries of the jurisdictional or biogeographic classification. Appling this to the EEZ layer allows the user to find all species occurrences beyond national jurisdictions. For the delineation of marine protected areas or assessments of criteria for marine spatial planning to be practical, biological data beyond national jurisdiction need to be further filtered based on target taxa in a region of interest during the period of time in question. These interactive tools are implemented on the OBIS-SEAMAP website (Halpin et al. 2009).

Alternative indicators of biodiversity

In addition to species richness (the number of distinct taxa in a sample), which is already provided in the OBIS-SEAMAP online mapping tools, we have now implemented the dynamic calculation of 3 biodiversity indices: the Shannon, Simpson and Hurlbert indices. Table 1 summarizes the formulas used to calculate these additional indices. Although the formulas are different, the common inputs are the numbers of animals per species for all species in a given sample (e.g. a study area). The integration of multiple data types in the OBIS-SEAMAP database helps fill taxonomic, spatial and temporal gaps (Fujioka et al. 2014b), which in turn improves the reliability of bio-

diversity indices. Careful consideration, however, must be paid to normalizing the quantities of each data type when conducting these statistical calculations. For example, with visual line-transect surveys, each record is assumed to represent an independent sighting and provides a quantification of the number of animals present (Buckland et al. 1993, Thomas et al. 2010). However, while a series of locations of a telemetry-tagged or photoidentified animal contribute a number of individual spatial location records, these records represent only one animal. Detections using PAM sensors also produce a number of individual records that may be associated with a single animal or a group of animals. However, the quantity of observations estimated from PAM records may have different meanings (Fujioka et al. 2014a), and the estimation of species abundance from detections is still at an early stage of development (Marques et al. 2009, Martin et al. 2013).

OBIS-SEAMAP uses unique classification codes to distinguish data types (Fujioka et al. 2014b) and the normalization of the species observations data for biodiversity index calculations is performed per data type before the results are aggregated. For example, after records are extracted based on taxonomic, spatial and temporal criteria, unique animal or device identifiers from records of photo-identified or telemetry-tagged animals, respectively, are counted and regarded as the number of individuals. For visual line-transect surveys, the group size is summed in calculations to represent the number of individuals sighted. Many of the PAM records in the OBIS-SEAMAP database represent the number of detections per binned time period and do not include an estimated group size (Fujioka et al. 2014a). The locations recorded are usually those of the sensors, unless the localized positions of the animals detected are deter-

Table 1. Formulas for the species diversity indices implemented in OBIS-SEAMAP, where S is the number of species, N is the total number of individual animals, N_i is the number of individuals of the ith species, and p_i is the proportion of the ith species (N_i/N). In the Hurlbert index, n is a common sample size, which was arbitrarily chosen as 20 in the calculations

Index	Formula	Max. value	Reference
Shannon	$-\sum_{i=1}^{S} p_i \ln p_i$	$\ln S$	Shannon & Weaver (1962)
Simpson	$\dfrac{1}{\sum_{i=1}^{S} p_i^2}$	S	Simpson (1949)
Hurlbert	$\sum_{i=1}^{S}\left(1 - \dfrac{(N-N_i)!(N-n)!}{(N-N_i-n)!N!}\right)$	S	Hurlbert (1971)

Table 2. Summary of how and where the species diversity calculations implemented in a prototype of the OBIS-SEAMAP database obtain the number of individuals from different data types

Data type	Number of individuals
Visual sighting	Group size in a record
Passive acoustic	
Number of detections	Unquantified and excluded from calculations
Presence or absence	Unquantified and excluded from calculations
Estimated group size with sensor locations	Estimated group size in a record but excluded from calculations due to location uncertainty
Estimated group size with animal locations	Estimated group size in a record
Telemetry	Number of unique device identifiers
Photo-identification	Number of unique animal identifiers

mined through intensive detection analyses and spatial triangulation. Due to these complexities, only PAM records having an estimated group size and localized animal position are included in the diversity calculations. Table 2 summarizes the treatments per data type. These data extraction and normalization processes are implemented in a single query to the OBIS-SEAMAP database in response to the user's inputs, allowing for dynamic calculations of multiple biodiversity indices simultaneously. For spatial representation, the diversity calculations are aggregated for a unit cell at a scale of 1.0, 0.1 or 0.01°. Users can choose one of the 4 species biodiversity indices to calculate and map the results (Fig. 1). The aggregation scale is automatically adjusted according to the current zoom-in level of the base map or users can select one of the 3 aggregation scales (Fig. 1). For temporal representation, the calculations are aggregated by a temporal scale of the user's choice from century to decade to year, and the results are visualized on interactive graphs (Fig. 2A). Scales of month and day are available as well, though these time scales may not be appropriate for biodiversity assessments. Estimation of seasonal changes over 4 seasons or 12 mo are also supported by these tools. To mitigate the possibility of misrepresentation of the species diversity indices due to biased sampling effort, the number of records these indices are calculated from or the effort hours of the surveys the records came from can be added to the graph so that changes in diversity indices are understood in the context of sample size and effort (Fig. 2).
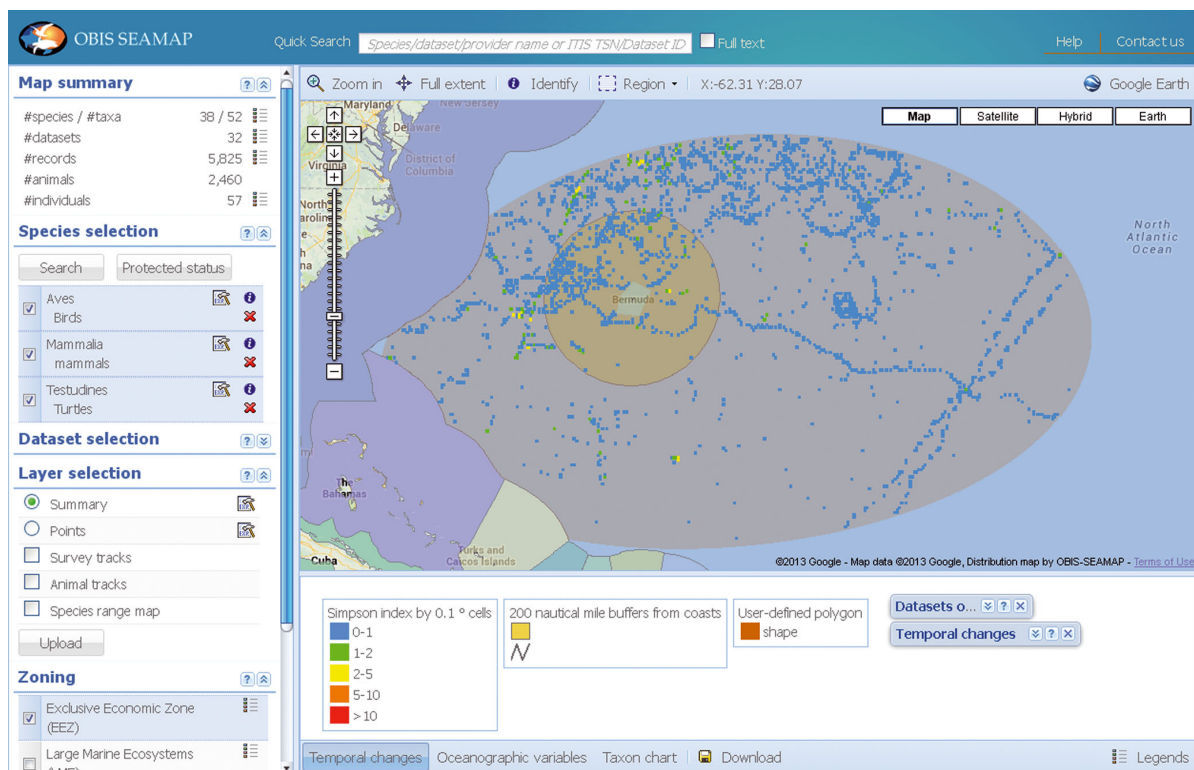

Fig. 1. Prototype map from the OBIS-SEAMAP data center showing the Simpson index calculated from biological data of marine megavertebrates within the Sargasso Sea study area, based on Laffoley et al. (2011). A spatial scale of 0.1° was chosen
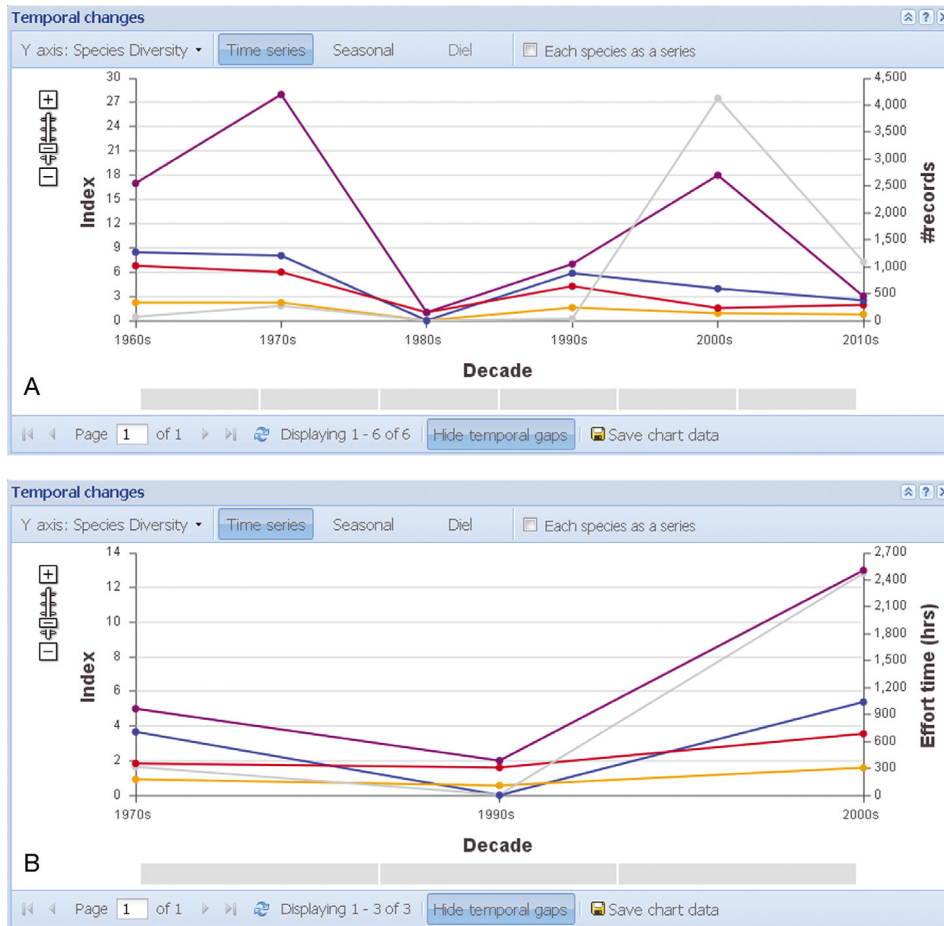
Fig. 2. Decadal changes in the 4 species biodiversity indices (purple: richness; blue: Hurlbert; red: Simpson; orange: Shannon) in the Sargasso Sea study area along with the number of records (A) and effort hours (B). The charts were captured from the OBIS-SEAMAP site. Gray lines represent the number of records (A) or effort hours (B) on the right-hand *y*-axis. Users can show or hide species richness for a better display, as it tends to be higher than the other 3. Users can also show or hide temporal gaps. The gap in the 1980s is hidden in (B)

CASE STUDY: BIODIVERSITY IN THE SARGASSO SEA

To demonstrate a potential use of the prototype tools for biodiversity assessments in the high seas, we examined the 4 species diversity indices in the greater Sargasso Sea ecosystem. The Sargasso Sea is a unique high sea ecosystem within the North Atlantic Subtropical Gyre characterized by floating *Sargassum* mats (Laffoley et al. 2011). The Sargasso Sea is believed to serve as an important migration pathway and feeding ground for many taxa (e.g. Martin et al. 1984, Laffoley et al. 2011), including sea turtles (Schwartz 1988, Manzella & Williams 1991, Hays et al. 2004), cetaceans (Stone & Katona 1987, Gero et al. 2009) and seabirds (Haney 1986). The Sargasso Sea was described as a site meeting the EBSA criteria through the CBD regional workshop process in 2012. The Sargasso Sea was ranked 'high' in all the 7 EBSA criteria except naturalness (CBD 2012).

Methods

We used the expected boundary of the Sargasso Sea compiled by the Sargasso Sea Alliance (Ardron et al. 2011, Laffoley et al. 2011). An ESRI shapefile of the boundary was uploaded as a study area using the region delineation feature of the OBIS-SEAMAP site and the extracted occurrence records of marine megavertebrates (marine mammals, seabirds and sea turtles) were mapped (Fig. 1). We qualitatively examined decadal changes of the 4 species biodiversity indices using the temporal chart features (Fig. 2).

To address the effect of sample size on the biodiversity indices, we investigated the relationship between the indices and the number of records or effort hours through simple linear regressions. The values of these measures were downloaded from the OBIS-SEAMAP site.

Results

Within the Sargasso Sea study area, 38 marine mammal, sea turtle and seabird species were observed in 5825 observation records from 32 data sets with a temporal coverage of 1966 through 2013. The records included telemetry data from 57 tagged animals of 4 sea turtles (*Caretta caretta*, *Chelonia mydas*, *Dermochelys coriacea* and *Eretmochelys imbricata*), 2 seabirds (*Puffinus gravis* and *Sterna paradisaea*) and 1 whale (*Physeter macrocephalus*).

Qualitatively, the species diversity indices except richness show a similar decadal trend with a continued decline since the 1960s, excluding the 1980s, when only 1 record was found (Fig. 2A, Table 3). Species richness increased from the 1990s to the 2000s but did not reach the same level as in the 1970s (Fig. 2A, Table 3). Effort data were associated with 7 data sets, and 25 data sets without effort data were excluded from the diversity calculation, resulting in a reduced temporal coverage from the 1970s to the 2000s with a gap in the 1980s (Fig. 2B, Table 3). With data sets limited to those having effort, the 3 indices also increased in the 2000s compared with the 1970s, similar to species richness. There were only 4 records in the 1990s, and Hurlbert's index was not calculated.

The number of records exhibits a positive but not significant effect on each of the 4 indices ($R^2 = 0.14$, $p = 0.46$; $R^2 = 0.11$, $p = 0.46$; $R^2 = 0.05$, $p = 0.60$; $R^2 = 0.28$, $p = 0.22$ for the Hurlbert, Shannon and Simpson indices, and species richness, respectively). Similarly, there is also a positive but not significant relationship found between the species diversity indices (except richness) and effort hours ($R^2 = 0.79$, $p = 0.30$; $R^2 = 0.78$, $p = 0.12$; $R^2 = 0.76$, $p = 0.13$ for Hurlbert, Shannon and Simpson, respectively). However, species richness is significantly affected by effort hours ($R^2 = 0.92$, $p = 0.04$).

DISCUSSION AND FUTURE DIRECTIONS

Data deficiency is a significant challenge in assessing marine biodiversity (Fautin et al. 2010, Webb et al. 2010), even for relatively well-studied marine mammals (Schipper et al. 2008). There has been little work to develop fully synthetic approaches to the design and management of marine protected areas (Halpern 2003, Halpern et al. 2007). The situation is even more challenging for conservation management in the high seas because the data coverage and knowledge is less complete and consistent than in coastal waters (Weaver & Johnson 2012). By definition, the high seas are beyond national jurisdictions and, thus, it is more difficult to accumulate biological data in the high seas than coastal waters as such data are usually archived in disparate institutions or national data centers. Our approaches to addressing these issues through the continued development of the global OBIS biogeographic data center are 3-fold: (1) to collect data from individual providers worldwide while establishing strong collaborative relationships with national agencies; (2) to integrate multiple data types to extend coverage of taxonomic, spatial and temporal gaps; and (3) to develop a publicly accessible research and development framework to provide complementary, multi-perspective approaches to ecological assessments through an integrated biological database that facilitates marine conservation activities. For example, identifying which protected species occur in a particular area and how and when they use different habitats is a critical step to designing conservation strategies for those species (Hooker et al. 1999, Louzao et al. 2006). In the Sargasso Sea study area, 7 species listed as endangered or threatened by the US Endangered Species Act and the IUCN Red List (2 cetaceans, 1 seabird and 4 sea turtles) were recorded in 25 data sets (Fig. 3). In addition to species status, better understanding of the seasonal distributions or move-

Table 3. Decadal change in number of records, effort hours, and species diversity indices in the Sargasso Sea study area. Values to the left and right of a slash (/) were calculated from all 32 datasets and 7 datasets for which effort data were available, respectively. NA: not available

Decade	No. of records	Effort hours	Richness	Shannon	Simpson	Hurlbert
1960s	69/NA	NA	17/NA	2.23/NA	6.79/NA	8.47/NA
1970s	271/9	316.35	28/5	2.22/0.92	6.00/1.84	8.04/3.67
1980s	1/NA	NA	1/NA	0/NA	1/NA	NA/NA
1990s	34/4	4.50	7/2	1.60/0.56	4.25/1.60	5.85/NA
2000s	4130/104	2474.68	18/13	0.90/1.59	1.55/3.56	3.95/5.39
2010s	1088/NA	NA	3/NA	0.76/NA	1.93/NA	2.49/NA

ments of target species is essential for delineating dynamic marine management areas. Our prototype framework is capable of visualizing seasonal changes in the number of individuals sighted in a particular region (e.g. the Sargasso Sea; Fig. 4).

For a better understanding of biological data and derived species diversity indices with limited data, it is crucial to examine where and when the data collection effort was conducted. Our prototype framework maintains effort data for both visual line-transect
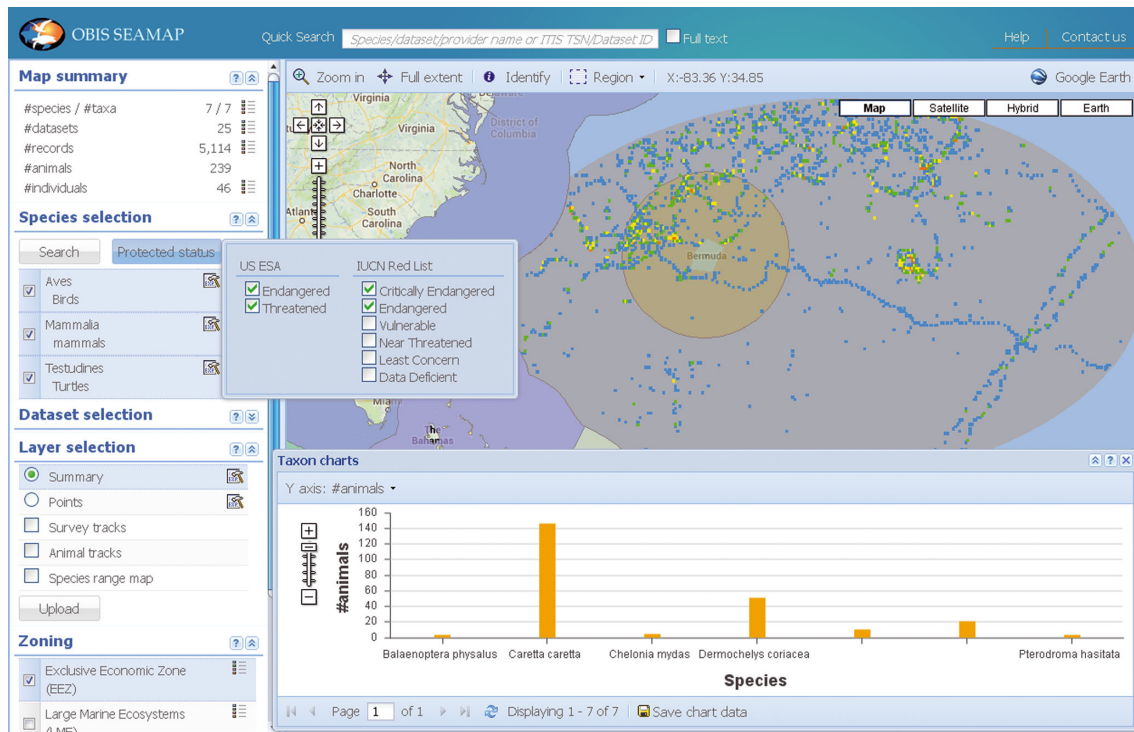
Fig. 3. Prototype map from the OBIS-SEAMAP website showing occurrences of species listed as endangered or threatened in the US Endangered Species Act (ESA) and IUCN Red List in the Sargasso Sea study area along with a taxon chart displaying the number of individuals observed per species. Bars from left to right are *Balaenoptera physalus*, *Caretta caretta*, *Chelonia mydas*, *Dermochelys coriacea*, *Eretmochelys imbricata*, *Megaptera novaeangliae* and *Pterodroma hasitata*. Two of the *x*-axis labels are not shown due to space constraints
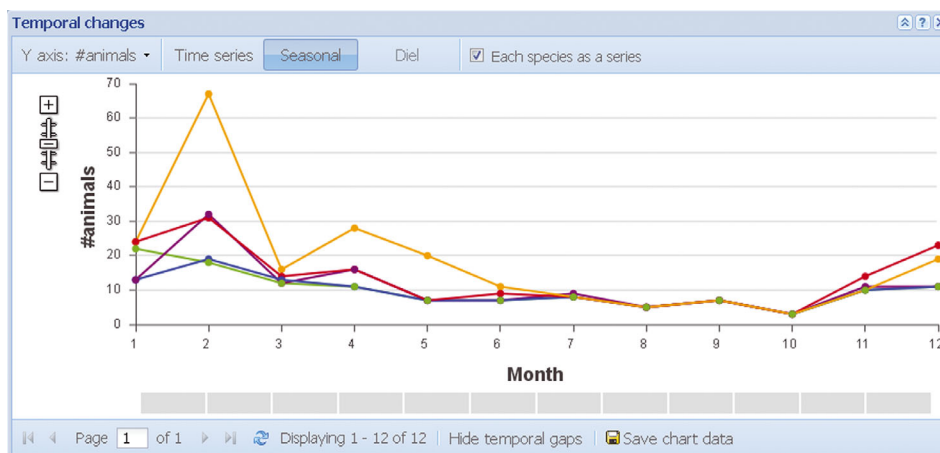

Fig. 4. Monthly changes in the 5 protected species observed in the Sargasso Sea study area (orange: *Caretta caretta*; red: *Dermochelys coriacea*; blue: *Chelonia mydas*; purple: *Megaptera novaeangliae*; green: *Eretmochelys imbricata*). The graphing feature of the OBIS-SEAMAP website allows users to display the top 5 species in terms of the *y*-axis measure (e.g. the number of individuals observed, in this case) when the 'Each species as a series' checkbox is checked

surveys and PAM. By adding a time series of the effort hours to the decadal change in the species diversity indices in the Sargasso Sea case study, the chart qualitatively indicated that species richness followed a trend related to effort hours, which was also supported by a simple linear regression. The peak of the species richness in the 2000s in the Sargasso Sea study area can be attributed to the fact that more surveys were conducted and a wider variety of taxa was observed in this period. The other 3 diversity indices did not present a strong relationship with either the number of records or the effort hours. However, the decadal trend was different when the observation data were limited to those associated with effort. More intensive statistical analyses will be required to further investigate the relationship between additional covariates, but this case study indicates that the incorporation of survey effort data is a necessary component for the appropriate interpretation of bio-diversity assessments. It is also worth reiterating the challenge of data deficiency. In the Sargasso Sea case study, the number of records was significantly reduced when data sets were limited to those associated with effort data in the 1970s, 1990s and 2000s, and the diversity indices were not calculated in the 1960s, 1980s and 2010s due to the lack of records from data sets with effort (Table 3). More high-quality data need to be gathered to produce more reliable statistical results.

We posit that the development of spatio-temporal exploratory tools to allow for the comparison of alternative biodiversity indices and to assess biogeographic data in a global biogeographic database is essential to support ongoing biodiversity assessment and conservation efforts in the high seas, such as the CBD EBSA identification process. We also believe this framework will prove to be useful for the implementation of ecosystem-based management and the potential delineation of marine protected areas. This article is not intended to promote the exclusive use of the 3 biodiversity indices examined here for all biodiversity assessments in the high seas but to illustrate the application of prototype tools in combining multiple data types and assessing different components and scales of biodiversity. We encourage researchers to devise and suggest additional approaches to estimate biodiversity for different objectives, approaches and goals of marine conservation and management (e.g. Halpern et al. 2012, Stuart-Smith et al. 2013). Since the OBIS prototype framework is flexible, new approaches or indices can be readily incorporated into future efforts.

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