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Defining ecologically, geographically, and politically coherent boundaries for the Northern Gulf of Mexico coastal region: Facilitating ecosystem-based management

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ABSTRACT

Ecosystem-based management (EBM) is an integrated approach that recognizes the complex interactions within an ecosystem. Proper facilitation of EBM techniques require explicitly defined spatial boundaries, but biophysical processes, human activities, and the ecosystems that they influence operate at various scales. Careful thought to combine ecological, physical, and regulatory boundaries to define spatial scales of coastal regions can be a tedious yet significant early step towards the meaningful application of ecosystem-based management. We recommend nine coastal regions for the Northern Gulf of Mexico by creating both regulatory and biophysically meaningful spatial boundaries. A basic framework illustrating the utility of publicly available spatial datasets for defining the seaward, landward, and lateral boundaries of coastal regions is provided. These nine coastal regions will be key in creating spatial criteria for the Northern Gulf of Mexico, within which differences in ecosystem services can be measured, and temporal changes in ecosystem services can be tracked. The framework developed here is meant to build capacity for EBM and serve as a starting point for the continued discussion and modification of sensible ecological, geographical and political boundaries.

1. Introduction

Ecosystem-based management (EBM) is an integrated approach to management that recognizes the complex interactions within a place-based system (Toonen et al., 2011). This approach considers the entire ecosystem, including humans, and often employs ecosystem services to measure system health (Samhouri et al., 2012). Ecosystem services are the products and outcomes from which humans can profit and benefit when an ecosystem is healthy, productive, and resilient (such as sustainable fisheries, eco-tourism, coastal flood protection, etc.) (McLeod et al., 2005).

The emphasis on managing places rather than relying on a uni-dimensional variable or a single species has been widely accepted both nationally and internationally; three examples are the U.S. Commission on Ocean Policy, Pew Ocean Commission and Millennium Ecosystem Assessment, and the United National Environment Programme (Borja et al., 2009; Crowder and Norse, 2008; Douvere, 2008; Dell'Apa et al., 2015). The U.S. Commission on Ocean Policy's An Ocean Blueprint for the 21st Century devotes a chapter to advancing a regional approach to EBM (USCOP, 2004). Although there have been successful EBM approaches in large-scale applications (e.g., Tallis and Polasky, 2009; Ruckelshaus et al., 2015) there are few examples of ecosystem-wide practice at the level of local and regional coastal environments where most management decisions are made (Douvere, 2008; Katsanevakis et al., 2011; but see Leslie et al., 2015). On their own, many regulatory bodies and stakeholders lack the necessary framework, legal authority, and operational tools needed to facilitate an ecosystem approach in the coastal environment (Arkema et al., 2006; Heenan et al., 2016). One such tool is a framework to define spatial boundaries of the focal ecosystem and appropriate spatial scales at which pertinent biophysical processes and human activities operate (Crowder and Norse, 2008). Herein, we define reproducible and meaningful spatial boundaries of coastal regions needed to build capacity for an EBM for the northern Gulf of Mexico.

Defining meaningful boundaries of coastal ecosystems is a crucial initial step towards coastal EBM, but it can be daunting to understand the complexities of such dynamic and open systems (Crowder and Norse, 2008; Stelzenmüller et al., 2013; Leslie et al., 2015). An

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unavoidable consideration is to define the ecosystem services that are critical to the desired functioning of the particular system. Ecosystem services are influenced by a suite of ecological and social factors, often measured using a range of available datasets that have various spatial scales (Halpern et al., 2008). Consequently, EBM initiatives are difficult to implement and their outcomes difficult to quantify, unless the levels of ecosystem services are systematically and periodically evaluated. Therefore, keys to defining the spatial boundaries used in EBM efforts include consideration of the ecosystem services to be measured, and the spatial and temporal scales corresponding to available data.

Government jurisdictional borders are common and logical boundaries that typically correspond with spatial coverage of monitoring efforts of the associated regulatory and natural resource agencies (Dallimer and Strange, 2015). These agencies usually influence and direct management actions within their jurisdiction. Agency monitoring efforts generally represent long-term and consistent datasets for large-scale coastal systems. However, agency-defined jurisdictional borders notably do not always match the ecological scales at which coastal systems function (Cowen et al., 2006). These can range from trans-global in scale, to a specific isolated habitat unit. Alternatively, attempts to define boundaries based solely on the biophysical processes of an ecosystem can be contentious and could result in unmanageably large units (Leslie et al., 2015). Therefore, careful consideration is needed to define appropriate spatial scales which combine ecological, physical, and regulatory boundaries for management of coastal regions. Although tedious, it is a significant early step towards the meaningful application of ecosystem-based management.

Coastal ecosystems in a current state of distress can benefit most from effective ecosystem-based management initiatives (Halpern et al., 2008). The coastal zone of the Northern Gulf of Mexico is subject to numerous ecosystem stressors such as overfishing, nutrient loading and other pollutants, invasive species, habitat loss, and sea-level rise (Halpern et al., 2008). Additionally, major tropical storms and hurricanes are periodic, and one of the world's largest hypoxic areas frequently forms along its coast (NMFS, 2012). The warm sub-tropical water of the Gulf coast supports highly productive fisheries and also attracts rapidly developing human populations, diverse industries, and comprises many of the nation's leading ports in terms of tonnage and commercial fish landings (Karnauskas et al., 2013). We present a framework to define coherent and reproducible spatial boundaries of coastal regions across the Northern Gulf of Mexico, in order to facilitate assessment of large-scale ecosystem health useful to ecosystem-based management in this region. Herein we define and recommend spatially explicit coastal regions for the Northern Gulf of Mexico using both regulatory and biophysically meaningful spatial boundaries.

2. Methods

The Northern Gulf of Mexico includes over 2600 km of coastline located within five states of the USA, from the Texas border with Mexico to the tip of Florida's peninsula, and contains a complex network of bayous, inlets, tidal rivers, bays, and islands. Coastal zone is defined as the transitional area that straddles the open ocean and the continent. Spatial boundaries were chosen based on a classification system that collectively considered political, ecological, and geographical boundaries. This is an important difference from boundaries for ecoregions, which are defined strictly by their distinctive geography and climate, because many data that are essential to characterizing and monitoring ecosystem services are reported at jurisdictionally defined spatial scales.

This framework for defining spatial boundaries of coastal regions focuses on a number of well-known and easily reproducible national spatial datasets (Table 1). The table presents potential options for defining seaward and landward spatial boundaries that can be used to identify and select among well-documented and easily reproducible spatial datasets for coastal regions of the United States. It is meant to be

Table 1
Simplified framework to defining spatial boundaries for coastal regions of the United States. This table is meant to be a simple guide and does not include all potential options for defining spatial boundaries for coastal regions in the U.S.

	Steps to defining spatial boundaries	Option	Datasource	Description
1	Define Seaward Boundary	Include only county-linked data	US Census Department, TIGER/Line County Layer (USCB, 2016)	Includes all counties, if coastal includes submerged lands out to 3 miles seaward from the mean high tide line.
		Include all non-federal submerged lands	USGS Digital Offshore Cadastre - Submerged Lands Act Boundary Line (USGS, 2002)	Includes all state coastal submerged lands as determined by the Submerged Lands Act (SLA) which extends from 3 to 9 miles seaward from the mean high tide line depending on the state in question.
		Include all federal submerged lands	NOAA, USEEZ: Boundaries of the Exclusive Economic Zones of the United States and Territories (NOAA, 2016b)	Includes all U.S. federal waters out to 200 nautical miles from the mean high tide line.
		Include all submerged lands to a certain depth contour	Data source varies by spatial extent of study	
2	Define Landward Boundary	Include only submerged lands	NOAA Mean High Water Line (NOAA, 2016a)	Includes all submerged lands at the mean high tide line as determined by NOAAs Office of Coast Survey Shorelines
		Include all Coastal Counties	US Census Department, TIGER/Line County Layer (USCB, 2016)	Includes all counties and equivalent in the U.S., requires hand selection of coastal counties.
		Include Coastal Zone Management Program Counties	USGS Coastal Zone Management Counties (USGS, 2009)	Includes the 492 coastal zone management program counties and county equivalents published by NOAA.
		Include all lands to a certain topographic contour	USGS National Elevation Dataset (USGS, 2015a)	Includes basic bare earth elevation information for the United States
		Include all coastal watersheds	USGS Hydrologic Unit Code (USGS, 2015b)	Includes all coastal watersheds by varying level of classification using the USGS Hydrologic Unit Code Classifications
		Include all coastal land-based ecoregions	EPA Ecoregions of North America (USEPA, 2016)	Includes land-based ecoregions by level
3	Define Lateral Boundaries	Includes numerous options, and should include careful consideration of scale of ecosystem services being measured and data availability.		

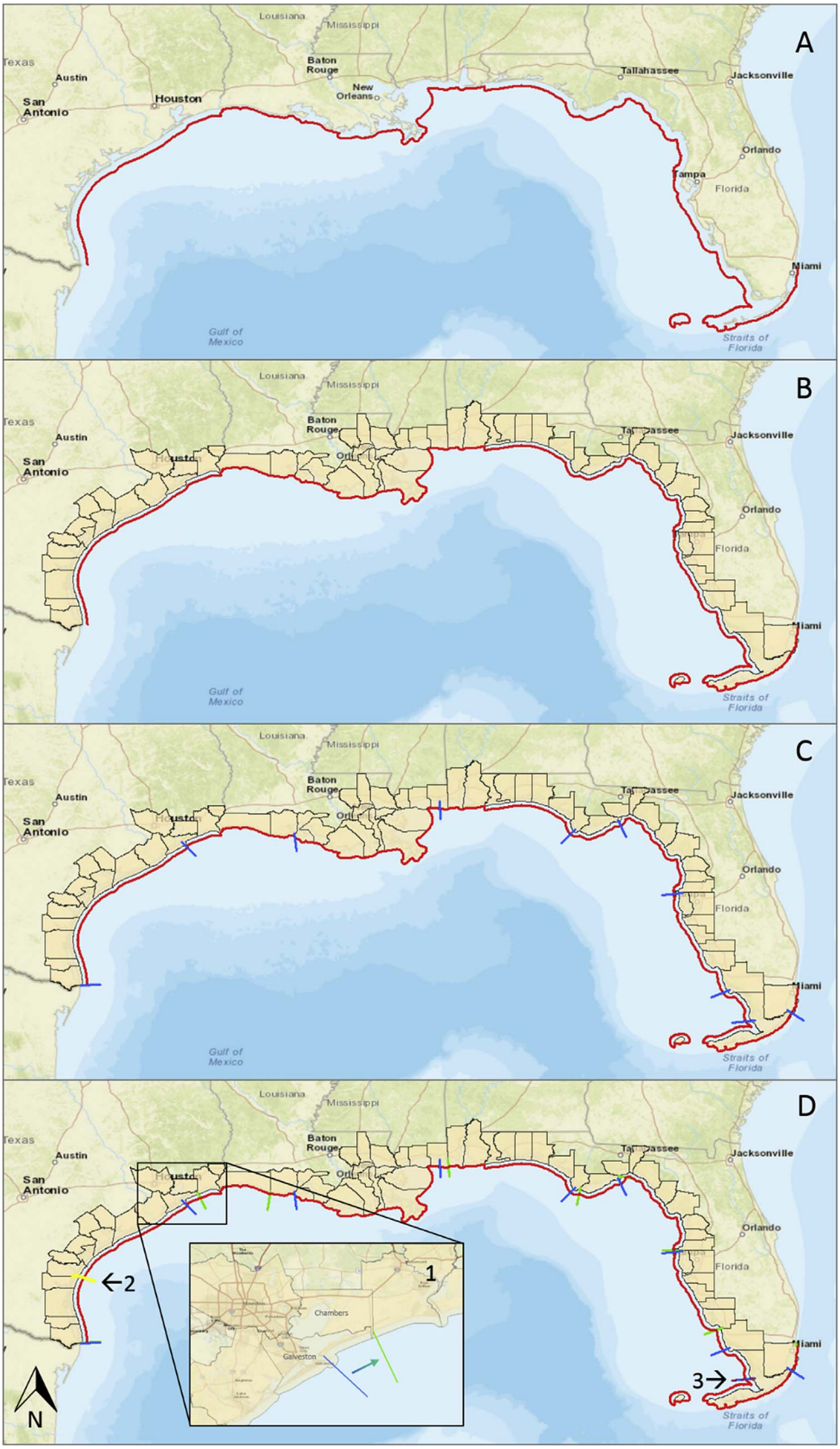

Fig. 1. Illustration of the steps used to define the spatial boundaries for coastal regions of the Northern Gulf of Mexico. A) Defining the seaward boundary using the submerged lands act FEDSTATE layer (USGS, 2002). B) Defining the landward boundary using the TIGER/Line layer (USCB, 2016). C) Digitizing the lateral boundaries (blue lines) defined by Terrell (1979), and D) Modifying the lateral boundaries on a case-by case basis (green lines represent modified boundary). D.1 illustrates and example of the lateral shift of the region boundary between Region F7a and F6. D.2 shows the placement of the new boundary (yellow line) splitting F7 into two new regions. D.3 shows where a lateral boundary (blue line with red dashes) from Terrell (1979) was removed. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a simple guide and does not include all potential datasets to consider when defining spatial boundaries of coastal regions. We then used options from within this framework to demonstrate the process of defining spatial boundaries for coastal regions of the Northern Gulf of Mexico.

Our first step was to define the seaward and landward boundaries of the coastal zone. We identified boundaries that fit our objective, which was to define both regulatory and ecologically coherent coastal regions of the Northern Gulf of Mexico, in order to assess ecosystem services for the purpose of informing assessment of outcomes of ecosystem-based management in this region. We highlight the nearshore ecosystems that are most affected by their proximity to the land such as the uniquely complex network of bayous, bays, tidal rivers, and barrier islands found along the Northern Gulf of Mexico. Therefore the offshore boundaries were defined by the Submerged Lands Act, State Seaward Boundary, which defines the seaward limit of the state's submerged lands and the landward boundary of federally managed lands (which extends 9 miles offshore from the mean high tide line for TX and FL, and 3 miles for LA, MS, and AL) (USGS, 2002) (Fig. 1A). Choosing this jurisdictional boundary was influenced greatly by availability of data useful for future assessment of ecosystem services. This spatial boundary facilitates the use of state-based resource management datasets when assessing services such as fisheries, water quality and related areas influenced by management actions.

The landward boundary was extended inland to include all coastal counties (including any county that borders marine or brackish waters) from the US Census Bureau's U.S. Current County and Equivalent National TIGER/Line Shapefile (USCB, 2016) (Fig. 1B). This boundary was important to include for future assessment of socio-economic ecosystem services that are often found in datasets at the county level (e.g. census data). Furthermore, coastal ecosystems are impacted by human actions on the adjacent land, such as pollution, development, freshwater inflow restrictions, habitat alteration, and industry.

The third step was to define the lateral boundaries of individual coherent regions within the coastal zone. For our purposes these are not meant to be boundaries of individual ecosystems, rather clusters of similarly-functioning ecosystems, and should be scalable down to the ecosystem level where desired. There are numerous classifications of coastal areas that utilize structural, functional, and geographical categories (examples: Terrell, 1979; Cowardin et al., 1979, Inman and Nordstrom, 1971; Spalding et al., 2007; Finkl, 2004; Engle et al., 2007). We selected the Fish and Wildlife Service, 1979 publication of the physical regionalization of coastal ecosystems of the United States and its Territories (Terrell, 1979), because this is the most comprehensive and detailed regional classification scheme for coastal ecosystems that encompasses our entire study area. However, it requires some modification for our use because it is primarily based on hydrological and geological characteristics and does not correspond with jurisdictional boundaries or management units. The boundary lines for the nine original regions reported in the Northern Gulf of Mexico were digitized in ArcGIS 10.1 (Fig. 1C). On a case-by-case basis, each lateral boundary was assessed and modified based on biological (habitat) and political jurisdictional considerations (Fig. 1D). In most situations, the boundary lines were adjusted laterally to align with the nearest county line that best represented the classification conditions in the adjacent physical region. Using county lines as the lateral boundaries for the regions is important for future efforts that combine datasets organized by county or bay-system to inform ecosystem based management. For example, the boundary line between Terrell's F6 and F7 regions was shifted to the county boundary between Chambers and Jefferson County (Fig. 1D.1). If not modified the existing lateral boundary lines would have potentially forced exclusion of county-wide data sources from Chambers and Galveston Counties which would have presented difficulty in assigning to either adjacent region's ecosystem services assessment. Therefore the lateral boundary was adjusted so that both counties (which comprise a single estuary) were included in a single region (Fig. 1D.1). Similarly, the lateral boundary between F5 and F6 was shifted to the west because Vermilion Parish straddles the ecological boundary between the Chenier Plain and the Mississippi Delta. The same rationale described above was used to shift the boundary to avoid partitioning a single estuary.

Two major alterations were made to the Terrell regional classifications. The first was splitting region F7 into two new regions (Fig. 1D.2). The Laguna Madre is a shallow hypersaline lagoon dominated by vast seagrass beds with very little water exchange with the adjacent Gulf of Mexico (Britton and Morton, 1989; TDWR, 1983). Because of the uniqueness of this coastal region, Terrell's region F7 was split in two at the boundary of Kleberg and Nueces Counties. The second alteration to the Terrell regional classifications was to combine the D3 and D4 regions by removing the boundary located in Monroe County (Fig. 1D.3). This was done because Monroe County spanned both regions which could pose issues with future ecosystem service assessment due to data sources with limited geographic information (e.g., county-level data only). Additionally, the ecological descriptions of the two regions are similar, which includes numerous complexly-structured mangrove islands.

Finally, counties bordering the water's edge for Texas and Florida (where the submerged lands of the state extend out to 9 miles according to the submerged lands act) were snapped to the seaward boundary to include the adjacent state waters. Counties and adjacent state waters were then grouped by the modified region in which they were contained, creating masking features to support analysis of data for subsequent ecosystem-based management initiatives.

3. Results

Resulting spatial boundaries of the nine regions (Fig. 2, Table 2, and Electronic supplement 1) can be used in evaluation of ecosystem-based management initiatives for the Northern Gulf of Mexico. Regional descriptions are modified from Terrell (1979). The eastern extent of the study area is defined by the combined D3-D4 region (Everglades and Ten Thousand Islands) and includes three counties from Miami-Dade to Collier County. This region is described as coastline that is dominated by extensive swamps and numerous mangrove islands and includes the Florida Keys and the Dry Tortugas. Region F1 (Central Barrier Coast) extends from Lee County to the northern border of Pinellas and Hillsborough Counties. F1 has sandy beaches with few rocky areas, estuaries with barrier islands, and extensive marshes with adjacent shallows. Region F2 (Big Bend Drowned Karst) is a more rugged shoreline extending from Pasco to Wakulla County. This region supports high fish production and has rocky bottom, wide shallows with clear water and extensive seagrass beds, oyster bars, and marshes. Region F3 (Apalachicola Cuspate Delta) is defined by Franklin County and has barrier islands with smooth sand beaches, mud-bottom bays, and turbid water with little to no seagrass. The North Central Gulf Coast is Region F4 and runs from Gulf County to Mobile County; it has high energy white sand beaches, clear water, and extensive dune systems and barrier islands. Region F5 (Mississippi Delta) includes coastal areas that are highly influenced by the Mississippi River from Jackson County to Vermilion Parish; it has extensive marsh and barrier islands with widespread shallows where the sediments are silty and the water is turbid. Region F6 (Strandplain-Chenier Plain System) has extensive marsh systems with cheniers present; freshwater enters from several river systems, but not from the Mississippi River. Regions F7a and F7b are the upper and lower Texas Barrier Island Systems, which run from Chambers to Nueces County and Kleberg to Cameron County respectively; they are lagoon systems formed by drowned river mouths and barrier islands. The upper region, F7a has extensive marshes with regular freshwater inflow; the lower region, F7b has extensive shallows, seagrass is common and freshwater inflow is limited, thus, becoming hypersaline at times.

4. Discussion

The most important prerequisites for defining spatial boundaries to facilitate ecosystem-based management are considering the ecosystem services you plan to measure, and the data needed to measure those services. More commonly, county boundaries are used when defining the lateral boundaries of coastal regions for coastal health studies (Halpern et al., 2014; Elfes et al., 2014). Although most jurisdictional

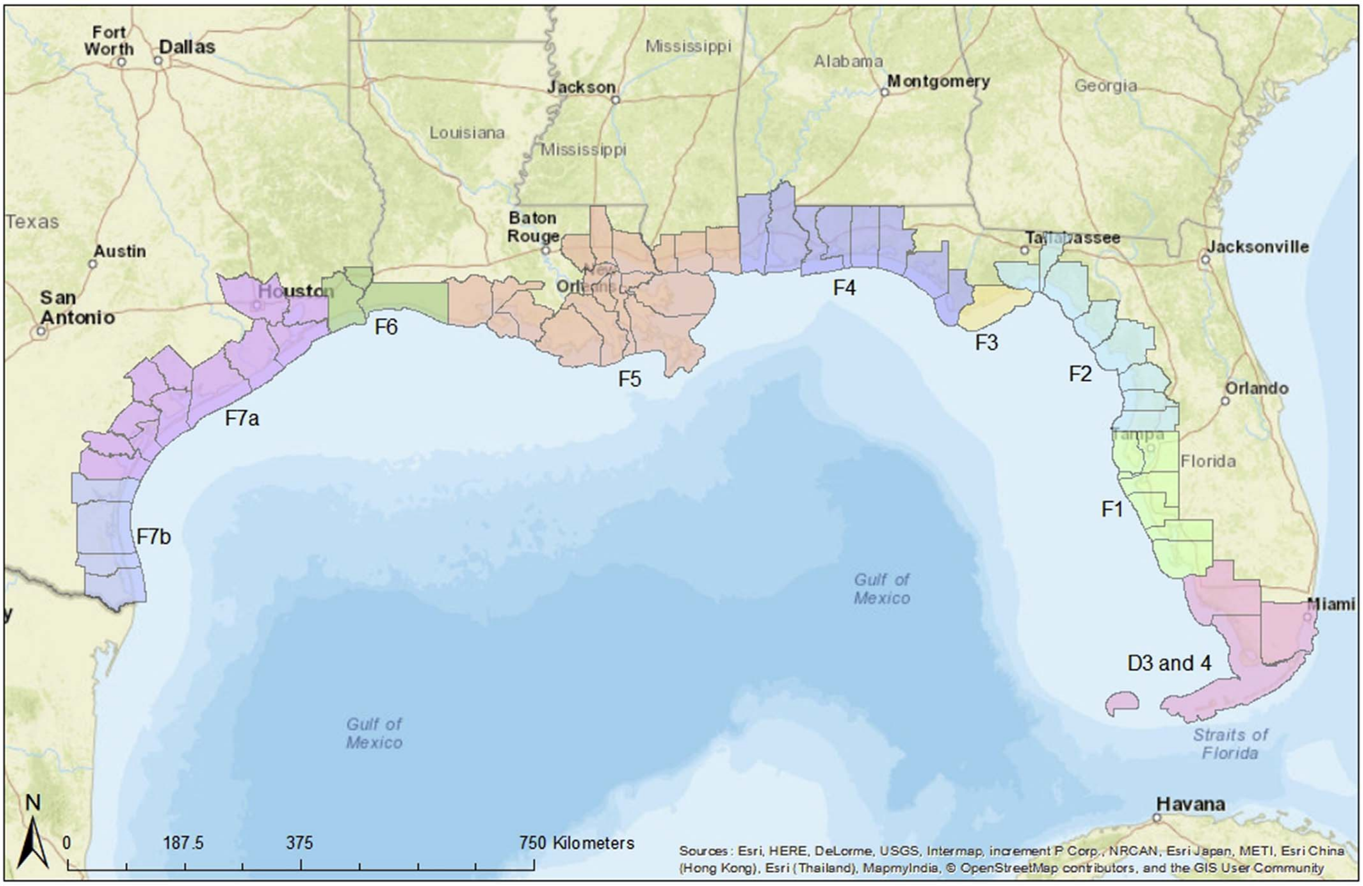

Fig. 2. Spatial Boundaries of nine coastal regions of the Northern Gulf of Mexico. Region descriptions and boundaries correspond to Table 2 and electronic supplements 1 and 2.

boundaries were created without regard for ecological boundaries in terms of resource management, many resource datasets are spatially defined by jurisdictional boundaries. This has created a fragmentation in governance and inefficient resource monitoring that in many cases does not coincide with biophysical ecosystems and mechanisms (Crowder and Norse, 2008). For example, many county or state boundaries are waterbodies and in the case of Sabine Lake, an enclosed coastal bay in Region F6, the county and state boundaries (Texas-Louisiana) split the bay in half. Re-drawing state, or even county lines is not a realistic solution to improve management capabilities of coastal ecosystems that occur at jurisdictional crossroads. Instead it is necessary to create ad hoc classification schemes that preserve the existing sociopolitical boundaries, while forming new spatial boundaries for the purpose of EBM that accommodate ecosystem functions to the maximum extent possible. The locations of the lateral boundaries used in this study were informed by ecologically and physically meaningful classifications (Terrell, 1979), but had to be adjusted to work within the context of data at available spatial scales.

There are several examples and methodologies for defining coastal or ocean spatial boundaries in order to evaluate ecosystem health (Halpern et al., 2012, 2014; Yáñez-Arancibia et al., 2013; USEPA, 2012). Specifically (and comparable in technique), Halpern et al. (2014) defined five distinct sub-regions along the west-coast of the U.S. using both jurisdictional and ecological boundaries. They included

Table 2
Ecological descriptions and lateral boundaries for the nine coastal regions for the Northern Gulf of Mexico. Corresponds to Fig. 2 and electronic supplements 1 and 2.

Region	Description	Lateral Boundary
D3 and 4	Everglades and Ten Thousand Islands: coastline dominated by extensive swamps and numerous mangrove islands (including Florida Keys).	Miami-Dade to Collier County
F1	Central Barrier Coast: Sandy beaches with few rocky areas, estuaries with barrier islands and extensive marshes with adjacent shallows.	Lee to Pinellas and Hillsborough Counties
F2	Big Bend Drowned Karst: Rugged Shoreline, rocky bottoms, wide shallows with clear water and extensive seagrass beds, oyster bars, and marshes, supporting high fish production.	Pasco to Wakulla County
F3	Apalachicola Cuspate Delta: barrier islands present, smooth sand beaches, mud-bottom bays, turbid water with little to no seagrass.	Franklin County
F4	North Central Gulf Coast: High energy white sand beaches, clear water, extensive dune systems and barrier islands.	Gulf County to Mobile County
F5	Mississippi Delta: Extensive marsh and barrier islands, sediments silty, water turbid, extensive shallows	Jackson County to Vermilion Parish
F6	Strandplain-Chenier Plain System: Extensive marsh systems, cheniers present, freshwater inflow but lacking influence from Mississippi.	Cameron Parish to Jefferson County
F7a	Upper Texas Barrier Island System: Lagoon system formed by drowned river mouths and barrier islands with marshes, regular freshwater inflow.	Chambers to Nueces County
F7b	Lower Texas Barrier Island System: Hypersaline lagoon system formed by drowned river mouths and barrier islands with shallow water and seagrass common, limited freshwater inflow.	Kleberg to Cameron County

consideration of county-level data sources available; however, the seaward boundary extended to include all federal waters, which allowed the authors to focus on ocean health more so than the emphasis of coastal health in our study. Halpern et al. (2014) were successful in evaluating ecosystem health in the context of their defined spatial boundaries by calculating a regionalized Ocean Health Index. This index has the capacity to be quite useful for resource managers on the West Coast of the U.S. to measure impacts made by ecosystem-based management initiatives.

The spatial boundaries defined in this study and most coastal systems world-wide span multiple governmental boundaries. Therefore, effective coordination between the various stakeholders is essential when moving towards meaningful ecosystem based management of coastal ecosystems. However, doing so is a tedious and long-term process, as demonstrated in the Chesapeake Bay coastal ecosystem, which was referenced as a model for regional ecosystem-based management by the U.S. Commission on Ocean Policy (Boesch, 2006). The Chesapeake Bay Commission works with numerous governmental stakeholders to define and measure ecosystem-based management goals (Chesapeake Bay Program, 1999; Boesch, 2006). Despite over two decades of effort, the Chesapeake Bay continues to face the same challenges that many coastal systems encounter, such as population growth and land-based pollutants, but through careful monitoring, related improvements are being realized (Dell'Apa et al., 2015). The Chesapeake Bay management program highlights the coordination necessary when managing a large region that spans multiple states, counties, and bays, such as the regions being proposed in this paper. Along the Northern Gulf of Mexico there are seven national estuary program (NEP) locations located in five of the nine coastal regions described in this paper. The NEP was developed to address environmental issues that transcend political jurisdictions on an ecosystem level (Imperial and Hennessey, 1996). One region-specific group in the Gulf of Mexico that is working to inform ecosystem-based management is the Gulf of Mexico Alliance (GOMA) ecosystems services assessment cross-team initiative. They work to describe, measure, and disseminate information about coastal ecosystem services for improved resource management (GOMA, 2017). In all successful examples of ecosystem-based management, spatial boundaries were pre-defined in a reproducible fashion by using ecological reasoning (McBride and Houde, 2004). The choices made during this phase of ecosystem-based management impact which ecosystem services can be measured and the data sources that can be used.

Ecosystem services measured in EBM initiatives will always be impacted by external processes and factors no matter how inclusive you are when defining the spatial boundary of a coastal system. For example commercially or recreationally important highly migratory fisheries can be managed at local or state levels, but they are inevitably influenced by activities that occur at much larger scales, globally in some cases (Palumbi, 2004; Cowen et al., 2012). Ecosystem spatial scales range from the whole earth to individual isolated habitats, and understanding the range and impacts of factors at these scales are central to effective ecosystem management (Crowder and Norse, 2008). Beyond highly migratory fisheries, the coastal regions identified in our study are undoubtedly influenced by external forces that span the defined seaward, landward, and lateral boundaries. Coastal regions that are situated at the land-sea interface are uniquely influenced by climate variability expressed over the adjacent land and open water (Cloern et al., 2016). For example, contributing watersheds extend across entire continents and can have significant impacts on coastal ecosystems as a result of precipitation and run-off. Therefore, it will be necessary to identify ways to account for this influence on coastal regions from outside of its spatial boundary, such as salinity or nutrient loading, by including them in evaluation metrics for the EBM plan. Recognizing and accounting for such externalities is an important step in qualifying and defining boundaries for ecosystem-based management.

5. Conclusions

While ecosystem-based management is widely accepted as a useful management concept, actual examples of regional-scale practice are limited. The first step in moving towards meaningful ecosystem-based management of coastal zones is to define the spatial boundaries of the "managed ecosystems". As discussed, this complicated task must incorporate biological, physical, and socio-economic scales while understanding that the defined boundaries are imperially porous.

This paper provides a framework and a tool for defining spatial boundaries for the purpose of ecosystem-based management initiatives. Once defined, the coastal regions will be crucial in creating criteria with which differences in ecosystem services can be measured spatially, and changes in ecosystem services can be tracked temporally. Nine coastal regions were defined for the Northern Gulf of Mexico using both regulatory and biophysically meaningful spatial boundaries. It is important to note that all coastal ecosystems are heterogeneous, and the framework developed here should be carefully evaluated, modified and enhanced by local experts for application in other regions. Future work will apply these spatial boundaries in the development of a coastal health index for the Northern Gulf of Mexico.

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Appendix A. Supplementary data

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