Ecological Indicators 44 (2014) 26–39

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Towards marine ecosystem based management in South Florida: Investigating the connections among ecosystem pressures, states, and services in a complex coastal system

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ARTICLE INFO

Article history:
Received 5 April 2013
Received in revised form
23 September 2013
Accepted 17 October 2013

Keywords:
DPSIR
Ecosystem based management
Ecosystem services
MARES
Social–ecological systems

ABSTRACT

Marine ecosystem based management plans are gaining popularity with natural resource managers, but examples of their successful implementation remain few. The complexity inherent in marine ecosystems presents a major obstacle to understanding how individual ecosystem pressures impact multiple ecosystem states that in turn impact the provisioning of ecosystem services. To create and implement successful ecosystem based management plans will require tools for understanding these processes. Over the past three years integrated conceptual ecosystem models of the coastal marine environment have been developed as part of the Marine and Estuarine Goal Setting for South Florida (MARES) project. Here we use these conceptual models in conjunction with a modified DPSIR model, expert opinion and matrix-based analyses to explore the direct and indirect relative impact of 12 ecosystem pressures on 11 ecosystem states and 11 ecosystem services identified through MARES. Within the South Florida coastal ecosystem the most pervasive pressures were freshwater delivery, temperature effects of climate change, and impacts of climate change on weather. For the study region the least pervasive pressures were recreational fishing, commercial fishing, and invasive species. The most at risk ecosystem states, as determined by cumulative impacts were fish and shellfish, protected species, and marine birds. By the same measure, the least at risk states were oyster reefs and inshore flats. The most at risk ecosystem services were existence of a natural system, pristine wilderness experience, and non-extractive recreation. The least impacted ecosystem services were commercial extraction, recreational fishing and climate stability. When the relative direct and indirect (i.e. including state to state interactions) impacts of ecosystem pressures were traced to individual ecosystem services, it was apparent that within the study domain a lack of freshwater delivery to coastal estuaries was the predominant pressure, and recreational fishing had the lowest relative impact on the provisioning of ecosystem services. Through this expert opinion analysis and exploration of the interaction strength among various ecosystem pressures, states, and ecosystem services, we can begin to understand the diverse manners in which ecosystem services are impacted by various pressures. In so doing we provide a tool for resource managers to understand the trade-offs among individual user groups and the possible impact on provisioning of ecosystem services that may occur when considering various management strategies.

1. Introduction

In recent years, marine ecosystem based management (EBM) has received growing attention as a framework for mitigating anthropogenic impacts on the world's oceans, but its implementation has proved challenging (Halpern et al., 2008a,b; Samhouri et al., 2010; Tallis et al., 2010). Global-scale analyses have generated quantitative comparisons among pressures impacting different portions of the marine environment (e.g. Halpern et al., 2012), but owing to the complexities in the successful implementation of EBM (see below), the knowledge generated by these broad-scale analyses provides limited guidance for actionable science at smaller spatial scales (Game et al., 2013). To understand the unique properties, stressors, interactions, and vulnerabilities of local and regional marine ecosystems, and how to successfully manage complex coastal systems, will require complementary

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http://dx.doi.org/10.1016/j.ecolind.2013.10.026

focused analyses (Stelzenmuller et al., 2010; Teck et al., 2010; Altman et al., 2011; Grech et al., 2011; Game et al., 2013).

In theory, EBM is a holistic strategy for dealing with the complexities of diverse ecosystems; its strength lies in the ability to simultaneously explore the trade-offs among social, cultural, economic, and environmental factors that may influence an ecosystem, and to find optimal solutions for all stakeholders (Leslie and McLeod, 2007). In practice, and despite federal mandates to utilize EBM approaches (Lubchenco and Sutley, 2010) a move from traditional single-sector management strategies to holistic EBM has been slow. Some local-regional scale EBM plans have been developed (e.g. the Puget Sound Partnership, Massachusetts Ocean Management Plan), but in many instances, particularly within the realm of fisheries management, the implementation of EBM is viewed as a sequential process where first single-species stock assessment methods are explored and adapted to assemblages of multiple species, after which it is believed managers will become more receptive to an ecosystem approach to managing fisheries, which ultimately will lead to a broader acceptance and application of multi-sectoral EBM of complete ecosystems, including humans (Agardy et al., 2011).

One of the primary challenges associated with the successful implementation of EBM is consensus building among a diverse group of stakeholders (Leslie and McLeod, 2007). Without a clear and unified vision of what defines the ecosystem in question and what aspects of the ecosystem people care about, endpoints and management targets remain elusive (Game et al., 2013). Making this challenge greater is the high degree of complexity inherent in ecosystems and a lack of understanding about how various pressures impact ecosystem states and services. In addition, those involved in the creation of an EBM plan need to identify which metrics can be used to gauge the success of various management strategies. Without predefining critical ecosystem components and metrics, evaluating the success of an EBM plan can be tenuous and uncertain (Leslie and McLeod, 2007; Game et al., 2013). Another challenge to the successful implementation of EBM is a paucity of examples of successfully implemented EBM approaches that can act as a blueprint for others to follow (Leslie and McLeod, 2007). Finally, while it is unrealistic to manage every aspect of the marine environment, there is a need to identify and prioritize the key components of an ecosystem, which can and should be the focus of management actions (Altman et al., 2011; Game et al., 2013).

In this paper, we highlight a marine EBM project addressing these challenges in South Florida and provide guidance on how to quantify the relative strength of "the complex interconnections that exist among many species, habitat types, and human activities" in an ecosystem threatened by various pressures both natural and anthropogenic (Altman et al., 2011; Kelble et al., 2013). We introduce a matrix-based method for estimating the interaction strength among ecosystem pressures, states, and services, and show how these data can be used to implement marine ecosystem based management successfully. This methodology could be categorized as a qualitative or semi-quantitative ecosystem risk assessment (*sensu* Hobday et al., 2011), as it builds upon extensive scoping, identifies the most vulnerable ecosystem states, and explores all possible pressure to state to ecosystem service interactions within the MARES study domain (see Sections 1.1 and 2 below). Furthermore through an exploration of the direct and indirect pathways by which various pressures impact the provisioning of ecosystem services we provide a manner for decision-makers to explore the susceptibility of states to impacts and the inherent trade-offs among possible management actions and the costs and benefits to multiple user groups. We base this analysis on reviews of published documents, grey literature, as well as information gathered from key personnel and collaborative MARES workshops from 2009–2012.

1.1. MARES

From late 2009–2012 more than 100 South Florida scientists, managers, and stakeholders have participated in a protracted planning process called the MARine and Estuarine goal Setting (MARES) project. MARES is an attempt to make holistic ecosystem-based management more central to restoration activities in South Florida, and to rectify the shortcomings identified from the Comprehensive Everglades Restoration Plan (CERP), the world's largest and most expensive ecosystem restoration effort (please see Doren (2009) and articles therein, Nuttle and Fletcher, 2013a). For an in-depth description of the MARES process and the defining habitats, species, ecology, and socio-economic components of this system please see Nuttle and Fletcher (2013a,b) and Kelble et al. (2013), Leeworthy et al., Lorenz et al., Lovelace et al., Ortner et al., Patterson et al. (all this issue). The stated goal of MARES is to "reach a science-based consensus about the defining characteristics and fundamental regulating processes of a South Florida coastal marine ecosystem that is both sustainable and capable of providing the diverse ecosystem services upon which our society depends" (Nuttle and Fletcher, 2013a). To achieve this goal, MARES addresses the primary EBM challenges outlined by Leslie and McLeod (2007) (see above). First, MARES developed integrated conceptual ecosystem models through consensus-building workshops that included resource managers, representatives of federal (e.g. US National Park Service, National Oceanic and Atmospheric Administration, US Geological Survey, US Environmental Protection Agency, US Fish and Wildlife Service), state (e.g. Florida Department of Environmental Protection, Florida Fish and Wildlife Conservation Commission, South Florida Water Management District), county (e.g. Miami-Dade County, Broward County, Monroe County), and non-Governmental Organizations (e.g. Audubon, The Nature Conservancy), stakeholders, and biophysical and human dimensions scientists. MARES identified quantitative ecosystem indicators of both the biophysical and human components of the ecosystem that should be used to evaluate the efficacy of management strategies. Lastly, if successful, MARES will provide an example of a successfully implemented EBM approach.

The integrated conceptual ecosystem models depicted the key attributes of the ecosystem and the key linkages to human society (Nuttle and Fletcher, 2013a). To create these models the MARES project built upon a Drivers-Pressures-State-Impact-Response (DPSIR) framework (Harremoes, 1998). The DPSIR framework evolved from a Pressure-State-Response model describing the interactions between pressures impacting various ecosystem states, and the responses that in turn influence pressures (Bowen and Riley, 2003). The DPSIR model was meant to explain cause-and-effect relationships among indicators that describe how human society impacts the various states comprising an ecosystem, and has been widely adopted for its ability to better communication among policymakers, stakeholders, and scientists (Kelble et al., 2013). However, traditional DPSIR models lack a direct linkage to ecosystem services, and so the original DPSIR model was adapted to create an EBM-Driver-Pressure-State-Ecosystem Service-Response (DPSER) model (Kelble et al., 2013). In the EBM-DPSER model Drivers, such as human population growth, reflect the ultimate causes of impacts on ecosystems, but management actions rarely target underlying human needs (e.g. the energy requirements associated with an increasing human population; Kelble et al., 2013). Therefore, in this study we focus on the pressures that manifest from these ultimate drivers (e.g. ocean acidification resulting from fossil fuel burning), and which are the targets of management responses. With this in mind we identified the predominant pressures to the coastal marine ecosystem (e.g. recreational fishing, boating activities, marine construction) along with their

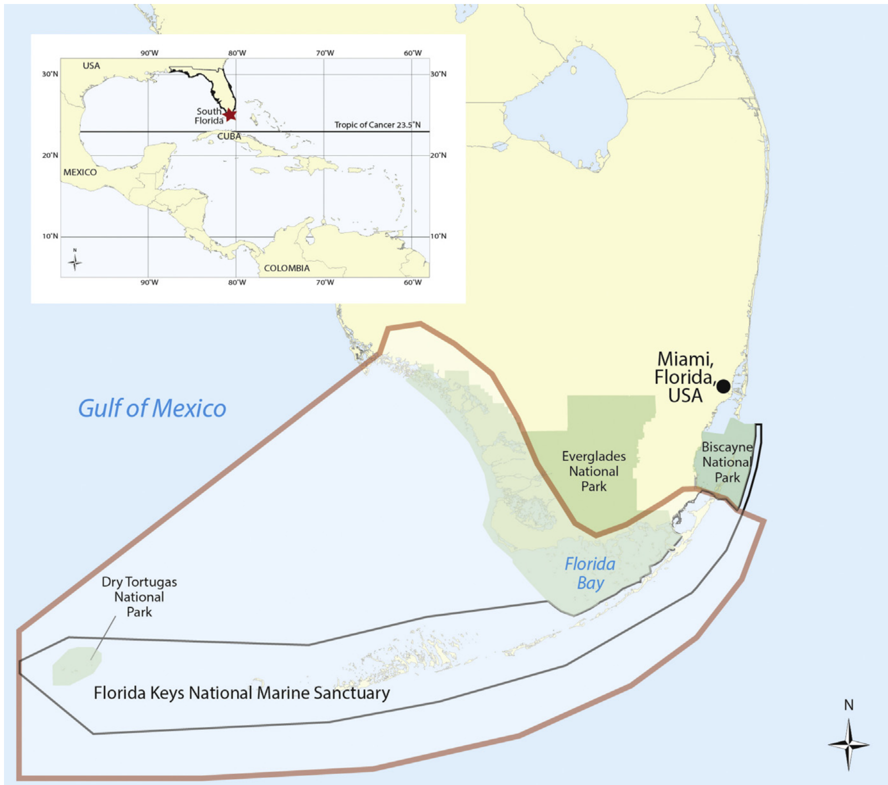

Fig. 1. Map of South Florida coastal ecosystem. Outlined in brown is the region taken into consideration when experts quantified interactions among *pressures*, *states*, and *ecosystem services*. Inset map shows study region (red star) within Florida, USA and the wider Caribbean. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

connections to ecosystem states, which in turn affect the ecosystem services that benefit human society.

2. Methods

2.1. Study region

The MARES project area spans from the southwest Florida shelf down to the Florida Keys, eastward into Florida and Biscayne Bay, and northward to the St. Lucie River estuary on the northeast coast of Florida. For this investigation, a more focused study region within the MARES domain was defined that included the Florida Keys National Marine Sanctuary and the coastal waters of Everglades National Park (i.e. estuarine waters where psu > 0; Fig. 1). The northeastern boundary of the study region was formed where the Florida Keys are closest to the Florida mainland, at the intersection of Card Sound to the south and Biscayne Bay to the north. The southern boundary was formed by the stretch of Florida Keys spanning in a southwesterly direction towards Fort Jefferson and Dry Tortugas National Park; the southernmost edge of the study system was seaward of the Florida Keys National Marine Sanctuary boundary. The western boundary of the study system stretched northeast from near the Tortugas Ecological Reserve in the southwest to the geomorphological break between the Barrier Islands Province and the Ten Thousand Islands Province, near Marco Island, Florida. These provinces are two predefined geomorphological provinces within the study area (Nuttle and Fletcher, 2013a; Ortner et al. this issue). The reason to focus on this MARES sub-region was two-fold. The first reason was logistical: to provide intellectual tractability in the scoring of ecosystem interactions. Dialogue with participants regarding the geographic domain of the study suggested the selected scale was such that it captured ecosystem variability, but reduced the heterogeneity to a sufficient degree that experts were confident in scoring the linkages among ecosystem *pressures*, *states*, and *ecosystem services* (see below). Secondly, this is an area that has two main entities with overarching trust obligations for the coastal ecosystem (Everglades National Park and the Florida Keys National Marine Sanctuary). These two resource management entities both participated heavily in this process and plan to use the results to help inform future decisions.

2.2. Identifying ecosystem pressures, states, ecosystem services and interactions

Through the MARES process stakeholders were tasked with developing (1) integrated conceptual ecosystem models (ICEMs) depicting the current scientific understanding of the critical components comprising the ecosystem, and (2) quantitative ecosystem indicators of these. The ICEMs were developed for each of the ecosystem *states* identified in the MARES process. For an in-depth discussion on the process of developing the ICEMs please see Nuttle and Fletcher, 2013a,b. From these ICEMs three broad modules were defined for this study (*pressures*, *states*, and *ecosystem services*). These three modules were comprised of 34 individual components for the study system: 12 ecosystem *pressures*, 11 ecosystem *states*, and 11 *ecosystem services* (Table 1; please see Appendix A for individual component definitions). *Pressures* are the various physical, chemical, and biological factors that directly influence an ecosystem. *States* are defined by specific attributes or characteristics of an ecosystem, and *ecosystem services* are defined as the benefits people may derive from the marine environment (Farber et al., 2006; Kelble et al., 2013). There are direct interactions among ecosystem *pressures* and ecosystem *states* in the EBM-DPSER model, which in turn directly act upon other ecosystem *states* and *ecosystem services*.

Table 1
List of 34 ecosystem components identified through the MARES process. Specific definitions for each component can be found in the appendices.

Ecosystem module		
Pressures	States	Ecosystem services
Accelerated sea level rise	Beaches	Aesthetic environment
Boating activities	Coastal wetlands	Climate stability
Climate change (temperature)	Coral and hardbottom	Commercial extraction
Climate change (weather)	Fish and shellfish	Existence natural system
Commercial fishing	Inshore flats	Historic and cultural resources
Disease	Mangrove keys	Non-extractive recreation
Freshwater delivery	Marine birds	Pollution treatment
Invasive species	Oyster reefs	Pristine wilderness experience
Marine construction	Protected species	Protection from storms
Marine debris/ghost traps	Seagrass	Recreational fishing
Ocean acidification	Water column	Science and education
Recreational fishing		

Using the ICEMs developed by MARES, 193 unique interactions among the 34 different components were identified (i.e. 60 *pressure* to *state* interactions, 53 *state* to *state* interactions, and 80 *state* to *ecosystem service* interactions).

2.3. Quantifying interaction strength

To quantify the relative interaction strength of these 193 linkages among *pressures*, *states*, and *ecosystem services*, a two-day workshop was held on August 22–23, 2012. As part of this information gathering exercise, 25 participants scored two sequential questions for each of the 193 direct interactions (386 total questions), based on their expert opinion (i.e. 14 of 21 participants self-reported as having worked in this geographic domain for more than 20 years, 6 individuals had 10 to 20 years of experience, while only one participant had less than 5 years of experience; 4 individuals did not provide these data). Participants were asked to consider the strength of the various interactions relative to the other listed *pressures* (or *states*). Generalizing, these questions were:

1. How strong is the direct effect of *X* on *Y*?
2. What proportion of *Y* is directly affected by *X*?

Adapting the methodology of Altman et al. (2011), each question was scored from 0 (no effect) to 5 (strong effect). These individual scores were summed to generate a relative interaction strength ranging from a low of 0 to a high of 10 for each of the 193 direct interactions (i.e. each element (a_{ij}) within the three interaction matrices represents the mean score given by the 25 experts and can range from 0 to 10). A relative interaction strength score of 0 would indicate that there is no direct effect of *X* on *Y*; zeroes are indicated by "nan" (i.e. not a number) within the individual interaction matrices. A score of 5 would indicate an intermediate impact, relative to other *pressures* (or *states*, see below) under consideration. A score of 10 would indicate that all respondents scored the direct effect of *pressure X* as the greatest impact to *state Y*, relative to the other *pressures*.

These data were used to create three interaction matrices: *pressure* to *state*, *state* to *state* and *state* to *ecosystem service*. We calculated cumulative effect scores for individual *pressures* and *states* (upon *states* and *ecosystem services*) by summing across each row; $a_{i.}$ is the row sum:

$$a_{i.} = \sum_{j=1}^{n} a_{ij} \tag{1}$$

These data were used to rank the relative cumulative effect of *pressures* upon *states*, *states* upon *states*, and *states* upon *ecosystem services*. Similarly, by summing down individual columns in the three interaction matrices we quantified the relative cumulative impacts to individual *states* (from *pressures* and other *states*) and *ecosystem services*; from these we created relative rankings of cumulative impact. Additionally, from the *state* to *state* interaction matrix we quantified the asymmetry among the *state* to *state* interactions to determine if a given *state* had a greater cumulative impact on other *states*, or was it more greatly impacted by other *states*. For each *state*, asymmetry was calculated as the ratio of cumulative *state* effects (i.e. the *state X* row sum) to cumulative *state* impacts (i.e. the *state X* column sum). Finally, we explored the *state* to *ecosystem service* interactions and as above calculated and ranked the relative impact to each *ecosystem service*. The cumulative *ecosystem service* impact score (i.e. column sum) is assumed to represent the relative interaction strength connecting ecosystem *states* to the provisioning of each *ecosystem service*. The number of *states* impacting each *ecosystem service* represents the breadth of ecosystem *states* upon which the *ecosystem service* relies. A low number of *states* suggests the provisioning of an *ecosystem service* is dependent on few components of the ecosystem, while a relatively high number of *states* suggests the origin of an *ecosystem service* is more diffuse and it depends on, and can be impacted by, many *states* comprising the broader ecosystem. For this study we assume the inherent value of each *ecosystem service* is equivalent, and we make no assertions about their relative intrinsic or economic values.

2.4. Direct impacts

To quantify how an individual ecosystem *pressure* directly impacts individual ecosystem *states* and ultimately *ecosystem services*, we modified the matrix-based methodology of Altman et al. (2011) to calculate proportional impact scores. We explored the proportional contribution of individual ecosystem *pressures* to single *states* by calculating the proportion of the column vector within the *pressure* to *state* matrix attributable to each ecosystem *pressure*. The proportional contribution of a given component, p_{ij}, provides a mechanism for making relative comparisons among all *pressures* simultaneously and was calculated as:

$$p_{ij} = \frac{a_{ij}}{a_{.j}} \tag{2}$$

where $a_{.j}$ is the column sum:

$$a_{.j} = \sum_{i=1}^{n} a_{ij} \tag{3}$$

These proportional values (p_{ij}) were multiplied by the cumulative interaction values (a_{ij}) found in the *state* to *ecosystem service* interaction matrix (i.e. the individual values calculated in the *state* to *ecosystem service* matrix). The values were used to calculate the contribution of an individual *pressure* to each *ecosystem service* by summing across all *states* to create a single direct ecosystem *pressure* to *ecosystem service* impact score. These direct scores were then used to calculate the relative impact of each *pressure* to *ecosystem services* in the MARES region.

2.5. Indirect impacts

In addition to direct impacts, ecosystem *pressures* can indirectly impact *ecosystem services* as mediated through the *state* to *state* interaction matrix. Mechanically indirect impact scores were calculated as above, but with an additional multiplicative step to include the proportional impact of individual *states* on other ecosystem *states* being considered. These indirect impact scores were used to quantify the relative contribution of individual ecosystem *pressures* to various *ecosystem services*, and provide insight regarding the relative importance of direct vs. indirect impacts and the provisioning of *ecosystem services*.

3. Results

3.1. Ecosystem pressure to state interactions

Of the 60 *pressure* to *state* qualitative linkages identified from ICEMs developed as part of MARES, the single largest impact of an ecosystem *pressure* on an ecosystem *state* was from *accelerated sea level rise* to *mangrove keys* (9.7 out of a maximum interaction score of 10); conversely the lowest quantified impact was from *disease* to *marine birds* (3.6). The relative (mean ± se) interaction strength among all 60 ecosystem *pressures* and ecosystem *states* was 6.4 (±0.2, Table 2). The mean effect of individual *pressures* across all ecosystem *states* ranged from 4.6 (±0.5, *invasive species*) to 8.3 (±0.8, *accelerated sea level rise*). Cumulative *pressure* effect (i.e. the value of *pressure* interaction strengths summed across all ecosystem *states*) ranged from 7.4 (*recreational fishing*) to 62.4 (*freshwater delivery*), with a mean cumulative effect of 32.1 (±5.0). The mean impact to each *state* viewed across all ecosystem *pressures* ranged from 5.2 (±0.6, *marine birds*) to 7.6 (±0.7, *beaches*; Table 2). The cumulative impact to each *state* from all *pressures* (i.e. values of *state* impacts summed across all ecosystem *pressures*) ranged from 20.6 (*oyster reefs*) to 45.5 (*protected species*), with a mean cumulative impact of 35.0 (±2.4).

3.2. Ecosystem state to state interactions

Interaction strengths among ecosystem *states* were bi-directional and asymmetric (Table 3). Of the 53 *state* to *state* linkages the single greatest relative impact was from the *water column* to *oyster reefs* (9.4); the lowest scored interaction strength was from *mangrove keys* to *beaches* (1.7). Across all 53 interactions the mean effect strength (±se) was 5.3 (±0.2). The mean effect of each ecosystem *state* across all other ecosystem *states* ranged from 3.9 (± 0.8, *mangrove keys*) to 7.3 (± 0.5, *water column*). Cumulative *state* effects from one ecosystem *state* to all other ecosystem *States* (i.e. the row sum of all effects from a single ecosystem *state* to all other *states*, Table 3) ranged from 10.2 (*inshore flats*) to 65.3 (*water column*) with a mean cumulative effect of 25.4 (± 4.6). The mean impact to each *state* from all other ecosystem *States* ranged from 3.8 (± 0.7, *beaches*) to 9.4 (± 0.0, *oyster reefs*). Cumulative *state* impacts caused by all other ecosystem *states* (i.e. the column sum of all impacts to a single ecosystem *state*) ranged from 9.4 (*oyster reefs*) to 53.2 (*fish and shellfish*); the low cumulative impact to *oyster reefs* was a result of it being impacted by one other *state* (*water column*). The *water column* had the greatest asymmetry score (2.12 = the ratio of cumulative effects from the *water column* and cumulative impacts to the *water column*); the *water column* had more than twice as great an impact upon other ecosystem *states* relative to

Table 2
Ecosystem *pressure* to *state* interaction matrix. Each matrix element (a_{ij}) represents mean values across all expert respondents (see methods). Mean effect strength is the mean (± standard error (se)) of all values across a given row and mean state impact represents the mean of all values down each column. Cumulative effects or impacts represent the row or column sum.

From ecosystem pressure	To ecosystem state												
	Protected species	Fish and shellfish	Coral and hardbottom	Beaches	Coastal wetlands	Water column	Mangrove keys	Marine birds	Seagrass	Inshore flats	Oyster reefs	Mean effect strength (se)	Cumulative effect of pressure
Freshwater delivery	nan	6.38	4.68	5.65	7.12	6.78	4.16	6.67	6.05	6.19	8.77	6.24 (0.41)	62.43
Climate change (temp.)	7.16	6.70	8.87	nan	6.71	7.23	6.37	6.61	7.30	nan	nan	7.12 (0.28)	56.95
Climate change (weather)	nan	nan	6.47	8.24	9.00	6.05	8.03	nan	nan	6.34	6.55	7.24 (0.44)	50.66
Accel. sea level rise	5.53	nan	nan	9.53	8.95	nan	9.68	nan	nan	7.82	nan	8.30 (0.77)	41.51
Marine construction	7.11	nan	nan	8.47	nan	4.57	4.00	nan	nan	4.41	5.27	5.64 (0.72)	33.82
Boating activities	6.88	nan	5.75	nan	nan	3.87	nan	6.00	5.18	nan	nan	5.54 (0.50)	27.68
Disease	6.24	5.15	7.88	nan	nan	nan	nan	3.60	4.12	nan	nan	5.40 (0.77)	26.99
Ocean acidification	nan	nan	9.07	nan	nan	7.50	nan	nan	6.95	nan	nan	7.84 (0.63)	23.52
Marine debris/ghost traps	6.33	4.38	nan	6.29	nan	nan	nan	4.17	nan	nan	nan	5.29 (0.59)	21.18
Invasive species	nan	5.59	nan	nan	5.14	nan	3.63	4.10	nan	nan	nan	4.62 (0.45)	18.47
Commercial fishing	6.27	7.76	nan	nan	nan	nan	nan	nan	nan	nan	nan	7.01 (0.75)	14.03
Recreational fishing	nan	7.43	nan	nan	nan	nan	nan	nan	nan	nan	nan	7.43 (–)	7.43
Mean state impact (se)	6.50 (0.22)	6.20 (0.46)	7.12 (0.72)	7.64 (0.72)	7.39 (0.73)	6.00 (0.60)	5.98 (1.01)	5.19 (0.57)	5.92 (0.58)	6.19 (0.70)	6.86 (1.02)		
Cumulative impact to state	45.51	43.39	42.70	38.18	36.93	35.99	35.87	31.15	29.61	24.75	20.59		

Table 3
Ecosystem *state* to *state* interaction matrix. Each matrix element (a_{ij}) represents mean values across all expert respondents (see methods). Mean effect strength is the mean (± standard error (se)) of all values across a given row and mean state impact represents the mean of all values down each column. Cumulative effects or impacts represent the row or column sum.

From ecosystem state	To ecosystem state												
	Fish and shellfish	Protected species	Marine birds	Water column	Seagrass	Mangrove keys	Beaches	Coral and hardbot-tom	Coastal wetlands	Inshore flats	Oyster reefs	Mean effect strength (se)	Cumulative effect of state
Water column	8.70	7.22	nan	nan	6.83	5.79	5.61	9.00	6.00	6.74	9.43	7.26 (0.48)	65.31
Coastal wetlands	6.51	6.40	7.40	5.43	nan	5.07	3.05	nan	nan	nan	nan	5.64 (0.62)	33.86
Marine birds	4.94	2.67	nan	3.16	4.17	5.44	4.28	nan	4.33	3.83	nan	4.10 (0.32)	32.82
Fish and shellfish	nan	5.52	7.76	nan	4.86	nan	nan	6.14	nan	nan	nan	6.07 (0.62)	24.29
Seagrass	7.50	6.45	3.86	6.18	nan	nan	nan	nan	nan	nan	nan	6.00 (0.77)	24.00
Mangrove keys	4.84	4.06	7.11	3.26	nan	nan	1.67	nan	2.44	nan	nan	3.90 (0.79)	23.38
Beaches	nan	6.72	5.72	3.47	nan	2.80	nan	nan	3.24	nan	nan	4.39 (0.77)	21.95
Protected species	3.76	nan	nan	nan	5.48	nan	4.51	3.52	nan	nan	nan	4.32 (0.44)	17.27
Coral and hardbottom	7.53	4.93	nan	3.63	nan	nan	nan	nan	nan	nan	nan	5.36 (1.15)	16.09
Oyster reefs	5.09	nan	nan	5.64	nan	nan	nan	nan	nan	nan	nan	5.36 (0.27)	10.73
Inshore flats	4.36	nan	5.81	nan	nan	nan	nan	nan	nan	nan	nan	5.09 (0.72)	10.17
Mean state impact (se)	5.92 (0.57)	5.50 (0.54)	6.28 (0.59)	4.40 (0.49)	5.33 (0.57)	4.78 (0.67)	3.82 (0.67)	6.22 (1.58)	4.00 (0.77)	5.29 (1.45)	9.43 (-)		
Cumulative impact to state	53.24	43.97	37.66	30.77	21.33	19.11	19.11	18.67	16.01	10.57	9.43		

Table 4
Ecosystem *state* to *ecosystem service* interaction matrix. Each matrix element (a_{ij}) represents mean values across all respondents (see methods). Mean effect strength is the mean (±standard error (se)) of all values down a given row and mean state impact represents the mean values down each column. Cumulative effects or impacts represent the row or column sum.

From ecosystem state	To ecosystem service												
	Existence natural system	Pristine wilderness experience	Non-extractive recreation	Science and education	Aesthetic environ-ment	Historic and cultural resources	Protection from storms	Pollution treatment	Climate stability	Recreational fishing (EcoServ)	Commercial extraction (EcoServ)	Mean Effect strength (se)	Cumulative effect of state
Water column	9.07	8.53	8.74	5.93	7.96	nan	nan	6.13	5.20	7.57	nan	7.39 (0.51)	59.12
Coral and hardbottom	7.67	7.38	8.27	6.93	7.33	5.47	5.25	nan	nan	nan	7.20	6.94 (0.37)	55.50
Coastal wetlands	7.63	7.80	5.69	5.35	6.63	nan	7.09	5.50	6.20	nan	nan	6.49 (0.34)	51.89
Fish and shellfish	7.76	7.19	6.86	6.20	nan	5.38	nan	nan	nan	9.43	8.52	7.34 (0.52)	51.35
Seagrass	7.45	7.05	5.64	5.27	6.50	nan	5.76	5.45	5.73	nan	nan	6.11 (0.28)	48.85
Beaches	6.28	4.95	8.00	4.94	8.17	6.33	6.67	nan	nan	nan	nan	6.48 (0.49)	45.34
Marine birds	7.72	8.56	6.89	6.11	7.78	4.88	nan	1.61	nan	nan	nan	6.22 (0.89)	43.55
Mangrove keys	5.06	6.28	5.28	4.00	5.89	4.11	4.67	2.67	2.94	nan	nan	4.54 (0.41)	40.89
Protected species	7.14	6.90	5.95	7.33	6.22	4.57	nan	nan	nan	nan	nan	6.35 (0.42)	38.12
Oyster reefs	4.68	3.86	nan	4.49	nan	5.18	5.09	4.22	nan	nan	nan	4.59 (0.21)	27.53
Inshore flats	4.55	3.86	2.95	2.91	nan	nan	3.94	nan	2.14	nan	nan	3.39 (0.36)	20.35
Mean ecosystem service impact (se)	6.82 (0.45)	6.58 (0.50)	6.43 (0.54)	5.41 (0.39)	7.06 (0.30)	5.13 (0.27)	5.50 (0.42)	4.26 (0.73)	4.44 (0.80)	8.50 (0.93)	7.86 (0.66)		
Cumulative impact to ecosystem service	70.46	68.49	61.30	56.57	56.47	35.92	34.53	25.59	20.07	16.99	15.72		

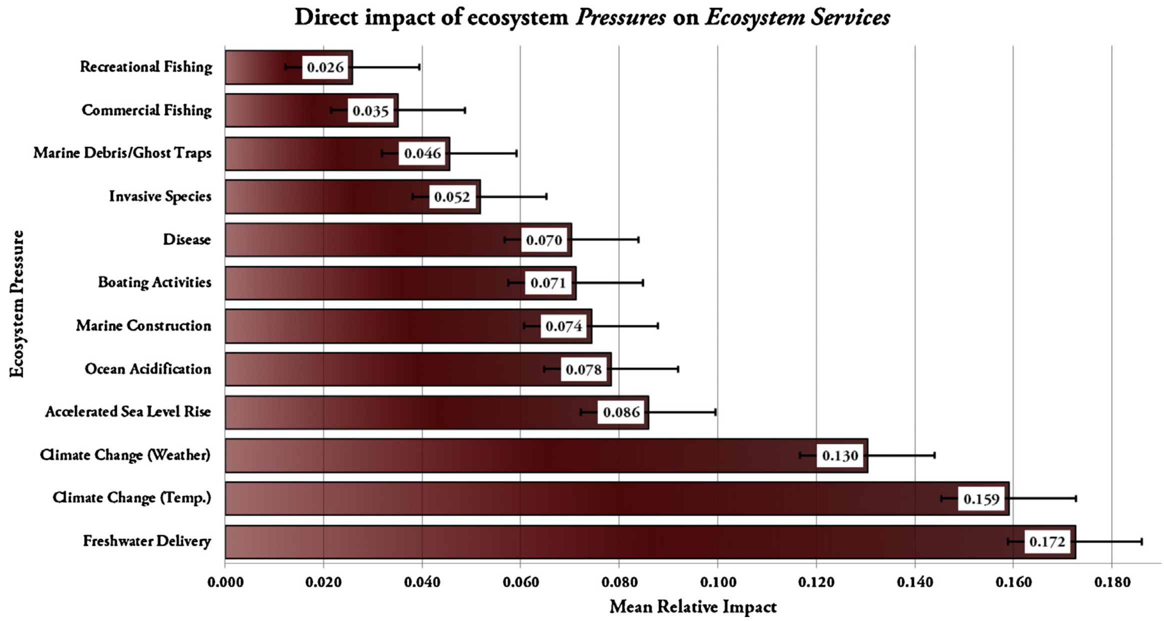

Fig. 2. Relative direct impact of ecosystem *pressures* to *ecosystem services*. Error bars represent standard error of mean impact of individual ecosystem *pressures* across all *ecosystem services*.

how much it was impacted by other *states*. *Protected species* had the lowest asymmetry score (0.39) suggesting it was impacted by other ecosystem *states* 2.6 times more than it impacted other *states*. *Inshore flats* and *seagrass* had the most symmetrical impact scores, 0.96 and 1.13 respectively, suggesting that their impact to/from other ecosystem *states* was similar in magnitude.

3.3. Ecosystem state to ecosystem service interactions

Of the 80 ecosystem *state* to *ecosystem service* interactions, the single largest impact was from the *state-fish and shellfish* to the *ecosystem service – recreational fishing* (9.4, Table 4); the lowest quantified impact was from *marine birds* to *pollution treatment* (1.6). The mean (±se) interaction strength among all 80 ecosystem *states* and individual *ecosystem services* was 6.0 (±0.2, Table 4). The mean effect of a single ecosystem *state* across all *ecosystem services* ranged from 3.4 (±0.4, *inshore flats*) to 7.4 (±0.5, *water column*). Cumulative *state* effects to *ecosystem services* ranged from 20.4 (*inshore flats*) to 59.1 (*water column*, Table 4); mean cumulative effect was 43.9 (±3.5). While having a relatively low cumulative *ecosystem service* impact (17.0), *recreational fishing* had the highest mean impact to *ecosystem services* (8.5 ± 0.9). *Pollution treatment* had the lowest mean *ecosystem service* impact (4.3 ± 0.7). The cumulative impact to each *ecosystem service* from all *states* ranged from 15.7 (*commercial extraction*) to 70.5 (*existence of a natural system*; Table 4).

3.4. Direct impacts of ecosystem pressures on individual ecosystem services

Direct relative impacts were quantified as the interaction strength of *pressures* to *states* that directly impact *ecosystem services* (i.e. excluding indirect interactions among the various ecosystem *states* quantified in Table 3). Within the study domain *freshwater delivery* and *climate change (temperature)* were the predominant ecosystem *pressures* impacting *ecosystem services* when *pressures* are quantified as a proportion of individual *ecosystem services* (Fig. 2). *Freshwater delivery* had the largest mean impact to individual *ecosystem services* (0.172 ± 0.008). This suggests that on average, *freshwater delivery* represents 17.2% of the total *Pressures* impacting each *ecosystem service*. The proportional direct impact of *freshwater delivery* to individual *ecosystem services* ranged from 0.13 (13% of *commercial extraction*) to 0.23 (23% of *pollution treatment*; Fig. 3); *climate change* (*temperature*) contributed between 12% (*historic and cultural resources*) and 18% of impacts to individual *ecosystem services* (*climate stability*, *commercial extraction*, and *recreational fishing*; Fig. 3). *Recreational fishing pressure* had the lowest mean relative impact across all *ecosystem services* (0.026 ± 0.01), but it had the 4th and 6th largest proportional impact on the provisioning *ecosystem services recreational fishing* (0.1) and *commercial extraction* (0.09; Figs. 2 and 3).

3.4.1. Direct impacts of ecosystem pressures on total ecosystem services

When individual *pressures* are viewed relative to all ecosystem *pressures* rather than their relative contribution to individual *ecosystem services* (Section 3.4), the relative impact of individual *pressures* to total system *ecosystem service* provisioning can be estimated (Fig. 4). The greatest proportional impact of a single ecosystem *pressure* to MARES *ecosystem services* was the impact of *freshwater delivery* to *existence of a natural system* (0.027). This single impact represents 2.7% of all *pressure* to *ecosystem service* interactions within the study domain (Fig. 4). Summed across *ecosystem services, commercial extraction* had the lowest aggregate impact from all *pressures* (0.033) while aggregate impacts to *existence of a natural system* represent 0.155 (i.e. 15.5%) of all impacts within the study domain (Fig. 5).

3.5. Indirect impacts of ecosystem pressures on individual ecosystem services

Relative indirect impacts were quantified in the same manner as direct impacts (above), but with an additional multiplicative step to account for proportional interactions among the various ecosystem *states*. For example, *beaches* account for 20.2% (3.24/16.01) of the cumulative impacts to *coastal wetlands* (Table 3). Similar to the direct impacts, *freshwater delivery* and *climate change (temperature)* had the greatest mean (±se) relative indirect impact on individual *ecosystem services*: 17.5% (±0.3%) and 16.8% (±0.2%), respectively. *Freshwater delivery* accounted for between 16.5% and 20.2% of the indirect impacts to each *ecosystem service*. The *ecosystempressures*

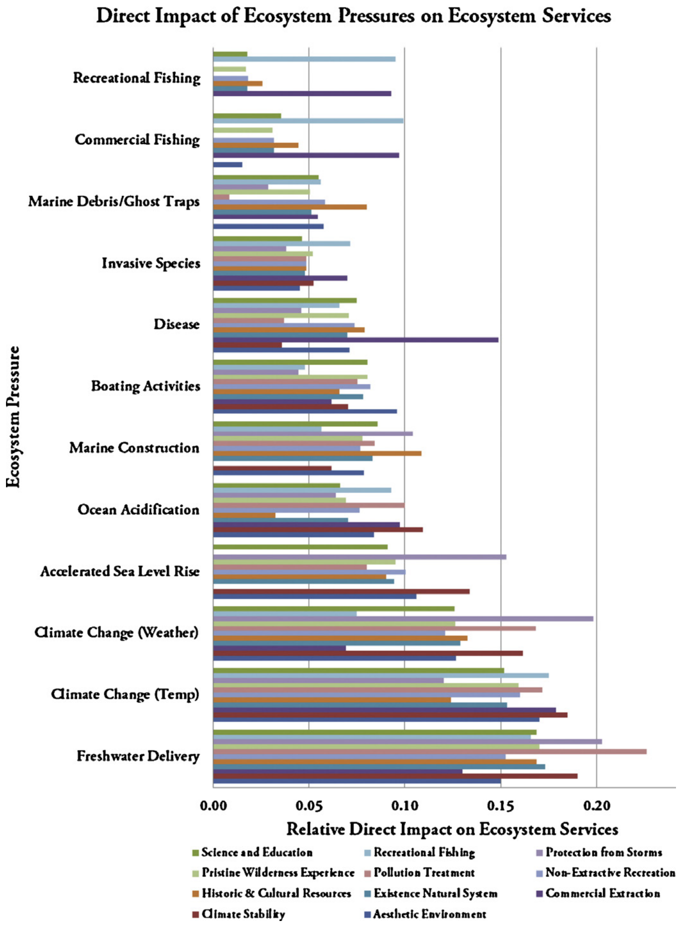

Fig. 3. Relative direct impact of ecosystem *pressures* broken down by individual *ecosystem services*. Values represent the proportional contribution of individual *pressures* to individual *ecosystem services*; summing across all 12 *pressures*, each *ecosystem service* sums to 1.

with the lowest relative indirect impact on *ecosystem services* were *commercial* (2.6% ± 0.3%) and *recreational fishing* (1.4% ± 0.2%; Fig. 6). The largest proportional indirect impact of an *ecosystem pressure* to an *ecosystem service* was *freshwater delivery* to *recreational fishing* (20.2%, Fig. 7). The ecosystem *pressure* – *recreational fishing* had the lowest individual indirect impact, 0%, on *recreational fishing* (the *ecosystem service*). While this result may seem counter-intuitive, there are no *indirect* impacts on the *ecosystem services* generated from *recreational fishing* opportunities because all of the impacts from recreationally harvested marine resources are *direct* impacts.

3.5.1. Indirect impacts of ecosystem pressures on total ecosystem services

When indirect *pressures* were scaled relative to their proportional impact to all *ecosystem services* in the study domain, the greatest indirect impact was from *recreational fishing* to *commercial extraction (ecosystem service)*. This single impact represents 1.4% of all possible indirect pressure to ecosystem service impacts within the study system. The *ecosystem service recreational fishing* received the lowest aggregate indirect impact across all ecosystem *pressures* (7.8%), while the greatest aggregate indirect impact was to *commercial extraction* (10.0%).

4. Discussion

One of the outstanding challenges with EBM is distilling the complexity of ecosystems, including human activities, and understanding how myriad ecosystem components interact with one another (Crain et al., 2008; Altman et al., 2011). Managers are in need of tools for identifying which pressures have the greatest cumulative effect on ecosystems, providing critical information necessary for prioritizing management actions (Game et al., 2013). To develop this body of knowledge will require the development and application of methods that quantify how various drivers and pressures interact with the components comprising ecosystems, which ultimately impact the provisioning of ecosystem services. In this study we adapted a matrix-based method to explore those *pressure–state–ecosystem service* interactions and highlight several critical interactions within the South Florida coastal ecosystem. Our analyses indicate multiple pressures impact the delivery of ecosystem services, but the relative magnitude of these interactions can differ by an order of magnitude. The single greatest *pressure* on an ecosystem *state* was *accelerated sea level rise* on *mangrove keys* (Table 2). Considering many *mangrove keys* are already inundated during local high water events, their continued ability to act as critical habitat for nesting birds, small mammals and reptiles, as well as providing nursery habitat for reef fishes is uncertain (Enos, 1989); the relative weight given to this *pressure* to ecosystem *state* interaction appears warranted.

When cumulative effects of individual *pressures* are considered relative to their impact on the 11 *ecosystem services* considered here, *freshwater delivery* represents the greatest direct and indirect *pressure* impacting *ecosystem services* within the study domain. The critical importance of freshwater delivery to Florida Bay estuaries, as highlighted in Everglades restoration plans and by this result, has been well-documented in numerous studies (e.g. see Hunt and Nuttle, 2007; Doren, 2009; Nuttle and Fletcher, 2013a, and references therein). When the cumulative impact of all *pressures* to individual ecosystem *states* was calculated we were able to identify *protected species*, *fish and shellfish*, and *coral and hardbottom* as the most impacted ecosystem States within our study system, suggesting the sustainability of these three *states* is most at risk (Table 2; Figs. 2 and 6; for in-depth discussion of these individual ecosystem *states*, please see companion papers in this issue).

In a similar manner, we assessed how various ecosystem *states* interact with one another. Individual relative impacts among ecosystem *States* ranged from as low as that of *mangrove keys* on *beaches* (1.7) to as great as the impact of the *water column* on *oyster reefs* (9.4; Table 3). However, like the relative impacts of *pressures* on *states*, the highest and lowest individual impacts viewed in isolation can be misleading. In the *state* to *state* interaction matrix, individual *states* may be directly impacted by other *states*, but they also may have a direct impact on those same *states*. *Oyster reefs* are impacted directly by a single *state*, the *water column*, and they in turn impact two other *states*, *fish and shellfish* and the *water column*; the cumulative value of all impacts to and from Oyster Reefs is 20.2. However, the single linkage between the *water column* and *oyster reefs* is a critical link. Relative to other *states*, *oyster reefs* face the lowest cumulative impact, but this also means if something were to happen to degrade the quality of the *water column*, there could be a direct negative impact on *oyster reefs*. Conversely, if management actions were to better the water quality within the ecosystem there could be a direct positive impact on Oyster populations. In comparison, *mangrove keys* have the single lowest impact to another *state* (1.7 on *beaches*) and the lowest mean effect on other *states* (3.9 ± 0.79), but they have a cumulative impact of 42.5 because they interact with ten other ecosystem *states* (Table 3). Therefore, the four possible *states* impacting *mangrove keys* (*water column*, *coastal wetlands*, *marine birds*, and *beaches*) or the six *states* possibly impacted by *mangrove keys* (*fish and shellfish*, *protected species*, *marine birds*, *water column*, *beaches*, and *coastal wetlands*) act to dilute any single impact by dissipating and re-distributing that impact across many other ecosystem *states*, lessening the

Fig. 4. Relative direct impact of individual *pressures* to *ecosystem services* scaled by all *pressures* within the ecosystem (i.e. together all 12 sub-plots sum to 1). Area of coloured region represents relative magnitude and distribution of *pressures* impacting various *ecosystem services* in the study region. Please note, *climate change* (temp.) and *freshwater delivery* are plotted on larger scales (max value = 0.03) than other sub-plots (i.e. max value = 0.02).

relative per-*state* impact to or from this ecosystem component. However, there is also a negative side to having a relatively high degree of connectivity with other ecosystem *states*. If a deleterious impact occurs in one of the connected ecosystem states, there is the possibility this negative impact, albeit dissipated in magnitude, could be "transmitted" to other connected ecosystem *states*. When cumulative impacts are summed across all possible *state* to *state* interactions, the *water column* has the greatest number of interactions (16) as well as the greatest cumulative to and from impact (96.1), suggesting its critical importance to the overall functioning of the ecosystem. *Fish and shellfish* had the highest cumulative impacts from other *states* followed by *protected species* (Table 3). This dependence on other ecosystem *states* indicates a greater susceptibility to ecosystem level changes, suggesting *fish and shellfish* and *protected species* have the highest risk of perturbation which could lead to an undesirable condition.

The magnitude of the row sums in the *state-to-state* interaction matrix (Table 3) provides the ability to compare the degree to which individual *states* act as a drivers of change within the ecosystem; the greater the magnitude, the greater the relative effect of a *state*

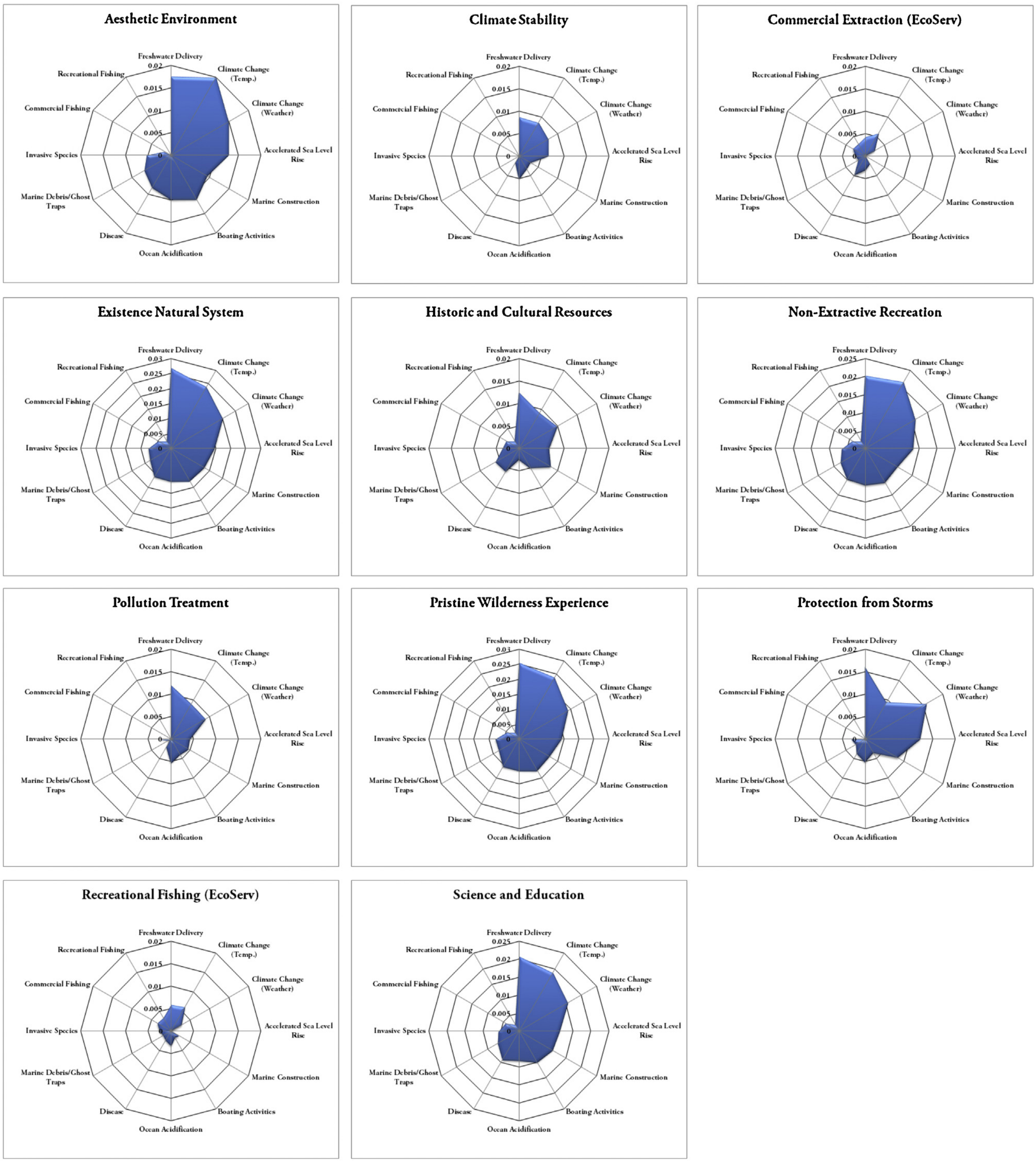

Fig. 5. Relative direct impact to individual *ecosystem services* by *pressures* scaled by magnitude of all *pressures* within the ecosystem (i.e. together all 11 sub-plots sum to 1). Area of coloured region represents relative magnitude and source of *pressures* impacting various *ecosystem services* in the study region. Please note different scales in sub-plots; *existence of a natural system* and *pristine wilderness experience* max value = 0.03, *non-extractive recreation* and *science and education* max value = 0.025, for all other subplots max value = 0.02.

on other *states*. The magnitude of the column sums indicates the degree to which a *state* is impacted by other *states*. The asymmetry between the effect caused by a given *state* (i.e. the row sum) and the impact to that same *state* from other ecosystem *states* (i.e. the column sum) provides an indication of how susceptible individual *states* are to impact. For example, the asymmetry between the number of *states* being impacted by the water column (i.e. 9) and *states* impacting the *water column* (i.e. 7) was similar (Asymmetry = 9/7 = 1.3). However the asymmetry in the magnitude of those same interactions was greater (2.12). When impact asymmetry is viewed by magnitude, the *water column* had the greatest asymmetry value, while *coastal wetlands* had the second highest asymmetry score (2.11). Asymmetry values suggest that within the study domain *coastal wetlands* and the *water column* are less susceptible to impacts from other *states* relative to their effect upon the other *states*. *Protected species* and *fish and shellfish* are most susceptible to impacts from other ecosystem *states* relative to their effect upon other *states* (asymmetry = 0.39 and 0.46, respectively).

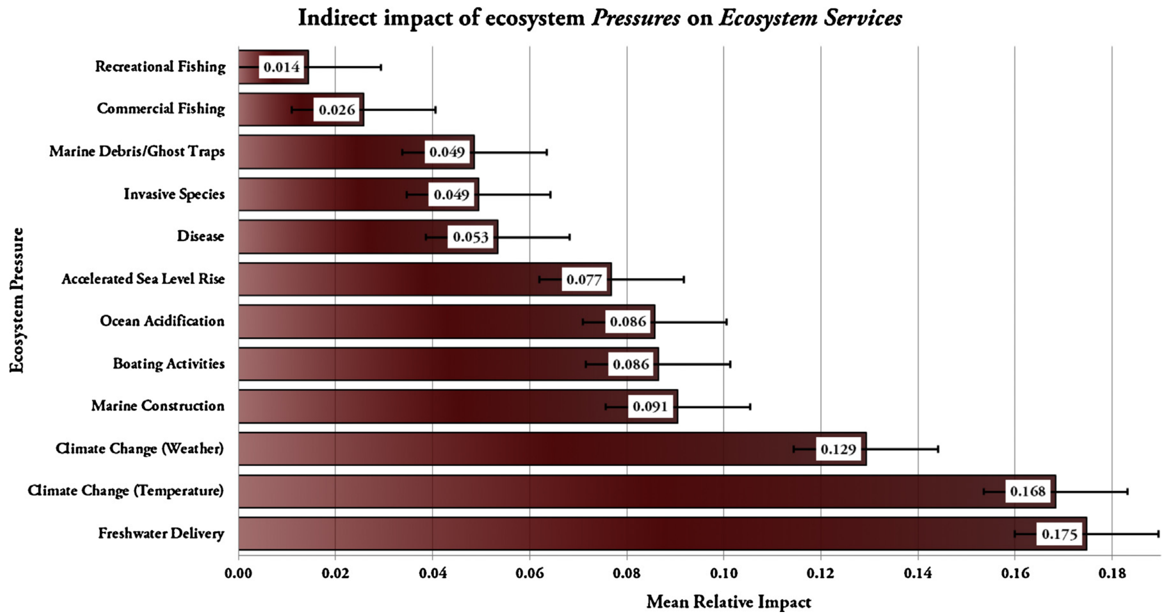

Fig. 6. Relative indirect impact of ecosystem *pressures* to *ecosystem services*. Error bars represent standard error of mean indirect impact of individual ecosystem *pressures* across all *ecosystem services*.

The few studies that have investigated the connection between ecosystem *states* and *services* have focused primarily on how individual *state* components, such as habitat types, provision *ecosystem services* (e.g. Halpern et al., 2008a,b; Stelzenmuller et al., 2010; Teck et al., 2010; Altman et al., 2011; Grech et al., 2011; Hutchinson et al., 2013). In this study the matrix showing the connection between all ecosystem *states* and *services* (Table 4) suggests that multiple ecosystem *states* contribute to the provisioning of each *ecosystem service*. The cumulative *ecosystem service* impact score in conjunction with how many *states* contribute to each *ecosystem service* provides a greater understanding of the magnitude to which provisioning depends on a holistic, integrated ecosystem rather than individual *states* comprising the ecosystem. The number of *states* contributing to an *ecosystem service* ranges greatly. The *services commercial extraction* and *recreational fishing* are provided by only two *states*, while *pristine wilderness experience*, *existence of a natural system*, and *science and education* are provided by all 11 *states*. The mean number of ecosystem *states* contributing to individual *ecosystem services* was 7.3 ($\pm$1.0). This finding suggests that the provisioning of *ecosystem services* within the study domain, with the possible exceptions of *recreational fishing* and *commercial extraction*, is dependent on an integrated ecosystem, and their continued provisioning depends on the ecosystem continuing to function as a whole.

The matrix of the interaction strength between ecosystem *states* and *services* also provides a tool for understanding how individual *states* contribute to the provisioning of *ecosystem services*. When the impact of individual *states* is viewed as a function of their impact upon *ecosystem services* we can begin to rank the relative importance of individual *states* to the provisioning of *ecosystem services*. Each of the ecosystem *states* contributed to the provisioning of between six and nine *ecosystem services*. *Mangrove keys* contributed to the greatest number of *ecosystem services* (9); however it had the second lowest mean contribution (4.5 $\pm$ 0.4). The *water column* and *coral and hardbottom* had the greatest cumulative contributions to *ecosystem services* (59.1 and 55.5, respectively; Table 4), while *oyster reefs* (27.5) and *inshore flats* (20.35) had the lowest cumulative contributions to *ecosystem services*. This would suggest that management efforts such as improving the quality of the *water column* or protecting benthic habitats comprising *coral and hardbottom* would provide a greater benefit to the overall provisioning of *ecosystem services* within the study region. An additional factor to consider when ranking the value of ecosystem *states* is areal extent. *beaches*, *oyster reefs* and *inshore flats* have a critical ecological role and form necessary habitat for numerous species within the MARES domain (Nuttle and Fletcher, 2013a,b), but when compared with the areal extent of the *water column* they are relatively sparse, contributing to their lower overall rank within the study region.

However, while each of the above interactions (i.e. *pressure* to *state*, *state* to *state*, and *state* to *ecosystem service*) capture the individual impacts of various ecosystem components on one another, they fail to account for the variety of direct and indirect pathways by which a given pressure may impact the provisioning of a particular *ecosystem service*. By tracing the flow of individual *pressures* as mediated through the various ecosystem *states* we were able to quantify the relative direct impact of individual *pressures* to individual *ecosystem services* (Figs. 4 and 5) as well as generate rankings of the relative risk caused by individual *pressures* to *ecosystem services* (Figs. 2 and 6). When cumulative *pressures* are viewed broadly and in terms of the things people care about, we can identify the greatest contributors to *ecosystem services*. Within the study domain, as was previously mentioned, *freshwater delivery* had the greatest direct impact; negative alterations in *freshwater delivery* represent the greatest risk to continued provisioning of *ecosystem services* within the South Florida coastal ecosystem. Given the critical importance of freshwater flow within the Everglades ecosystem (Doren, 2009 and references therein), this result is not surprising. The greater Everglades is rainfall-driven; alterations in the hydrological properties and patterns in the upstream portions of the Everglades has important implications for the health of downstream coastal regions comprising the MARES domain, and their ability to provide *ecosystem services* (Rudnick et al., 1999; Sklar et al., 2005).

When direct and indirect impacts of individual ecosystem *pressures* were assessed the magnitude of direct impacts was (owing to the multiplicative nature of the matrix analyses) an order of magnitude greater than indirect effects. Because of this, comparing the magnitude of direct and indirect impacts is of limited utility; a more useful comparison is made by exploring the relative

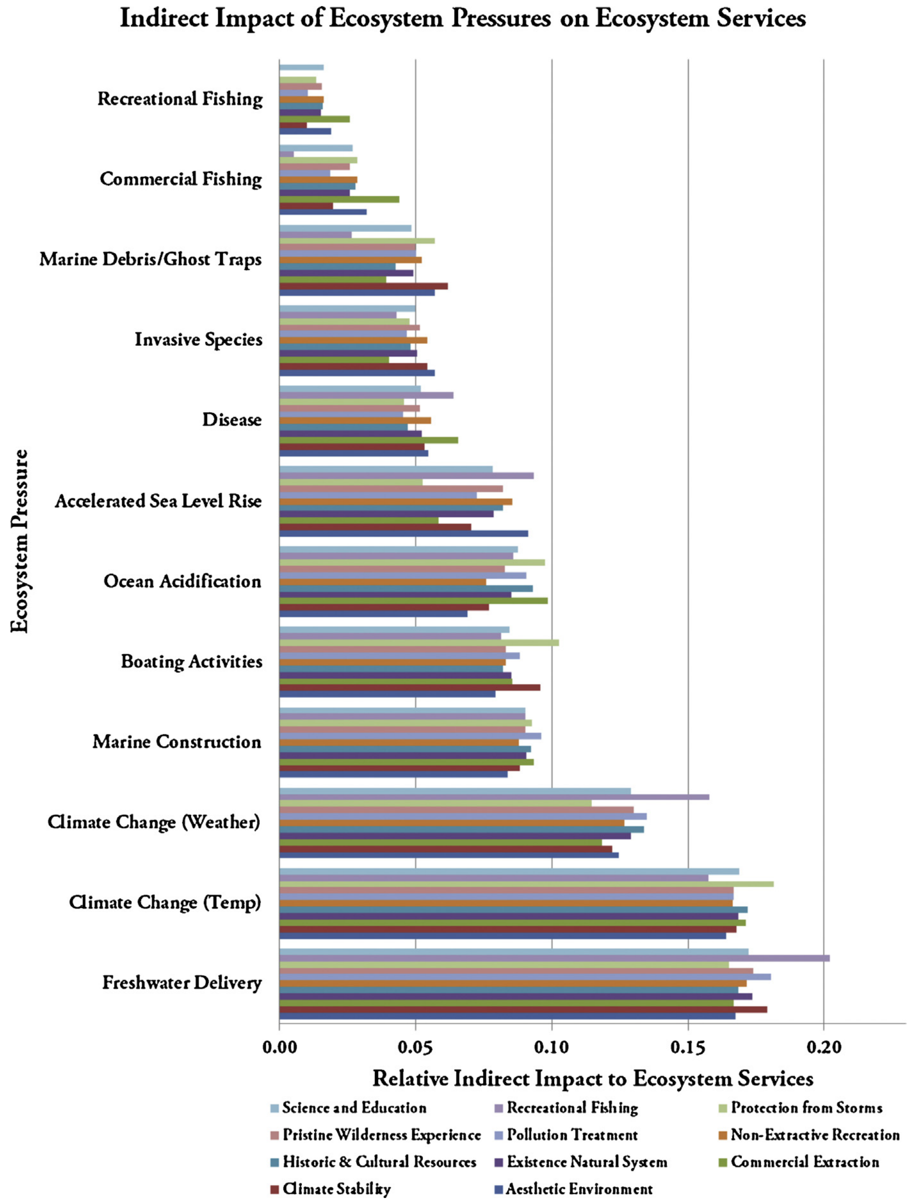

Fig. 7. Relative indirect impact of ecosystem *pressures* broken down by individual *ecosystem services*. Values represent the proportional contribution of individual *pressures* to individual *ecosystem services*; summing across all 12 *pressures*, each *ecosystem service* sums to 1.

rankings generated from these results. In each of the assessments, the top three *pressures* were (1) *freshwater delivery*, (2) *climate change (temperature)*, and (3) *climate change (weather)*. The three lowest ranking direct and indirect *pressures* were also the same; the bottom two *pressures*, *commercial fishing* and *recreational fishing*, present the lowest risk of impact to *ecosystem services* (Figs. 2 and 4). Throughout the study domain there is limited commercial extraction (e.g., lobster, sponge, and shell collecting), so *commercial fishing* ranking lower is perhaps not surprising; a more surprising result is that of *recreational fishing*. Recent studies have suggested *recreational fishing*, fishing activities conducted by individuals for sport or leisure, can result in decreases in fish stocks which in turn may impact entire ecosystems (Jackson et al., 2001; Coleman et al., 2004; Cooke and Cowx, 2006). In 2011, estimates suggest between 24 and 57 million recreational fishing trips occurred in the state of Florida (US Dept of Commerce, 2012; US Dept of the Interior, 2013). From these data a plausible a priori hypothesis would have been that *recreational fishing* was one of the larger *pressures* within the region, and its inclusion in this study suggests that regional experts consider it an important *pressure* within the study region. However, when the *pressure* generated by *recreational fishing* is viewed in the broader context of the entire South Florida coastal marine ecosystem and relative to the arguably more pervasive *pressures* such as *climate change* and *accelerated sea level rise*, the relative impact of *recreational fishing* becomes greatly diminished.

Resource managers are asked frequently to make decisions having less than perfect knowledge of system behaviour, where data availability is low and scientific uncertainty high (Game et al., 2013). In these situations, benefits and costs of various management actions are asymmetric; costs are direct and immediate to one group of stakeholders, while the generation of benefits to others is more diffuse and protracted (Cook and Heinen, 2005). The information and methodology provided here can be used as a tool to better inform these kinds of decisions and to target the impact of management actions. For example, there are numerous management actions aimed at lessening damages, whether perceived or real, caused by recreational fishing activities. As a first order approximation of putative risk to ecosystem services caused by various impacts, visual results generated from this study suggest recreational fishing pressure has relatively minor interactions with relatively few ecosystem services (Fig. 4). When relative impacts from the various pressures are displayed by their relative impact on individual ecosystem services (Fig. 5), it can be seen that effective management actions should target those pressures with relatively large and pervasive impacts (e.g. freshwater delivery). More specifically our results suggest that within the study domain the lowest cumulative *pressure* is caused by *recreational fishing*. The proportion of *pressure* attributable to *recreational fishing* activities represents ~17% of the total impact to *fish and shellfish* (Table 2). Additionally, the pressure *recreational fishing* contributes 10% of the *ecosystem service recreational fishing* and 9% of the *ecosystem service commercial extraction* (Fig. 3). Therefore, management actions aimed at reducing the impact of *recreational fishing* pressure to increase overall *ecosystem service* production will have a direct and immediate impact on those participating in recreational fishing, but this action will have limited effectiveness at improving the overall level of *ecosystem services* provided by the South Florida coastal ecosystem. On the contrary, management efforts aimed at bettering *freshwater delivery* will generate higher relative returns to all user groups by having the greatest relative impact across all *ecosystem services*, including the *ecosystem service – recreational fishing*. In this way, managers can, through a relatively transparent process, identify trade-offs among possible management actions and better guide the decision-making process.

5. Conclusions

This matrix-based exploration of the relative impacts of ecosystem *pressures* to ecosystem *states* and *services* has identified several critical interactions within a portion of the South Florida coastal ecosystem. When considering direct and indirect *pressures*, *freshwater delivery* is the greatest threat to the continued provisioning of *ecosystem services* within the entire system, while *recreational fishing* represents the *pressure* with the lowest impact. The broader public relies upon the sustainability of the entire suite of *ecosystem services* considered here, but the continued provisioning of these *services* will require wise stewardship and management of the ecosystem *states* and *pressures* which impact the continued flow of these *services*. For resource managers tasked with protecting the coastal environment in this region, our findings provide an approach for understanding the relative susceptibility of individual *state* components comprising the greater marine ecosystem and can be used to suggest and guide strategies for managing the *pressures* under consideration. However, the effective management of coastal marine environments necessitates a broader acceptance of holistic management strategies. To achieve this acceptance will require an understanding of the trade-offs that occur among different user groups of the region and the use of transparent mechanisms, such as the method presented here, during the decision-making process. By highlighting management actions that minimize the costs to individual user groups, while optimizing the benefits to other user groups, we can begin to provide examples of the successful implementation of marine ecosystem based management strategies. Ultimately, this can help increase the acceptance and understanding of EBM among the broader public and improve our ability to sustainably manage and conserve the marine environment.

Acknowledgements

We would like to thank all those individuals and agencies involved in the MARES process. We would like to also thank two anonymous reviewers and Peter Ortner and Joe Boyer for constructive comments on an earlier draft of this manuscript. This work was made possible with support from the University of Miami, Cooperative Institute for Marine and Atmospheric Studies; the National Oceanographic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory; and the University of Florida, Florida Sea Grant.

Appendix A. Definitions of ecosystem components used in study

Appendix A1. Ecosystem *pressures*

Ecosystem *pressure*	Definition
Accelerated sea-level rise	The anticipated increase in the rate of sea-level rise
Boating activities	Damage that occurs due to boating activities, does not include fishing
Climate change (temperature)	Deviations from typical/historical seasonal temperature patterns in air and/or water
Climate change (weather)	Changes in weather patterns that are anticipated to occur as a result of climate change
Commercial fishing	Harvesting of living marine resources to sell for commercial purposes
Disease	A disorder of structure or function in a human, animal, or plant, esp. one that produces specific signs or symptoms or that affects a specific location and is not simply a direct result of physical injury
Freshwater delivery (to estuaries)	Quality, quantity, timing, and distribution of freshwater flow from rivers, canals, stormwater drains, and wastewater to estuaries; includes land-based sources of pollution
Invasive species	Non-native species that threaten ecosystems, habitats or species
Marine construction	Construction that takes place within or adjacent to the marine ecosystem
Marine debris/ghost traps	Anthropogenic materials discarded or left/lost in the marine environment
Ocean acidification	As CO_2 levels increase in the ocean the pH and aragonite saturation state are lowered
Recreational fishing	Any harvest of marine resources for recreation or personal consumption, not commercial sale

Appendix A2. Ecosystem *states*

Ecosystem *state*	Definition
Beaches	Sandy shorelines from the dune zone to the offshore edge of the surf zone
Coastal wetlands	The saltwater zone on the mainland that is landward of the coastal margin, which includes marshes, flats, mangroves and the intermittent creeks in these areas.
Coral & hardbottom	Structures made from calcium carbonate secreted by corals and the limestone platform covered by a thin layer of sediments with a sparse mixture of stony and soft corals, macroalgae, and sponges
Fish and shellfish (excluding oysters)	Fish and shellfish (other than oysters) that are hunted by commercial and recreational fisheries or protected by management; and the prey species required to support them
Inshore flats	Flat bottom, sub- or intertidal habitats that lack epifaunal oyster or sea grass and are located inside the outer coastal margin
Mangrove keys	Mangrove islands located in both the populated Florida Keys and the unpopulated islands found within Florida Bay
Marine birds	All bird species that are dependent upon the marine ecosystem for habitat or prey
Oyster reefs	Reef structure developed by oysters (e.g. *Crassostrea virginica*)
Protected species	All marine species protected by the Endangered Species or similar Act that are not fish
Seagrass	Submerged areas dominated by rooted, aquatic, vascular plants
Water column	The physical, chemical and biological characteristics of the water column, including suspended benthic sediment, phytoplankton, and zooplankton

Appendix A3. Ecosystem services

Ecosystem services	Definition
Aesthetic environment	The experience of sensing the marine environment
Climate stability	The ability of the environment to buffer changes in climate through feedback loops
Commercial extraction	Harvesting of living or non-living marine resources to sell for commercial purposes
Existence (of a) natural system	The benefit derived from knowing a particular environment exists, although you may never actually experience it; also the benefit of leaving a natural environment to future generations
Historic and cultural resources	Resources that are important to the local culture or represent the history of the local community
Non-extractive recreation	Recreation that does not include recreational fishing or attempting to experience pristine wilderness
Pollution treatment	The reduction of pollutant concentrations that occur within the natural environment
Pristine wilderness experience	The benefit of experiencing an environment with minimal disturbance by humans
Protection from storms	The buffer from storm surge and damage provided by the natural environment
Recreational fishing	The ability to harvest marine resources for recreation or personal consumption, not commercial sale
Science and education	Education of all people, the resources and environment to undertake scientific discovery

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