Ecosystem-based management for military training, biodiversity, carbon storage and climate resiliency on a complex coastal land/water-scape

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A B S T R A C T

The Defense Coastal/Estuarine Research Program (DCERP) was a 10-year multi-investigator project funded by the Department of Defense to improve understanding of ecosystem processes and their interactions with natural and anthropogenic stressors at the Marine Corps Base Camp Lejeune (MCBCL) located in coastal North Carolina. The project was aimed at facilitating ecosystem-based management (EBM) at the MCBCL and other coastal military installations. Because of its scope, interdisciplinary character, and duration, DCERP embodied many of the opportunities and challenges associated with EBM, including the need for explicit goals, system models, long-term perspectives, systems complexity, change inevitability, consideration of humans as ecosystem components, and program adaptability and accountability. We describe key elements of this program, its contributions to coastal EBM, and its relevance as an exemplar of EBM.

1. Introduction

Although the phrase "ecosystem-based management" first appeared in the literature about 30 years ago, ecologists have been advocating most of its fundamental elements for nearly a century (Grumbine 1994). These elements included a focus on entire communities of organisms rather than single species, attention to spatial relationships, and management for natural disturbance and the changes it produces (e.g., Leopold 1941; 1949; Shelford 1933; Watt 1944). Over this same period, ecologists called attention to the arbitrary boundaries of most management jurisdictions relative to the scale of key ecosystem processes and need for cooperation across those boundaries (e.g., Shelford 1933). Today, ecosystem-based management (EBM) is an explicit goal for a variety of public agencies and private organizations.

The U.S. Department of Defense (DoD) has committed to implementing EBM at all military installations (Goodman 1996; Kendall 2013), which represent the wide variety of ecosystems across the United States. Most installations contain an urbanized cantonment area and training/testing areas that are a mix of heavily disturbed areas and areas maintained in a natural or semi-natural state (Demarais et al., 1999). Training ranges are cleared areas whose vegetative cover differs significantly from the historical. Nevertheless, large portions of many installations harbor native communities and have become refugia for threatened and endangered species (Warren and Büttner 2008; Stein et al., 2008).

Like all federal agencies, the DoD must meet environmental

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regulatory standards (e.g., water and air quality) and laws (e.g., the National Environmental Policy Act and the Endangered Species Act). However, the military mission also depends on conservation of natural ecosystems and their key ecological processes to provide training realism (Stein 2008). Coastal military installations are increasingly impacted by encroachment from surrounding areas, climate change and sea-level rise (SLR, Ratcliff and McKee Smith 2011). These changes complicate implementation of EBM and compliance with environmental regulations (e.g., Nilsson and Bohman 2015).

DoD has provided technical guidance to all military installations world-wide on how to project SLR scenarios out through 2100 (see Parris et al., 2012) to ensure comparability across installations and regions. Similar guidance from DoD on other climate change effects (DoD, 2019) was recently released for military installations across all regions of the United States that discussed recurrent flooding, droughts, desertification, wildfires, and thawing permafrost and their potential impacts for consideration by military installations.

Marine Corps Base Camp Lejeune (MCBCL) occupies over 62,000 ha in eastern North Carolina (Fig. 1). MCBCL's biologically diverse terrestrial, estuarine, wetland and coastal barrier island ecosystems are critical to the mission of military training and readiness, and they provide essential ecosystem services to the installation and surrounding communities.

The Defense Coastal/Estuarine Research Program (DCERP) was a 10-year (2007–2017) integrated program of basic and applied research on the natural MCBCL ecosystems. It was funded and overseen by the DoD's Strategic Environmental Research and Development Program (SERDP) and its goal was the development of conceptual and mechanistic models to help guide EBM at MCBCL. The program consisted of 19 discrete research projects that were distributed among four ecosystem modules: Aquatic/Estuarine (rivers, creeks, and estuary), Coastal Wetlands (salt and brackish marshes), Coastal Barrier (island), and Terrestrial (pine and hardwood forests). To support the needs of these research projects, an additional research project focused on the development of uniform historical and projected patterns of climate change for this region. The goals and methods for each of these projects are presented as supplementary materials (Research Project Goals and Methods).

During its first five years, DCERP established a basic monitoring and research program to improve the understanding of ecosystem function, structure, and condition and their interactions with natural and anthropogenic stressors, with an emphasis on military training impacts. Carbon and climate were central foci of the program during the final five years. Coastal carbon cycle studies focused on evaluating tradeoffs between carbon management and other management decisions (Crosswell et al., 2017; Davis et al., 2017; Czapla et al., 2020b: Gold et al., 2020). Other studies evaluated how climate change would affect various ecosystem processes (Anderson et al., 2014; McTigue et al., 2019; Paerl et al., 2014; Rodriguez et al., 2018).

Because of its interdisciplinary, multi-ecosystem character, the DCERP was an exemplar of many of the elements and challenges associated with EBM. It was guided by the National Ocean Policy (Lubchenco and Sutley 2010) definition of EBM:

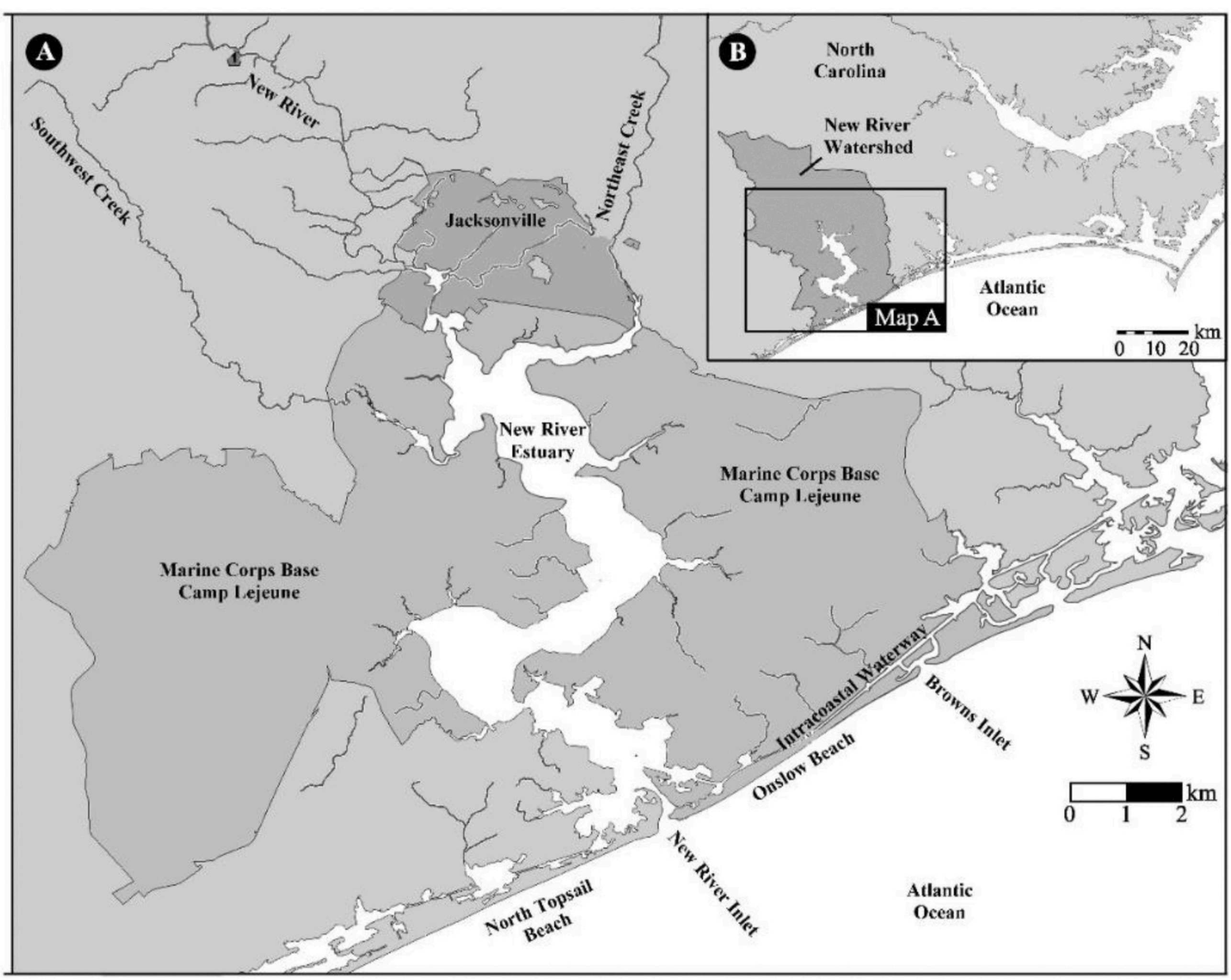

Fig. 1. Map of Marine Corps Base Camp Lejeune and surrounding environments.

“EBM is an integrated approach to resource management that considers the entire ecosystem, including humans. It requires managing ecosystems as a whole instead of separately managing their individual components or uses. EBM considers all the elements that are integral to ecosystem functions and accounts for economic and social benefits as well as environmental stewardship concerns. It also recognizes that ecosystems are not defined or constrained by political boundaries. The concept of EBM is underpinned by sound science and adaptive management as information or changing conditions present new challenges and opportunities.”

Explicit operational goals and models that connect ecosystem function to human activities and ecosystem services are prerequisites for EBM (Lee 1993). Successful EBM implementation depends on six principles. These are; 1) long-term perspectives are essential, 2) diversity and complexity matter, 3) boundaries and context must be understood, 4) ecosystem change is inevitable and necessary, 5) humans are ecosystem components, and 6) successful management depends on adaptability and accountability (Christensen et al., 1996). Below, we use these prerequisites and principles to describe the challenges and key findings of this program.

Several papers have addressed important challenges to successful EBM implementation (e.g., Yaffee 1999; Curtice et al., 2012; DeFries and Nagrenda 2017). Four challenges stand out. 1. Systems approaches imply cross-jurisdiction problem solving that is often in conflict with organizational hierarchy. 2. Long-term monitoring and research objectives often are not consistent with agendas set by administrative cycles (i.e., fiscal years, electoral cycles, changing military commanders). 3. Decision support tools for implementing EBM must be accessible and reliable. 4. Adaptive management acknowledges uncertainty and implies risk taking. We discuss these challenges in the context of the development and execution of DCERP in this paper’s conclusions.

1.1. Explicit goals and models are prerequisites to EBM

MCBCL’s mission is military preparedness. EBM is predicated on *measurable* goals that specify future processes and outcomes necessary to accomplish that mission (Christensen et al., 1996). Working with MCBCL managers, such goals were articulated for each ecosystem module (Table 1). In many cases, these goals corresponded to federal or state regulatory requirements such as water quality standards and recovery of endangered species populations. In other cases, goals were defined in terms of the ecosystem conditions necessary to sustain the military mission such as sustaining the barrier island to support amphibious training and the terrestrial forest structure needed for combat training. We also explored the potential impacts of climate change (warming, altered precipitation amounts and patterns) and SLR on the ability of MCBCL to achieve its training mission. Currently, the DoD has no programs in place to manage carbon storage and emissions at its installations. However, we were asked to explore the potential for such management at MCBCL and its potential synergies or tradeoffs regarding EBM goals.

Table 1
Primary goals for ecosystem based management at the marine corps base camp lejeune (MCBCL), North Carolina.

Ecosystem	Key MCBCL Management Goals[a]
Aquatic/ Estuarine	Ensuring that MCBCL supports continued military training use of the New River, the New River Estuary, and Onslow Bay, while complying with the Clean Water Act (CWA)
Coastal Wetlands	Preserving the integrity of the amphibious maneuver areas, including Onslow Bay, the New River, and the adjoining training areas
Coastal Barrier	Preserving the integrity of the amphibious maneuver areas, including Onslow Bay, the New River, and the adjoining training areas and airspace of MCBCL and Ensuring that MCBCL supports all required military training activities, while complying with the Endangered Species Act (ESA) and other wildlife requirements
Terrestrial	Enhancing future training uses of MCBCL ranges, training areas, and Ensuring that MCBCL supports all required military training activities, while complying with the ESA and other wildlife requirements

[a] These goals come from the MCBCL’s Integrated Natural Resources Management Plan (MCBCL, 2006). Specific objectives were developed for each goal based on discussions between DCERP researchers and MCBCL managers.

Lee (1993) argued that EBM must be informed by models that describe our best understanding of how managed ecosystems work, including human impacts. Computer models of various kinds and complexity were central to each research project; however, Lee was referring to conceptual models that depict interconnections among a complex set of ecological and social variables across multiple temporal-spatial scales. Furthermore, managers must acknowledge that such models are incomplete and potentially flawed (Lee 1993). We used an overarching conceptual model of the MCBCL ecosystem to describe its complexity, organize research, and facilitate collaboration among projects (Fig. 2). This overarching conceptual model allowed the research team to visualize complex relationships among the processes and stressors associated with each of the systems and to identify where these processes were interconnected across media boundaries. Similarly, more detailed conceptual models were developed for each of the four ecosystem modules. The logic model used to communicate our science-based findings to multiple audiences and stakeholders is provided in supplementary materials (Logic Model). Funding limitations dictated that not all processes or stressors could be studied; however, these conceptual models were helpful in prioritizing activities to address MCBCL’s most critical management concerns, informing research objectives associated with the ecological processes selected for study, and enhancing communication between managers and researchers.

1.2. Long-term perspectives are essential

Sustainable EBM requires long (intergenerational) time horizons (e.g., World Commission on Environment and Development 1987). Our research program was designed to address MCBCL’s long-term management goals. Nevertheless, selection of appropriate timeframes for each module were complicated by differences in the spatial and temporal dynamics of each ecosystem. To understand the processes within and among the various ecosystem modules, environmental measurements must be made in ways that allow for connections among the modules. For example, before implementation of the monitoring and research program to study carbon flux, researchers harmonized sampling methods to ensure that data were collected at the appropriate frequencies and spatial scales, and that measurement units were compatible across all projects to yield comparable results. Time spans for various carbon measurement and modeling activities also varied among the ecosystems and research goals. Intervals between data points varied from minutes in the estuary to seasonally in the coastal marshes to decades for the forest landscape, through millennia for the barrier island. Rectifying timescales was especially challenging for the development of a carbon budget for the estuary; hourly, daily and seasonal measurements were required to establish long-term baseline trends in carbon flux in the context of episodic events such as major storms that bring terrestrial sediments to the estuary (Crosswell et al., 2017). To detect change in trends and determine the cause of the change, measurements need to be collected over a long period of time with the same methods and frequency. This difference in timescales was a challenge for communication and data transfer among ecosystem modules, just as it is a challenge for implementation of EBM at active military installations.

1.3. Diversity and complexity matter

Biodiversity is important to the sustainability of ecosystem processes and services in each of the MCBCL ecosystems (e.g., Tilman et al., 2014. Its relevance to the MCBCL military mission is best exemplified by

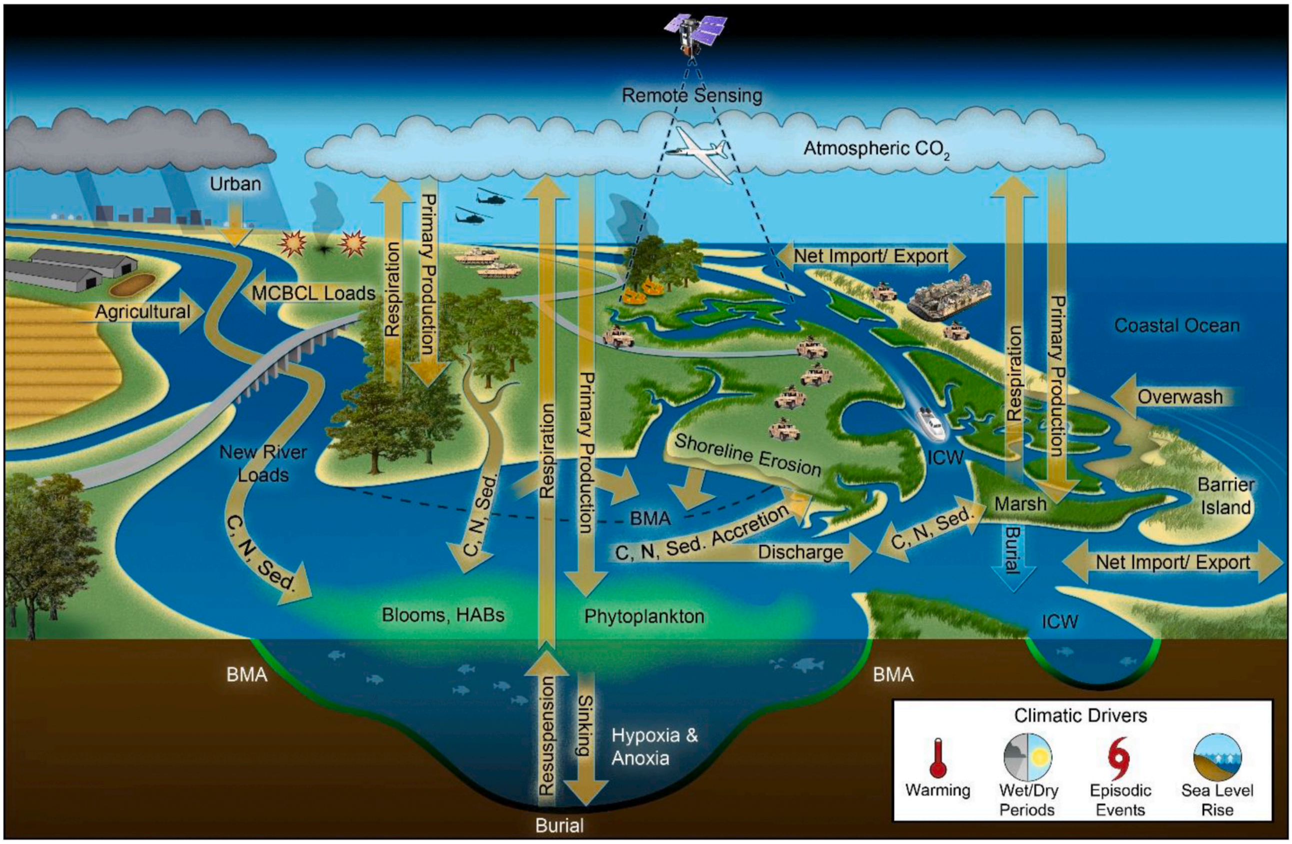

Fig. 2. DCERP conceptual model developed for Marine Corps Base Camp Lejeune ecosystems. C = carbon; N = nitrogen; Sed = sediment; HABs = Harmful Algal Blooms; BMA = Benthic Microalgae; ICW= Intracoastal Waterway.

management of the forests and barrier island for federally endangered species. For example, the red cockaded woodpecker (RCW, *Picoides borealis*) depends on complex structure and diversity of longleaf pine forests maintained by fire (Fig. 3). The Terrestrial Module focused on management strategies to restore and enhance RCW habitat, enhance carbon storage, as well as maintain conditions suitable for military training. The results of field studies and model simulations informed MCBCL management prescriptions to meet these goals (Mitchell et al., 2015; Walters et al., 2017). Furthermore, such management was shown to be ideal for maintaining overall avian species diversity (Walters et al., 2013).

1.4. Boundaries and context are always a challenge

Management and research boundaries are often poorly aligned with the spatial domains of key ecosystem processes. Arbitrary boundaries represent an important challenge for research and management of estuarine nutrient cycles and productivity. Although MCBCL occupies 85% of the estuarine shoreline, it has little control over the riverine portion of the watershed that dominates nutrient inputs to the estuary. DCERP studies revealed that 64% of estuarine nitrogen comes from off-Base agricultural, urban and suburban sources, and only 15% comes from MCBCL's land runoff and wastewater treatment facility (WWTF) (Fig. 4). The predominance of nonpoint nutrient sources in the watershed creates a strong relationship between nutrient loading and changes in river flow (Hall et al., 2013). In the context of an increasing frequency of flood-inducing, high precipitation events in the region (Paerl et al., 2019), elevated nutrient runoff will likely exacerbate water quality problems associated with excessive phytoplankton production.

Although MCBCL currently is not now a major source of the plant growth-limiting nutrient nitrogen, projected population increases and associated land use changes both on- and off-Base coupled with changing climatic conditions will influence future estuarine nitrogen loads (Gold et al., 2019). To protect water quality and meet regulatory standards, MCBCL managers will likely need to adopt a more holistic approach to reduce nitrogen releases from Base lands and its WWTF, and collaborate across political boundaries with city and county managers to develop an effective nitrogen management plan for the entire watershed.

1.5. Change is inevitable and necessary

Management goals are often stated in terms of desired future ecosystem conditions, but these goals might be better expressed as desired ecosystem response to change. This is particularly true for ecosystems adapting to sea level rise (SLR). Coastal wetlands connect aquatic and terrestrial ecosystems, help to protect MCBCL's shoreline from wind and wave erosion, sequester carbon and trap nutrients, while providing vital habitat for fish and shellfish (Currin 2018). Salt marshes occupy the intertidal zone, where their production and long-term sustainability rely on a series of ecogeomorphic feedback mechanisms that allow marshes to maintain their position in the tidal frame by either increasing their surface elevation or migrating landward (Fig. 5; Brinson et al., 1995; Morris et al., 2002; Kirwan et al., 2016a). There is increasing confidence that sea level along the North American south Atlantic coastline will increase by 1.1 m by 2100 (Sweet et al., 2017). During the course of DCERP, the U.S. south Atlantic coastline experienced an acceleration of SLR, and relative SLR measured from 2008 to 2018 at a secondary tide gauge established at MCBCL on Mile Hammock Bay was 9.8 ± 5.1 mm y^{-1} (Valle-Levinson et al., 2017). Therefore, managers need to envision desired future ecosystem extent and function with increasing sea level, and determine how to achieve those conditions.

Numerous observations make clear that MCBCL tidal systems are

Fig. 3. Compared to unrestored pine lands (upper photo), MCBCL's Longleaf pine restoration efforts (lower photo) enhance plant and avian diversity, long-term carbon storage, as well as suitability of the land for military training.

already experiencing increased inundation and intrusion of salt water (Ensign and Noe, 2018), and there has been a recent shift toward more flood and salt tolerant vegetation (from *Juncus roemaerianus* to *Spartina alterniflora*) in the lower part of the estuary (McTigue et al., 2019). Measures of marsh surface elevation change show that although marshes located in the lower estuary are building elevation at a rate similar to the long-term SLR, only a few of the MCBCL marshes were able to increase their surface elevation to keep pace with the accelerated SLR experienced during the study period (Davis et al., 2017).

Landward marsh migration is an important mechanism providing marsh resilience to SLR, especially in systems unable to maintain their position in the tidal frame (Kirwan et al., 2016a). At MCBCL, measurements of past conditions and model predictions of the future both illustrate that the migration of marshes into adjacent uplands has

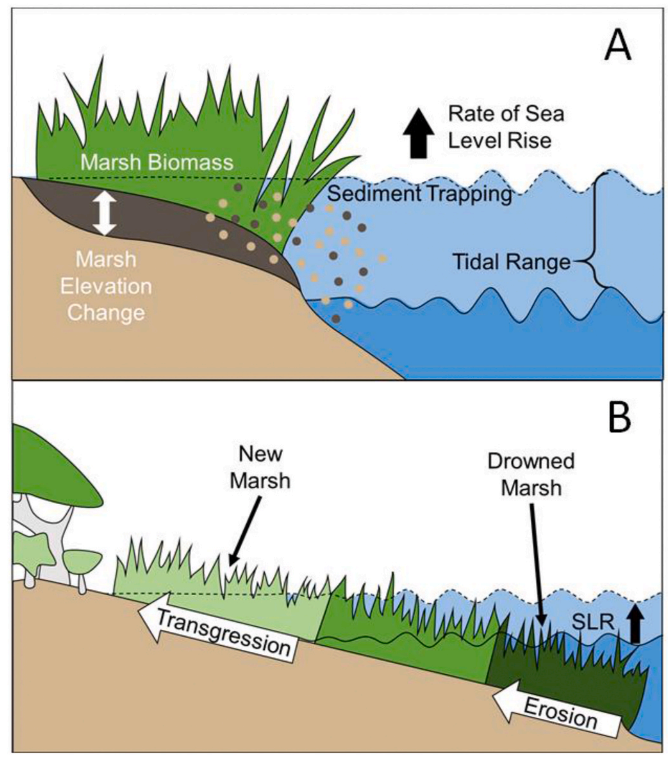

Fig. 5. Marshes can maintain their position in the tidal frame by either A) increasing surface elevation through feedbacks between marsh elevation, marsh biomass, and sediment trapping, which are moderated by tidal range and rate of SLR, or B) transgressing to higher ground inland. Illustration by Quentin Walker.

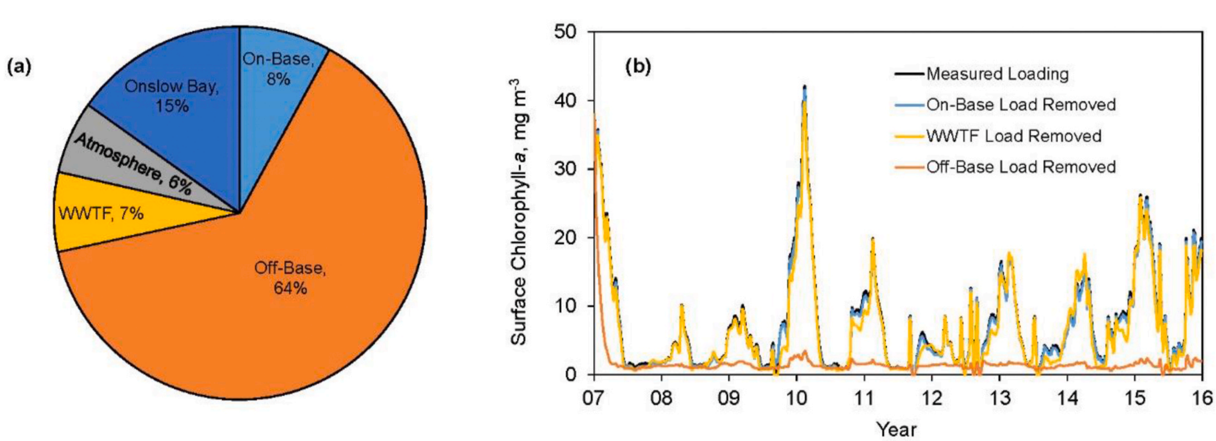

Fig. 4. (a) Relative contribution of annual total nitrogen (TN) to the NRE. On- and Off-Base = watershed area on and off MCBCL, respectively; WWTF = MCBCL wastewater treatment facility; Atmosphere = direct deposition to NRE Onslow Bay = from the ocean. (b) Modeled chlorophyll-a concentrations in the NRE under measured (observed) loading rates and various scenarios with different sources were removed (results are from Aquatic/Estuary research projects AE-2 and AE-3; methods are described in supplementary materials, Research Goals and Methods).

occurred, and that marsh expansion into upland forests will be vital to maintaining future marsh extent on MCBCL (Kirwan et al., 2016b; Scheider et al., 2018). Shoreline erosion is another threat to salt marshes, and in the New River Estuary, an analysis of shoreline erosion rates between 1956 and 2004 showed an average marsh shoreline erosion rate of -0.18 m y^{-1}, resulting in a 9 m retreat of the marsh shoreline over that time (Currin et al., 2015). However, marsh erosion was less than the erosion rate of unvegetated sediment banks (-0.39 m y^{-1}), due to the wave attenuation capability of fringing marshes (Currin 2018). Predictions of greater wave energy with warmer oceans indicate that shoreline erosion will become a greater challenge to fringing marshes in the future (Zhang and Li 2019).

1.6. Humans are ecosystem components

North Carolina's coastal barrier islands are dynamic and are exemplars of how human values dictate differences in human intervention on island dynamics (e.g., Pilkey et al., 1998). There is minimal development on MCBCL's 12-km-long barrier island except for several dozen cottages, pavilions, an observation tower, and several storage facilities. The beach and back barrier salt marshes are critical training environments for amphibious landings and deployments. MCBCL also values the beach as a recreational asset for its Marines as well as critical habitat for species of concern. Historically, MCBCL has assumed that its multiple objectives of training, recreation and conservation are best served by understanding the natural long-term dynamics of this barrier island and managing its activities to accommodate inevitable change. To minimize adverse human impacts, MCBCL strictly controls access to dune areas, limits vehicular traffic to designated ingresses/egresses, and employs passive erosion abatement (i.e., sand fences, sea oat plantings). MCBCL does not attempt to halt normal beach dynamics using beach re-nourishment or hardened structures (i.e., groins).

In contrast, densely developed Topsail Island, southwest of MCBCL, is managed differently. There, the primary management focus is maintaining the current position of an eroding shoreline to preserve beachfront properties. Unlike MCBCL, extensive land development on Topsail Island has led to loss of natural dune and back barrier ecosystems and implementation of unsustainable protection strategies (i.e. sandbags, beach replenishment, and an inlet realignment project) to forestall further shoreline erosion (Fig. 6).

The Coastal Barrier Module focused on supporting MCBCL's adaptive management approach for the beach. Investigators determined that natural forces from storm, wave, and wind activity far exceeded any anthropogenic impact from military training (McNinch et al., 2017). Historical surveys and direct measurements showed that the southern part of the barrier including the training area was rapidly eroding (Rodriguez et al., 2012). SLR is raising the elevation at which beach erosion happens with significant changes in beach morphology occurring during and after episodic major storm events (Theuerkauf et al., 2014). Researchers advised MCBCL managers to consider moving the training area and any new infrastructure to the north end of the island that has higher elevation, more developed dune structure, and active beach accretion. Beach morphology modeling suggested that relocation of training assets to the island's north end would allow training to

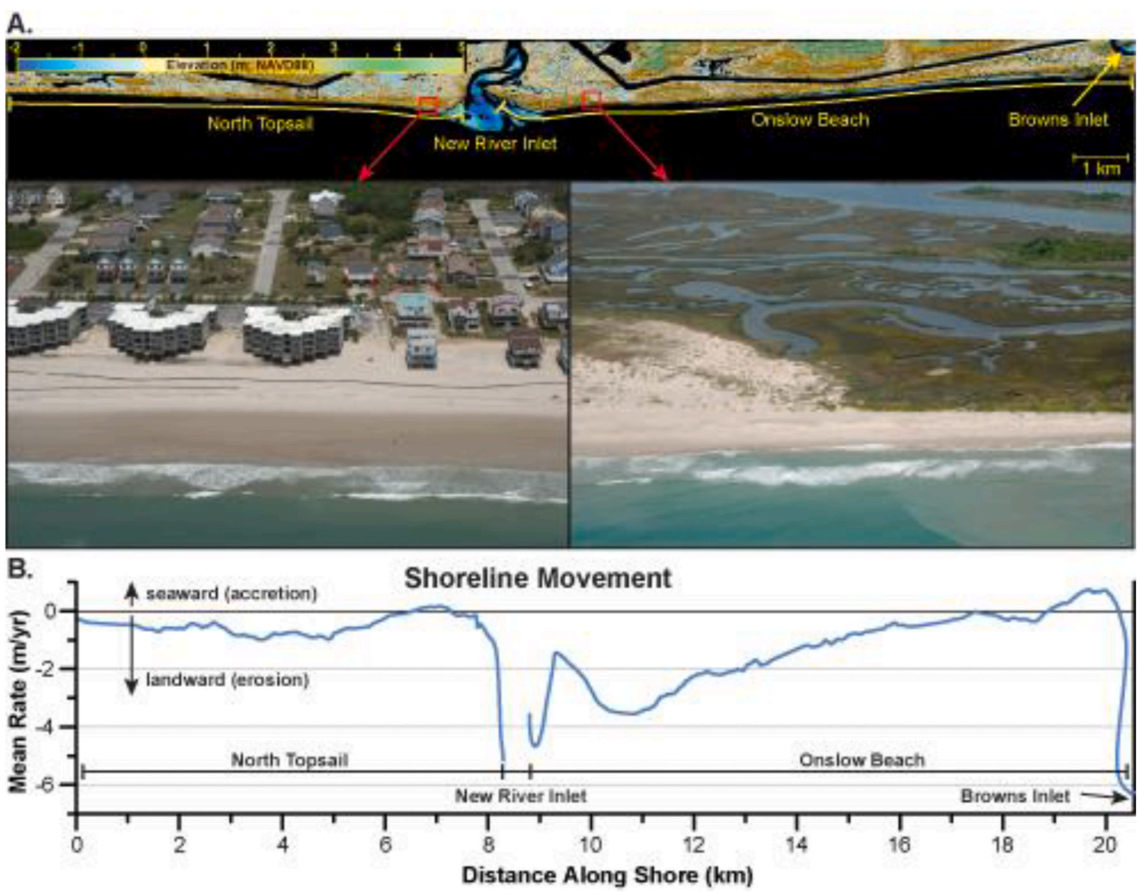

Fig. 6. Contrast between relatively natural landscape of Onslow Beach to high-density ocean front development at North Topsail Beach. The shoreline is moving landward at a lower rate along North Topsail than Onslow Beach, in part, due to management actions to protect infrastructure, such as inlet realignment, beach nourishment, and placement of sandbags. Topography data collected in 2016 and obtained from https://coast.noaa.gov. Oblique photographs taken in 2008 (Morgan, 2019). Average shoreline movement was measured using a simple end-point method based on the 1949 or 1952 and 2016 (North Topsail) or 2017 (Onslow Beach) shorelines obtained from http://deq.nc.gov/about/divisions/coastal-management.

continue uninterrupted by the effects of storms and SLR for 50 years (McNinch et al., 2017).

Whether or not the coastal barrier can keep pace with SLR will vary from location to location depending on offshore sediment supply, longshore currents, prevailing wave and wind patterns, overwash processes from periodic storms, and the rate of SLR. Implementation of mitigation and/or adaptation strategies will thus depend on continued monitoring. Aerial photography from drones or aircraft, and satellite imagery, are effective tools for such monitoring (Currin et al., 2015; Rodriquez et al., 2018).

1.7. Successful management depends on adaptability and accountability

Adaptation to environmental change and understanding of such change is a key EBM element. The results of DCERP coastal wetland research provided a foundation for developing and testing adaptive management approaches to improve the sustainability and resilience of MCBCL salt marshes to SLR and erosion. Fertilizer additions resulted in short-term increases in marsh surface elevation, with the response moderated by inundation, and may increase marsh resilience to SLR in some settings (Davis et al., 2017). At sites with long inundation periods such as at Traps Bay Marsh there may be no response to fertilization since accumulated sulfide inhibits uptake of nitrogen by the plants (Czapla et al., 2020a). Fertilizer addition may also not be appropriate at the edge of tidal creeks, as N additions can increase microbial decomposition and resulted in a five-fold increase in net C loss (Czapla et al., 2020b). The recognition that low-lying and ponded marshes were especially vulnerable to drowning and open-water conversion led to a partnership with the U.S. Army Corps of Engineers to conduct pilot projects to test thin-layer dredged sediment application as a means to provide marshes with 'elevation capital' and increase resiliency to SLR (Fig. 7). The response of low lying *Spartina alterniflora* marsh to thin layer sediment additions in this pilot program matched model predictions based on field observations.

Currently, ~20% of the NRE shoreline is hardened with rip-rap, bulkheads, or other erosion controls (Currin et al., 2015). Hardened shorelines have detrimental consequences for future marsh sustainability, impeding marsh migration and reducing sediment inputs that can contribute to vertical sediment building (Mariotti and Carr, 2014; Currin 2018). For example, sediment bank erosion in the New River Estuary generates enough sediment (~18,600 m^3) to sustain vertical marsh accretion commensurate with long-term SLR (~12,000 m^3; Currin et al., 2015). The removal of hardened structures at the marsh-upland boundary is key to marsh landward migration and maintaining the contribution of marshes to long-term natural flood protection and carbon storage potential (Temmerman et al., 2013; McTigue et al., 2019) Living shorelines offer an option that provides protection from wave energy, maintains marsh habitat, and can facilitate marsh migration on undeveloped land (Currin 2018). An analysis of the wave energy in the New River Estuary demonstrated that most of the shoreline was suitable for living shoreline utilization (Currin et al., 2015). Subsequently, living shorelines have been implemented at several sites in the New River Estuary.

Science is unlikely to inform EBM "unless scientists are involved with managers and the public in adaptive management processes" (Christensen et al., 1996). Such involvement presents challenges to all parties. Managers are often concerned that scientists will not address the issues most relevant to their specific management challenges or that results will not be effectively communicated. Scientists are concerned that narrowly defined research around such management challenges may neglect unknown factors or fail to see sustainable management alternatives (Aljerf and Choukaife 2016). The public is often concerned that research programs within a management unit will be designed only to benefit that unit or neglect key issues outside its boundaries. Each of these concerns emerged and was addressed as DCERP was being developed and implemented.

In its early stages, enthusiasm of MCBCL managers for DCERP was muted. MCBCL resources were limited and, however well-funded, DCERP had the potential to draw on MCBCL resources without producing products relevant to military training needs. DCERP scientists had a limited understanding of MCBCL managers' information needs. Thus, meetings between managers and scientists were essential early in the program during a 6-month planning period. That early dialogue was not only important in shaping the research of each ecosystem module, but it established personal relationships between scientists and managers. Those relationships facilitated frequent check-ins, information sharing, and collaboration over the program's entire tenure, and its many specific management recommendations were enhanced by these interactions (Table 2). The research findings that supported these recommendations are detailed in supplementary materials, Significant

Fig. 7. Application of dredged sediment from the Atlantic Intracoastal Waterway to marsh pond. The filled pond was subsequently planted with *Spartina alterniflora*, maintaining the integrity of the marsh platform adjacent to the navigation channel.

Table 2
Key management recommendations for each of the DCERP Ecosystem Modules.

Ecosystem	DCERP Management Recommendations
Aquatic/ Estuarine	● Protecting the water quality of the New River Estuary must be a cooperative effort involving all users of the watershed. ● Continued monitoring of riverine and estuarine water quality is needed to measure effects of both human inputs (nutrients) and climate change (storm frequency and intensity, increasing temperature, and SLR) impacts to inform future management decisions. ● Traditional stormwater wet retention ponds may not be effective in protecting downstream water quality; managers should regularly maintain wetland ponds and consider use of dry ponds. ● MCBCL needs to maintain or reduce current levels of nutrient and sediment inputs to the estuary through planned development and minimizing stormwater runoff.
Coastal Wetlands	● When shoreline stabilization is required, a living shoreline approach with salt marsh habitat is preferred to shoreline armoring with hard structures. ● Buildings, roads, and other infrastructure should be located away from wetlands and shorelines to allow for migration of marshes and coastal protection from storm surge.
Coastal Barrier	● Continue current practices of restricting vehicle traffic to well-defined corridors to help temper shoreline erosion and overwash. ● Avoid development of permanent buildings and structures on areas of the barrier experiencing significant erosion so that infrastructure losses are minimized. ● Re-locate military training activities to the more stable, higher elevation north end of the island that is accreting.
Terrestrial	● Mechanical thinning of the midstory in loblolly pine forests must be followed by prescribed burning within 5 years to benefit longleaf pine restoration. ● Forest management that specifically targets habitat conditions for the RCWs results in habitat changes that benefit the biodiversity of terrestrial ecosystems in general and the total avian community specifically; therefore, this should be continued.

Findings and Management Implications.

Almost none of the investigators had conducted studies on a live-fire military installation, which led to potential safety concerns for the MCBCL. More importantly, there were concerns that researchers might interrupt military training maneuvers. Appointment of a SERDP onsite coordinator with experience conducting ecological research on a military installation helped manage logistics for the team, minimize safety concerns, and alleviate resource burdens to MCBCL. Researchers adjusted their site selection and methods to meet the safety precautions of the installation, for example, areas next to live fire ranges could not be sampled by traditional in-field measurements therefore remotely gathered data was used as surrogates.

DCERP was accountable for its work and results at multiple levels so that its outcomes could be relevant to other coastal installations and the surrounding communities. The DCERP Technical Advisory Committee (TAC), composed of distinguished scientists representing expertise in each of the ecosystem modules, ensured the quality of the science and the integration and synthesis across ecosystems. The Regional Coordinating Committee (RCC) which included representatives of city, county, state and federal agencies and nongovernmental organizations provided input from stakeholders beyond the arbitrary boundaries of MCBCL. The TAC and RCC met with the DCERP Team every year to share results and exchange information. At the end of the program, two public meeting were conducted and outreach materials (e.g., factsheets, graphics, story maps) were published to translate outcomes to the public.

It is important that assessments among military installations be comparable across diverse regions and mission purposes. As part of DCERP, the TAC provided input from scientists familiar with other military installations and served to ensure comparability of assessments among diverse locations. It is of equal importance, however, that assessments and actions be tailored to address unique local conditions and management priorities. This was provided to the DCERP team by the RCC which provided the structure to tailor research to local conditions, ensured coordination of monitoring activities across installation/civilian boundaries, and provided information to the DCERP team on other relevant research/monitoring results for consideration. This coordination will be essential in the context of future climate change as both DoD installations and civilian systems/infrastructure will be impacted similarly.

2. Conclusions

Several papers have addressed important challenges to successful EBM implementation (e.g., Yaffee 1999; Curtice et al., 2012; DeFries and Nagrenda 2017). Four challenges were particularly important for DCERP.

1. **Systems approaches imply cross-jurisdiction problem solving that is often in conflict with organizational hierarchy.** SERDP mandated an intensive 6-month planning period prior to implementation of research activities and regular meetings among the DCERP researchers and MCBCL managers. These requirements added to program costs but were critical to establishing organizational structures and communication strategies to ensure that DCERP focused on the most important management challenges. They also facilitated a culture of trust and collaboration.
2. **Long-term monitoring and research objectives often are not consistent with agendas set by administrative cycles (i.e., fiscal years, electoral cycles, changing military commanders**). Over the span of a decade, DCERP was unable to accommodate all changes in MCBCL management priorities. Changes in management priorities are inevitable in a 10-year program, and adaptation was essential to DCERP's success. For example, two years into DCERP, the "Grow the Force" initiative was inaugurated with the goal of increasing the number of military and civilian personnel at MCBCL by nearly 10,000. This initiative led directly to research aimed at understanding the impacts of changes in storm water quantity and quality that might result from increased development in the cantonment area (Gold et al., 2017).
3. **Decision support tools for implementing EBM must be accessible and reliable.** A significant portion of DCERP was dedicated to developing effective and reliable decision support tools to address various management objectives. DCERP's RCW decision support tool has been used by MCBCL managers to set forest habitat restoration objectives, and its beach morphology model has raised awareness of the need to relocate training activities on the barrier island to the northern end that has higher elevation dunes and whose shoreline is accreting rather than eroding like the shoreline in the current military training area.
4. **Adaptive management acknowledges uncertainty and implies risk taking.** Uncertainty in future conditions and research results can be threatening to managers. Over time, MCBCL managers became more willing to take actions using the best available science while acknowledging uncertainties and supporting the science to resolve them. Over the duration of the DCERP, concerns about climate change and associated SLR increased (SERDP 2013). Initially, MCBCL managers were skeptical that changes in sea level were relevant to the military mission; however, by the end of DCERP, they were eager to understand how SLR may jeopardize their future military training operations, and what steps might be taken to mitigate such impacts. Adaptive management to SLR will depend on continued monitoring of both the coastal barrier and coastal wetlands ecosystems. Potential mitigation strategies such as wetland fertilization and application of dredged sediment require additional evaluation. DoD should explore strategies for adaptation to likely changes on the barrier island associated with SLR.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111755.

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