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PRACTICAL ARTICLE

Tradeoffs in habitat value to maximize natural resource benefits from coastal restoration in a rapidly eroding wetland: is monitoring land area sufficient?

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Louisiana contains nearly 40% of estuarine herbaceous wetlands in the contiguous United States, supporting valuable ecosystem services and providing significant economic benefits to the state and the entire United States. However, coastal Louisiana is a hotspot for rapid land loss from factors including hurricanes, land use change, and high subsidence rates contributing to high relative sea-level rise. The Coastal Protection and Restoration Authority (CPRA) was established after major hurricanes in 2005 to coordinate coastal restoration in Louisiana and develop the Louisiana Coastal Master Plan. The LA Coastal Master Plan uses numerical modeling of multiple scenarios to select a suite of restoration projects based on maximum land area created and flood reduction (as proxies for ecosystem value). Using potential value to aquatic, terrestrial, and social resources, our work compared habitat value of shallow open water areas to emergent wetland. While potential resource benefits varied by emergent wetland salinity type and emergent wetland versus water, they were similar, suggesting that restoration planning based primarily on wetland land area may not achieve the maximum possible ecosystem benefits. After nearly 20 years of integrated restoration planning in coastal Louisiana, a reassessment of restoration planning decision drivers may be beneficial to ensure maximum benefits from coastal restoration. As a result of the *Deepwater Horizon* oil spill, settlement funds will be a major support to coastal restoration in Louisiana for many years. Assessing potential habitat value to multiple natural and social resources in Louisiana has potential to maximize synergy with large northern Gulf of Mexico restoration programs.

Key words: coastal resilience, co-benefits, ecosystem management, ecosystem resources, Gulf of Mexico, Louisiana

Implications for Practice

- After nearly 20 years, a reassessment of restoration planning decision drivers may be beneficial to ensure maximum benefits from coastal restoration in Louisiana.
- Loss of coastal wetlands initially creates shallow open water that still has high potential habitat value for many natural resources.
- Loss of ecosystem benefits due to land loss will be overestimated without accounting for the potential value of shallow open water habitat.
- Demonstrating multiple natural and social resource benefits from coastal restoration has potential to increase linkages to large Gulf of Mexico restoration programs.

Introduction

Coastal Louisiana contains approximately 37% of all estuarine herbaceous wetlands in the contiguous United States, which provide valuable ecosystem services including fisheries production, mammal and alligator production, carbon sequestration, recreation, wave attenuation, and storm surge reduction (Couvillion et al. 2011; Visser et al. 2012; Batker et al. 2014). Louisiana's fresh, intermediate, brackish, and saline emergent wetlands, as well as the associated shallow submerged aquatic vegetation (SAV), provide vital nursery habitat for fish (Beck et al. 2001; Minello & Rozas 2002; Minello et al. 2003). However, coastal Louisiana is a hotspot for habitat change and rapid land loss (42.9 km^2 per year; 1985–2010 mean) resulting from multiple factors including hurricane disturbance, significant land use change, and high subsidence rates contributing to high

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relative sea-level rise (Day et al. 2000; Yuill et al. 2009; Newton et al. 2012; Couvillion et al. 2013; Bailey et al. 2014).

Since 1990, with the establishment of the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA), coastal restoration decisions in Louisiana have primarily focused on maintenance of emergent wetland area. The Coastal Protection and Restoration Authority (CPRA) was established as a result of major hurricanes in 2005 to coordinate coastal restoration in the state with the goals of increasing flood protection, natural processes, and coastal habitats, protecting cultural heritage, and supporting a working coast (Peyronnin et al. 2013; CPRA 2017; The Water Institute of the Gulf 2020). CPRA's Louisiana (LA) Coastal Master Plan is an integrated coastwide plan for restoration planning and implementation that was initiated in 2007 and updated in 2012 and 2017 (CPRA 2012; CPRA 2017). A fundamental component of the LA Coastal Master Plan uses numerically modeled future land area under different scenarios of coastal restoration to prioritize restoration activity (Meselhe et al. 2013; Peyronnin et al. 2013; Visser et al. 2013). After assessing decision drivers including carbon storage, habitat suitability, and multiple-criteria decision analysis, projected area of emergent wetland over a 20- and 50-year period was selected as the primary decision driver to select between habitat restoration project implementation scenarios (CPRA 2012; Groves & Sharon 2013; Peyronnin et al. 2013). Using a proxy metric as the decision driver supplemented with outputs for a range of additional decision criteria was determined to be effective for stakeholder engagement (CPRA 2012; Groves & Sharon 2013; Peyronnin et al. 2013). Recognizing the broad goals of CPRA, a focus on the proxy metric of emergent wetland area assumes that retaining area of emergent wetland will support fundamental ecosystems, associated ecosystem functions, and social benefits; in other words, that delivery of ecosystem functions will be directly related to emergent wetland area (Carruthers et al. 2020).

Since the *Deepwater Horizon* (DWH) oil spill in 2010 and the subsequent environmental settlement for USD$20.8 billion in 2016, settlement funds have been the major source of funding for coastal restoration in the northern Gulf of Mexico and will continue to be for at least the next decade (Henkel & Dausman 2020). In Louisiana, through the Natural Resource Damage Assessment (NRDA) alone, USD$5 billion was authorized to restore and conserve habitat and to restore damaged natural resources. A primary high-level goal of NRDA is to replenish and protect living coastal and marine resources, with requirements for Louisiana to report on progress in restoring a range of defined natural resources (Deepwater Horizon Natural Resource Damage Assessment Trustees 2016). Therefore, implementation of restoration projects in the state's LA Coastal Master Plan using NRDA funds requires understanding potential benefits to multiple natural resources.

This paper investigates three questions:

(1) Do emergent wetland salinity types vary in benefits to components of the values for aquatic and terrestrial habitat and societal well-being?
(2) What are relative habitat values of emergent wetland and shallow open water?
(3) Over a period of six decades of land loss, does inclusion of habitat value for land that eroded to shallow open water change the calculated rate of loss of habitat value?

Methods

Habitat Suitability Indices (HSIs)

Ten faunal HSIs and four related to societal wellbeing (hereafter referred as social indices) were selected from the 14 available species modeled for the 2012 Coastal Master Plan (Supplements S1 and S2). The 10 faunal HSIs used were largemouth bass (*Micropterus salmoides*), spotted seatrout (juvenile, *Cynoscion nebulosus*), brown shrimp (juvenile, *Farfantepenaeus aztecus*), white shrimp (juvenile, *Litopenaeus setiferus*), crayfish (wild caught, *Procambarus clarkia*), American alligator (*Alligator mississippiensis*), Gadwall (*Anas strepera*), Green-winged Teal (*Anas crecca*), Mottled Duck (*Anas fulvigula*), and Roseate Spoonbill (*Platalea ajaja*). These were divided into terrestrial and aquatic HSIs. The social indices were based on the potential to: (1) attenuate storm surge/waves, (2) support nature-based tourism, (3) provide freshwater for urban use, and (4) support agriculture/aquaculture. The social indices included factors related to salinity, flood depth, distance from population centers, and distance from places of interest (Supplement S1).

Quantifying and Integrating HSIs Across Coastal Louisiana

The spatial model developed as part of the 2012 Coastal Master Plan covered 342,233 cells (500×500 m^2 each) across coastal Louisiana with coastal land cover modeled for the subsequent 50 years (Fig. 1) (Meselhe et al. 2012). Since physical data input to calculate HSIs was taken from every grid cell, this avoided one common criticism of HSIs that they do not fully account for input data variability (Roloff & Kernohan 1999). Land cover classification from simulation year 10 was used to provide the best estimate for comparative habitat classifications and to calculate HSI scores. Vegetation classifications were based on the habitat definitions outlined by Sasser et al. (2014). Cells classified as "swamp," "other," and those not classified as either an emergent marsh (wetland) type or water were omitted. A total of 51,754 of the 500×500 m^2 model output cells had data to run all HSI models and were used for further analysis.

Individual species HSI scores were summarized for each emergent wetland type and open water areas to examine the variability in HSI scores by species. Then, integrated HSI scores were developed by taking an unweighted mean of all HSI scores by group (terrestrial, aquatic, and social) for each salinity habitat (fresh, intermediate, brackish, and saline) for both emergent wetland and open water areas. Comparisons within group between habitat types (open water and emergent wetland considered separately) were conducted using non-parametric Kruskal–Wallace tests; subsequent pairwise comparisons were evaluated using the Wilcoxon rank sum tests with Bonferroni *p*-value adjustment.

To examine the contemporary differences in integrated HSI scores between emergent wetland and open water habitats, across

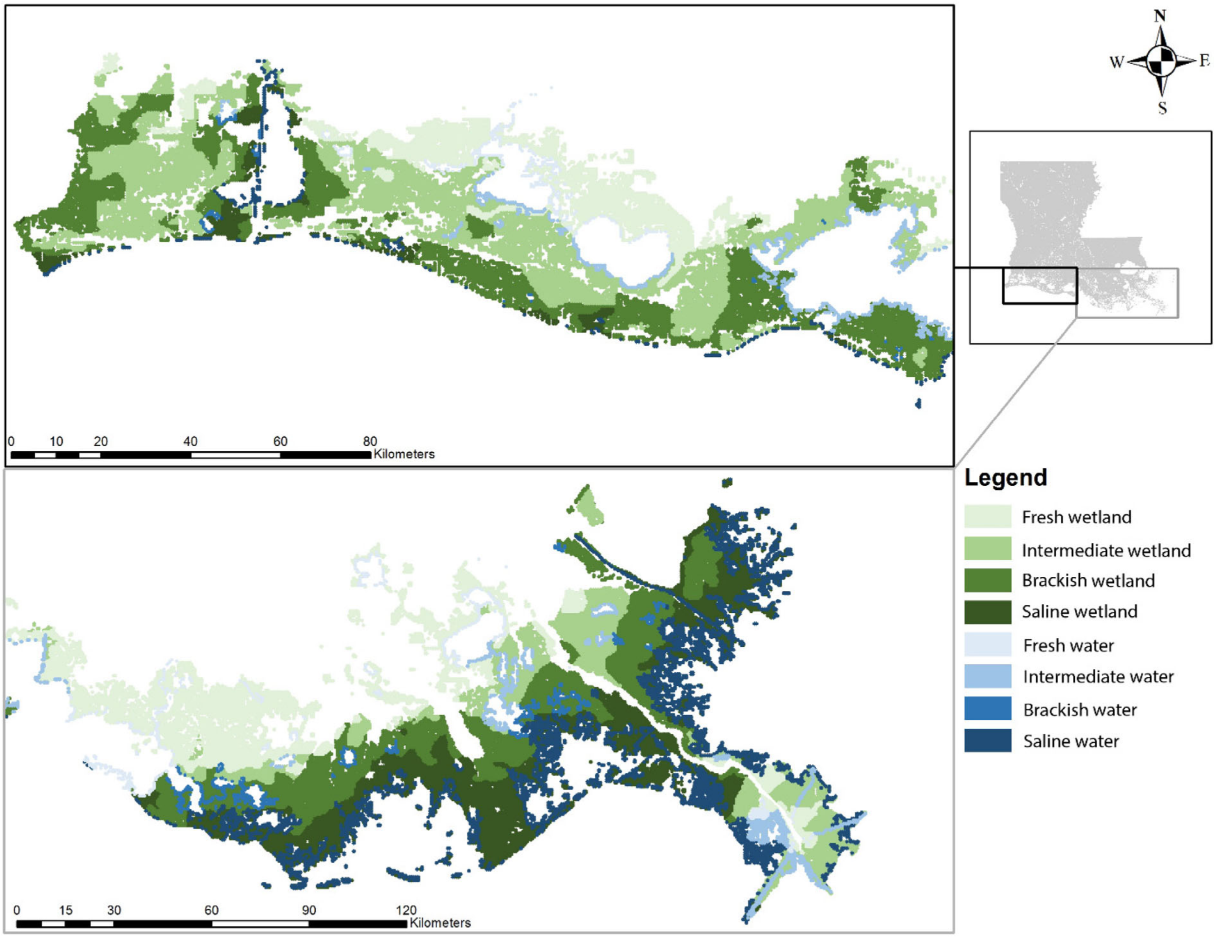

Figure 1. Classification of emergent wetland and water by salinity in coastal Louisiana (Sasser et al. 2014).

salinity, the integrated HSI values of each group, as well as of all groups combined, were assessed using Mann–Whitney *U*-tests. All statistical analyses were completed using the R statistical software programing environment (v3.4.3, The R Foundation for Statistical Computing, Vienna, Austria).

Historical Trends in Land Cover and Integrated HSIs

To investigate differences between integrated HSI scores when considering emergent wetland area alone (excluding open water), a hindcasting approach was used to examine temporal trends in integrated HSI based on historical emergent wetland cover between 1949 and 2013.

Existing emergent wetland type data for the Louisiana coast were derived for the following years: 1949 (O'Neil 1949), 1968 (Chabreck et al. 1968), 1978 (Chabreck & Linscombe 1978), 1988 (Chabreck 1988), 1997 (Chabreck & Linscombe 1997), 2001 (Linscombe & Chabreck 2001), 2007 (Sasser et al. 2008), and 2013 (Sasser et al. 2014). Data on emergent wetland type were collected using a survey methodology that has been consistent since 1988 to classify emergent wetlands based on vegetation types; prior to 1988, survey methodology varied. Based on vegetation community identity at each timepoint, it was possible to generate emergent wetland classifications based on salinity (fresh, intermediate, brackish, and saline) (Supplement S3). The relative areal extent of each of the four emergent wetland types in previous years was multiplied by the 2010 mean combined integrated HSI score for that emergent wetland category. Cells classified as open water at each time point were multiplied by the combined integrated HSI score for open water (no distinctions could be made by salinity). Historical integrated HSI values were modeled for each group separately (terrestrial, aquatic, social) as well as for all groups combined.

Simple linear regression was used to assess temporal trends in integrated HSI scores. For each dataset, HSI scores were analyzed first by excluding open water cells and then for combined emergent wetland and open water. Regression slopes from "emergent wetland" and "emergent wetland including open water" were compared using an analysis of covariance (ANCOVA, $\alpha = 0.05$).

Results

Integrating HSIs Across Coastal Louisiana

For emergent wetland habitat types, HSI scores calculated by CPRA (2012) were assigned to a total of 9,293 fresh, 11,737 intermediate, 13,178 brackish, and 10,121 saline emergent wetland type cells (Table S1). HSI scores were also available for 800 fresh, 1,308 intermediate, 613 brackish, and 4,704 saline open water cells (Table S2). Overall, terrestrial species showed relatively low HSI scores (mean HSI range 0.024–0.342) in emergent wetland, generally declining with increasing salinity (except alligators; higher suitability in intermediate emergent wetland). Aquatic species spanned a greater range of HSI in emergent wetland habitat (mean HSI range 0.037–0.806), generally higher (HSI > 0.3) in brackish emergent wetland. However, moderately high habitat suitability scores in open water (mean HSI range 0.017–0.695) indicated potential habitat value in areas not directly associated with emergent wetlands. The social indices of surge/wave attenuation and nature-based tourism showed high suitability in emergent wetland and open water habitat types, but agriculture/aquaculture and freshwater availability showed low suitability across all habitat types examined.

For all groups (aquatic, terrestrial, social), the mean integrated HSI scores were significantly different by emergent wetland salinity ($p < 0.01$, Kruskal–Wallace and Wilcoxon rank sum tests) (Fig. 2A). The highest integrated suitability was in saline emergent wetlands for aquatic species (HSI $= 0.522$, $p < 0.01$), a pattern driven by white and brown shrimp and spotted trout (Table S1). Saline emergent wetlands had the lowest integrated HSI scores for terrestrial species (HSI $= 0.077$, $p < 0.01$). Differences in social indices indicated higher suitability in fresh emergent wetland (HSI $= 0.311$, $p < 0.01$), no difference between intermediate and brackish emergent wetlands (HSI $= 0.272$ for both, $p = 0.320$), and lower suitability in saline emergent wetland (HSI $= 0.244$, $p < 0.01$).

When considering open water areas only, aquatic and terrestrial species differed significantly in mean integrated HSI scores by salinity ($p < 0.01$, Fig. 2B). Aquatic species in brackish water maintained higher HSI scores compared to fresh water (HSI $= 0.473$ and 0.282, respectively, $p < 0.01$). Terrestrial species, though they differed significantly by salinity ($p < 0.01$), reflected overall low mean HSI values (range from 0.009 in saline water to 0.039 in brackish water). Social indices were similar between fresh and brackish open water (HSI $= 0.239$, $p = 1.000$) and between intermediate and saline (HSI $= 0.210$ and 0.194 respectively,

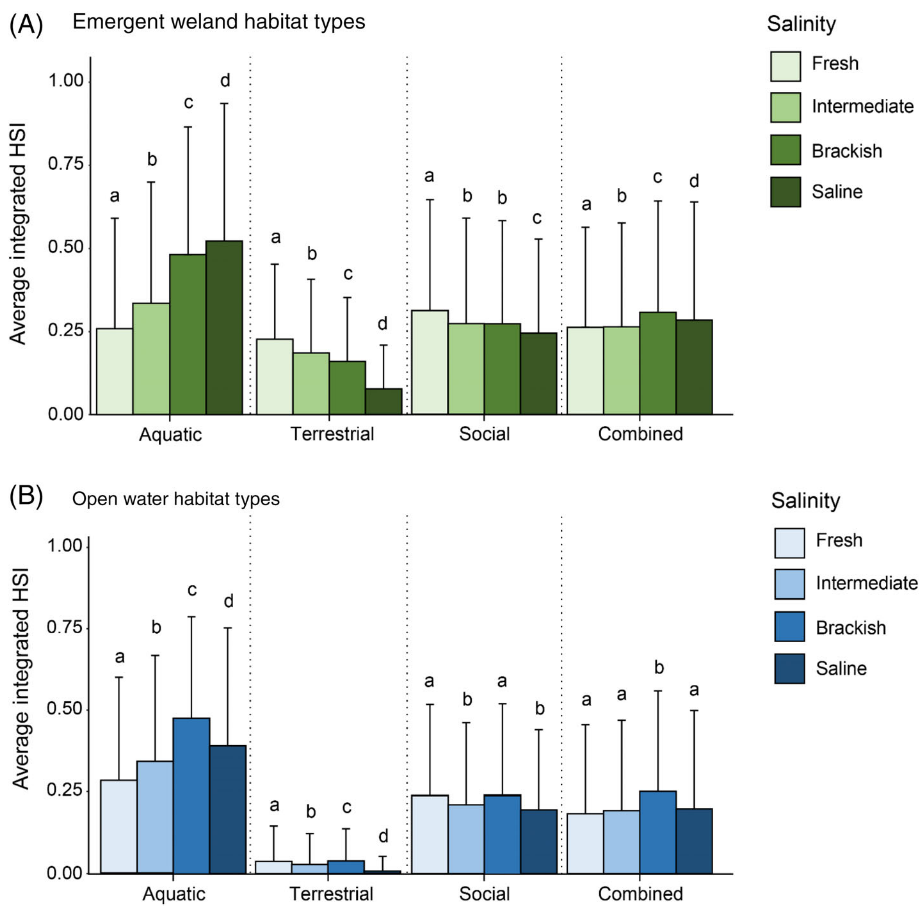

Figure 2. (A and B) Integrated HSI scores by species (aquatic, terrestrial, and social) and total combined for each salinity type in open water and emergent wetland habitats based on 2013 land classification of coastal Louisiana. Bars represent mean + SD. Letters indicate significant differences between wetland types for each group (Kruskal–Wallace rank sum test, pairwise Wilcox test, $\alpha = 0.05$). Aquatic fauna include brown shrimp, crawfish, largemouth bass, spotted trout, and white shrimp; terrestrial fauna include alligator, Gadwall, Green-winged Teal, Mottled Duck, and Spoonbill (see Supplements S1 and S2).

$p = 0.093$), but for fresh and brackish open water were higher than intermediate and saline ($p < 0.01$) (Table S2).

All groups were combined for emergent wetland and open water areas by salinity (Fig. 2A & 2B, "Combined"). Significant differences in combined integrated HSI scores were determined among all emergent wetland types ($p < 0.01$), with the highest combined HSI score in brackish emergent wetland areas (HSI = 0.307). The same pattern was found in open water combined HSI scores with the highest HSI value for brackish water (HSI = 0.251), but combined HSI values for fresh, intermediate, and saline open water were not significantly different.

The differences in integrated HSI scores between emergent wetland and open water areas (across all salinities) are shown in Figure 3. Integrated HSI was lower in open water areas ($p < 0.01$, Wilcoxon rank sum test) for each group separately as well as when combined (Fig. 3).

Historical Trends in Land Cover and Integrated HSIs

Based on the relative area of the four emergent wetland types (fresh, intermediate, brackish, saline) and total area of open water between 1949 and 2013, combined habitat suitability had negative slopes ($p < 0.05$, ANCOVA) (Fig. 4). The smaller negative slope (i.e., rate of decline) in combined HSI scores calculated for emergent wetland plus open water habitats indicates a significant contribution of open water to HSI.

Both aquatic and social groups had a more rapid decline in integrated HSI over time when considering emergent wetland areas alone (Table S3). There was no significant difference in rate of decline in integrated terrestrial HSI regardless of open water inclusion.

Discussion

For dynamic ecosystems such as coastal Louisiana that have a long history of anthropogenic intervention, management, and societal use of ecosystem resources, novel and comprehensive approaches are required to maximize ecosystem benefits from large-scale restoration. Integrating ecological knowledge with land management practices is essential for implementing realistic conservation strategies (Store & Jokimäki 2003) and has proven to be successful across a variety of habitat types and geographies (Brown et al. 2000; Tikkanen et al. 2007). Nonmarket valuation of ecosystem resources provides a way to be more fully inclusive in assessing costs and benefits to stakeholders, providing a more comprehensive range of potential values, such as habitat value (Johnston et al. 2009; Schröter et al. 2014). This work considered the implications of prioritizing restoration effort based upon assessment of emergent wetland area alone compared to including potential habitat value of shallow water resulting from emergent wetland loss.

Habitat Value of Different Emergent Wetland Salinity Types

A trend of higher habitat suitability for aquatic species was observed within more saline emergent wetland types, reflecting higher suitability scores for juvenile spotted seatrout, brown shrimp, and white shrimp. A stable sulfur isotope study in Louisiana also suggested the importance of open water habitat where two thirds of the juvenile brown shrimp production depended on open bays versus the remaining one of three depending on emergent wetlands (Fry 2008). Terrestrial species exhibited a generalized decrease in habitat suitability with increasing salinity reflecting a preference for shallow water depths, fresh emergent wetland vegetation, and the presence of SAV (Brooks & Dodge 1986). Observed social habitat suitability was greatest in fresh emergent wetland habitats, similar between brackish and intermediate emergent wetlands, and lowest in saline wetlands. Freshwater availability for drinking water and agriculture are critical drivers for high suitability scores for these particular social indices (Zedler & Kercher 2005). Because fresh emergent wetlands tend to have structural characteristics

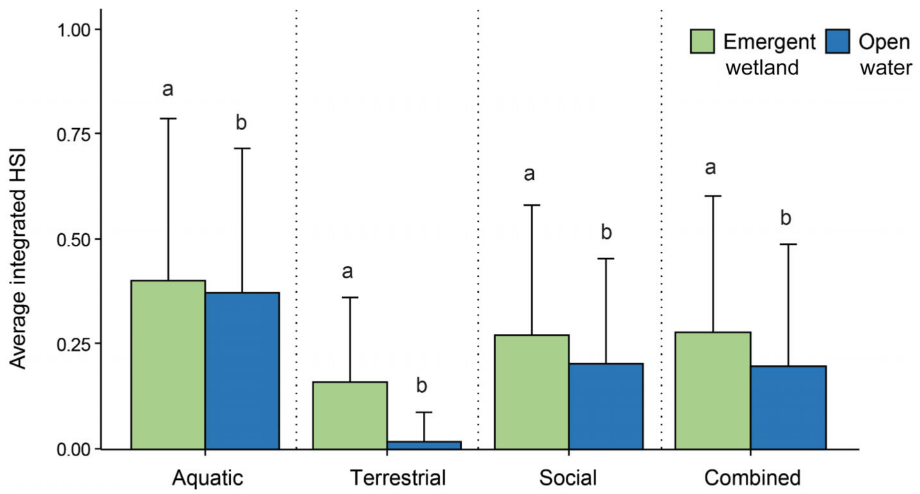

Figure 3. Integrated HSI scores by species group in emergent wetland and open water areas classified by the 2013 emergent wetland type classification for coastal Louisiana. Bars represent mean + SD and letters indicate significant pair-wise differences between emergent wetland and open water habitat types (Mann–Whitney *U* test, $\alpha = 0.05$).

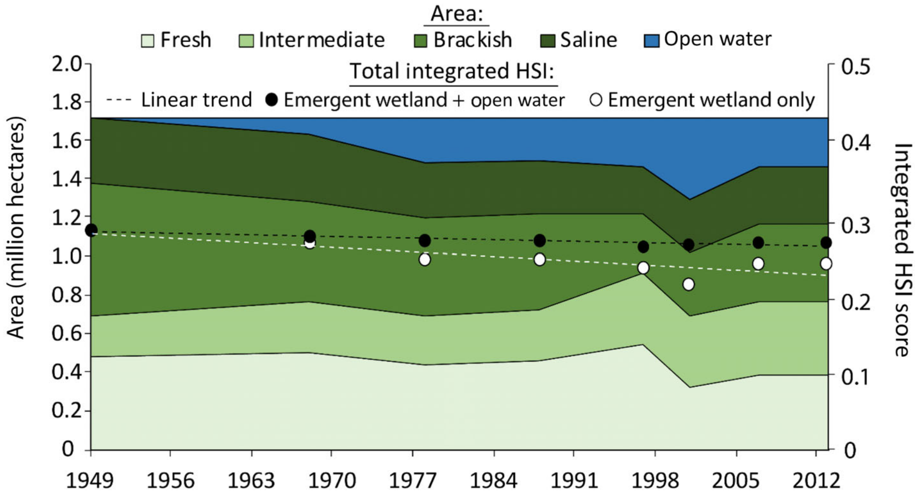

Figure 4. Area of habitat types (fresh, intermediate, brackish, saline emergent wetland, and total open water) in coastal Louisiana from 1949 to 2013. Estimates of integrated HSI scores (mean of all groups) over time for total emergent wetland habitat and emergent wetland habitat including open water are given with simple linear regression lines plotted for each dataset.

such as higher topography, they can protect communities from storm surge and emergent wetland vegetation can increase protection against waves even during high water and storm events (Engle 2011; Möller et al. 2014). Coastal Louisiana has high potential for nature-based tourism with birding, fishing, swamp tours and the Cajun culture making all emergent wetland salinity habitats potentially suitable in this regard (Luzar et al. 1995).

The identified differences in potential habitat value of fresh, intermediate, brackish, and saline emergent wetlands for a range of aquatic, terrestrial, and social ecosystem values can inform restoration prioritization. Based upon the need for different ecosystem services, the relative proportions of each salinity emergent wetland type could be used as a modifier in selecting scenarios of potential restoration projects to maximize benefits and ensure that multiple ecosystem resources are supported.

Assessing Ecosystem Value of Emergent Wetland and Water Over Time

Shallow open water areas had lower integrated habitat suitability; however for all aquatic and social metrics considered it was similar to the emergent wetland value and none approached zero (attributing no value to shallow open water). In addition, variation in habitat suitability for aquatic, terrestrial, and social metrics was different between emergent wetland and open water areas. This suggests that restoration planning based primarily on optimizing land area (Groves & Sharon 2013; Peyronnin et al. 2013) may not be realizing the maximum possible ecosystem benefits from that restoration.

Habitat suitability was found to have declined over the past six decades, correlated to areal loss of emergent wetland. The lower scores for the terrestrial and social groups in open water areas compared to emergent wetland may help explain this trend. However, when potential habitat suitability of open water areas was included with habitat suitability of emergent wetland, the rate of decline in habitat suitability was significantly less; this is supported by observations in Barataria Bay, Louisiana, where shallow non-vegetated bottom is increasingly being recognized as an undervalued habitat for some fish and shellfish species (Rozas & Minello 2015). For large-scale restoration programs, such as NRDA (Deepwater Horizon Natural Resource Damage Assessment Trustees 2016), that are required to report on potential natural resource value at a programmatic scale (100s km), using land area as the proxy metric of ecosystem value would overestimate reduction in ecosystem value with future land loss. Utilizing integrated habitat suitability can provide a clearer understanding of relative positive and negative effects of a portfolio of restoration projects on a range of natural resources. For coastal Louisiana, after almost 20 years of prioritizing restoration effort primarily based upon maximizing emergent wetland area, a reassessment of decision criteria may lead to increased benefits for multiple natural resources and increase synergy with the large Gulf of Mexico restoration funding programs.

Conclusion

The importance of an integrated approach when assessing habitat suitability in response to management actions, and of delivering effective and equitable resource management, is being increasingly recognized (Jakeman & Letcher 2003). Coastal Louisiana has some of the most rapid rates of emergent wetland loss globally and relies on a funcioning ecosystem for a wide range of economic resources. The current approach of prioritizing restoration effort primarily based upon maintenance of emergent wetland area may not be delivering the greatest possible overall ecosystem value from that restoration. Also, due to programmatic goals and reporting requirements of programs funded through Deepwater Horizon settlement funds, including a range of ecosystem values into Louisiana restoration prioritization has potential to increase synergy with those large-scale restoration programs. For the purposes of high-level restoration planning at large spatial scales (100s km), integrating a range of habitat suitability values into decision drivers has the potential to improve ecosystem outcomes from large-scale restoration.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Summary of habitat suitability index (HSI) scores (mean and variance) by emergent wetland type for each species.
Table S2. Summary of habitat suitability index (HSI) scores (mean and variance) by open water habitat type for each species.
Table S3. Hindcast historical trends (1949–2013) of potential ecosystem function.
Supplement S1. Habitat suitability indices.
Supplement S2. HSI variable inputs and formulae from the 2012 Coastal Master Plan (CPRA 2012).
Supplement S3. Summarizing emergent wetland plant communities in Coastal Louisiana.

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