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Meta-Analysis and Spatial Distribution of Ecosystem Services in Louisiana's Coastal Zone: Implications for Coastal Restoration

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ABSTRACT

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Coastal Louisiana is shaped by dynamic and complex nature–society relationships. In environmental policymaking, the ecosystem services framework is a common approach to conceptualizing this relationship. A meta-analysis of 46 studies from 1974 to 2019 was conducted, which contained 168 primary ecosystem services valuations for wetlands in coastal Louisiana. Ecosystem services values for freshwater, brackish, and saltwater wetlands are presented. Services include disturbance regulation, fisheries, gas regulation, primary production, nutrient regulation, recreation, and waste regulation. With these values, total ecosystem services values for all wetlands in the coastal zone were calculated. The results showed that freshwater wetlands provide ecosystem services values similar to those of saltwater wetlands and that the annual ecosystem services provisioning for the coastal zone totals more than $36.3 billion (2022 U.S. dollars). This study presents environmental policymakers and planners with an updated ecosystem services value database for effectively communicating the dynamic relationship between people and nature in Louisiana.

ADDITIONAL INDEX WORDS: *Spatial science, environmental policymaking, human dimensions, ecosystem values, nature–society relationships.*

INTRODUCTION

Coastal Louisiana is a model system of dynamic and complex nature–society relationships. Over the past century, humans have altered the natural ebb and flow of the coastal environment and depleted natural resources in the area (Bailey, Gramling, and Laska, 2014). This alteration led to the creation of the Louisiana Coastal Master Plan, under the Coastal Protection and Restoration Authority (CPRA), to protect and restore Louisiana's coastal environments and allow for a "working" coast, seeking a balance between economic growth for the state while protecting natural resources along the coast. The focus on the economy in policymaking led environmental scientists to develop new ways to communicate the value of natural environments, specifically the interconnectedness between society and nature (Costanza *et al.*, 2014).

Ecosystem services (ES) are the goods and services provided by natural systems to the human economy (Costanza *et al.*, 2014). Humans and their economies have always depended on natural systems, but the modern-day concept of ES began with Wilson and Matthews (1970). In this report, they studied the global ecological and climactic effects of human activities on nature and specifically called this relationship environmental services. The first financial evaluation of environmental services was done by Gosselink, Odum, and Pope (1974) for tidal marshes. Through the next decades, the concept of ES became popular and the predominant paradigm for understanding the value of natural systems to humans. Translating the biophysical world of nature into the economic systems of value and exchange provides the argument for protecting and valuing coastal environments (Mansfield, 2003).

Recently, ecosystem services valuations (ESVs) have been proposed as a way that policymakers could understand the ecological–economic trade-offs of alternative policies (Bouwma *et al.*, 2018; Greenhalgh *et al.*, 2017; Hanley and Barbier, 2009; Maes *et al.*, 2012; Vojinovic *et al.*, 2016) or could set payment for ecosystem services values (Farley and Costanza, 2010). The use of ESVs in policymaking has been contentious, with some authors supportive (Daily *et al.*, 2009; Engel, Pagiola, and Wunder, 2008; Fisher, Turner, and Morling, 2008; Heal *et al.*, 2005; Maes *et al.*, 2012) and others opposed (Child, 2009; McCauley, 2006; Redford and Adams, 2009). Daily *et al.* (2009) stated that the success of conservation is a product of understanding ecosystem functions and integrating that knowledge into policy. In contrast, McCauley (2006) argues that there is little evidence that market-based evaluation of nature leads to the commodification of nature, and even then, commodification is less effective in creating long-lasting gains in conservation than increasing people's love of nature. In Louisiana, ESVs are used as rationale for protecting and restoring the coastal zone in CPRA's Coastal Master Plan (CPRA Staff, 2017).

Use of Meta-Analyses for ESVs

Meta-analyses are used to synthesize multiple primary ESV studies through statistical analyses (Bal and Nijkamp,

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2001). Meta-analysis is a common approach for comparing ESVs on broader scales and between systems and for predicting the economic benefits for policy decisions (Moeltner and Rosenberger, 2008). Wetlands are highly productive environments that produce an abundance of ES (Brander, Florax, and Vermaat, 2006), including storm surge and flood protection, water quality improvement, food, and recreation (Ghermandi *et al.*, 2010). Meta-analyses of ESVs in wetland systems have focused on comparing ES between natural and manmade wetlands (Ghermandi *et al.*, 2010), understanding the impacts of proposed groundwater extraction projects on wetlands (Moeltner and Woodward, 2009), assessing the drivers of wetland values in agricultural landscapes to produce more reliable ESVs (Eric *et al.*, 2022), determining nonmarket values of urban wetlands (Boyer and Polasky, 2004), and distinguishing restoration priorities for increased ES provisioning (Meli *et al.*, 2014). Other studies have analyzed the use of meta-analysis techniques for effective benefit transfer in China (Zhou, Wu, and Gong, 2020), Mexico (Lara-Pulido, Guevara-Sanginés, and Arias Martelo, 2018), and Canada (He *et al.*, 2015) and for use in valuing loss because of climate change in Europe (Brander *et al.*, 2012). Various studies have focused on wetland environments in the United States (Brander, Brouwer, and Wagtendonk, 2013; Brander, Florax, and Vermaat, 2006; Brouwer *et al.*, 1999; Woodward and Wui, 2001). There is limited literature on ESV meta-analysis studies that specifically include Louisiana's wetlands (Shepard, Crain, and Beck, 2011). Barnes *et al.* (2015) conducted an analysis of the economic costs associated with land loss in Louisiana and found that it would cost from more than $2.1 billion over 25 years to $3.5 billion over 50 years to replace the natural capital lost from land loss in the coastal zone, but those authors did not calculate ESVs. This literature provides the conceptual and empirical basis for the present study. To our knowledge, this study is the first to perform a meta-analysis of the freshwater, brackish, and saltwater wetlands in Louisiana using only Louisiana-based primary ESV literature.

Spatial Analyses of ES

Numerous studies have valued ES using spatial techniques, with a range of applications. Examples include cost–benefit analyses (Birch *et al.*, 2010; Newton *et al.*, 2012), to connect ES to worldviews (Van Riper and Kyle, 2014), and socioeconomics (Vidal *et al.*, 2020), to identify priority areas for payment for hydrological services (Mokondoko *et al.*, 2018) and to identify management techniques and priorities for land use (Castro *et al.*, 2014; Deng, Li, and Gibson, 2016; Gao *et al.*, 2021). In Louisiana, spatial understanding of ES has been used to implement water hyacinth (an invasive species in Louisiana) management techniques (Wainger *et al.*, 2018), to identify best practices to enhance land protection for the Atchafalaya Basin (Piazza *et al.*, 2015), and to quantify ES trade-offs for reforestation in the Mississippi Alluvial Valley (Barnett, Fargione, and Smith, 2016). Limited studies have used ES meta-analyses as the data for a spatial analysis (Brander *et al.*, 2012; Brander *et al.*, 2015). The present study adds to the literature in that respect.

ES in Louisiana

To date, the most comprehensive understanding of the ES provided by the Louisiana coastal zone is from Batker *et al.* (2010). Their report used a method of benefit transfer, termed value transfer, which uses previous primary studies to extrapolate the value of ES for a given geographic region (Batker *et al.*, 2010). They estimated the economic loss and gain for Louisiana's economy from land changes due to coastal land loss and restoration, respectively. The authors conducted a traditional literature review to find studies that valued wetland types, both in Louisiana and in other states, to construct a valuation table for the Mississippi River Delta. The present study builds on the methodology of Batker *et al.* (2010) and differs in that this study conducted a systematic review with meta-analysis to update the ESVs in the coastal zone and included the ESVs for the updated coastal zone boundary in Louisiana. Batker *et al.* (2010) found that in Louisiana, estimates of the total ES flows provided by the Mississippi River Delta range between $12 billion and $47 billion each year (2007 U.S. dollars [USD]). The asset value, which is calculated from the estimated flow of benefits the environment provides over a 100-year period, can be used as another form of ESV (Batker *et al.*, 2010). Based on the annual ES flows, the Mississippi River Delta has a total economic asset between $330 billion and $1.3 trillion, using a 3.5% discount rate (Batker *et al.*, 2010). In addition, the authors created an account of the ES provided by the Mississippi River Delta for 11 ES in different ecosystem types.

CPRA uses ES data to quantify the value of Louisiana's coast and as a call to support actions intended to preserve the working coast. For example, the 2017 Louisiana Coastal Master Plan states:

> *Coastal Louisiana's contribution to the nation's economy runs into the hundreds of billions of dollars each year, and our coastal wetlands are central to these contributions. From an economic standpoint alone, restoring the wetlands makes sense. Whether you look at it from the vantage point of an economist, an ecologist, or a coastal resident, the value of the landscape is clear.* (CPRA Staff, 2017, p. ES-13)

In the 2017 Coastal Master Plan, CPRA modeled how land cover will change in the future under various environmental conditions to showcase that the projects proposed by the Coastal Master Plan will help with land loss (CPRA Staff, 2017). These models fall into two major scenarios: a future with action (FWA) and a future without action (FWOA). The models are based on eustatic sea-level rise, subsidence, tropical storm intensity, tropical storm frequency, precipitation, and evapotranspiration. To determine how CPRA's modeled changes affect the larger socioecological system for the entire coastal zone, this study is the first, to our knowledge, to combine ES data with land cover data to show how ES provisioning is spatially distributed and how a FWA *vs.* a FWOA affects the level of ES provisioning, a proxy for the socioecological system in coastal Louisiana.

Although the ES framework is used as the rationale for valuing and protecting coastal Louisiana, limited studies have a detailed breakdown of all ES solely found in the coastal zone of Louisiana. Batker *et al.* (2010) used ESVs from other states to fill the gaps in their ESV data for the coastal zone and noted the lack of data for various ES. In Louisiana, there are large data gaps in the full understanding of the ES and economic benefits that the coastal zone provides the state (CPRA Staff, 2017). This study seeks to fill some of the gaps presented in Batker *et al.* (2010) and CPRA Staff (2017) as the first, to our knowledge, to perform a meta-analysis related to ES in the Louisiana coastal zone, and it is focused on breaking the valuations down into coastal systems to aid in utilization of these values for coastal environmental policymaking.

METHODS

Coastal wetlands are considered open-access nature; thus, in policymaking, they tend to be undervalued (Brander, Florax, and Vermaat, 2006). Coastal restoration has brought the value of Louisiana's wetlands to the front of policy decisions. The utilization of ES values in the Louisiana Coastal Master Plan invites in-depth study of all services provided by the wetlands in Louisiana.

Study Objectives and Location

This study aims to provide a detailed breakdown of all ES that have been valued for Louisiana's wetlands. The objectives of this study were to (1) determine the current monetary ES values for all services of fresh, brackish, and saltwater wetlands in coastal Louisiana for all units of valuation (including annual ES flows and ES stocks) and (2) identify how ES provisioning across the wetland types will change in a FWA and a FWOA. The site for this study is the State of Louisiana's Department of Natural Resources Coastal Zone, established in Louisiana Revised Statues Article 49 §214.24 (Angelle *et al.*, 2010).

Data Sources

Rather than conducting a traditional literature review, established ESV online databases, BlueValue and the National Ocean Economics Program (NOEP), were used. These two databases have readily available primary ESVs for coastal and marine ecosystems. BlueValue is an online database of coastal and ocean valuations through 2014 and is likely the most complete database of marine and coastal ESV studies (BlueValue, 2023). Search criteria in the BlueValue database included all ES available, all ES methodologies, and the entire temporal range of the database for the state of Louisiana. In BlueValue, 25 studies fit this criterion and were included in the initial database. NOEP does not compile a database of ESVs but produces a searchable bibliography of marine and coastal ES studies for 2004–19 (NOEP, 2020). In NOEP, a search for nonmarket valuation studies was conducted. For the search, NOEP has dropdown options to aid the researcher. For the categories of title, authors, and keywords, no selection was specified. For publication type, publication year, recreational activity, assets valued, methodology, and nonuse values, the selection was "Any." For location, "Louisiana" was selected, and for data source, "Original" was selected.

Seven studies in NOEP met the search criteria. To account for studies after 2019 and to cross-check for missing studies in BlueValue and NOEP, a search on Web of Science for the key terms "ecosystem services," "valuation," and "Louisiana" was conducted. Ten additional studies were added from the Web of Science search. While reading the studies presented in these three sources, additional studies that were referenced were noted, which resulted in adding four papers to the initial database. Many of the included studies contained multiple ESVs within their study. From these four sources, the initial ES database for Louisiana's coastal environments contained 46 studies and 168 ESVs for 1974–2019 (Table 1).

For assurance of data in the BlueValue database, four studies were selected at random to cross-check ES values and supplementary information provided by BlueValue. This includes units, methods of valuations, ecosystem type, and service valued. This quality assurance and quality control of the data led to exclusion of studies from the database (Supplementary Table 1). The exclusionary process resulted in a decrease in the number of studies and valuations included in the coastal Louisiana ES database (Table 1).

After initial exclusions, numerous discrepancies were found in the ES values presented in BlueValue data. Of the 70 ESVs, 65 valuations had at least one mistake (93%). Major issues with the valuations included incorrect ecosystem listed (40%), incorrect ES (17%), incorrect ESV (20%), incorrect or absent units (17%), and incorrect valuation methodology (7%). There were also ESVs present in the literature that were absent from the database (60%), as well as ESVs present in the database that were absent from the literature (3%).

Creation of a Coastal Louisiana ES Database

The present study is concerned with the ES provided by coastal environments in Louisiana. ESVs in the four data sources were taken and assigned to freshwater, brackish, or saltwater systems. This will aid in comparing the ESVs for each of those systems. From the database, ecosystems that had ESVs included freshwater, brackish, saltwater, barrier island, and oyster reef systems. Some studies listed their study ecosystem as "coastal wetlands" and did not indicate a specific salinity gradient in their valuation. For this study, those studies' valuations were included in freshwater, brackish, and saltwater analyses. In contrast, studies that stated a specific ecosystem, such as "tidal marsh" or "oyster reefs," were aligned with the related salinity gradient. Because of ecological and hydrological similarities, studies on tidal marshes have their values included in the saltwater system analyses and oyster reefs are included in brackish system analyses. Only one study focused on barrier island valuations, namely, Elmer's Island; thus, it was added to the saltwater system for analysis. A detailed description at the study level for ecosystem conversion for this database is in Table 2. From these studies, a comprehensive database of all ESVs in Louisiana's coastal zone was created, based on the previously discussed salinity gradient from freshwater to saltwater systems.

Meta-Analysis

All ESVs in the database were converted to 2022 USD using the Consumer Price Index Inflation Calculator (Bureau of Labor Statistics, 2022). ES valued in this meta-analysis

Table 1. *Details of ESVs and studies included in the initial data-collection database from each data source in the meta-analysis and the final database after the exclusion process.*

Data Source	No. of Studies		No. of Valuations		Years Included
	Initial	Final	Initial	Final	
BlueValue	25	14	109	70	1974–2014
NOEP	7	2	28	24	2006–19
Web of Science	10	5	24	20	2012–19
Referenced in other paper	4	2	7	4	2004–15
Total	46	23	168	118	1974–2019

Duplicate studies found within multiple data sources are not included in the total. Years included in the initial and the final database are the same.

included culture, disturbance regulation, fisheries, habitat, primary production, nutrient regulation, gas regulation, recreation, waste regulation, and total economic value (TEV). See Meli *et al.* (2014, table 1) for descriptions of principal wetlands ES. The values analyzed by unit type included seven annual flow units (per acre per year, all acres per year, per person per year, per household per year, per boat per year, per user per year, and per person per trip) and three stock units (per household, per acre, and per person). The minimum, maximum, ranges, and average ± 1 standard deviation estimates of each of the ES in the three coastal systems by each unit type were calculated. The analysis did not focus on defining the methodologies used for the ESVs, just on ecosystem and unit type. Results presented here focus on per acre per year, all acres per year, and per acre. For other units, see the published data archive in the Knowledge Network for Biocomplexity (van Heerden and Snyder, 2023).

Spatial Analysis

All spatial analyses were conducted in ArcGIS Pro version 3.0.3. ESVs from the database included ecosystem classifications on a salinity range from saltwater to freshwater. There are different biomes and ecological features within this gradient; however, the ESV primary data provided the basis for the characterization into freshwater, brackish, and saltwater wetlands. Spatial analysis focuses on these three ecosystem classifications. Land cover data from the U.S. Geological Survey (USGS) 2021 vegetation survey for coastal Louisiana was used, which combines aerial helicopter surveys, an analysis of NOAA's Coastal Change Analysis Program, and National Landcover Database data to house an output raster dataset for Louisiana (Nyman *et al.*, 2021). This initial raster dataset was clipped to the coastal zone of Louisiana for the remainder of analyses. The USGS raster grid codes were swamp, fresh, intermediate, brackish, saline, water, and other.

The raster was reclassified based on the grid codes into five categories: water (coincides with water), development and agriculture (includes other), freshwater (includes swamp and fresh), brackish (includes intermediate and brackish), and saltwater (coincides with saline). All spatial analyses were conducted in the North American Datum (NAD) 1983 State Plane Louisiana South Federal Information Processing System (FIPS) 1702 (meters) projection for its application with minimal distortion of area within that zone (Price, 2016). With these classifications, the raster was vectorized. The geodesic area of each of the polygons in U.S. survey acres was calculated. Summary statistics were run for each type of wetland and totaled the acres. For addition of ES, the polygons were merged based on ecosystem type and cross-checked so that the total acreage in the merged layer matched the summary statistics. From the merged layer, the total ES data were joined from the meta-analysis based on the ecosystem type and the total annual ES flow was calculated for all acres of freshwater, brackish, and saltwater wetlands found in the coastal zone.

To compare future ES provisioning in a FWA and a FWOA, CPRA's land change modeling dataset (CPRA, 2017) was used. This dataset includes predicted land change in a FWA and a FWOA in 10-year increments for the next 50 years under low, medium, and high environmental scenarios. The rasters were vectorized to create polygon feature classes. To create a future land cover map by wetland type, the land loss for each predicted scenario from the 2021 land cover data was erased. The union tool was used to add in the new land predicted to be built under the future scenarios. The outputs were polygon feature classes of predicted land cover under the 30 scenarios for each coastal system type, including freshwater, brackish, saltwater, and new land. Land area in U.S. survey acres was calculated with the same methodology as used previously.

New land was given an ES value equal to that of freshwater wetlands. This is because the locations of land building come from either natural deltaic land building from freshwater rivers, such as the Atchafalaya Delta (Xu and Mena, 2023), or manmade diversions on the Mississippi River and its tributaries (Kenney *et al.*, 2013). This analysis extrapolated that new land would provide relatively similar ES values as freshwater wetlands because of this hydrological similarity (Carpenter *et al.*, 2007).

RESULTS

Freshwater wetlands had ESVs for disturbance regulation, fisheries, gas regulation, nutrient regulation, primary production, recreation, waste regulation, and TEV. Brackish wetlands had ESVs for disturbance regulation, fisheries, primary production, recreation, waste regulation, and TEV. Saltwater wetlands had ESVs for disturbance regulation, fisheries, primary production, recreation, waste regulation, and TEV. Table 3 presents the details of how many valuations are present for freshwater, brackish, and saltwater systems by the three unit types. All calculations of the minimum, maximum, range, average, and standard deviation for all ES within those three ecosystems and by the three units are in Supplementary Table 2. All

Table 2. *ES studies in the coastal Louisiana ES database based on system classification.*

Included Studies	Ecosystem Types Presented in Article	Justification of System Classification	System in Database
Farber, 1987	Freshwater and saltwater wetlands	Authors stated that they were valuing the range from freshwater to saltwater wetlands	Freshwater, brackish, and saltwater
Costanza, Farber, and Maxwell, 1989[†‡]	Saltwater wetlands and brackish marsh	Authors stated specific ecosystem	Saltwater and brackish
Petrolia, Interis, and Hwang, 2014	Coastal wetlands	Authors stated no specific salinity gradient	Freshwater, brackish, and saltwater
Barbier *et al.*, 2013	Coastal wetlands	Authors stated no specific salinity gradient	Freshwater, brackish, and saltwater
Landry *et al.*, 2011	Coastal wetlands	Authors stated no specific salinity gradient	Freshwater, brackish, and saltwater
Gosselink, Odum, and Pope, 1974[‡]	Tidal marsh	Authors stated specific ecosystem	Saltwater
Southwick, Foster-Turley, and Allen, 2008[‡]	Coastal wetlands, saltwater wetlands, and open water	Authors presented multiple ES values, ranging from saltwater to freshwater ecosystems	Freshwater, brackish, and saltwater
Barbier, Acreman, and Knowler, 1997[‡]	Saltwater wetlands	Authors stated specific ecosystem	Saltwater
Bergstrom *et al.*, 1990	Coastal wetlands	Authors stated no specific salinity gradient	Freshwater, brackish, and saltwater
Caffey, Paudel, and Hall, 2003[‡§]	Saltwater wetlands and barrier islands	Authors stated specific ecosystem	Saltwater and barrier islands
Whitehead and Haab, 2001	Coastal wetlands	Authors stated no specific salinity gradient	Freshwater, brackish, and saltwater
Adusumilli, 2015	Coastal wetlands	Authors stated no specific salinity gradient	Freshwater, brackish, and saltwater
Petrolia and Kim, 2011[‡]	Saltwater wetlands	Authors stated specific ecosystem	Saltwater
Petrolia, Moore, and Kim, 2011[‡]	Saltwater wetlands	Authors stated specific ecosystem	Saltwater
Kim and Petrolia, 2013	Coastal wetlands	Authors stated no specific salinity gradient	Freshwater, brackish, and saltwater
Farber, 1996[†]	Coastal wetlands and brackish marsh	Authors included values related to coastal wetlands and to brackish marsh	Freshwater, brackish, and saltwater
Cardoch *et al.*, 2000[‡]	Saltwater wetlands	Authors stated specific ecosystem	Saltwater
Breaux, Farber, and Day, 1995	Coastal wetlands	Authors stated no specific salinity gradient	Freshwater, brackish, and saltwater
Humphries and La Peyre, 2015[†‖]	Brackish marsh and oyster reefs	Authors stated specific ecosystem	Brackish
Bergstrom, Dorfman, and Loomis, 2010[†]	Estuarine environments	Authors stated specific ecosystem	Brackish
Jenkins *et al.*, 2010[¶]	Freshwater wetlands	Authors stated specific ecosystem	Freshwater
Rutherford, 2017[¶]	Freshwater wetlands	Authors stated specific ecosystem	Freshwater
LDWF, Socioeconomics Research and Development Section and Marine Fisheries Division Staff, 2004[‖]	Oyster reefs	Authors stated specific ecosystem	Brackish

[¶] *Studies with valuations of specifically freshwater services.*
[†] *Studies with valuations of specific brackish services.*
[‡] *Studies of specific saltwater services.*
[§] *Studies with specific barrier island services.*
[‖] *Studies with specific oyster services.*
All other studies did not state a specific type of environment within the coastal zone but just used the broad "coastal wetlands" ecosystem classification.

Table 3. *Total ESV estimates for each service within each system for per acre per year, ES flows for all acres per year, and ES stocks for per acre included in the coastal Louisiana ES database.*

Service	Per Acre per Year	All Acres per Year	Per Acre
Brackish			
Disturbance regulation	1	0	2
Fisheries	2	1	5
Primary production	1	0	0
Recreation	1	5	0
TEV	1	1	1
Waste regulation	1	1	1
Total	7	8	10
Freshwater			
Disturbance regulation	1	0	2
Fisheries	0	3	0
Gas regulation	1	0	0
Nutrient regulation	1	0	0
Primary production	1	0	0
Recreation	2	5	0
TEV	2	1	1
Waste regulation	0	1	3
Total	8	10	6
Saltwater			
Disturbance regulation	2	1	3
Fisheries	5	3	7
Primary production	1	0	0
Recreation	1	6	2
TEV	2	1	3
Waste regulation	3	2	4
Total	14	13	19

ESVs are rounded to the nearest $100 if greater than $1000 and to the nearest $10 if less than $1000.

Comparison of ESVs across the Systems

ESVs were compared for the three systems for ES including disturbance regulation, recreation, primary production, fisheries, and waste regulation (Table 4). What follows are qualitative comparisons between units and systems.

Per Acre per Year Comparison

A cross-ecosystem ESV comparison was conducted on a unit basis of per acre per year (Figure 1). Waste regulation had the highest ESVs and disturbance regulation had the lowest across the systems. Freshwater and brackish wetlands had the highest ESVs for disturbance regulation ($360). Saltwater wetlands had the highest ESVs for fisheries ($1700) and waste regulation ($7900). Brackish wetlands had the highest ESV for primary production ($2800). Gas regulation and nutrient regulation were only valued in freshwater wetlands and had an average ESV of $4700 and $4300, respectively. Saltwater and brackish wetlands had the highest ESVs for recreation ($740). When all ESVs for each service were combined, saltwater wetlands had a total ESV of $12,100 per acre per year, compared with a TEV of $13,700. Brackish wetlands had a total ESV of $4100 per acre per year, compared with a TEV of $1000.

Freshwater wetlands had a total ESV of $11,700 per acre per year, compared with a TEV of $1900. When comparing the total ESV calculated from all services, saltwater wetlands had the highest value per acre per year, followed closely by freshwater wetlands (Figure 2).

Table 4. *Calculation of total ESVs by system and unit type.*

Service Valued	Saltwater	Brackish	Freshwater
Per acre per year			
Disturbance regulation	310	360	360
Fisheries	1700	60	—
Gas regulation	—	—	4700
Primary production	1900	2800	1900
Nutrient regulation	—	—	4300
Recreation	740	740	400
Waste regulation	7900	130	—
TEV	13,700	1000	1900
Total	12,550	5090	11,660
All acres per year			
Disturbance regulation	7,890,600	—	—
Fisheries	160,621,500	85,282,000	31,285,700
Recreation	502,208,100	459,477,700	635,679,000
Waste regulation	1,723,200	3,319,900	3,319,900
TEV	11,246,400	11,246,400	11,246,400
Total	672,443,400	548,079,600	670,284,600
Per acre			
Disturbance regulation	1700	60	60
Fisheries	2600	1200	—
Recreation	320	—	—
Waste regulation	122,700	15,700	29,000
TEV	197,100	10,800	10,800
Total	127,310	16,960	29,060

(Column header "System" spans Saltwater, Brackish, Freshwater.)

TEVs are not included in the calculated totals presented here. Values are rounded to the nearest $100 and presented in 2022 USD. Dashes are services with no valuations under that unit type (per acre per year, all acres per year, or per acre).

All Acres per Year Comparison

On the basis of per-year annual flow, recreation had the highest average ESVs and disturbance regulation had the lowest for all ecosystems (Table 4). Disturbance regulation was only valued for saltwater wetlands and averaged an ESV of $7,890,600. Saltwater wetlands had the highest ESV for fisheries ($160,621,500). Freshwater wetlands had the highest ESV for recreation ($635,679,000). Brackish and freshwater wetlands had the highest ESV for waste regulation ($3,319,000). Taking the sum of all ESVs for each service within each system, saltwater wetlands had a total ESV of $672,443,400, brackish wetlands had a total ESV of $548,079,600, and freshwater wetlands had a total ESV of $670,284,500. From this data, the coastal wetlands of Louisiana have a total annual ES flow value of $1,890,807,600. This is comparable to the TEV of each system, which is $33,739,200.

Per Acre Stock Value Comparison

Waste regulation had the highest ESVs, and recreation had the lowest. Saltwater wetlands had the highest ESVs for disturbance regulation ($1700), fisheries ($2600), and recreation ($320). Freshwater wetlands had the highest ESV for waste regulation ($29,000). Combining the ESVs for each service, the total ESV for each system is as follows: Saltwater wetlands provide a value of $127,300, compared with a TEV of $197,100. Brackish wetlands provide a value of $16,900, compared with a TEV of $10,800. Freshwater wetlands provide a value of $29,100, compared with a TEV of $10,800.

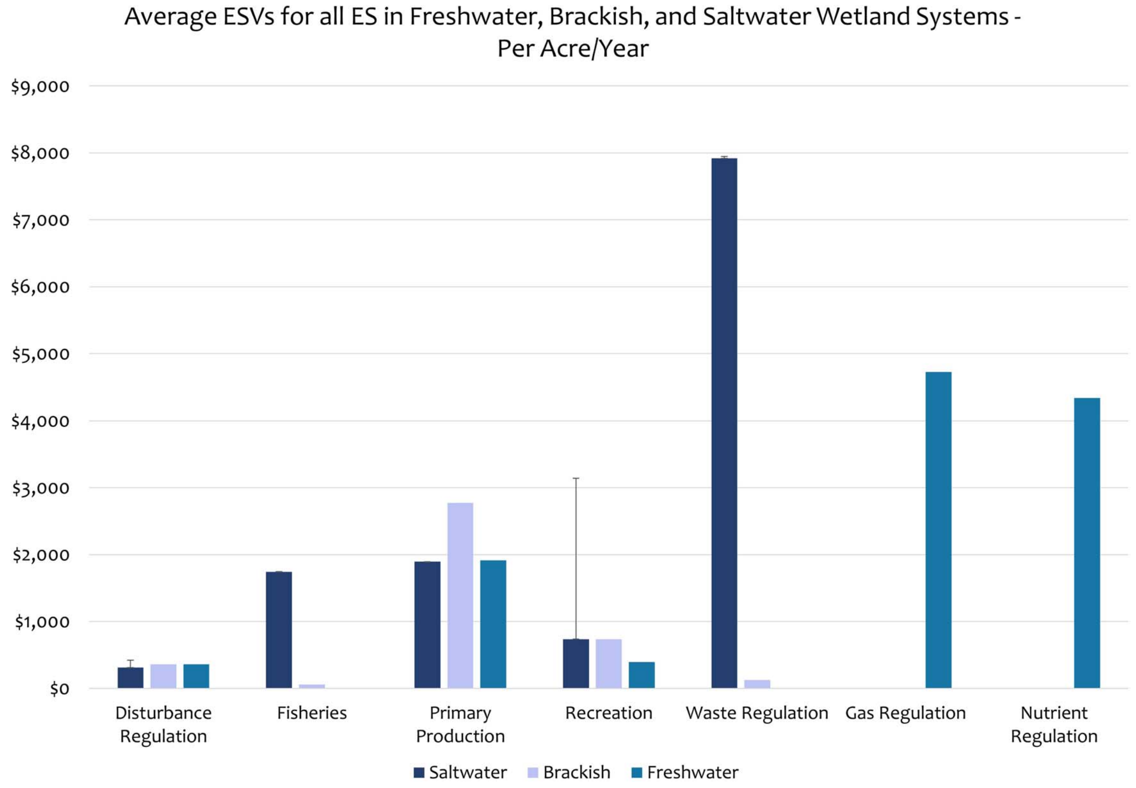

Figure 1. Comparisons of the mean annual ES provided by saltwater, brackish, and freshwater systems in an annual flow unit of per acre per year. Columns that do not have a standard error bar only included one value in the average calculation. Units are in 2022 USD.

Comparison of Values for Each of the Services within the Same System

The ESVs for each of the services found within the same ecosystem type were compared.

Saltwater System

Per acre per year, waste regulation had the highest average ESV ($7900) for the saltwater system. Disturbance regulation had the lowest ($310). Between those, fisheries equaled $1700, primary production equaled $1900, and recreation equaled $740. For all acres per year, the greatest difference in ESVs was between recreation and waste regulation. Recreation was valued at $502 million, fisheries were valued at $160 million, disturbance regulation was valued at $7.9 million, and waste regulation was valued at $1.7 million. When evaluating stock ESVs, they ranged from $320 for recreation to $122,700 for waste regulation. The values between those included $1700 for disturbance regulation and $2600 for fisheries.

Brackish Water System

For the flow per acre per year, primary production had the highest ESV ($2800) in the brackish system. Fisheries were the lowest ($60). The values between those included $360 (disturbance regulation), $130 (waste regulation), and $740 (recreation). When valuing ES for total acres per year, the largest ESV was $459 million for recreation. The smallest was $3.3 million for waste regulation. The value between those included $85.3 million for fisheries. Stock values in the brackish system on a per-acre scale ranged from $60 for disturbance regulation to $15,700 for waste regulation. Fisheries were valued in the middle at $1200.

Freshwater System

For the freshwater system, annual flow values on a per-acre scale ranged from $4700 (gas regulation) to $360 (disturbance regulation). ESVs between those two included $4300 (nutrient regulation), $1900 (primary production), and $400 (recreation). On a broader scale of all acres per year, the largest value was recreation, with an average value of $635 million. The smallest was waste regulation, with a value of $3.3 million. Fisheries were valued at $31.3 million. For stock values on a per-acre scale, two services were valued. Disturbance regulation was the smallest ($60), and waste regulation was the highest ($29,000).

Spatial Analysis

From the reclassification of the 2021 land cover dataset (**Figure 3**), the total acreage calculations found 2,151,500 acres of freshwater wetlands, 1,303,000 acres of brackish wetlands, and 456,500 acres of saltwater wetlands in the coastal zone of Louisiana, rounded to the nearest hundred. This totaled 3.91 million acres of wetlands in the coastal zone. In total, freshwater wetlands provide a total annual ES flow value of $25.2 billion, brackish wetlands provide a value

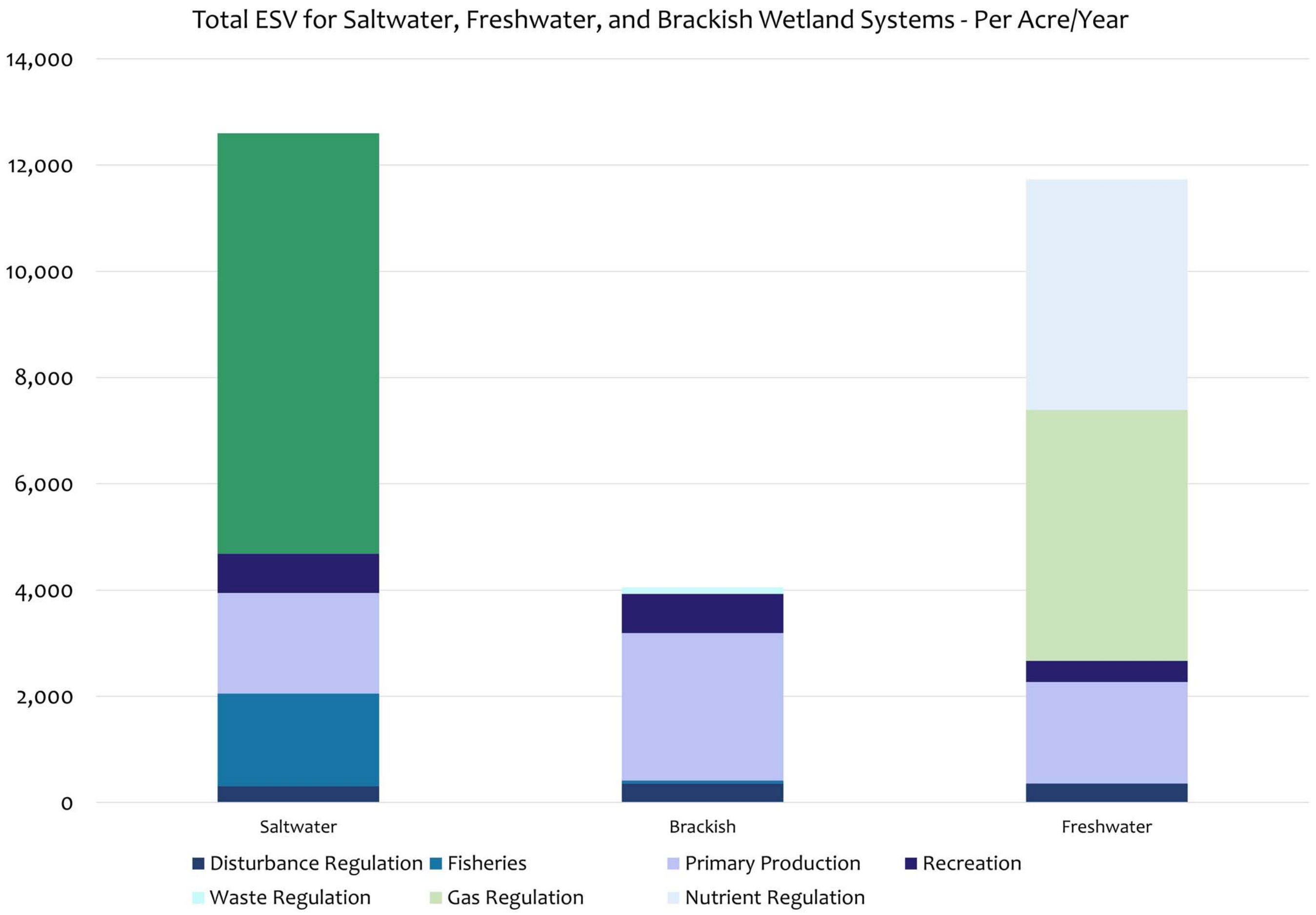

Figure 2. Total ESV calculated for each system, per acre per year. Units are in 2022 USD.

of $5.3 billion, and saltwater wetlands provide a value of $5.6 billion. The total annual flow value for all acres of wetlands in coastal Louisiana is $36.3 billion (Table 5).

The total annual flow ESVs for each of the ES found in freshwater, brackish, and saltwater wetlands are presented in Table 6. For all acres of wetlands in coastal Louisiana, freshwater wetlands provide a higher ESV for four of the six ES valued: disturbance regulation ($774 million), gas regulation ($10.1 billion), primary production ($4.11 billion), and nutrient regulation ($9.33 billion). Brackish wetlands provide the highest total ESV for recreation ($959 million). Saltwater wetlands provide the highest total ESV for waste regulation ($3.62 billion).

FWA *vs.* FWOA

Across all environmental scenarios (low, medium, and high), a FWA ensures a higher level of annual ES flows and ES stocks than does a FWOA. However, the largest differences in future ES flows and stocks in the predictions are found in the high environmental scenario. Currently, there are 3.91 million acres of wetlands. Fifty years from now, under the low environmental scenario, a FWOA results in a 17% wetland loss, compared with an 11% loss under a FWA. For the high environmental scenario, a FWA will have a loss of 45% of wetland acreage, compared with 62% in a FWOA.

Regardless of a FWA or a FWOA, freshwater wetlands maintain the highest levels of acreage, ES flows, and stocks for both high and low environmental scenarios (Supplementary Table 3). In a low environmental scenario, a FWA predicts $2.55 billion more in annual ES flows than does a FWOA. Of that amount, $1.8 billion is found in freshwater wetlands. In a high environmental scenario, a FWA predicts $6.08 billion more in annual ES flows than does a FWOA. Freshwater wetlands account for $5.22 billion of that total.

To visualize these losses, Figure 4 highlights the spatial land loss under these two future scenarios in the high environmental scenario, the year 50 prediction, and their related ES annual provisioning. The largest spatial extent of losses of acreage are from saltwater and brackish wetlands across the coastal landscape. In a FWOA, there are only three locations with significant land building: the Wax Lake Delta front, the Atchafalaya Delta front, and along the Birds Foot Delta front. However, in a FWA, land building is more spread out along the freshwater–brackish wetland boundaries. There are also large areas of land building in the SW region,

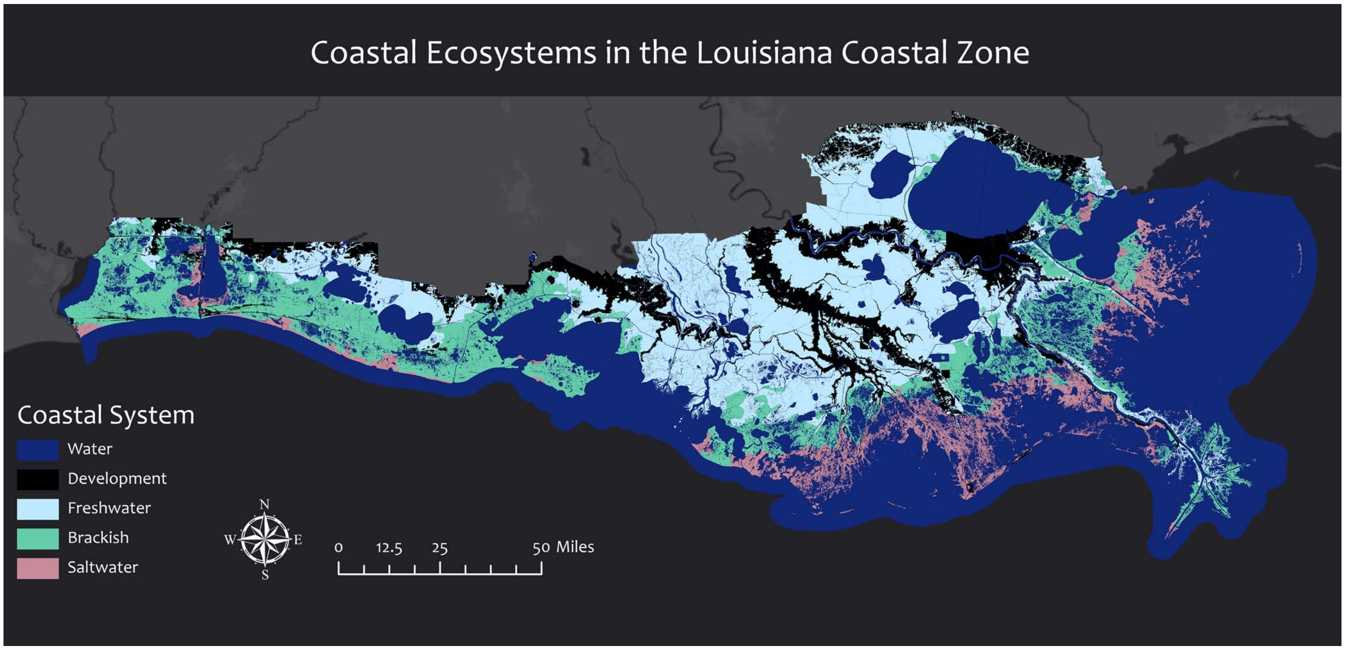

Figure 3. Distinguished coastal systems for acreage calculation, based on 2021 vegetation data from USGS.

whereas none occurs in a FWOA. In 50 years, 38% of wetlands will remain in a FWOA, compared with 55% in a FWA. A FWA provides an annual ES provisioning value of $22.7 billion, whereas a FWOA provides $15.9 billion. The trend across the coastal zone of Louisiana, whether there is action in the future, is a significant wetland conversion to open water and land loss across the entire landscape.

DISCUSSION

The present study adds to the literature with respect to identifying a preliminary spatial distribution of ES provisioning of freshwater, brackish, and saltwater wetlands in coastal Louisiana. Freshwater and saltwater wetlands had a similar per-acre flow value. In Louisiana, a key focus of restoration has been within brackish and saltwater systems, such as barrier island restoration and marsh creation (CPRA Staff, 2017), but this study suggests that freshwater wetlands serve a similar economic value as saltwater. Coastal restoration in Louisiana will rely heavily on freshwater and sediment diversions from the Mississippi River into coastal wetlands (CPRA Staff, 2017). This finding suggests that the introduction of freshwater may provide different services and alterations to the ecological communities in those brackish saltwater systems but may continue to provide high levels of ES provisioning. Coastal development and population density have a large influence on wetland health and land loss with climate change (Das *et al.*, 2020; Klemas, 2012). The spatial proximity of coastal development to freshwater wetlands may serve as a driver of future ES provisioning in the coastal zone and should be a topic of future research.

When comparing the ESVs among the services, cultural services, like recreation, tended to be valued higher than regulatory services, such as storm surge and flooding regulation, per acre per year. This suggests that protecting the culture of coastal Louisiana should be treated similarly to protecting the regulatory and provisioning services. In addition, some ES have higher substitutability with manufactured goods. Environmental policymaking for restoration builds on this idea (Gollier, 2019), giving provisioning and regulating

Table 5. *Calculation of total acreage and annual ES flow for all acres of freshwater, brackish, and saltwater wetlands in coastal Louisiana.*

Ecosystem Type	Total Acres in Coastal Louisiana	Total Annual ES Flow (USD)
Freshwater	2,150,500	25,233,382,600
Brackish	1,303,000	5,280,110,900
Saltwater	456,500	5,572,384,200
Total	3,910,000	36,255,877,700

Table 6. *Calculation of total annual ESVs for each service in each coastal wetland type based on spatial analysis.*

ES	Coastal System Freshwater	Brackish	Saltwater
Disturbance regulation	774,180,000	469,080,000	141,597,200
Fisheries	—	73,945,300	795,406,500
Gas regulation	10,160,089,000	—	—
Primary production	4,111,648,500	3,614,326,600	864,492,300
Nutrient regulation	9,325,632,600	—	—
Recreation	851,487,700	959,397,300	336,120,400
Waste regulation	—	$163,487,400	$3,615,082,800

Values are rounded to the nearest $100 and presented in 2022 USD. Dashes are services with no valuation data for ESVs in per acre per year.

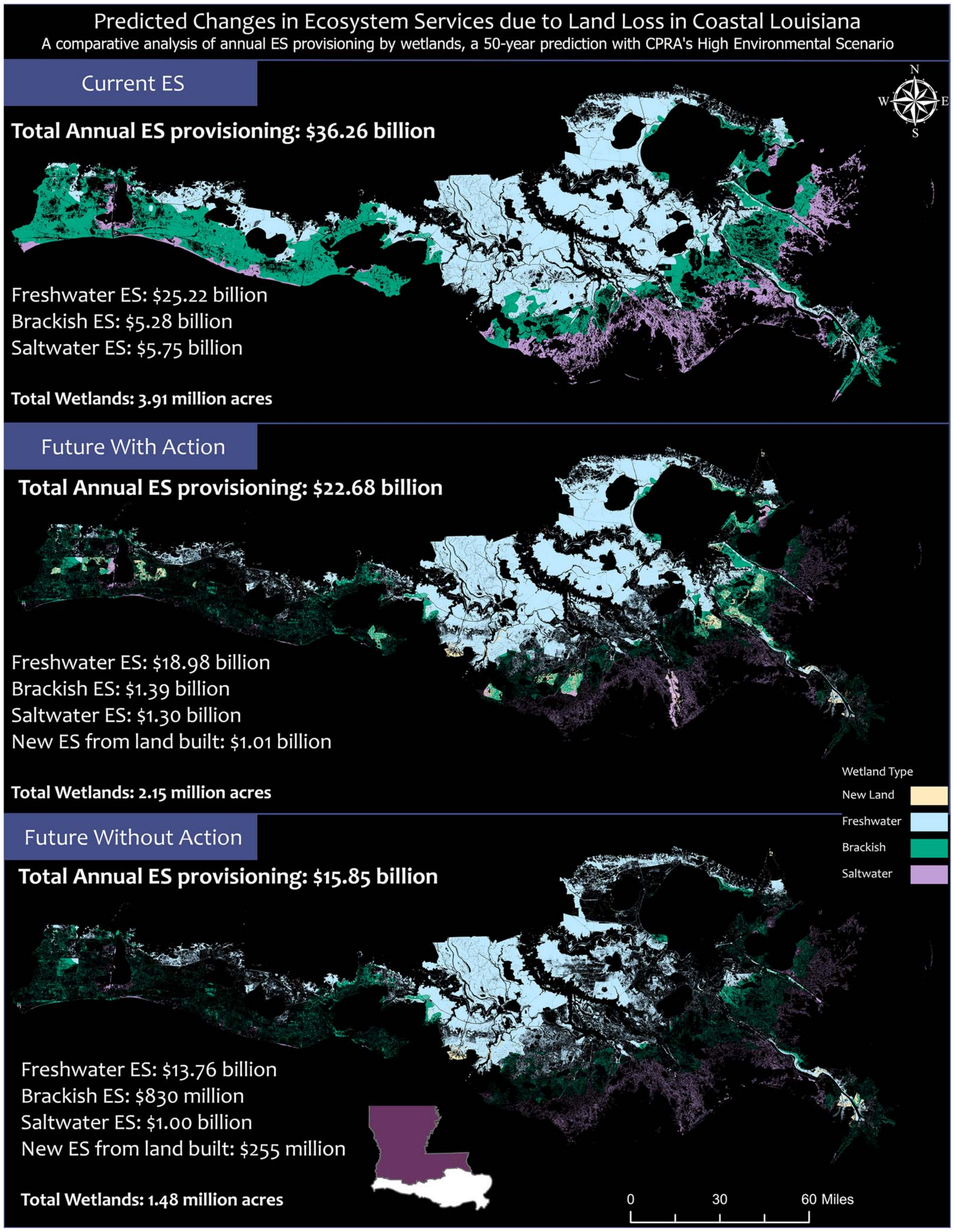

Figure 4. Predicted changes in ES because of land loss in coastal Louisiana. The top map shows the current ES provisioning in freshwater, brackish, and saltwater wetlands for the coastal zone. The middle map shows the predicted ES provisioning for these wetlands under a FWA. The bottom map shows future ES provisioning in a FWOA for coastal Louisiana.

services higher substitutability than other ES, such as culture. This nonsubstitutability for cultural ES may inherently increase its priority in creating policy that acknowledges the role of the dynamic relationship between people and nature. More research is needed on how Louisiana coastal residents are using and placing value on coastal wetlands in Louisiana. By distinguishing whether economic utility or cultural services are largely driving the nature–society relationships in coastal Louisiana, researchers and policymakers can increase the effectiveness of communicating environmental policy decisions regarding coastal restoration.

Distinguishing the differences in ES provisioning by ecosystem type can provide a more accurate prediction to the spatial extent that these ES will change with coastal land loss and coastal restoration activities. For the 3.91 million acres of wetlands in the coastal zone, the total annual ES flow value is $36.3 billion. This is comparable to the TEV of $33.7 billion from the data, and it aligns with the range presented in CPRA Staff (2017). However, for ESVs on the basis of total acreage per year, the total annual flow is $1.89 billion. This is significantly lower than the TEV and spatial calculation value for total annual flows. This finding suggests that when conducting primary ESV studies, researchers should consider the scale of the study, because it shows that ESVs calculated on a larger scale tend to be undervalued. The present findings build on those reported in Batker *et al.* (2010) by updating the ESVs provided by the Louisiana state coastal zone, and they complement those of Meli *et al.* (2014). Some studies have targeted ESVs for specific coastal restoration policy actions in Louisiana, such as comparing the costs and benefits of marsh creation and diversions (Caffey, Wang, and Petrolia, 2014), evaluating the economic performance of nearshore and offshore sediments for barrier island restoration (Caffey *et al.*, 2022), and simulating economic costs and benefits for oyster reef restoration and habitat (Petrolia, Walton, and Cebrian, 2022). The results of this study serve as a guide for policymakers to have a full dataset of ESVs to be used for coastal Louisiana. The results can be used to communicate the value of Louisiana's wetlands to policymakers and to calculate how changes in the coastal landscape can alter these services. Future research should target how these different wetland types and their associated ES can be affected by different restoration strategies to better communicate people's utility and dependence on Louisiana's working coast.

The public-good characteristics of wetland environments (Brander, Florax, and Vermaat, 2006) make them a priority in environmental policymaking in Louisiana. The present study provides, to our knowledge, an original contribution in terms of creating a cross-system comparison of the ESVs in Louisiana's wetlands. Compared with previous meta-analyses of ESVs, this study extends the findings of Batker *et al.* (2010) by updating the ESV values and diversifying the units used in the meta-analysis. For a broader scope, this research identifies that although many ES are comparable across salinity gradients in wetland environments, the ESVs vary on large ranges. This provides the foundation for future primary ESV studies to acknowledge that wetland ESVs are highly variable, and studies should account for the estuarine spatial extent used in the valuation.

Numerous online databases provide ESVs for ES in the United States and around the world. The BlueValue database is promoted by NOAA's Office of Coastal Management (NOAA, 2023). These databases are more easily accessible for policymakers and professionals than searching for primary ESV literature. This is important for access to these ESVs for science communication and policymaking; however, online ESV databases should be used with caution, as noted by the large discrepancies the authors found between the ESVs in the BlueValue database and those presented in the original studies. For a completed, quality assured and quality-controlled database of the ESVs for Louisiana's coastal wetlands, refer to the published database of van Heerden and Snyder (2023) in the Knowledge Network for Biodiversity.

To our knowledge, this study was the first to spatially investigate ES provisioning in Louisiana's coastal zone and the potential losses of ES under a FWA and a FWOA. This study showed that ES are not uniformly distributed across the coastal landscape in Louisiana, and a FWA will be more effective in reducing the loss of ES than a FWOA. Land loss and related loss of wetland acreage will be the driving factor in future coastal ES values in Louisiana. Even in a FWA, the total annual ES flows will only be 60% of what they are currently. However, a FWOA will have total annual ES flows that are 40% of what they are currently. The future of coastal Louisiana, no matter what future action takes place, will result in a significant loss of annual ES flows. Compared with current ESVs for all wetlands in coastal Louisiana, differences between a FWA and a FWOA under the low and the medium environmental scenarios are minimal. However, in both, a FWA provides a higher level of ES provisioning than a FWOA. The largest difference in annual ES provisioning is found in the high environmental scenario. In that scenario, a FWA ensures 19% higher ES provisioning than does a FWOA. In 50 years, coastal Louisiana's annual ES provisioning in a FWA will be $22.7 billion, compared with $15.9 billion in a FWOA. With the current and past rates of land loss, understanding the changes in ES provisioning across the environmental scenarios allows policymakers to see the level of effect their actions are having on ES provisioning.

With roughly half of the world's populations living in coastal zones (Crowell *et al.*, 2007), it is imperative that analyses of nature–society relationships be conducted so that other states and countries have the resources to approach these large-scale land loss issues when they need them. Future research should incorporate spatial land change with these ESVs to determine the future of ES provisioning for the state. This study is geographically limited to Louisiana, but the results can be applied to regions that are and will experience coastal land loss and must decide an appropriate path of action.

CONCLUSIONS

Restoration of Louisiana's coastal wetlands is imperative to protect the state from the coastal crisis. The present study aids policymakers in understanding how ES provisioning varies across the three major wetland types: freshwater, brackish, and saltwater. Freshwater wetlands serve a high level of annual ES provisioning per acre in comparison to other systems, which is significant for preparing to introduce freshwater into basins adjacent to the Mississippi River. The dataset created from this study is substantially more comprehensive for Louisiana than those of past studies and will allow for more accurate communications of the value of coastal wetlands for environmental policy. This research highlights the complexity in ES provisioning, summarizes the differences in ESVs for freshwater to saltwater systems, and provides policymakers and environmental managers with a new path to using the ES framework to communicate the role of ES and ESVs in Louisiana's coastal zone. The results of this study highlight the importance of identifying how ES vary spatiotemporally to increase the effective application of ES in understanding the impacts of coastal restoration.

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