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Engaging coastal community members about natural and nature-based solutions to assess their ecosystem function

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ABSTRACT

Hazards in coastal ecosystems, such as flooding and land loss, demand natural and nature-based solutions from local communities due to the protective and non-protective services they provide when compared with traditionally engineered approaches. In this context, natural solutions are those that consider conserving existing habitats whereas nature-based solutions are those created by humans. These solutions support important coastal ecosystem functions, such as nutrient uptake, fisheries habitat, soil carbon storage, and surge attenuation. Our main research questions were: (1) Based on community engagement, what are the possible natural and nature-based solutions to address coastal hazards in Breton Sound Estuary, Louisiana? and (2) How do these community co-designed nature-based solutions support various ecosystem functions? To help answer these questions, we leveraged the competency group methodology to incorporate the local needs and traditional ecological knowledge of community stakeholders into collaborative ecosystem modelling. In total, fifteen members regularly met five times over an eight-month period to design nature-based solutions to address coastal hazards. Two nature-based solutions, created marshes and restored ridges, were identified most frequently by the competency group (> 75% occurrence) in a final survey. Associated ecosystem functions of the identified solutions were assessed with simulation models to determine future ecosystem functions of nutrient uptake, fisheries habitat, soil carbon storage, and surge attenuation after 20 years. By adding created marshes to an ecosystem, our model results indicate slight increases in nutrient uptake, likely increases to fisheries habitat and soil carbon storage capacity, as well as storm surge attenuation in some areas following ridge restoration. Quantifying these ecosystem functions with management actions has been limited and is needed to assess how natural and nature-based solutions impact local communities and resource users. This novel approach to modeling ecosystem-based solutions through a collaborative modeling process with researchers and residents can be applied elsewhere to assess the viability of natural and nature-based solutions.

1. Introduction

Coastal hazards such as flooding and land loss demand natural and nature-based solutions from local beneficiaries for their protective services as well as non-protective services or co-benefits compared to typical engineered approaches of bulkheads, seawalls, levees, and jetties (van Wesenbeeck et al., 2014; Arkema et al., 2017). Natural solutions are those that consider conserving existing habitats (e.g. salt marshes, mangrove forests, etc.) and nature-based solutions are those created by humans (e.g. oyster reefs, created marshes, restored ridges, and beach nourishment; Arkema et al., 2017; Scyphers et al., 2011). These nature-based solutions can be used in natural habitat settings or the urban environment to adapt and mitigate the impacts from climate change as well as improve human health and well-being (Kabisch et al., 2016; Raymond et al., 2017).

Natural and nature-based solutions in coastal environments support important ecosystem functions, such as surge attenuation, nutrient uptake, nursery habitats for fisheries, and soil carbon storage that influence the provision of ecosystem services (Barbier et al., 2011; Carruthers et al., 2017). For example, coastal wetlands can reduce water levels and flooding risk to communities (Barbier et al., 2013; Reed et al., 2018), take up nutrients and improve water quality (Jansson et al., 1994; DeLaune et al., 2005; Rivera-Monroy et al., 2013), provide nursery habitat for the fisheries (e.g., blue crabs, brown shrimp) that recreational and commercial fisherman depend upon (Peterson and Turner, 1994; Beck et al., 2001; Minello and Rozas, 2002), and store carbon in their soils to support climate regulation (Chmura et al., 2003; Baustian et al., 2017). Quantifying these ecosystem processes/functions and their related ecosystem services overtime has been limited (Arkema et al., 2017; Sutton-Grier et al., 2018) but are needed to assess how natural and nature-based solutions are influencing local ecosystems and communities (Millennium Ecosystem Assessment, 2005, Barbier et al., 2013; Costanza et al., 2017) especially in the face of climate change (Fargione et al., 2018).

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Numerical simulation models are helpful tools to quantify the magnitude of impact of natural and nature-based solutions to coastal communities but their utility is often lacking for stakeholders (Arkema et al., 2017). Model runs can be designed to include areas with and without natural or nature-based solutions that are often already considered in local or state-level restoration plans (Baustian et al., 2018a; Coastal Protection and Restoration Authority of Louisiana, 2017) that include long-term predictions (50 year model runs with climate change scenarios; Meselhe et al., 2013; White et al., 2018). Engagement with local communities can help ground truth the initial conditions of the models and prescribe natural and nature-based solutions and environmental scenarios (Hemmerling and Barra, 2019; Landström et al., 2011; Carruthers et al., 2017) but also provides a way to build relationships and trust among community members and scientists (Hemmerling et al., 2019). However, little effort has been done to incorporate inputs from coastal communities in the early planning phases even though current coastal residents have experienced drastic wetland loss during their lifetime (~25% of 1932 land area; Couvillion et al., 2017). Our main goal was to engage local communities via a competency group methodology (Hemmerling et al., 2019; Landström et al., 2011) to assess the types of natural and nature-based solutions they would be interested in and to address the knowledge gap about the related and potential ecosystem function via modeling exercises. Two main research questions were asked: (1) Based on community engagement, what are the possible natural and nature-based solutions to address coastal hazards in Breton Sound Estuary, Louisiana? and (2) How do these community co-designed nature-based solutions support ecosystem functions?

2. Materials and methods

2.1. Natural and nature-based solutions

The focus area for assessing how natural and nature-based solutions could influence local ecosystems and communities was in the Breton Sound Estuary, an area east of the lower Mississippi River (Fig. 1) that is dominated by wetlands with shallow estuarine open water areas that drain into the northern Gulf of Mexico (Hyfield et al., 2008). Habitat types in the local ecosystem include fresh to saline marshes, estuarine open water with oyster reefs, natural ridges and levees, barrier islands including dunes, mangrove wetlands, cypress/tupelo swamp, and seagrass beds (Carruthers et al., 2017). Natural and nature-based solution options that are relevant to this ecosystem were obtained from local and state coastal management reports (Coastal Protection and Restoration Authority of Louisiana, 2017) and peer-reviewed literature (Baustian et al., 2018b; Cobb et al., 2008; Cobell et al., 2013; de Mutsert et al., 2012; Dietrich et al., 2011; Hu et al., 2018; Meselhe et al., 2013; Rivera-Monroy et al., 2013; Visser and Duke-Sylvester, 2017; Wang et al., 2017; Hijuelos et al., 2016). Coastal restoration options were discussed with community members to evaluate potential solutions for a range of coastal hazards.

2.2. Community engagement

The Breton Sound Estuary is surrounded by the local communities of St. Bernard, Hopedale, and Delacroix, Louisiana, USA. Historically, this area has experienced challenges from hurricanes (e.g., Hurricane Katrina in 2005) and the *Deepwater Horizon* oil spill in 2010. As a result of this historic hazard exposure, local communities are committed to sustaining the coastal environment that supports their daily lives (Carruthers et al., 2017). > 25 members from these communities were invited to participate in the competency group discussions. Five meetings were planned in St. Bernard Parish, LA to seek feedback and insights from local stakeholders pertaining to the condition of the nearby Breton Sound Estuary system, any existing coastal hazards, the type of natural and nature-based solutions that could help reduce those hazards, and how to develop an ecosystem model capable of testing identified solutions (Table 1). To engage with local communities, the competency group methodology was applied that utilizes collaborations among local residents and participating scientists to assess and discuss environmental knowledge controversies (Landström et al., 2011) and details are discussed in Hemmerling et al. (2019). The competency group methodology allows for residents (n = 9 in this study; including commercial and recreational fisherman, greenhouse and marina owners) to work with natural and social scientists and engineers (n = 6 in this study) (Hemmerling et al., 2019). To facilitate group discussion, five meetings (about two hours each in the evenings with dinner served to accommodate working schedules of fishermen and others) were held over an eight-month period at the Los Isleños Center in the town of St. Bernard, LA. Most of the competency group members consistently attended all five meetings. There were some meetings were a few members (both scientists and residents) could not attend, but the major time commitment was discussed with the members prior to the scheduling of the meetings. The goals of the five meetings consisted of introductions and collaborative relationship building; learning how to build an ecosystem model together; how ecosystem models are calibrated and their utility; why natural and nature-based solutions should be considered; how to design ecosystem model runs; and to review model output and gain feedback (Table 1).

The competency group meetings were organized and facilitated by social scientists whereas the ecosystem modeling and natural and nature-based solution analysis was led by engineers and ecologists. Based upon outputs of the competency group meetings, a total of 21 natural and nature-based solutions were catalogued (Hemmerling et al., 2019) with 16 of the 21 selected for modeling (labeled with the prefix P###) and evaluation based on project summary documents written during meeting #5 (Table 1). Near the conclusion of meeting #5, competency group members were given a survey form that included a series of short Likert-type scale questions and opened-ended questions (Hemmerling et al., 2019; Meselhe et al., 2020) that also included a question for members to "please list the top five restoration projects" or natural and nature-based solutions. Not all ten members listed their top five, therefore a total of 44 projects were listed. Of those listed, marsh creation and ridge restoration type projects were most common (> 75% of the total).

Marsh creation projects (P001, P009, P011, P012), and ridge restoration projects (P004, P005, P006, P007) were then further evaluated in detail for ecosystem functions (see Table 2). These projects address two major coastal hazards (land loss and storm surge) that were frequently discussed by the competency group (Hemmerling et al., 2019). The four marsh creation projects were modeled together as one holistic nature-based marsh creation solution in Breton Sound Estuary (Table 2, Fig. 1). Three of the created marshes were designed to fill in shallow open water and restore the marsh habitat and the fourth was to maintain the shoreline edge around Lake Lery (Fig. 1). Restoration of historical ridges (project numbers P004, P005, P006, P007) was the most frequently occurring project type listed on the competency group's survey (Fig. 1, Table 2), likely due to concerns arising from storm surge.

2.3. Ecosystem models and environmental scenarios

Natural and nature-based solutions were assessed by utilizing a Delft3D ecosystem model known as the Integrated Biophysical Model. The model couples hydrodynamics, nutrient dynamics, vegetation dynamics, and morphodynamics (Baustian et al., 2018b) that are representative of the wetland vegetation and estuarine open water of the associated coastal ecosystem. Environmental scenarios that included future conditions (e.g., sea level rise and subsidence, hurricane-force winds and water levels, and drought conditions) were also considered by the competency group and incorporated in the ecosystem model to evaluate areas with and without nature-based solutions. Many of the model runs included the operation of the proposed Mid-Breton

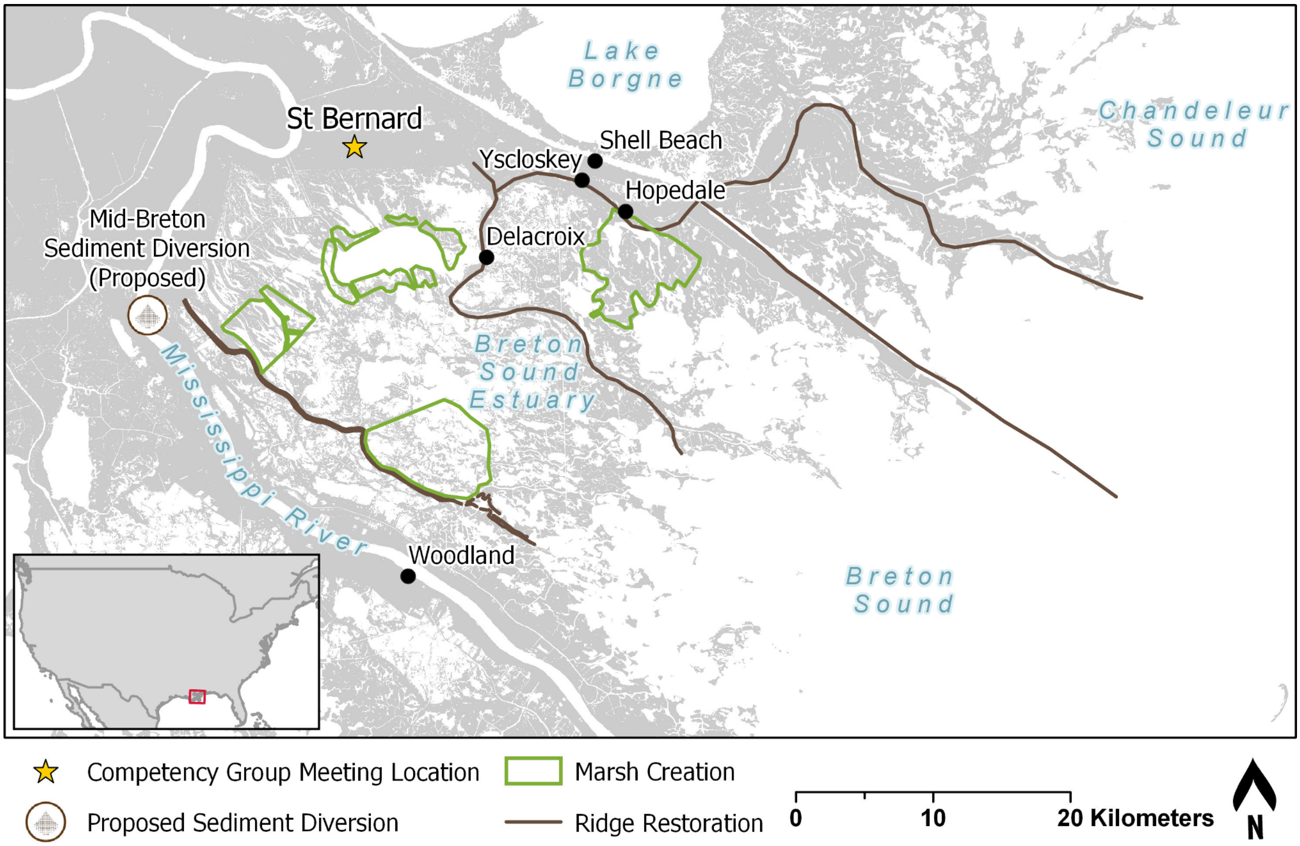

Fig. 1. Map of Breton Basin located west of the lower Mississippi River in southern Louisiana, USA with suggested nature-based solutions of marsh creation and ridge restoration.

Sediment Diversion, which included 991 $m^3\ s^{-1}$ (or 35,000 $ft^3\ s^{-1}$) of riverine water diverted from Mississippi River when it was at 28,316 $m^3\ s^{-1}$ (1,000,000 $ft^3\ s^{-1}$) with 70 $m^3\ s^{-1}$ (2,500 $ft^3\ s^{-1}$) baseflow from year 2020 to 2040.

The Integrated Biophysical Model domain was developed to cover the lower Mississippi River and its estuarine receiving basins, all of which are located south of the City of New Orleans, LA, USA (Fig. 2). The receiving basins, Barataria and Breton basins, as well as the Mississippi River Delta are primarily composed of fresh to saline herbaceous wetlands with interspersed canals and estuarine shallow lakes and bays that drain into the northern Gulf of Mexico (GOM). The Integrated Biophysical Model was calibrated using historical data measured from years 2009 and 2011 and validated with 2014 measurement data for water elevation, salinity, temperature, sediment load and accretion rates, water quality parameters including organic and inorganic nitrogen and phosphorus, and vegetation aboveground biomass. The model properly shows how salinity and water level variability affect the spatial distribution of vegetation taxa; how inundation influences vegetation biomass; how the presence of vegetation results in added flow resistance and potential trapping of mineral sediment; how organic matter accretion and mineral sediment deposition sustains wetlands; how nutrient availability/limitation affects growth; and how hydrodynamic forcing influence wetland loss through erosional processes. Detailed information about the model calibration and validation can be found in Baustian et al. (2018b)

To assess how historical ridges influence surge attenuation, the Delft3D model was coupled with the spectral wave model SWAN (Simulating Waves Nearshore, Booij et al., 1999) to consider locally generated wind waves as well as waves originating offshore. The hydrodynamic model (Delft3D D-FLOW) provides water elevation and flow field information to inform the wave model. The wave model provides wave information to the flow model for calculation of radiation stresses and combined wave-current bed shear stresses. The wave model grid was developed based on the Integrated Biophysical Model domain. Two-level nested computational domains were designed for the wave simulations (Fig. 3). The level-1 basin wide scale domain, which covers the entire Integrated Biophysical Model domain with 1.5 km grid resolution, provides water level and wave boundary conditions to the level-2 regional domain that encompasses the Breton Basin at 150 m grid resolution. Considering relatively short temporal duration of storm and cold front events (a couple of days), the morphodynamics, nutrient dynamics, and vegetation dynamics were not included in the surge attenuation modeling.

2.3.1. Model runs

Environmental scenarios that included sea level rise and subsidence were considered when designing the model runs (White et al., 2018). Three rates of eustatic sea level rise (ESLR), each with different acceleration values, were assumed for this analysis: 0.43, 0.63, and 0.83 m from 2015 through the end of 2064. These rates correspond to 1.0, 1.5, and 2.0 m of ESLR by 2100 when compared to 1992 sea level, respectively (Pahl, 2017). Relative sea level rise rates were assigned based upon these three ESLR rates and included a combination of subsidence values which varied spatially across the model domain. Previous studies have compiled subsidence measurements across coastal Louisiana and developed regional subsidence zones, with a representative range of subsidence rates for each zone (CPRA, 2012, Reed and Yuill, 2017). The medium scenario was only used for these model runs and included the 1.5 m of ESLR by year 2100. It was applied via a spatially varied subsidence rate equal to the 20th percentile value from the range of observed data within each subsidence zone described above. For example, the Breton Sound Estuary is located in a subsidence zone with a range of subsidence rates between 3 and 10 mm yr^{-1}. In this location, the resulting 20th percentile subsidence rate would be

Table 1
List of competency group (CG) meetings held at St. Bernard, Louisiana, USA to determine the most pressing coastal hazards, which natural, nature-based, and engineered solutions were being planned, and how to develop an ecosystem model to test these solutions.

CG meeting (No.)	Date	Goal	Key points by locals	Key meeting results
1	20 March 2018	Introductions	Vegetation is important; historical interest; key salinity range (8–19 ppt)	Confirmed community engagement, informative discussions
2	3 April 2018	Building a model together	Understanding wetland loss; hydrological restoration interests	Clarified model inputs and purpose
3	29 May 2018	Model calibration and utility	Concerns about subsidence assumptions in the model; marsh creation should be a parish service like maintaining roads; interested in water quality model output	Communicated concerns and interests about future changes to the model
4	25 June 2018	Natural and nature-based solutions and design model runs	Historical landscape interest (1932); hydrological restoration by creating marsh to reduce open water areas; tree plantings in forested wetlands	List of solutions and future conditions from the break out groups to design the model runs
5	10 October 2018	Review model output and gain feedback via evaluation forms	Enthusiasm for seeing their solution included in the model and the model outputs	Top five solutions from community; present this method and results elsewhere to other organizations

equal to 4.4 mm yr^{-1}. In the Breton Sound Estuary, these rates resulted in a total of 0.85 m of relative sea level rise during the 2015–2064 simulation period (0.63 m ESLR + 50 yr * 0.0044 m subsidence yr^{-1}).

Due to the short temporal duration of major storms, the surge attenuation model was simulated over a period of several days. During this simulation period it was assumed that the proposed sediment diversion (Mid-Breton Sediment Diversion) was not operational. The ridges were designed with + 1.5 m height from NAVD 88 based on the historical ridge footprint. Hurricane Katrina (2005) was used to evaluate the effect of the ridge restoration efforts on the surge attenuation. The wind fields for Hurricane Katrina were reconstructed using the National Hurricane Center (NHC)'s best track data (https://www.nhc.noaa.gov/data/#hurdat). The simulation was conducted for 3 days (28–30 August 2005).

2.4. Ecosystem functions

Ecosystem functions were quantified using a combination of model outputs and literature values for the proposed nature-based solutions of marsh creation (including the proposed Mid-Breton Sediment Diversion) and ridge restoration. Four main ecosystem functions were chosen based on the interests of the competency group (as related to the nature-based solution and the capability of the models) including: nutrient uptake, fisheries habitat, short-term carbon storage, and surge attenuation. The potential nutrient uptake was estimated based on the model output from the nutrient dynamics model (Delft3D D-WAQ) that provides a nutrient budget (sources and sinks) of the estuary (Smits and van Beek, 2013). Nutrient uptake rates (g N m^{-2} yr^{-1}) were estimated based on the modeled total influx of dissolved inorganic nitrogen (DIN) from potential sinks, such as dentification in the sediment/soils and assimilation of vegetation (Table 4). The potential fisheries habitat was estimated based on the percent land in the estuary (Minello and Rozas, 2002) The potential short-term soil carbon storage was calculated based on the area of marsh (m^2) and the short-term carbon accumulation rate (382 ± 55 g TC m^{-2} yr^{-1}) from basins in coastal Louisiana that also include fresh to saline marsh habitats (Baustian et al., 2017, Baustian et al. In Review). The potential to attenuate storm surge was estimated using Delft3D hydrodynamics (D-FLOW) coupled with SWAN model output (Booij et al., 1999).

3. Results

3.1. Natural and nature-based solutions

Coastal Louisiana's deltaic ecosystem contain a level of habitat diversity that is well suited to support numerous opportunities to incorporate natural and nature-based solutions (Table 3). Table 3 is not intended to be a comprehensive coverage of all natural and nature-based solutions; rather it provides a template of how various solutions can be used alone or in combination with engineered solutions to restore an ecosystem function and provide an ecosystem service. It also provides examples of what modeling tools are available to perform the analysis. Natural solutions considered irrelevant to coastal Louisiana include coral reefs and marram grass as listed in van Wesenbeeck et al. (2014).

3.2. Ecosystem functions

Three main model runs were utilized to illustrate and evaluate how proposed nature-based solutions (eight projects in total) could influence ecosystem functions (Fig. 1, Table 2). To serve as a control or a business as usual condition for the competency group, the first model run included no projects (P000) or no new nature-based solutions (Table 2). All model output was evaluated at year 20 to assess the potential ecosystem function with or without nature-based solutions (Table 2).

Table 2
List of modeled projects (P###) that include proposed natural and nature-based solutions and environmental scenario that was discussed with the competency group and the related potential ecosystem function.

Project No.	Project Description	Nature-based Solutions	Scenario	Ecosystem Function Evaluated
P000	Proposed sediment diversion	None	Medium	None
P001, P009, P011, P012	Marsh creation and proposed sediment diversion	Created Marshes	Medium	Nutrient uptake; fisheries habitat; soil carbon storage
P004, P005, P006, P007	Historical Ridge Restoration	Ridges	Medium	Surge attenuation

3.2.1. Nutrient budget

The competency group proposed four main marsh creation projects as nature-based solutions (project numbers P001, P009, P011, and P012) in Breton Sound Estuary (Fig. 4).

3.2.2. Marsh creation and proposed sediment diversion

The potential ecosystem functions evaluated for these proposed nature-based solutions of marsh creation projects with a proposed sediment diversion include nutrient uptake, fisheries habitat, and soil carbon storage. The total DIN uptake for the model run with no nature-based solutions was -47.6 g N m^{-2} yr^{-1}. The addition of marsh creation projects to the landscape resulted in slight increase to the total DIN uptake (Table 4). Potential fisheries habitat resulting from the inclusion of the marsh creation project (as well as the proposed sediment diversion) could realize a 17% increase in the amount of available land in the estuary when compared to the control (P000) at year 20 (Table 5). The resulting marsh area at year 20 also could influence the potential soil carbon storage at a range between 1.2 and 1.6×10^{-1} Tg TC yr^{-1} (Table 5).

3.2.3. Ridges

The competency group proposed a series of ridge restoration projects (P004, P005, P006, and P007) as nature-based solutions in Breton Sound Estuary (Table 2, Fig. 5). The community members were most interested in how these ridges could dampen the water levels from major weather events such as a strong and persistent south-east wind or the hurricane-force winds observed in the year 2005 due to Hurricane Katrina. Ridge restoration projects were able to reduce surge heights by -1.2 m locally (Fig. 5). The ridges, however, can also trap storm surge, resulting in a local increase in surge height by 1.5 m. This is due to the influence of wind direction, the path of the hurricane, and orientation of ridges (see Appendix A for animation). Even though some areas will be protected from flooding by ridges when surge heights are lower than the designed ridge height (+1.5 m height from NAVD 88), these protected areas will eventually be flooded when surge heights exceed the ridge height.

4. Discussion

Natural and nature-based solutions are an important option to address coastal hazards facing many communities worldwide because they emphasize an ecosystem approach to support ecosystem functions and subsequent ecosystem services (Cohen-Shacham et al., 2016; Thorslund et al., 2017). In coastal Louisiana, USA the ongoing

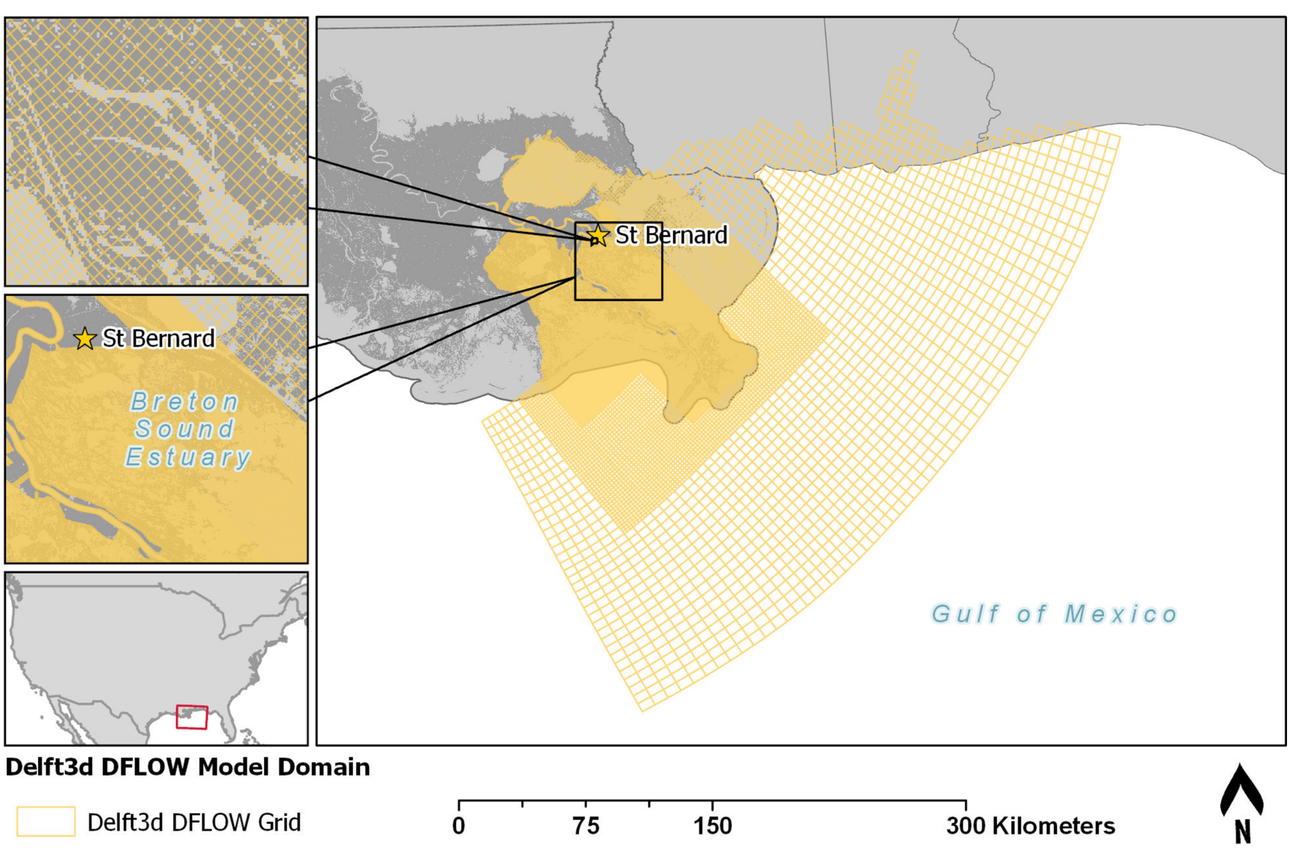

Fig. 2. The Delft3D model domain and grid cells of the Integrated Biophysical Model located in coastal Louisiana, USA.

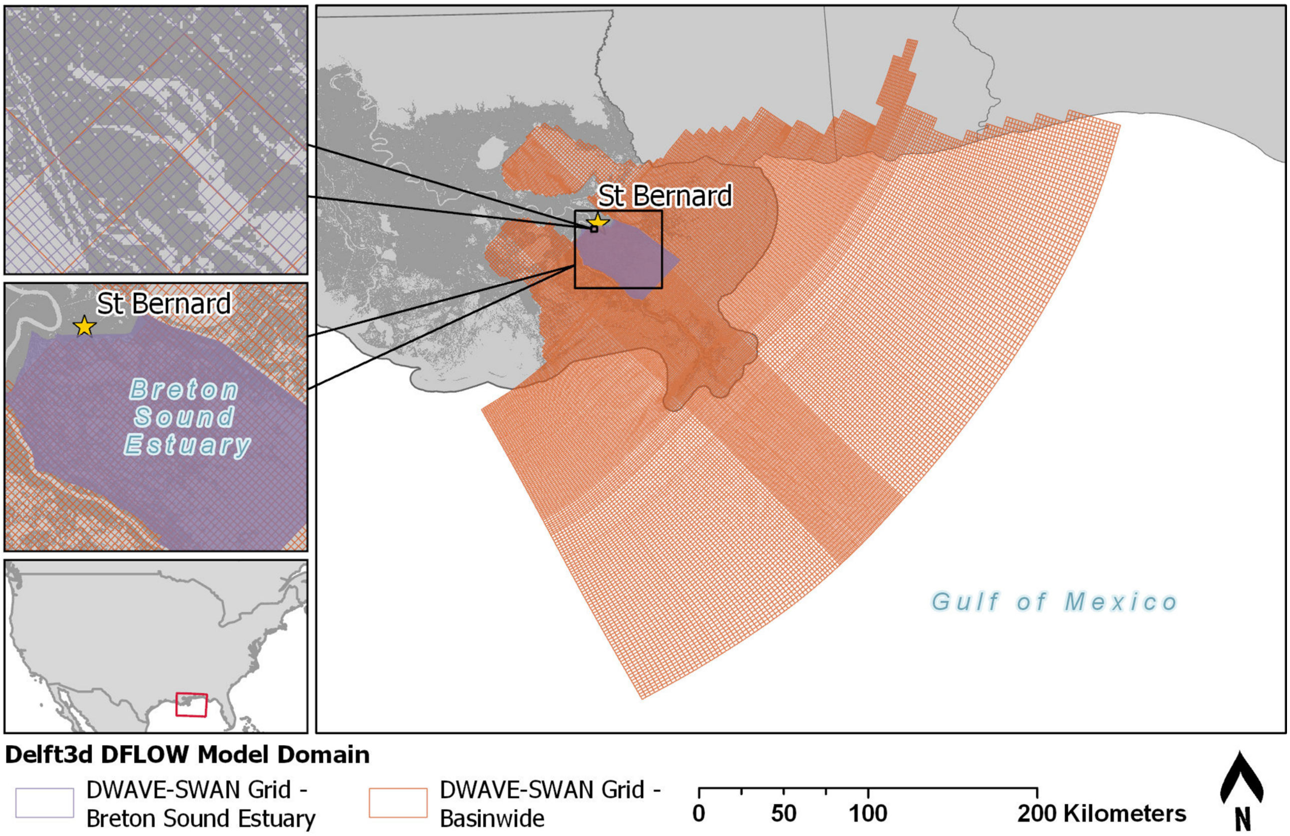

Fig. 3. The Delft3D D-WAVE-SWAN model domain and grid cells located in coastal Louisiana, USA.

discussion of coastal restoration includes projects that incorporate various natural and nature-based solutions and is supported by the state government (Coastal Protection and Restoration Authority of Louisiana, 2017), local officials (St. Bernard Parish Government, 2017), and community members. Engagement of local communities from the beginning of project implementation to completion is often limited (Hemmerling and Barra, 2019; Crawford et al., 2017) but is needed to incorporate traditional ecological knowledge into natural and nature-based solutions and to foster local buy-in regarding use of these modeling tools. Other studies have realized that engagement of communities is essential to determine the linkages between ecosystem functions, ecosystem services, and human well-being (Mavrommati et al., 2014; Arkema et al., 2017). In our study, the societal benefit, or ecosystem service occurring from a natural or nature-based solution, was evident and deemed a priority. This is likely due to the experience that many of these coastal communities have with wetland loss and flooding and the resultant understanding of the value associated with preserving or restoring these coastal habitats. Capturing their local knowledge was vital to ensure the proposed nature-based solutions were addressing concerns and needs of residents (Hemmerling and Barra, 2019).

Organizing five meetings was a significant time commitment for all competency group members but was ultimately helpful following the development of relationships that allowed for honest discussion between local residents and scientists. As evidence to the trust built over the course of the competency group meetings, many of the members who were reticent to voice their concerns at the beginning became increasingly open by meeting #5 (Hemmerling et al., 2019). This approach could be applied to other ecosystems where nature-based solutions are a viable option and where local communities have a high interest. It is recommended that at least one year of time be invested so that numerous meetings can occur. Utilizing competency groups allowed for a more inclusive process where local residents felt their voices where heard and that certain members did not have too much of an influence on the discussion or decision making process (Hemmerling et al., 2019).

Natural and nature-based solutions provide protective and non-protective functions and this study highlights how two types of nature-based solutions (marsh creation and ridge restoration) can influence the ecosystem by quantification of certain functions at year 20. Created marshes have the potential to improve water quality by contributing to the nutrient uptake processes (via assimilation by marsh vegetation or by nitrification-dentification pathways in soils/sediments; Twilley et al., 1999; Rivera-Monroy et al., 2013). Our model output suggested that the increase of wetland area (vegetation and soils) from the created marshes after 20 years could enhance the removal of nitrogen (by about 2 g DIN m^{-2} yr^{-1}). Our modeled nutrient uptake rates are within modeled and field observations in this area, such as wetland vegetation assimilation rates (this study = –22 to −27 g N m^{-2} yr^{-1} compared to the other study of −25 g N m^{-2} yr; Conner and Day, 1987) and dentification rates (this study = −12 g N m^{-2} yr^{-1} compared to others of −4.5 to −36 g N m^{-2} yr^{-1} (Twilley et al., 1999; DeLaune et al., 2005; Hyfield et al., 2008; Rivera-Monroy et al., 2013). The short-term storage of soil carbon in these coastal ecosystems can also be influenced by the addition of created marshes (via increase by $1.2–1.6{\cdot}10^{-1}$ Tg TC yr^{-1}) after 20 years. In coastal Louisiana, it is estimated that created marshes over 20 years old accumulate total carbon between 124 and 214 g m^{-2} yr^{-1} (Abbott et al., 2019) and that about 5.5–7.3 Tg TC yr^{-1} is stored in the Louisiana coastal marsh soils on the short term (Baustian et al., 2017, Baustian et al. In Review). Thus, these four created marshes alone could contribute an additional ~0.5% of that storage per year. By adding created marshes into this estuary, important marsh edge habitat is potentially available (increase of 17% of marsh land in that area) for commercially important juvenile blue crabs and brown shrimps (Minello and Rozas, 2002), two fisheries essential to the livelihood of the community members in our competency group. Recovering the ecosystem functions of nutrient uptake, soil

Table 3
Coastal hazards in Breton Sound Estuary, Louisiana, USA and the natural or nature-based solutions proposed, their related ecosystem functions and services. List of simulation models provided are examples of how to quantify the ecosystem function. Ecosystem services terminology adapted from the Millennium Ecosystem Assessment framework (Millennium Ecosystem Assessment, 2005) and Costanza et al. (2017). Example model references refer to: 1 = Dietrich et al. (2011), 2 = Cobell et al. (2013), 3 = Rivera-Monroy et al. (2013), 4 = Baustian et al., 2018b, 5 = Hijuelos et al. (2016), 6 = de Mutsert et al. (2012), 7 = Meselhe et al. (2013), 8 = Wang et al. (2017), 9 = Hu et al. (2018), 10 = Cobb et al. (2008), 11 = Visser and Duke-Sylvester (2017).

Coastal Hazard	Natural or Nature-Based Solution	Engineered Approaches	Ecosystem Function	Ecosystem Service	Example Models	Example Model References
Major Storm Flooding (hurricanes/ cyclones)	Swamp; marsh; oyster reefs; sand nourishment and dunes	Seawalls; levees; bulk heads	Wave attenuation	Water regulation	Wave and surge attenuation	1, 2
Degraded water quality	Swamp; marsh; oyster reefs	N/A	Nutrient uptake	Water purification; nutrient cycling	Water quality and wetland vegetation	3, 4
Decrease in fisheries	Swamp; marsh; oyster reefs; sand nourishment and dunes	N/A	Fisheries habitat	Recreation; food	Suitable habitats and food webs	5, 6
Sea level rise	Swamp; marsh; sediment diversions	Seawalls; levees; bulk heads	Soil carbon storage	Climate regulation	Morphodynamics; vegetation and nutrient dynamics	4, 8
Nuisance Flooding (Winter storms/ rain-induced)	Oyster reefs; ridges, retention ponds	Levees, elevated structures	Wave attenuation and flood stage reduction	Water regulation	Hydrology and wave dynamics	9, 10
Altered hydrology (access canals)	Infill of canals; reconnecting isolated hydrologic units	Water control structures	Fisheries habitat	Recreation; food	Hydrology and suitable habitats	5, 7
Salinity intrusion	Ridges; marsh	Salinity control structures; freshwater diversions	Fisheries habitat	Recreation; food	Hydrology, vegetation, and suitable habitats	5, 11

carbon storage, and marsh edge habitat compared to reference conditions can take over 10 years in these restored wetland habitats because the hydrodynamics needs to be established (Thompson et al., 1995) and the emergent vegetation needs to colonize, build biomass and contribute to the soil organic matter pools in restored wetland habitats (Zedler and Callaway, 1999; Craft et al., 2002) that influence nutrient uptake processes such as assimilation and denitrification (Hernandez and Mitsch, 2007), and provide essential edge habitat including food resources and protection for juvenile nekton (Minello and Zimmerman, 1992). These time lags should be considered when measuring and modeling the ecosystem functions of restored habitats. Future work should also consider linking food web models or habitat suitability indices to biophysical models to assess how nature-based solutions may impact fisheries habitats and production (Baustian et al., 2018a; de Mutsert et al., 2012; Hijuelos et al., 2016).

The restoration of historical ridges was a nature-based solution favorite by locals. These ridges could dampen surge height (~1 m) from Hurricane Katrina force-winds in specific areas of the estuary depending on the storm movement, which determines the flooding time and period. This modeled surge height was within range of other local modeling studies (Cobell et al., 2013). Ridge restoration can also change hydrodynamic conditions such as salinity regime and residence time, leading to changes in sediment deposition, water quality, and vegetation dynamics in this ecosystem. Marsh creation projects can also influence surge height (Wamsley et al., 2009) but that was not evaluated in this study. Therefore, further investigations on how combined ridge and marsh restoration projects influence total ecosystem condition and function are warranted. To support comparison, quantification of these ecosystem functions should be conducted within the same modeling framework presented by this research.

5. Conclusion

Various natural and nature-based solutions are available to urban and coastal communities, especially in the face of climate change (Kabisch et al., 2016). Engagement with local communities in coastal Louisiana helped to identify relevant natural and nature-based solutions, including marsh creation and historic ridge restoration projects, and also encouraged local buy-in surrounding the benefits of coastal restoration (Hemmerling et al., 2019). Not only do these natural and nature-based solutions protect local communities from immediate coastal hazards, quantification of the associated co-benefits, or ecosystem functions, to include nutrient uptake, fisheries habitat, and soil carbon storage, can also be important and attempts to quantify them has been limited to date (Arkema et al., 2017; Sutton-Grier et al., 2018). This project provides an example of how a community co-designed ecosystem model can help quantify these associated ecosystem functions and advances the understanding of how proposed nature-based solutions function within an ecosystem. Modeling ecosystem-based solutions through a collaborative modeling process with researchers and local communities is an effective way to assess natural and nature-based solutions in coastal areas and can be applied elsewhere with major ecosystem-based restoration initiatives.

CRediT authorship contribution statement

Melissa M. Baustian: Conceptualization, Formal analysis, Investigation, Writing - original draft. **Hoonshin Jung:** Methodology, Software, Investigation, Writing - review & editing, Visualization. **Harris C. Bienn:** Methodology, Resources, Writing - review & editing, Visualization. **Monica Barra:** Methodology, Writing - review & editing. **Scott A. Hemmerling:** Methodology, Writing - review & editing. **Yushi Wang:** Methodology, Writing - review & editing. **Eric White:** Methodology, Writing - review & editing. **Ehab Meselhe:** Methodology, Writing - review & editing.

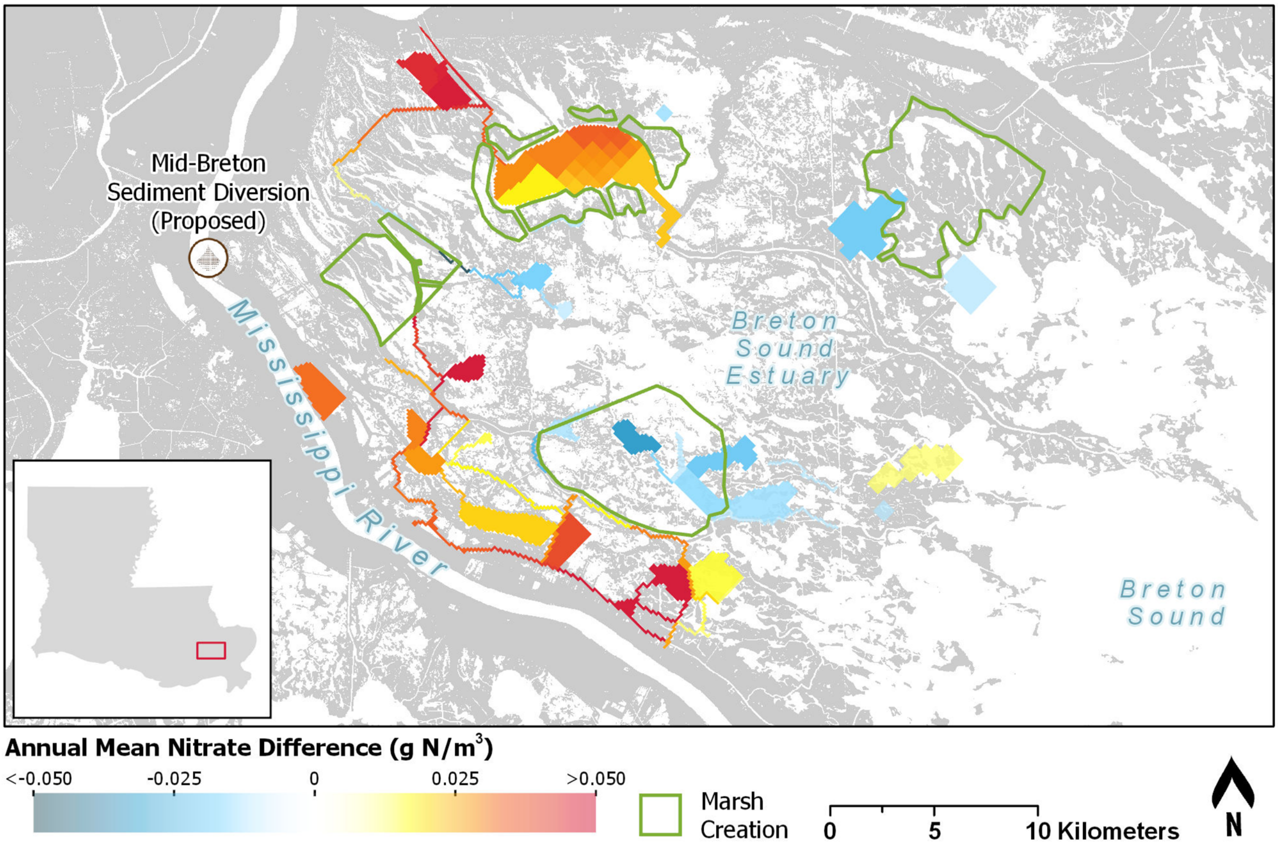

Fig. 4. Locations of proposed created marshes (outlined areas) and sediment diversion (Mid-Breton) and differences of estuarine open water annual mean nitrate concentrations at year 20 between model runs with solutions of created marshes (P001, P009, P011, P012) and without (P000). Negative values (green shading) on the landscape indicate that model run with solutions had lower nitrate concentrations compared to model runs without solutions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Modeled mass balance of dissolved inorganic nitrogen (DIN) of sediment/soil fluxes in Breton Sound Estuary. Positive fluxes indicate release, or a source and negative fluxes indicate uptake or a sink (*).

Sediment/Soil fluxes	Mass Flux (g DIN m^{-2} yr^{-1})	
	Proposed sediment diversion (P000 – no solutions)	Marsh Creation and proposed sediment diversion (P001, P009, P011, P012 – with solutions)
Water	−12.85	−9.99
Atmosphere	0.68	0.72
Mineralization	46.89	48.43
Denitrification*	−12.41	−12.23
Vegetation*	−22.38	−27.03
Storage	0.07	0.10
Sum of uptake fluxes (*)	**−47.6**	**−49.3**

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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Table 5
Model output (based on medium environmental scenario and at year 20) of the potential ecosystem functions from proposed projects (Project No.) that represented natural and nature-based solutions of marsh creation projects (modeled together – P001, P009, P011, P012) discussed with the competency group. Project P000 has no new nature-based solutions.

Project No.	Modeled potential ecosystem function		
	Fisheries Habitat	Soil Carbon Storage	
	Land (% of total area)	Marsh Area (m^2)	Range (Tg TC yr^{-1})
P000	37%	2.8×10^8	9.3×10^{-2} to 1.2×10^{-1}
P001, P009, P011, P012	54%	3.7×10^8	1.2×10^{-1} to 1.6×10^{-1}

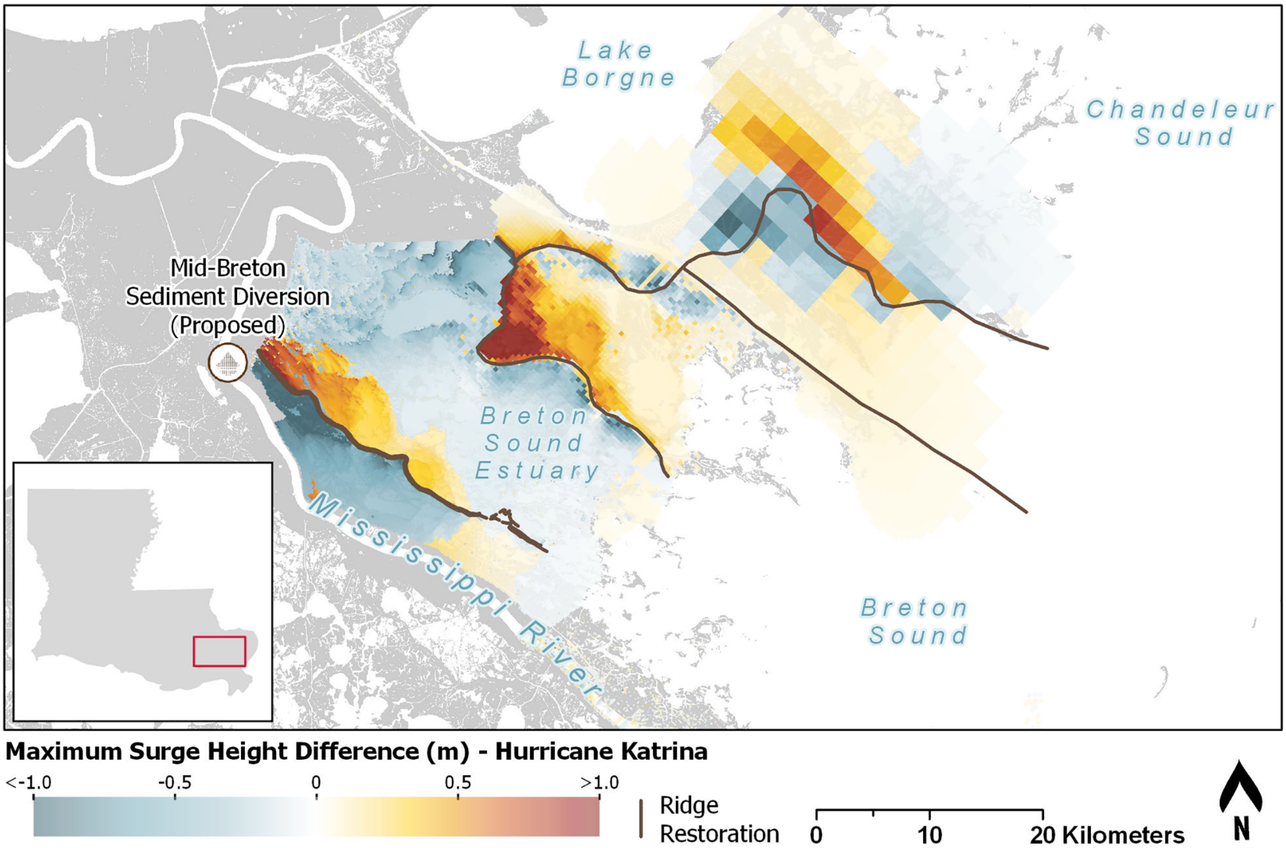

Fig. 5. Surge height difference (m) between model runs with nature-based solutions of ridge restoration (P004, P005, P006, P007) and without (P000). Negative values (blue shading) on the landscape indicate that model run with solutions had lower surge height than without solutions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoena.2019.100015.

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