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Forecasting the Effects of Coastal Protection and Restoration Projects on Wetland Morphology in Coastal Louisiana under Multiple Environmental Uncertainty Scenarios

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ABSTRACT

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Few landscape scale models have assessed the effects of coastal protection and restoration projects on wetland morphology while taking into account important uncertainties in environmental factors such as sea-level rise (SLR) and subsidence. In support of Louisiana's 2012 Coastal Master Plan, we developed a spatially explicit wetland morphology model and coupled it with other predictive models. The model is capable of predicting effects of protection and restoration projects on wetland area, landscape configuration, surface elevation, and soil organic carbon (SOC) storage under multiple environmental uncertainty scenarios. These uncertainty scenarios included variability in parameters such as eustatic SLR (ESLR), subsidence rate, and Mississippi River discharge. Models were run for a 2010–2060 simulation period. Model results suggest that under a "future-without-action" condition (FWOA), coastal Louisiana is at risk of losing between 2118 and 4677 km^2 of land over the next 50 years, but with protection and restoration projects proposed in the Master Plan, between 40% and 75% of that loss could be mitigated. Moreover, model results indicate that under a FWOA condition, SOC storage (to a depth of 1 m) could decrease by between 108 and 250 million metric tons, a loss of 12% to 30% of the total coastwide SOC, but with the Master Plan implemented, between 35% and 74% of the SOC loss could be offset. Long-term maintenance of project effects was best attained in areas of low SLR and subsidence, with a sediment source to support marsh accretion. Our findings suggest that despite the efficacy of restoration projects in mitigating losses in certain areas, net loss of wetlands in coastal Louisiana is likely to continue. Model results suggest certain areas may eventually be lost regardless of proposed restoration investment, and, as such, other techniques and strategies of adaptation may have to be utilized in these areas.

ADDITIONAL INDEX WORDS: *Wetland change, sea-level rise, surface elevation, soil organic carbon, marsh creation, diversions, coastal restoration, Louisiana, wetland loss, coastal modeling.*

INTRODUCTION

Coastal Louisiana wetlands support the largest commercial fishery in the lower 48 states, provide habitat for important species of fish and wildlife, mitigate storm surge, and support five of the largest ports in the United States (Costanza *et al.*, 2008; Feagin *et al.*, 2010; Gedan *et al.*, 2011; NOAA, 2010; Twilley, 2007). Coastal wetlands are also net sinks for greenhouse gases and sequester a significant amount of carbon within soils (Chmura *et al.*, 2003; DeLaune and White, 2011; Hopkinson, Cai, and Hu, 2012; Laffoley and Grimsditch, 2009; Morris *et al.*, 2012). The high biological productivity of coastal marshes throughout coastal Louisiana contributes to soils rich in organic matter, especially in fresher marsh communities (Markewich *et al.*, 2007). Unfortunately, wetland loss, defined here as the conversion of subaerial wetland to a persistently inundated, open-water condition, occurs throughout coastal Louisiana. Between 1932 and 2010, coastal Louisiana has experienced a net wetland loss of approximately 4877 km^2 (Couvillion *et al.*, 2011). Recent trend analyses (1985–2010) indicate that coastal Louisiana wetlands are being lost at an average rate of 42.9 km^2 per year. If this loss were to occur at a constant rate, it would equate to losing an area approximately

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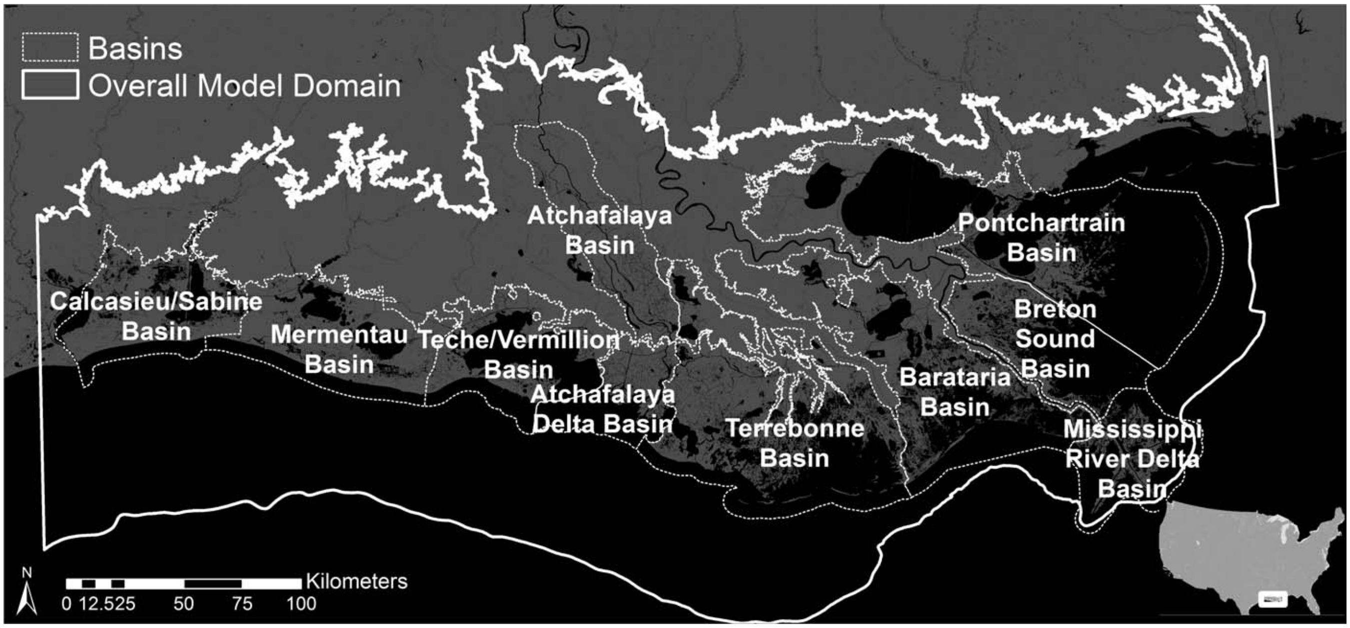

Figure 1. Map of the study area.

equivalent to an American football field every hour (Couvillion *et al*., 2011).

Causal mechanisms of this wetland loss include a reduction of sediment supply from the Mississippi River and other sources; altered hydrology as a result of the construction of levees, roads, and canals; sea-level rise (SLR); saltwater intrusion; wind/wave induced erosion; and other interacting factors such as subsidence (Blum and Roberts, 2009; Chen and Zhao, 2012; Day *et al*., 2000; Kim *et al*., 2009; Nyman and DeLaune, 1999; Törnqvist *et al*., 2006). The consequences of wetland loss include the loss of ecosystem services such as critical habitat for fish and wildlife, soil organic carbon (SOC) storage capacity, nitrogen retention and removal capacity (*e.g*. denitrification), and storm surge mitigation capacity (Craft *et al*., 2009; DeLaune and White, 2011; Rivera-Monroy *et al*., 2013).

Landscape change in coastal Louisiana has been modeled as part of other programs, including Coast 2050 (Coast 2050 Plan, 1998; Reed and Wilson, 2004); Louisiana Coastal Area (LCA; USACE, 2004); the Coastal Louisiana Ecosystem Assessment and Restoration Program (CLEAR; Twilley *et al*., 2008; Visser *et al*., 2008); and the 2007 Master Plan Model (CPRA, 2007). These models enhanced our understanding of landscape dynamics and processes as well as the potential changes that could affect coastal Louisiana wetlands. These models, however, were limited by the assumption that historical loss rates would remain unchanged into the future (Barras *et al*., 2003; Visser *et al*., 2008). This assumption was sufficient for these previous efforts because the models did not have to take into account variability and uncertainty in parameters such as SLR and subsidence. In addition, data limitations hindered the previous landscape-change models from considering many processes and causal mechanisms of wetland change and the ability to assess specific ecosystem services such as SOC storage.

In support of Louisiana's 2012 Coastal Master Plan (Peyronnin *et al*., 2013), a spatially explicit wetland morphology model was developed for coastal Louisiana using geographic information systems, remote sensing, field data, and simulation modeling (Steyer *et al*., 2012). This model was one component of a suite of linked models used to predict change in multiple ecologic, biologic, and socio-economic components of the Louisiana coastal system. Other models utilized in this effort include an ecohydrology model (Meselhe *et al.,* 2013), a vegetation change model (Visser *et al.,* 2013), and a suite of other models described in Peyronnin *et al*. (2013).

The wetland morphology model was used to predict the landscape effects of protection and restoration projects on morphologic variables including wetland area, landscape fragmentation, surface elevation, and SOC storage under critical environmental uncertainties such as accelerated eustatic SLR (ESLR) and subsidence. Our objectives were to predict the effects of protection and restoration projects on wetland morphology at coastwide, basin, and project scales. The results provide insight regarding areas in which coastal wetland landscapes might be stable and sustainable, where they could be susceptible to loss, and where protection/restoration measures might slow or reverse trends of loss.

METHODOLOGY

Study Area

The overall study domain encompasses an area of 86,890 km^2 (Figure 1) in the northern Gulf of Mexico, consisting of a mosaic of wetland plains, deltaic lobes, uplands, and open water.

Excluding uplands, the Louisiana coastal area constitutes an area of approximately 37,780 km^2. Land area in this region is a dynamic concept, with exact measures of area in constant flux, but in 2010, land comprised approximately 14,499 km^2 of the coastal zone with an additional 2295 km^2 of interior wetlands in the Atchafalaya Basin (Table 1). Coastal Louisiana is classified into 10 hydrologic basins (Figure 1), separated largely by current or abandoned distributary channels and their adjacent levee deposits (Cahoon *et al*., 1995; Day *et al*., 2000). Vegetation across coastal Louisiana is classified into five zones, which include forested wetlands and fresh, intermediate, brackish, and saline marshes. These vegetation zones run roughly parallel to the coast (Gosselink, 1984; Markewich *et al*., 2007; Visser *et al*., 2003). This leads to 50 possible basin/vegetation-type groups in coastal Louisiana; however, not all vegetation types occur in each basin. For the purposes of this analysis, 42 distinct basin/vegetation-type groups were analyzed.

Model Description

The wetland morphology model is composed of relative elevation and landscape change submodels. The relative elevation submodel determines coastal wetland surface-elevation change in response to factors such as SLR and subsidence by examining the roles of both organic matter and mineral sediments on wetland vertical accretion and surface elevation. The landscape change submodel predicts coastwide land area and landscape fragmentation in response to surface elevation change, incorporates changes attributable to other factors such as hurricanes, and predicts the effects of protection and restoration projects. The backbone of the wetland morphology model is the relative elevation submodel, but the two submodels are dynamically linked by a marsh collapse algorithm (Couvillion and Beck, 2013) in which vegetated area is converted into open water when salinity and inundation thresholds are exceeded because of elevation change.

Relative Elevation Submodel

In the relative elevation submodel, vertical accretion is estimated by

$$H = \frac{Q_{\mathrm{sed}} + Q_{\mathrm{org}}}{10,000 \times \mathrm{BD}}, \tag{1}$$

where H is the rate of vertical accretion (cm/y), Q_{sed} is mineral sediment accumulation rates ($g/m^2/y$) forecasted by the ecohydrology model (Meselhe *et al*., 2013), Q_{org} is organic matter accumulation rates ($g/m^2/y$), the constant 10,000 is a conversion factor from cm^2 to m^2, and BD is soil bulk density (g/cm^3).

Mineral-sediment accumulation is assumed to represent the long-term net available sediment input (*i.e*. deposition – erosion and resuspension) in the system. Mineral-sediment accumulation is provided by the ecohydrology model. Refer to Meselhe *et al*. (2013) for details regarding the calculation of sediment retention. A total of the sediment load retained is provided for coarse-scale hydrologic "boxes." These boxes vary in size from a minimum of 0.4 km^2 to a maximum of 3706 km^2 with a mean of 205 km^2. Total sediment load for each box is distributed at a finer resolution (30-m grid) using a distribution probability surface based upon existing stream networks, elevation gradients, and proximity to the source of sediment. First, total sediment deposition load (grams) in an ecohydrology model box over the 5-year period was calculated by the product of sediment load ($g/m^2/y$) (provided by the ecohydrology model) and box area (m^2). Then the sediment load (grams) was estimated per grid cell (30 m $\times$ 30 m = 900 m^2) by multiplying the total sediment amount by the redistribution weighting surface.

Organic matter contributions to vertical accretion are determined by mineral-sediment accumulation (Q_{sed}), soil BD, and percentage of organic matter content (OM%). Organic matter content is estimated by a curvilinear relationship between OM% and BD observed using *in-situ* sediment core data from the Coastwide Reference Monitoring System (CRMS) (Steyer *et al*., 2003; http://www.lacoast.gov/crms2/Home.aspx). Organic matter accumulation rates (Q_{org}) can be estimated by

$$Q_{\mathrm{org}} = Q_{\mathrm{sed}} \times \frac{F_{\mathrm{org}}}{F_{\mathrm{min}}}, \tag{2}$$

where Q_{org} and Q_{sed} are defined for Equation 1; F_{org} is the fraction of organic matter mass in total soil mass at equilibrium, which is equivalent to organic matter content (OM%) divided by 100; and F_{min} is the fraction of inorganic matter mass in total soil mass ($1 - F_{\mathrm{org}}$) at equilibrium. This method assumes that site-specific long-term organic matter accumulation can be derived from the relationship between long-term mineral matter accumulation and organic matter accumulation at equilibrium, and there would be no organic matter accumulation when mineral material accumulation is zero.

Landscape Change Submodel

The landscape-change submodel incorporates accretion (calculated by the relative elevation submodel), tracks elevation changes as a result of subsidence, then updates landscape topography and bathymetry according to Equation 3:

$$E_{t2} = E_{t1} + H - S, \tag{3}$$

where E_{t2} is the adjusted surface elevation (m NAVD88); E_{t1} is the starting surface elevation (m NAVD88); H is the vertical accretion, as defined in Equation 1 (converted to m and summed over the $t_1 - t_2$ time period); and S is subsidence (m).

The landscape-change model then translates those vertical changes into changes to the horizontal composition of the landscape (land/water area). The translation of elevation changes into landscape-configuration changes is done primarily by the use of inundation depth-based marsh-collapse thresholds, as described in Couvillion and Beck (2013).

The marsh-collapse threshold concept is based upon research linking excessive flooding to inhibited growth and mortality of many coastal wetland species (Howard and Mendelssohn, 1995; Mendelssohn and McKee, 1988; Webb and Mendelssohn, 1996). Though these studies have established the link between excessive depth, duration, or frequency of flooding, specific measures of thresholds beyond which mortality is probable remained elusive for many coastal vegetation types. Therefore, this effort utilized previous research, field studies, remotely sensed analyses, and recommendations of an expert panel to

Table 1. *Net Land Area change (km^2) projections by basin for "Future-without-action" and Master Plan alternatives under multiple environmental uncertainty scenarios, 2010–2060.*

		Moderate Scenario					Less Optimistic Scenario	
Basin	Starting Land Area (km^2) 2010	FWOA Land Area (km^2) 2060	MP Land Area (km^2) 2060	Net change 2010–2060 FWOA (km^2)	Net change 2010–2060 MP (km^2)	Difference MP vs. FWOA (km^2)	FWOA Land Area (km^2) 2060	MP Land Area (km^2) 2060
Atchafalaya Delta	576.5	677.9	677.5	101.4	101.0	−0.4	656.6	651.1
Barataria	2682.3	2222.2	2596.8	−460.1	−85.5	374.6	2112.1	2424.4
Breton Sound	662.8	355.9	669.5	−306.9	6.7	313.6	316.8	540.8
Calcasieu/Sabine	1495.0	1348.5	1559.0	−146.5	64.0	210.5	851.8	1025.8
Mermentau	1914.1	1706.0	1840.7	−208.1	−73.4	134.7	1040.9	1181.8
Miss. River Delta	294.5	164.5	76.0	−130.0	−218.5	−88.5	62.0	61.1
Pontchartrain	2377.5	2084.6	2379.2	−293.0	1.7	294.7	2007.4	2326.4
Teche/Vermilion	1239.4	1172.4	1210.8	−67.0	−28.6	38.4	1078.9	1117.3
Terrebonne	3256.1	2698.6	3012.6	−557.5	−243.5	314.0	1924.2	2490.4
Atchafalaya Basin	2295.4	2262.3	2253.7	−33.2	−41.7	−8.5	2239.4	2234.3
Total	16,793.8	14,693.0	16,276.0	−2100.8	−517.8	1583.0	12,290.1	14,053.3

Note: Differences in total basin Land Area change and coastwide Land Area change figures given elsewhere in this document reflect change in areas outside of basin boundaries. Refer to Figure 1 for basin and overall model domain delineations.

develop marsh-collapse uncertainty ranges, as seen in Table 2 (Couvillion and Beck, 2013; Steyer *et al.*, 2012).

Inundation depth in space was calculated by comparing surface elevation (adjusted for subsidence and vertical accretion) with water level, which was provided by the ecohydrology model. The impacts of ESLR are considered by the ecohydrology model, and, as such, the extent of ESLR for a given area is provided. After the elevation change of a specific pixel of land is calculated, a mean depth of inundation is calculated, and if the value exceeds the marsh-collapse threshold for a given model scenario (specific to that vegetation community type), that area converts from a land category to open water. In order for that location to convert back into land, accretion will have to offset the impacts of subsidence and ESLR and reach a point where elevation meets or exceeds mean water level (MWL). At that point, the area will revert back into land, and the vegetation model will forecast the vegetation community type of that area.

The impacts of saltwater intrusion and vegetation community-type changes, as forecasted by the vegetation model, are also considered in this submodel. As a change in community type may alter a marshes' tolerance to inundation, the submodel incorporates vegetation model output to alter an area's marsh-collapse uncertainty ranges accordingly. If, for example, a brackish area converts to saline as a result of saltwater intrusion, the collapse threshold for that area would decrease to the lower value appropriate to saline marsh, and collapse would become more probable as a result.

This submodel also considers the influences of coastal processes other than inundation-dependent factors on collapse and wetland change. This was done primarily by incorporating historical land-change trends (Couvillion *et al*., 2011). Wetland loss unrelated to inundation was projected in space by applying historical wetland-loss rates specific to causal mechanisms such as hurricane-induced losses. These losses were isolated from historic trends utilizing temporal bracketing for episodic events such as hurricanes and hindcasting using observed SLR. Wetland loss is distributed across the landscape using loss probability surface, which was developed by weighting multiple criteria including elevation, distance to water bodies, land cover, historical land-loss trend, percentage of time inundated, and fragmentation. See Steyer *et al*. (2012) for more details regarding the loss probability surface.

The landscape change submodel is also capable of incorporating and forecasting the effects of restoration measures. Different types of restoration such as marsh creation projects, sediment diversions, bank stabilizations, shoreline protections, ridge restorations, and hurricane protections can be modeled. Projects can be placed on the landscape at user-defined

Table 2. *The marsh collapse thresholds for different vegetation types across coastal Louisiana.*

	Threshold Range		
Marsh Type	Salinity (ppt)[a]	Inundation (depth, cm)	Rationale and Justification
Swamp	4–7		Gary Shaffer (*personal communication*)
Fresh	6–8		Expert Panel (*personal communication*)
Intermediate		30.7–38.0	Largest uncertainty range resulting from the combination of two methods: 32–38 cm (CRMS), 30.7 to 35.7 cm (RS)
Brackish		20.0–25.6	Largest uncertainty range resulting from the combination of two methods: 20–25 cm (CRMS), 20.1 to 25.6 cm (RS)
Saline		16.0–23.5	Largest uncertainty range resulting from the combination of two methods: 16–18 cm (CRMS), 16.9 to 23.5 cm (RS)

[a] Eight-week average growing season.
Note: RS = remotely sensed data.

Table 1. Extended.

Less Optimistic Scenario			Moderate with HSLR Scenario				
Net change 2010–2060 FWOA (km^2)	Net change 2010–2060 MP (km^2)	Difference MP vs. FWOA (km^2)	FWOA Land Area (km^2) 2060	MP Land Area (km^2) 2060	Net change 2010–2060 FWOA (km^2)	Net change 2010–2060 MP (km^2)	Difference MP vs. FWOA (km^2)
80.1	74.6	−5.5	634.7	631.6	58.1	55.1	−3.1
−570.3	−258.0	312.3	2118.8	2423.9	−563.6	−258.4	305.2
−346.0	−122.0	224.0	326.6	546.5	−336.3	−116.3	219.9
−643.2	−469.2	174.0	787.5	979.3	−707.5	−515.7	191.7
−873.2	−732.3	140.9	1079.8	1371.3	−834.3	−542.8	291.5
−232.5	−233.3	−0.9	65.4	62.1	−229.1	−232.4	−3.3
−370.1	−51.1	319.0	2005.9	2198.5	−371.7	−179.0	192.7
−160.5	−122.2	38.4	1057.9	1105.8	−181.5	−133.6	47.9
−1331.9	−765.8	566.2	1837.1	2499.5	−1419.0	−756.6	662.4
−56.0	−61.1	−5.1	2237.7	2232.3	−57.8	−63.1	−5.3
−4503.7	−2740.5	1763.2	12,151.3	14,050.9	−4642.5	−2742.9	1899.6

construction parameters such as starting elevation. The fate of said projects is then forecast via the previously discussed methodologies. The long-term maintenance of project benefits will be controlled largely by the maintenance of a site's elevation at a level that exceeds the collapse thresholds.

Model Limitations

The wetland morphology model is limited by its inability to accurately estimate the spatial distribution and accumulation of sediment contributed by hurricanes and storms (Steyer *et al.*, 2012). It is difficult to estimate spatial patterns regarding hurricane/storm sedimentation because of the difficulty in projecting the path and intensity of these events in the future. Therefore, a constant hurricane sediment load (assumed to be 1000 g/m^2/y) was delivered to each ecohydrology box based on previous research (Nyman, Crozier, and DeLaune, 1995; Turner *et al.*, 2006). The model also does not directly take into account the influence of wetland plant growth and below-ground soil processes, such as soil compaction and organic matter decomposition, on vertical accretion. This is because of data limitations and limited scientific understanding regarding the relative influences of above- and below-ground biophysical processes on vertical accretion in coastal Louisiana vegetation communities. Nevertheless, the ultimate long-term effects of these below-ground soil processes are reflected in the submodel through an observed empirical relationship between mineral- and organic-matter accumulation and BD. Finally, time constraints imposed by this effort prevented examination of the positive feedback between vegetation and marsh vertical accretion at a finer temporal resolution than a 25-year interval.

Model Outputs

The wetland morphology model produced spatial patterns of landscape composition (land and water area), fragmentation (percent edge), soil vertical accretion rates, soil surface elevation, and SOC storage and sequestration for the period of 2010–2060. These outputs are provided for each 5-year interval during the period of study. Outputs are calculated at two spatial resolutions: 30 m and 500 m. The two resolutions have different utilities for specific purposes and applicability to subsequent, coupled models. Each of the outputs is discussed in further detail below.

Landscape Composition (Land and Water Area)

Land area (defined as wetlands where mean surface elevation is higher than mean sea level) and water area (defined as areas whose surface elevation is less than mean sea level—excluding areas protected by levees or other water control features that allow land to exist below MSL).

Percent Land

Percent land is defined as the percentage of land in each 500-m grid cell, as calculated via the original 30 m output.

Fragmentation (Percent Edge)

Percent edge is defined as the percentage of edge in each 500-m grid cell, with "edge" being defined as a 10-m buffer on the land/water interface as calculated via the original 30-m output.

Soil Vertical Accretion

Soil vertical accretion is defined as the vertical growth of soil attributable to the accumulation of mineral sediment and organic matter over the simulation period.

Surface Elevation

Surface elevation is defined as the soil surface position relative to NAVD88.

SOC Storage and Sequestration

The percent land is used to examine and predict changes in SOC storage in the top meter of soil, as described in Equation 4:

$$\mathrm{SOC} = \frac{\mathrm{BD} \times \mathrm{OM\%}}{2.2} \times 100\,\mathrm{cm} \times 25\,\mathrm{ha} \times \%\mathrm{Land}, \qquad (4)$$

where SOC is the total SOC (metric tons per grid cell), BD is as defined in Equation 1; OM% is organic matter content; and 2.2 is an OM/carbon conversion factor (Steyer *et al.*, 2012).

Model Calibration

The wetland morphology model was calibrated by comparing simulated and observed vertical accretion at specific sites across coastal Louisiana. For a given amount of sediment accumulation, the variations in BD and OM% values determine the degree of uncertainty in estimating vertical accretion rates (see Equations 1 and 2). Therefore, representative BD and OM% have to be examined and applied because of the nonequilibrium nature of BD and OM% with depth in the wetland soils of coastal Louisiana (*e.g.* Markewich *et al.,* 2007). We define the representative BD and OM% as the values of these parameters that are capable of describing long-term (multidecadal) vertical accretion rates in soil. In other words, the simulated vertical accretion rates should match closely with the observed rates while using the representative BD and OM% values in model simulation. Furthermore, BD and OM% are largely determined by their locations within various landscape units (*i.e.* combinations of hydrologic basin and vegetation types) that control the supply, transport, and accumulation of mineral sediment and accumulation of organic matter. Therefore, BD and OM% were calibrated for each basin/vegetation group in coastal Louisiana. The specific calibration procedures are described as follows.

Calibration from Long-Term ^{137}Cs Dated Data. Observed long-term sediment accumulation and vertical accretion rates based on ^{137}Cs dating technique were available for 47 soil cores (to a depth of ~50 cm) at 30 sites that were collected across coastal Louisiana during 2006–2007 (Piazza *et al*., 2011). These soil cores cover nine basin/vegetation groups. The vertical accretion rates for the sites within each of the nine basin/vegetation groups were estimated from a range of BD values. First, a BD value from the possible BD range (0.02 to 1.50 g/cm^3) was selected and extrapolated for a basin/vegetation group; the relationship between OM% and BD (Equation 5), developed using CRMS soil data, was used to estimate OM% for that basin/vegetation group,

$$\mathrm{OM\%} = 100.2e^{(-4.7828\times \mathrm{BD})}. \tag{5}$$

Second, the site-specific organic accumulation rate was calculated from the observed site-specific sediment accumulation rate and group-level OM% using Equation 2. Then, the vertical accretion rate for each site within the basin/vegetation groups was estimated from the site-specific mineral sediment and organic matter accumulation rates and the assigned group-level BD value using Equation 1.

Third, the estimated vertical accretion rates (H_{sim}) at the sites in a basin/vegetation group were then compared with the observed accretion rates (H_{obs}) to calculate the root mean square error (RMSE) using Equation 6. Vertical accretion rates were estimated and RMSE was calculated under the same BD/OM% set for all nine basin/vegetation groups,

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{1}^{n}(H_{\mathrm{obs}} - H_{\mathrm{sim}})^2}{n}}. \tag{6}$$

Finally, the previous processes were repeated for other BD values in the range of 0.02 to 1.5 g/cm^3 at an interval of 0.02 g/cm^3 to get the RMSE for all BD/OM% sets. The BD/OM% combination with the minimum RMSE for a basin/vegetation group was treated as the "representative BD/OM%."

Calibration from Short-Term CRMS Data. Observed short-term (typically <2 years) soil BD, organic matter, and accretion data from CRMS were used to derive representative BD/OM% values for more basin/vegetation groups. Because the relative elevation submodel requires long-term (multidecadal) sediment accumulation rates to estimate long-term vertical accretion, the sediment accumulation and vertical accretion from CRMS soil and feldspar data needed to be converted into long-term rates. Piazza *et al*. (2011) provided both long-term and short-term sediment accumulation and vertical accretion data from 15 pairs of sites (one historical research site with ^{137}Cs dating since 1963 and one CRMS monitoring site with feldspar marker data). As such, these data were used to examine the relationships between long-term and short-term rates in sediment accumulation and vertical accretion.

First, BD and OM% of the top layer (0–4 cm) for each CRMS site was selected to estimate short-term sediment accumulation. This layer was selected because Louisiana coastwide long-term accretion rates are normally less than 2 cm/y (Jarvis, 2010), and feldspar marker data are normally measured within 2 years (Folse *et al*., 2008).

Second, short-term sediment accumulation rate (SEDIN[st] in g/m^2/y) from feldspar-based short-term accretion rate measurements (H[st] in cm/y) was estimated using the following method (refer to Hatton, DeLaune, and Patrick, 1983; Nyman *et al*., 2006):

$$\mathrm{SEDIN(st)} = \mathrm{BD}(0\text{–}4\,\mathrm{cm}) \times H(\mathrm{st}) \times (1 - \mathrm{OM\%}/100). \tag{7}$$

The short-term sediment accumulation rate was converted to a long-term rate (SEDIN[lt] in g/m^2/y) by the relationship derived from Piazza *et al*. (2011) data:

$$\mathrm{SEDIN(lt)} = 0.2557 \times \mathrm{SEDIN(st)} + 214.52. \tag{8}$$

Third, long-term ^{137}Cs-based vertical accretion rates (H[lt]) from CRMS feldspar-based short-term accretion rates (H[st]) were estimated based on the relationship derived from Piazza *et al*. (2011) data:

$$H(\mathrm{lt})/H(\mathrm{st}) = -1.2368 \times \mathrm{Elevation(m, NAVD88)} + 1.0391. \tag{9}$$

There were 249 CRMS sites with estimated long-term sediment accumulation and vertical accretion rates that were used in calibration (170 sites) and validation (79 sites).

Finally, we used the previously described methods (in the section "Model Calibration") to derive representative BD/OM% values for a total of 25 basin/vegetation groups. For those basin/vegetation groups that had calibrated BD/OM% from both long-term and short-term data, the BD/OM% values calibrated from long-term data were treated as the representative BD/OM%.

Rules in Determining Representative BD/OM% Values for the Remaining Basin/Vegetation Groups. From the LCA S&T and CRMS databases, we were able to calibrate BD/OM% for 25 of a total of 41 observed basin/vegetation groups (excluding the "other" land-cover category). Representative BD/OM% values for the remaining 16 groups were determined via CRMS 0–24-cm averaged BD/OM% values where available, and, where unavailable, BD/OM% values were assigned from a similar basin/vegetation-type group.

Restoration Projects and Scenarios of ESLR and Subsidence

Initially, 397 projects were evaluated for consideration of inclusion in the 2012 Coastal Master Plan. These 397

Table 3. *Environmental uncertainty parameter values utilized for the modeling scenarios. Only those parameters most influential to the wetland morphology model are shown.*

Environmental Uncertainty	Plausible Range	Moderate Value	Moderate with High Sea-Level Rise Value	Less Optimistic Value
Sea-level rise (m over 50 years)	0.16 to 0.8	0.27	0.78	0.45
Subsidence (mm/y)[a]	0 to 35	0 to 19	0 to 19	0 to 25
Mississippi River discharge				
% of annual mean	−7 to +14[b]			−5
mean annual discharge (cfs)		534,000	534,000	509,000
Marsh collapse threshold				
Swamp (ppt)	4–7	6	6	5
Fresh marsh (ppt)	6–8	7	7	7
Intermediate marsh (depth, cm)	31–38	34	34	33
Brackish marsh (depth, cm)	20–26	23	23	21
Saline marsh (depth, cm)	16–23	21	21	18

[a] Values vary spatially.
[b] Adjusted for seasonality.

restoration and protection projects were placed into 49 groups for modeling. In the initial screening step, synergistic effects of projects were avoided as each project was to be evaluated purely on its own merits. Model groups were purposefully developed to include only spatially disparate projects in a given group, thereby eliminating the possibility of synergistic effects and enabling the isolation of benefits from individual projects.

These individual projects were then compiled into a final restoration and protection alternative, which became the 2012 Coastal Master Plan. The final Master Plan included 109 projects across the coast that represented a diverse mix of project types. For more details on this plan formulation process, refer to Peyronnin *et al*. (2013) and http://www.coastalmasterplan.louisiana.gov/.

The Master Plan project group and a “future-without-action” (FWOA) group were then modeled for the 50-year time period (2010–2060) under three future environmental uncertainty scenarios: “moderate,” “less optimistic,” and “moderate with high SLR.” The uncertainty parameters included ESLR, subsidence rate, storm intensity and frequency, Mississippi River discharge, rainfall, evapotranspiration, Mississippi River nutrient concentrations (nitrogen and phosphorus), and marsh collapse thresholds. The parameters most influential to the wetland morphology model and associated values of each uncertainty scenario are shown in Table 3. Further details regarding these environmental scenarios are provided in Peyronnin *et al*. (2013).

RESULTS AND DISCUSSION

Model Validation

As a first step regarding model validation, we compared model-simulated vertical accretion rates with literature values at both basin and coastwide scales to see if simulated vertical accretion rates are in the ranges that have been observed by previous studies. We found that simulated accretion rates are, in general, within the range of observed values from the literature (Table 4). The exception is the Calcasieu/Sabine Basin, where the model tends to underestimate accretion rates, possibly as a result of less sediment transport and deposition in this part of the Louisiana coast (Meselhe *et al*., 2013; Steyer *et al*., 2012).

The wetland morphology model was also validated by comparing simulated and observed vertical accretion using 14 basin/vegetation-type groups assessed using 79 CRMS sites (not used in calibration) with derived long-term sediment accumulation and vertical accretion rates. The overall relative error (RE, in %) for all groups was calculated according to Equation 10:

Table 4. *Comparison of simulated vertical accretion rates to observed rates from literature at basin and coastwide scales.*

Basin	Modeled Average Accretion (cm/y)	Modeled SD Accretion (cm/y)	Accretion Range from Literature (cm/y)	Source
Pontchartrain	0.67	0.51	NA	NA
Breton Sound	0.87	0.47	0.42–1.72	DeLaune *et al*., 2003
Mississippi River Delta	0.73	0.3	NA	NA
Barataria	0.89	0.51	0.59–1.40	Hatton *et al*., 1983; DeLaune *et al*., 1989
Terrebonne	0.66	0.46	0.07–0.99	DeLaune *et al*., 1989; Nyman *et al*., 1993
Atchafalaya Delta	1.6	1.03	1.4–2.7	DeLaune *et al*., 1987; Majersky *et al*., 1997
Teche/Vermilion	0.58	0.54	0.29–0.70	Bryant and Chabreck, 1998
Mermentau	0.54	0.34	0.12–0.98	Cahoon, 1994; Bryant and Chabreck, 1998
Calcasieu/Sabine	0.28	0.22	0.36–0.90	DeLaune *et al.,* 1989; Bryant and Chabreck, 1998; Steyer, 2008
LA Coastwide	0.69	0.55	0.25–1.78	Nyman & DeLaune, 1999
			0.46–0.76	Piazza *et al*., 2011
			0.59–0.98	Nyman *et al*., 2006

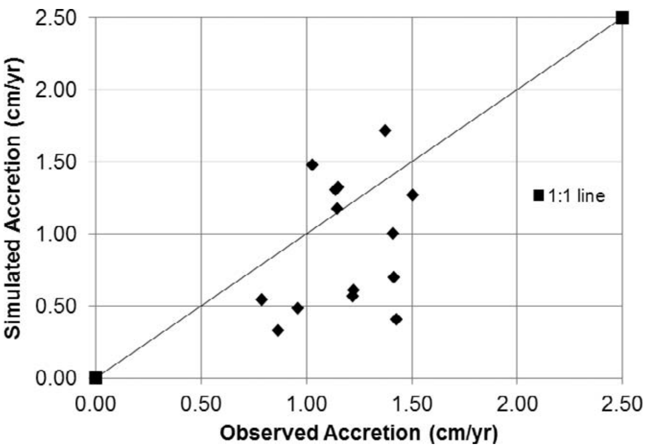

Figure 2. Validation of the wetland morphology model using an independent set of CRMS data that are classified into 14 basin/vegetation groups.

$$\mathrm{RE} = \frac{\sum_{i=1}^{n}\{H_{\mathrm{sim}}/H_{\mathrm{obs}} - 1\}}{n}. \tag{10}$$

Validation results indicate that the relative elevation submodel tends to underestimate the observed vertical accretion rates with a RE of –22% (Figure 2). This can be attributed to the relationship in estimating long-term sediment accretion rates from short-term feldspar marker measurements (Equation 8). The relationship identifies that a small portion (<26%) of the short-term sediment deposition would be incorporated into long-term sediment accumulation. Steyer *et al*. (2012) tested this relationship and found that it tends to produce a lower long-term sediment accumulation rates when compared to observed long-term accretion rates.

Assessments of Coastal Restoration and Protection in the Master Plan

Model results suggest that implementation of the 2012 Coastal Master Plan will result in an overall benefit in terms

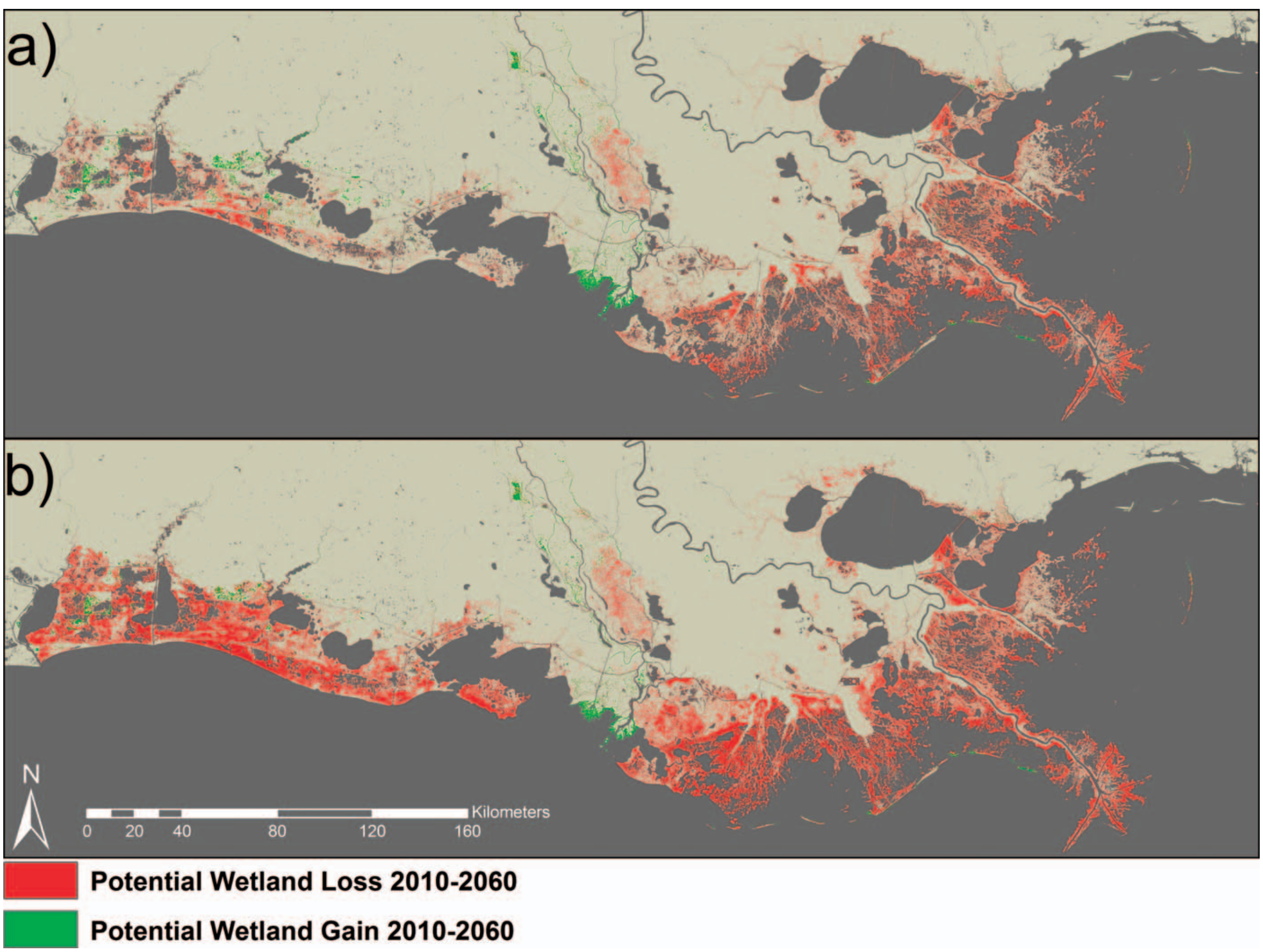

Figure 3. Map of potential wetland area changes under a "Future-without-action" condition for moderate (a) and less optimistic (b) environmental uncertainty scenarios, 2010–2060.

of percent land, surface elevation, and SOC under all environmental uncertainty scenarios compared to that of FWOA. The changes to a fourth parameter "percent edge," are less easy to interpret but are discussed in further detail subsequently in this article along with each of the other specific parameters. In the following sections, we assess the benefits of the Master Plan in terms of each model output at various spatial scales: coastwide, basin, and project.

Coastwide Assessment—Wetland Area Change

Under a FWOA condition, coastal Louisiana is potentially at risk of losing between 2118 and 4677 km^2 of land over the next 50 years (Figures 3 and 4). This amounts to a potential loss of between 14.6% and 32.3% of the remaining coastal wetlands in the state over the next 50 years (figures exclude Atchafalaya Basin). While this is a large range of potential outcomes, it represents the influences of many important uncertainties, including ESLR, subsidence, sediment discharge, and marsh-collapse thresholds. Model results suggest that uncertainties in the rates of subsidence and ESLR contribute significantly to the variability in wetland change projections.

While the range of potential wetland loss leaves a great deal of uncertainty in what the future may hold, it is critical to present our uncertainty so that policy-makers and resource managers can prepare for a range of actions under these scenarios. The uncertainty range for wetland change projections under a FWOA condition represents anywhere from a 32.2% reduction to a 49.6% increase in the average wetland loss rates experienced from 1932–2010 (Couvillion *et al*., 2011). The moderate scenario estimate of 2118 km^2 is consistent with more recent trends from 1985–2010, while the less optimistic scenario estimate of 4677 km^2 would represent a more than doubling of the recent trends (Couvillion *et al*., 2011).

At a coastwide scale, the model forecasts net wetland area decreases under all the environmental scenarios in a FWOA condition (Figure 4). These results suggest that a net wetland loss in coastal Louisiana over the next 50 years will likely occur regardless of uncertainties in parameters that influence coastal wetland loss. The magnitude of those losses is less certain, but, without increased action, substantial wetland loss will continue and possibly accelerate in the future (Blum and Roberts, 2009; Kim *et al*., 2009; Nittrouer *et al*., 2012).

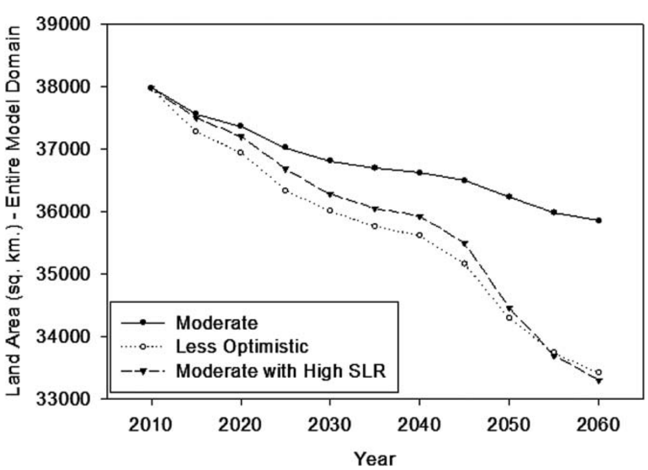

Figure 4. Wetland area change projections under a "Future-without-action" condition for multiple environmental uncertainty scenarios, 2010–2060.

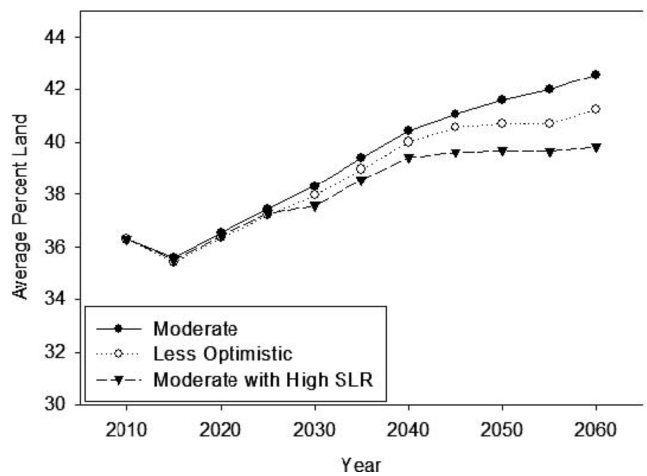

Figure 5. Average percent land projections in the Atchafalaya Delta for a "Future-without-action" condition under multiple uncertainty scenarios, 2010–2060.

While the majority of the coast will lose wetland area in a FWOA condition, model results suggest the Atchafalaya Delta Basin will gain wetlands even with no additional restoration activities in the region (Figure 5). The Atchafalaya Delta Basin contains two deltas, Atchafalaya River and Wax Lake Outlet, which have been gaining wetlands for the past 40 years (Blum and Roberts, 2009; Kim *et al*., 2009) at a combined rate of 1–3 km^2/y (Allen, Couvillion, and Barras, 2012). In a FWOA condition, model results suggest these two deltas combined will grow at average rates of 2.03 km^2/y under the moderate scenario and 1.16 km^2/y under the moderate with high sea-level rise scenario, which represents a 10% to 17% increase over the historical rates (1984–2010). In the Atchafalaya Delta Basin, the consistency between observed past trends and modeling forecasts highlights the ability of the model to forecast wetland building.

Model results indicate that implementation of the Master Plan will result in increased land area compared to a FWOA condition in a majority of the coast (Figure 6). Only a few areas, including the Mississippi River Delta and Atchafalaya Delta basins, exhibit decrease in land area as a result of the Master Plan implementation. The causes for these localized negative impacts will be discussed in further detail at the basin scale.

Land area benefits from a range of restoration projects, including sediment diversions and marsh creation projects, are evident throughout the Louisiana coast. Refer to Peyronnin *et al*. (2013) for a representation of projects that were modeled. As shown in Figure 6, benefits from large-scale marsh creation projects are clearly visible in areas such as the Biloxi Marshes (Location 1), on the western side of Bayou Lafourche (Location 2), and throughout the Chenier Plain (Location 3). Benefits

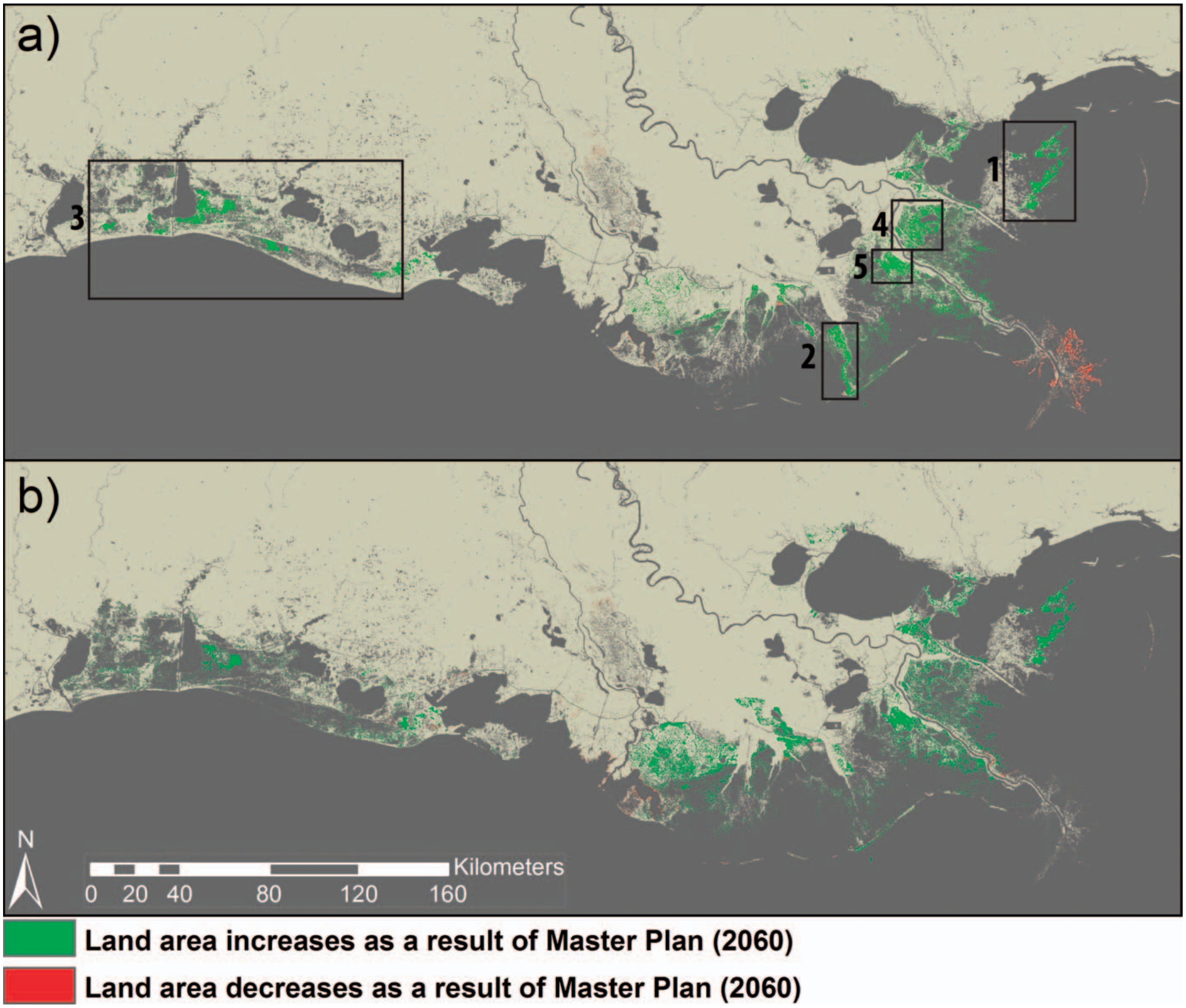

Figure 6. Projected land area increases and decreases with Master Plan implementation at the end of the simulation period (2060) under moderate (a) and less optimistic (b) environmental uncertainty scenarios. Increases and decreases are calculated by comparing FWOA model results to Master Plan model results in 2060. Locations represent the Biloxi Marshes (location 1), the western side of Bayou Lafourche (location 2), the Chenier Plain (location 3), upper Breton Sound (location 4), and the location of a proposed diversion near Myrtle Grove (location 5).

from large-scale sediment diversions are clearly visible in areas such as upper Breton Sound (Location 4) and from the proposed diversion near Myrtle Grove (Location 5).

Overall, land area change results suggest that between 40% and 75% of the wetland loss projected under a FWOA condition could be mitigated through implementation of the projects outlined by the Master Plan (Figure 7). It should be noted that land area gains in 2035 reflect the second implementation period of projects in the Master Plan (Peyronnin *et al*., 2013). The land area projections in the moderate scenario illustrate the reduction of land area losses over time as compared to the FWOA. The influence of high SLR and high subsidence rates, especially in the period of 2035–2060, is clearly evident in the less optimistic and moderate with high SLR scenarios.

Coastwide Assessment—Surface Elevation

Implementation of the Master Plan should result in improved mean elevation (both topographic and bathymetric surface elevation) compared to a FWOA condition under all environmental scenarios. Model results indicate that by 2060 under a FWOA condition, average coastwide surface elevation could be reduced by approximately 7 cm under a moderate scenario or as much as 22 cm under the less optimistic scenario

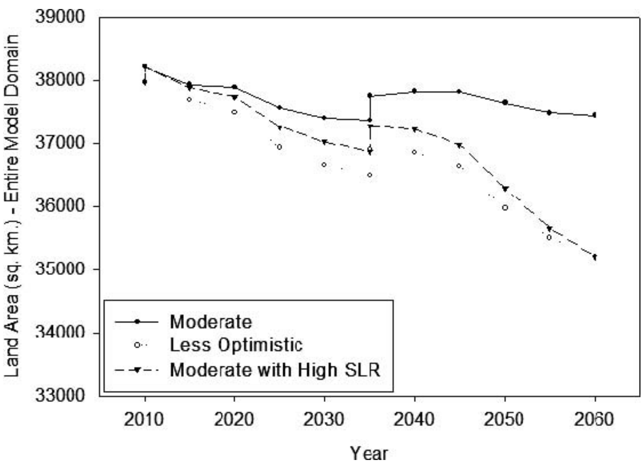

Figure 7. Wetland area change projections under the Master Plan for multiple environmental uncertainty scenarios, 2010–2060.

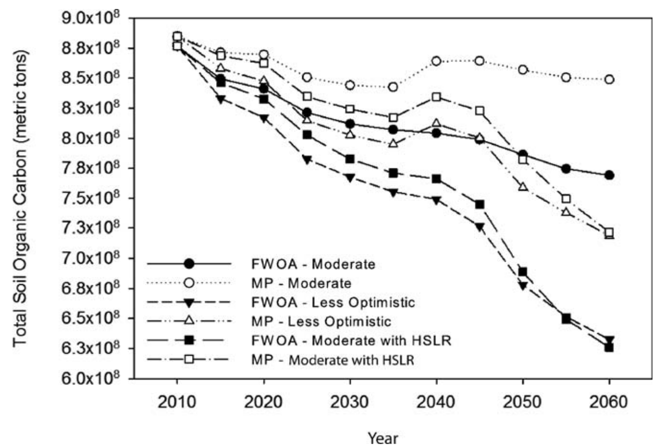

Figure 9. Average soil organic carbon projections in coastal Louisiana for "Future-without-action" and Master Plan alternatives under multiple environmental uncertainty scenarios, 2010–2060.

during 2010–2060 (Figure 8). In contrast, implementation of the Master Plan could lead to an average coastwide gain of approximately 3 cm under a moderate scenario or a mitigated reduction of 11 cm under the less optimistic scenario (Figure 8). Though the less optimistic scenario of the Master Plan still results in a net loss of elevation, implementation of the Master Plan will reduce the elevation deficit by half of what was seen under a FWOA condition. It is important to note that although the coastwide average elevation gains under the two scenarios of Master Plan implementation, net loss of wetlands over the 2010–2060 period is still projected in these scenarios (Table 1). This occurs as the slight elevation gains observed are insufficient for coastal wetlands to keep pace with rising sea levels.

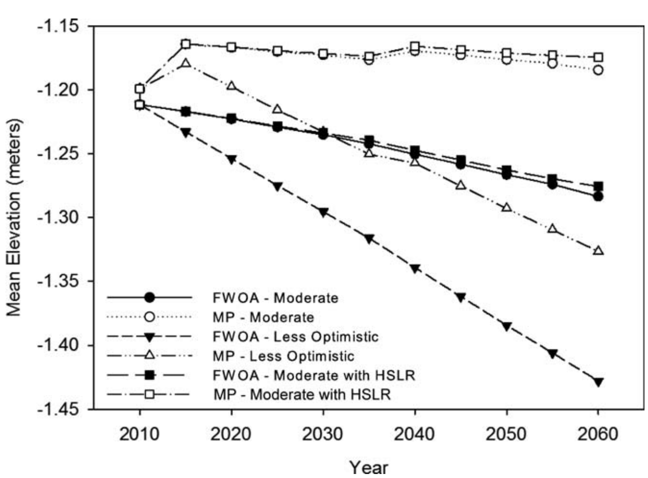

Figure 8. Surface elevation projections (NAVD88) under the Master Plan for multiple environmental uncertainty scenarios, 2010–2060.

Reduced sediment availability is the primary reason for the decrease in Louisiana marshes' ability to maintain elevation relative to rising sea levels (Blum and Roberts, 2009). Our model simulations of elevation dynamics also suggest that even with protection and restoration efforts in place, coastal Louisiana as a whole will most likely experience a net elevation loss (or deficit) in the next 50 years if predicted ESLR rates become reality. It should be noted that the benefits of protection and restoration in terms of elevation gain at basin and project scales (or local scale) should not be underestimated. We will discuss this in the "Project Scale Assessment" section.

Coastwide Assessment—SOC

Over the course of the next 50 years, the loss of SOC storage would continue in a manner similar to the trend in land area under a FWOA condition. Model results indicate that under FWOA, coastwide SOC storage in the top meter of soil could decrease by 107.5 million metric tons (MMT; 12%) under moderate scenario, 244 MMT (28%) under less optimistic scenario, and 250 MMT (30%) under moderate with high sea-level rise scenario, respectively (Figure 9). With the restoration projects proposed under the Master Plan, approximately 79, 86, and 95 MMT of SOC, respectively, could be preserved under these three scenarios, offsetting approximately 74%, 35%, and 38% of those losses (Figure 9).

In this study, we estimated that in 2010 coastal Louisiana contained approximately 877 MMT of SOC in the top meter of soil. Previous studies, which analyzed core data from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) Database, estimated total SOC storage in the upper meter of soil to be ~800–900 MMT (Markewich *et al.*, 2007; Zhong and Xu, 2009). Because wetlands serve as a net sink of CO_2, continued wetland loss would result in a large decrease in the amount of SOC and associated ecosystem services such as atmospheric CO_2 mitigation and nitrogen retention and removal (Craft *et al.*, 2009; DeLaune and White, 2011; Rivera-Monroy *et al.*, 2013).

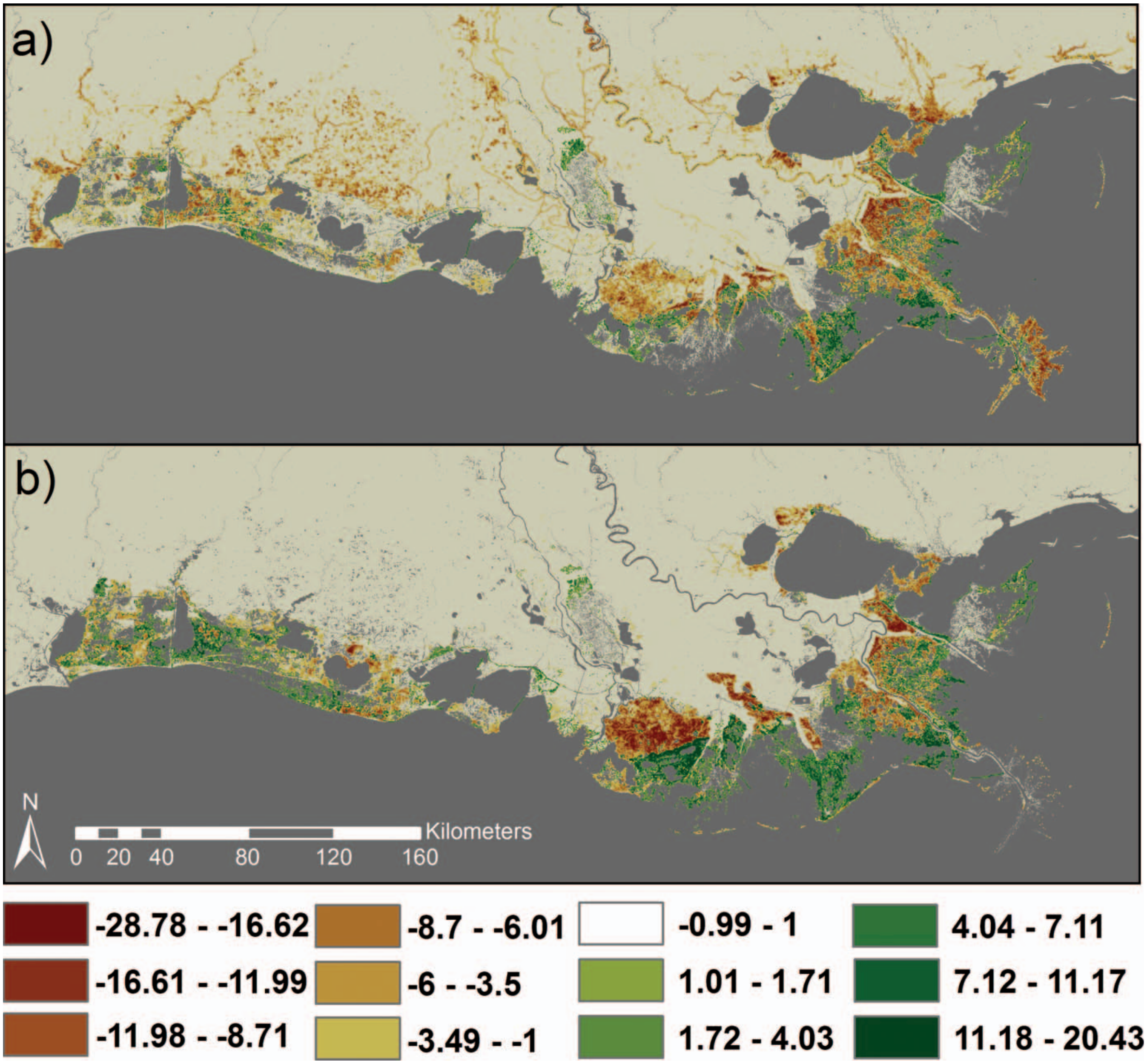

Figure 10. Projected increases and decreases in percent edge (% of each 500-m cell composed of edge) as a result of Master Plan implementation at the end of the simulation period (2060) under moderate (a) and less optimistic (b) environmental uncertainty scenarios. Increases and decreases are calculated by comparing FWOA model results to Master Plan model results in 2060.

Previous studies have estimated that coastal Louisiana has lost approximately 150 MMT of soil carbon since 1930 at a rate between 1.86 to 3.12 MMT/y (if 1 m depth of soil is assumed) (DeLaune and White, 2011). Our predicted SOC loss rate under the moderate scenario is 2.15 MMT/y, which is within the observed potential SOC loss since 1930; however, if coastal Louisiana experiences higher ESLR and subsidence similar to the less optimistic and the moderate with high SLR scenarios, we would see a SOC loss rate between 4.9–5.0 MMT/y, which would very likely double the currently observed SOC loss rate. This is primarily attributable to increased water depths under high RSLR that leads to submergence of marshes, loss of vegetation productivity, and exceedance of marsh-collapse thresholds (Couvillion and Beck, 2013; Kirwan and Mudd, 2012; Steyer *et al*., 2012).

Our models have shown that despite the implementation of protection and restoration projects, coastal Louisiana wetlands will not possess the same capacity to act as a net carbon sink in

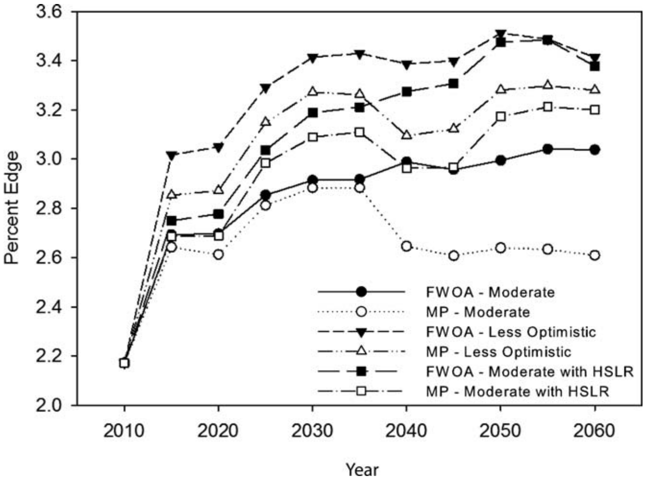

Figure 11. Average percent edge projections in coastal Louisiana for "Future-without-action" and Master Plan alternatives under multiple environmental uncertainty scenarios, 2010–2060.

the future; however, coastal protection and restoration efforts would reduce the rate of wetland loss (and thereby SOC loss). The benefit of coastal protection and restoration in restoring SOC sequestration capacity by land building and vegetation growth should not be underestimated when estimating carbon credit and ecosystem services. Proposed restoration efforts in the 2012 Coastal Master Plan would produce much higher SOC benefits (preserving 79, 86, and 95 MMT for the three scenarios over the 50 years) when compared to preserved SOC by restoration in the Coastal 2050 Plan (~14 MMT over 50 years; DeLaune and White, 2011).

Coastwide Assessment—Edge

Edge (defined as the interface between land and open water) is important to a large number of fishery species related to habitat utilization and suitability (Baltz, Rakockinski, and Fleeger, 1993; Browder, Bartley, and Davis, 1985; Browder *et al*., 1989; Reed, Hijuelos, and Fearnley, 2012). Implementation of the Master Plan would result in either increases or decreases (depending on location) in percent edge compared to a FWOA condition because of the high variability of this parameter. This variability occurs because both wetland loss and gain can lead to either increases or decreases in edge depending upon landscape configuration (Figure 10). Edge can initially increase as a result of wetland loss and the resulting fragmentation of the landscape. This increase continues until a certain point, at which the continued loss in wetland area (*i.e*. new open water) begins to lead to a decrease in edge, thus creating a curvilinear relationship between wetland loss and edge. This complex relationship was first hypothesized by Browder, Bartley, and Davis (1985).

FWOA model results show this curvilinear relationship, particularly in the less optimistic and moderate with high sea-level rise scenarios toward the end of the simulation period (Figure 11). Overall, the coastal landscape is forecasted to contain a lower average percent edge under the 2012 Master Plan than that under FWOA (Figure 11). This reduction in percent edge would negatively impact some marsh-edge species such as brown and white shrimp and certain species of birds (O'Connell and Nyman, 2010; Reed, Hijuelos, and Fearnley, 2012). On the other hand, the reduction in percent edge across the landscape (Figure 11) is, in part, an indication of improvement of spatial integrity resulting from the implementation of projects in the Master Plan.

Basin Scale Assessment—Wetland Area Change

Investigating patterns at a basin scale often provides an in-depth understanding of the drivers and stressors that affect the structure and function of coastal wetlands. Basins are hydrologically distinct units that have differing habitat, land and water compositions, and configurations. The nine hydrologic basins in coastal Louisiana (excluding the Atchafalaya Basin) have displayed varying patterns of historic wetland change (Barras *et al*., 2003; Couvillion *et al*., 2011), and model results illustrate how those patterns will change through time with and without the Master Plan (Figure 12).

Wetland area for most basins, with the exception of Atchafalaya Delta, is projected to decrease over the simulation period under a FWOA condition (Figure 12). Under a moderate FWOA condition, land area may decrease by 5.4% (Teche/Vermilion), 9.8% (Calcasieu/Sabine), 10.9% (Mermentau), 12.3% (Pontchartrain), 17.1% (Terrebonne), 17.2% (Barataria), 44.1% (Mississippi River Delta), and 46.3% (Breton Sound) over the simulation period. Under the less optimistic FWOA condition, land area may decrease by 13% (Teche/Vermilion), 43% (Calcasieu/Sabine), 45.6% (Mermentau), 15.6% (Pontchartrain), 40.9% (Terrebonne), 21.3% (Barataria), 78.9% (Mississippi River Delta), and 52.2% (Breton Sound) over the next 50 years (2010–2060).

The degree to which wetland loss can be offset varies by basin and environmental uncertainty scenario. For example, Barataria Basin, which includes multiple marsh creation, shoreline protection, and sediment diversion projects, is projected to maintain or build between 305 and 375 km^2 of wetlands compared to a FWOA condition (Table 1). Model results suggest that other basins that include large-scale sediment diversion projects are also capable of building or maintaining large wetland areas compared to a FWOA condition, including Breton Sound (220–314 km^2) and Terrebonne (314–662 km^2) (Table 1). Pontchartrain Basin, which only includes a few smaller scale diversions but many large-scale marsh creation projects, also maintained or built a substantial amount of wetland area as compared to a FWOA condition (193–319 km^2) (Table 1). All of the previously mentioned basins drew upon the substantial sediment resources contained within the Mississippi and Atchafalaya Rivers, and, consequently, sediment accretion and wetland building capacity were increased in these basins.

Basins in the Chenier Plain of SW Louisiana do not have a substantial potential sediment source, as is the case for many basins in the Mississippi River Deltaic Plain (MRDP). Consequently, the Master Plan projects utilize marsh creation, shoreline protection, ridge restoration, and bank line stabilizations as means of restoration in these areas (Peyronnin *et al*., 2013). These basins are forecasted to have more moderate

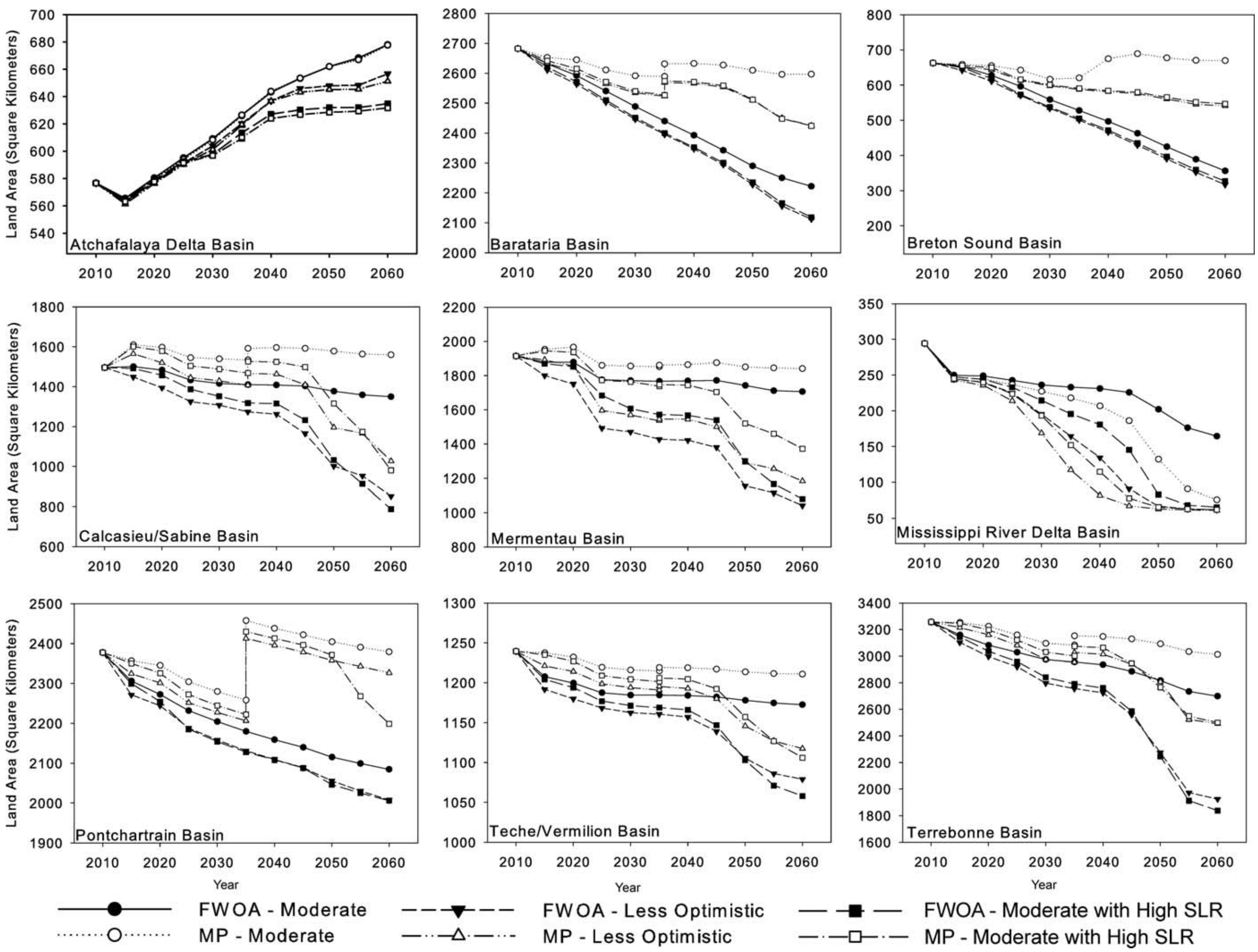

Figure 12. Land area projections by basin for "Future- without-action" and Master Plan alternatives under multiple environmental uncertainty scenarios, 2010–2060. Refer to Figure 1 for basin delineations. The sharp increases in wetland area in 2035 represent a considerable amount of marsh creation projects implemented in the second period of the Master Plan.

wetland maintenance and gain of wetland areas (Calcasieu/Sabine: 174–211 km^2; Mermentau: 132–292 km^2) by 2060 compared to a FWOA condition (Table 1). Teche/Vermilion Basin, which is generally considered to be marginally deltaic and received fewer projects under the Master Plan, is projected to have the smallest benefit from Master Plan incorporation (38–48 km^2) (Table 1). The lower overall net benefit area in these basins may reflect the lack of nourishment effects from diversions (Lane, Day, and Day, 2006; Twilley and Nyman, 2005). Without these nourishment effects, model results suggest that marsh creation, ridge restoration, and hydrologic restoration projects are not as effective at maintaining large wetland areas over time as large-scale sediment diversions. It is important to note that while these three basins experienced less benefits during 2010–2060 compared to a FWOA condition, they also experienced less net losses as a percentage of starting land area under a FWOA condition than most other basins. This occurs as these basins have historically been subject to lower subsidence and ESLR rates than most of the basins in the MRDP. Indeed, historic rates of wetland loss for these basins are far lower than those of Barataria, Breton Sound, Pontchartrain, and Terrebonne basins (Barras *et al*., 2003; Couvillion *et al*., 2011).

While in almost all portions of the coast the Master Plan represents an improvement in terms of percent land over the FWOA condition, the Mississippi River Delta and Atchafalaya Delta basins are notable exceptions. Projected land area in these basins is less in Master Plan than that of FWOA (Figure 12). This occurs as a large percentage of the discharge of the Mississippi and Atchafalaya rivers is being diverted upriver for the restoration diversions proposed in the Master Plan. This leads to lower sediment delivery and accretion rates in these

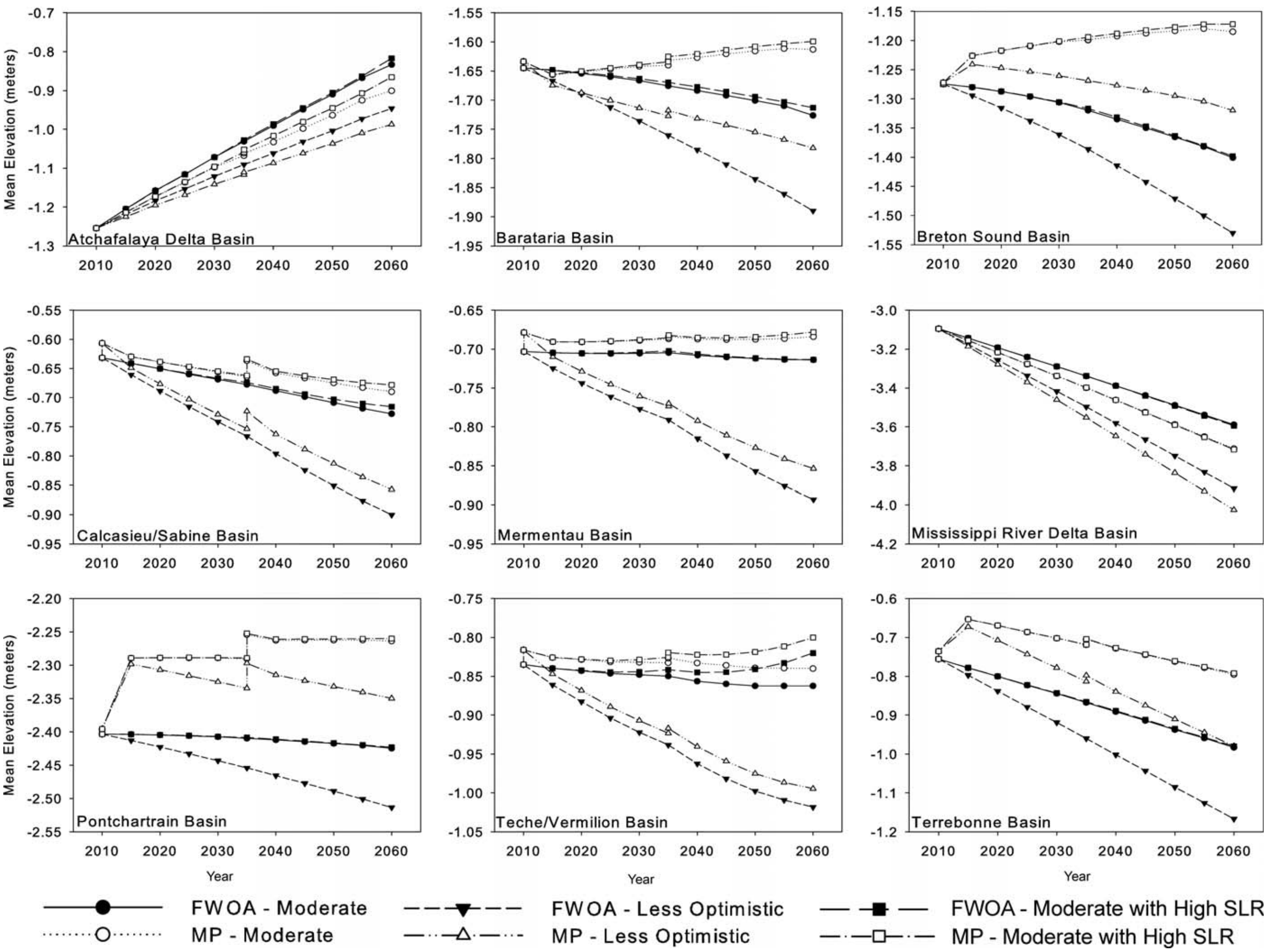

Figure 13. Projected average elevation (NAVD88) by basin for "Future-without-action" and Master Plan alternatives under multiple environmental uncertainty scenarios, 2010–2060.

basins under the Master Plan and consequently leads to additional wetland loss. The decreases in percent land in the Mississippi River Delta under all FWOA and Master Plan scenarios suggest that this delta is unsustainable because of high subsidence and ESLR projections.

Basin Scale Assessment—Surface Elevation

Mean simulated surface elevation tends to increase for most basins as a result of Master Plan incorporation, with a range of potential benefits from 2.2 cm (Teche/Vermilion Basin) to as high as 22.6 cm (Breton Sound Basin) over the simulation period (2010–2060) (Figure 13). Similar to the simulated land area patterns, elevation maintenance benefits of the Master Plan will be greatest in basins such as Breton Sound and Barataria, where sediment resources from the Mississippi River are available to support accretion (Meselhe *et al*., 2013; Steyer *et al*., 2012).

The two coastal basins that are exceptions to the increase in surface elevation by implementing the Master Plan are the Atchafalaya and Mississippi River Delta basins, in which Master Plan implementation will result in decreases of 4.1–6.7 cm and 10.8–12.4 cm, respectively, under the three environmental uncertainty scenarios (Figure 14). These decreases are a result of reductions in sediment available to these basins, leading to lower accretion rates and, consequently, elevation deficits over time.

One basin that is not generally considered in coastal processes is the Atchafalaya Basin. It is important to distinguish this basin from the Atchafalaya Delta Basin, which is considered a coastal basin (see Figure 1 for delineations of these basins). The Atchafalaya Basin is the nation's largest forested wetland area and functions as a floodway for 30% or more of the Mississippi River's water (Meade, 1996). As such, significant sediment is delivered to this basin, and, as a result, significant accretion is observed. Figure 14 illustrates that

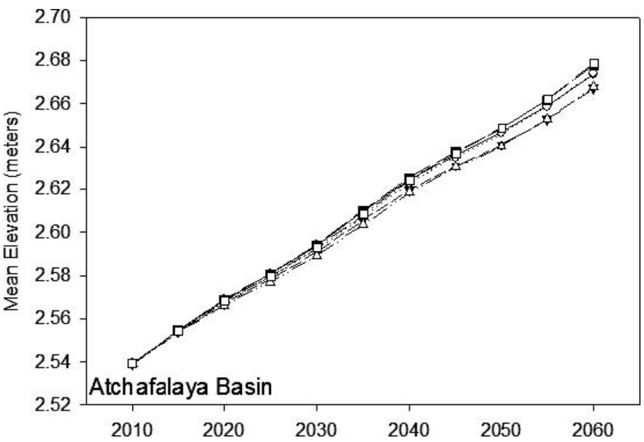

Figure 14. Projected average elevation (NAVD88) in Atchafalaya Basin for "Future-without-action" and Master Plan alternatives under multiple environmental uncertainty scenarios, 2010–2060.

under both FWOA and Master Plan conditions, the Atchafalaya Basin is projected to gain elevation at a consistent rate across environmental scenarios. This occurs because there is not much variability in the subsidence rate, and the effects of ESLR in this region are negligible. The difference in the mean elevation projections of the Atchafalaya Basin (Figure 14) and the Atchafalaya Delta Basin (Figure 13) in part underscores the influence of RSLR in projections.

Basin Scale Assessment—SOC

SOC storage among various hydrologic basins is spatially heterogeneous. Zhong and Xu (2009) estimated from the State Soil Geographic database (STATSGO) that the highest SOC storage occurs in river basins that have total SOC at 1 m depth ranging from 53 to 142 t/ha and a coastwide mean of 90 t/ha. Our estimates of surface meter SOC storage in the initial model year (2010) are 24.5 to 337.7 t/ha with a mean of 218 t/ha; however, the total river basin area in their study was 87,475 km^2, covering the upper watersheds, which have a lower SOC storage (normally <50 t/ha), that are not classified as coastal wetlands. In fact, in their study, the higher SOC storage to 1 m depth was found in coastal wetlands reaching up to 322.2 t/ha (Zhong and Xu, 2009). Additionally, in another related study, core-specific data from soil samples taken during 1996–2001 indicate that the mean surface meter SOC storage in the MRDP was 136–448 t/ha (Markewich *et al.*, 2007). Therefore, our SOC estimate is consistent with previous studies (Markewich *et al.*, 2007; Zhong and Xu, 2009).

The benefits of improved total SOC storage compared to the FWOA condition show spatial heterogeneity among different hydrologic basins under the three environmental uncertainty scenarios. Under the moderate scenario, Calcasieu/Sabine, Barataria, and Terrebonne are the top three basins with increases in SOC storage (20.7%, 18.7%, and 17.8%, respectively). Under the less optimistic scenario, the top three basins with increases in SOC storage would change to Terrebonne, Pontchartrain, and Calcasieu/Sabine (31.0%, 16.3%, and 15.9%, respectively). Under the moderate with high SLR scenario, the top three basins with increases in SOC storage would change to Terrebonne, Mermentau, and Calcasieu/Sabine (31.4%, 18.8%, and 15.8%, respectively). Because of the reduction in land area under restoration at the Mississippi River Delta, Atchafalaya Delta, and Atchafalaya Basin compared to that under FWOA, total SOC storage also shows a reduction under restoration in the Master Plan for these basins. Nevertheless, Mississippi River Delta and Atchafalaya Basin tend to have less reduction in SOC loss (restoration – FWOA) under the moderate with high SLR condition. Benefits of restoration in terms of SOC gain tend to increase under the moderate with high SLR scenario for Mermentau, Teche/Vermilion, and Terrebonne basins (Figure 15). Benefits of restoration would decrease from moderate to moderate with high SLR scenario for Atchafalaya Delta, Barataria, Breton Sound, Calcasieu/Sabine, and Pontchartrain basins because of the increased negative impacts of RSLR.

Project Scale Assessment

The influences of coastal protection and restoration projects on wetland morphologic variables vary with ecosystem properties in space such as distribution of vegetation, water, nutrients, and sediment. Therefore, it is often informative to analyze the benefits of specific protection and restoration projects at the project scale in order to understand the direct influences of various restoration efforts in specific areas. The Breton Sound Basin, shown in Figure 16, provides a good example for project scale assessment of restoration projects on wetland morphology. The Master Plan has three diversions planned in Breton Sound: Upper Breton Diversion (operating up to a maximum of approximately 7080 cubic m per second, cms); Mid-Breton Diversion (maximum 142 cms); and Lower Breton Diversion (1416 cms). The Master Plan also has a marsh creation planned at South Lake Lery (182 hectares), which is located in the Upper Breton Sound hydrologic unit.

Looking at the 2010 baseline conditions of the receiving basins (*i.e.* hydro boxes from the ecohydrology model), we found that landscape mean elevation, which is the average of bathymetry and topography, was substantially different between regions. The Upper Breton Sound is composed of 61.9% land and 38.1% water with a mean elevation of 0.22 m; whereas, the Middle and Lower Breton Sound Basins have a much lower percentage of land (47.1% and 19.8%, respectively) and lower mean elevation (0.05 m and –0.90 m, respectively). The deeper water depths in Lower Breton Sound, together with lower retention rates of sediments that are delivered through the Lower Breton Diversion, contribute to the inability to increase elevation over time under the less optimistic scenario (Figure 17). The Upper and Mid-Breton Diversions, which have receiving areas with a greater percentage of vegetated marsh and shallower water depths, are able to increase elevation over the 50-year period (Figure 17). This increase in elevation contributes to a much greater percentage of land in the Upper and Mid-Breton Sound Basin, as compared to the FWOA (Figure 18).

Our simulations with the mid-diversion (maximum 142 cms) indicate that surface elevation may increase 40 to 25 cm over the 50-year simulation period (or ~8 and 5 mm/y) under the

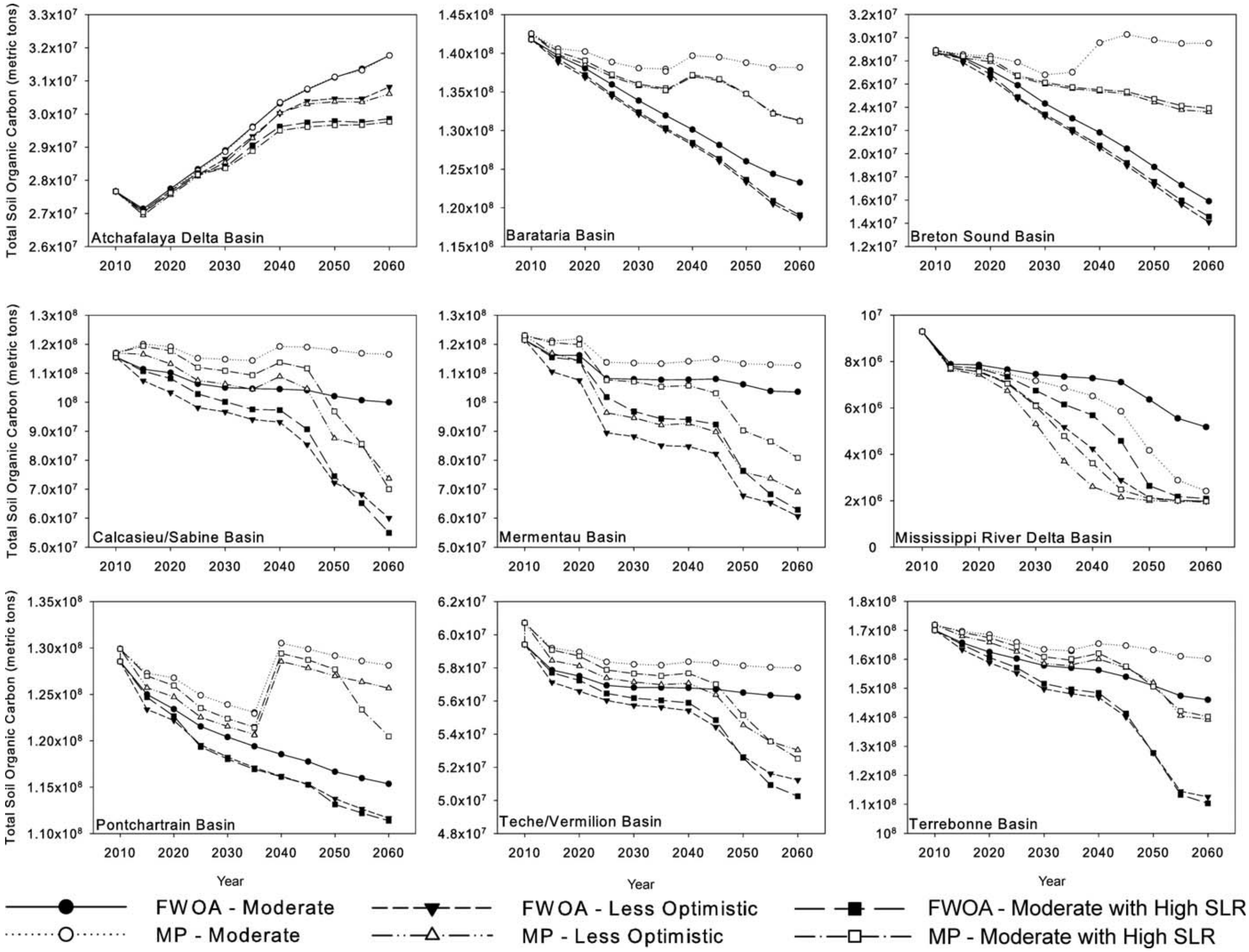

Figure 15. Projected surface meter soil organic carbon storage during 2010–2060 by basin for "Future without action" and Master Plan alternatives under multiple environmental uncertainty scenarios.

moderate and less optimistic scenarios, respectively. Lane, Day, and Day (2006) found that at the receiving marsh of the Caernarvon Diversion (maximum 142 cms), surface elevation increased from about 1.6 to 4.2 cm/y. They also found that elevations near the diversion site tended to increase significantly, while the middle and far sites tended to not change significantly. The difference in elevation gains between our study and Lane, Day, and Day (2006) is primarily attributable to the spatial variability in sediment discharge and differences in vertical accretion from river diversion as well as in the contributions from organic matter (Allison *et al*., 2012; Snedden *et al*., 2007; Steyer *et al*., 2012; Visser *et al*., 2013).

Though synergistic effects were excluded from the initial project-level screening runs, these effects were considered when the final Master Plan was modeled. An example of a synergistic effect could include a diversion supporting increased rates of accretion and the subsequent prolonged retention of a project such as a marsh creation. Diversions can also serve to nourish marsh creation projects by delivering freshwater nutrients that can stimulate organic production (Twilley and Nyman, 2005). As shown in Peyronnin *et al*. (2013), many projects were located in close proximity to each other in order to garner synergistic effects that may contribute to a sustainable and resilient coastal landscape.

The South Lake Lery marsh creation project (1.88 km^2) is an example of a project that benefits from a substantial sediment source provided by the proposed Upper Breton Diversion. The marsh creation project shows remarkable stability throughout the 50-year simulation period (Figure 19). This stability occurs as the result of the accretion fostered by the sediment from the diversion, which offsets the effects of RSLR in the region. Conversely, marsh creation projects that do not have a nourishment component, such as East Pecan Island (29.7 km^2), located in Mermentau Basin to the east of Freshwater

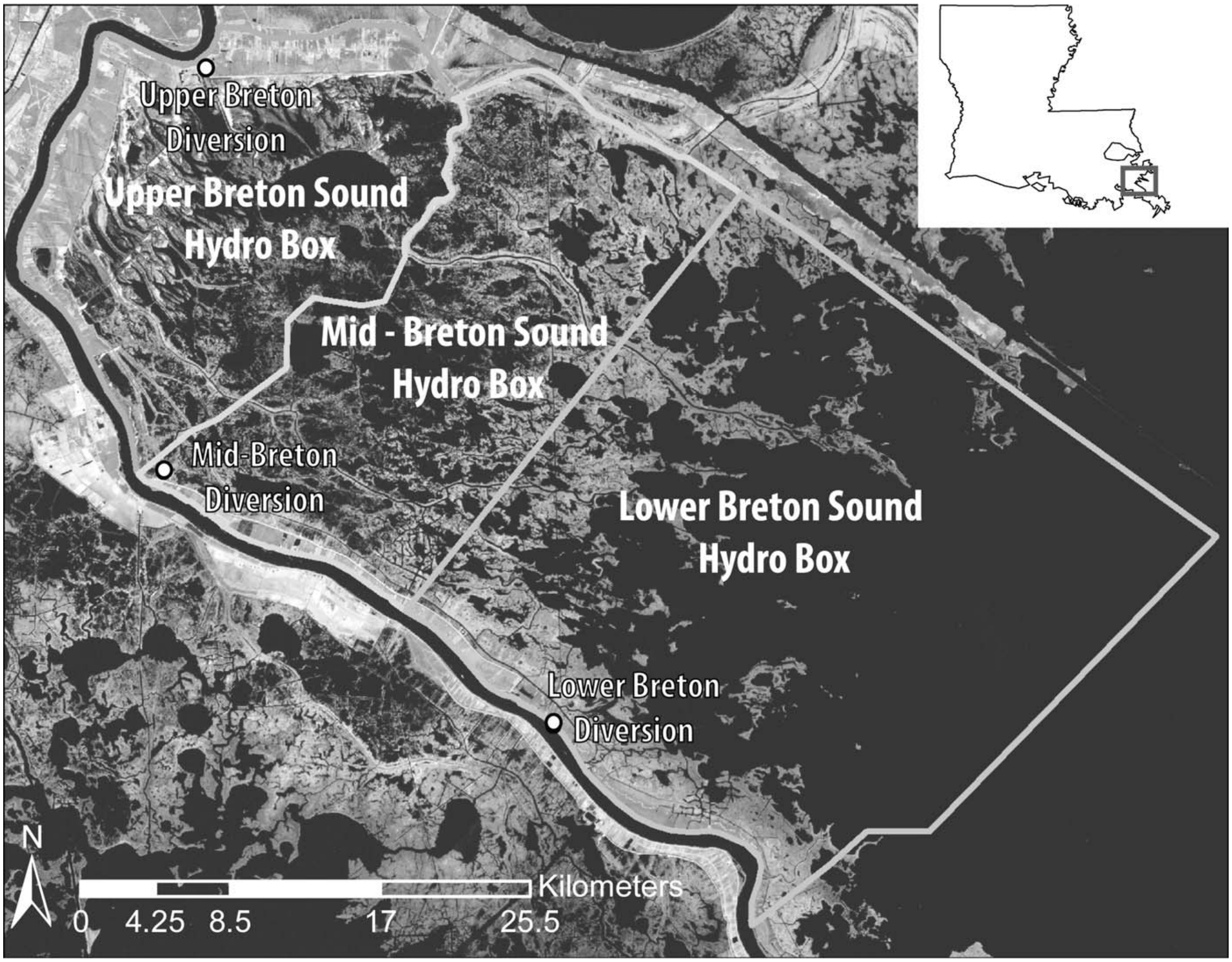

Figure 16. Map of hydrologic units and diversions influencing Breton Sound Basin.

Bayou, are susceptible to higher losses over time (Figure 20). The project shows only slight decreases in its overall percent land throughout a majority of the time; however, percent land is rapidly decreasing near the end of the observation period (Figure 20). These losses are attributable to accelerated SLR under the less optimistic scenario, which contributes to an elevation deficit, and marsh loss begins to be triggered. Without a significant sediment supply to maintain accretion rates, the project begins to deteriorate and land is lost.

SUMMARY AND CONCLUSIONS

Model results indicate that change in the coastal landscape of Louisiana is inevitable and each of the environmental uncertainty scenarios modeled indicate losses will continue to occur. Though wetland loss can be mitigated or even reversed in specific areas via restoration projects, at a coastwide scale, a net loss is still observed even with a substantial investment in restoration and protection. Continued loss of Louisiana's wetlands may result in impacts to not only our landscape structure but also beneficial ecosystem functions such as hurricane/storm protection, nursery habitats for commercial fish species, and essential stopover areas for migratory waterfowl.

In a FWOA condition, the dangerous combination of subsiding wetlands and rising sea levels could lead to marsh deterioration, erosion, and collapse. High primary productivity in Louisiana's marshes has historically resulted in large amounts of carbon sequestration; however, deterioration of wetlands through increased inundation and shoreline erosion greatly impacts the overall amount of SOC held within marsh soils. Shoreline erosion can also lead to increased edge habitat but could reduce landscape integrity.

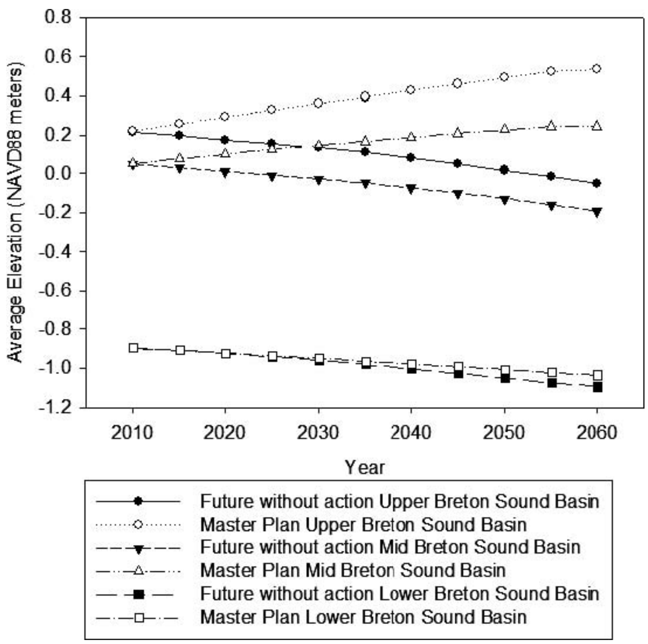

Figure 17. Average elevation projections (NAVD88) in upper, mid-, and lower Breton Sound Basin for "Future-without-action" and Master Plan alternatives under less optimistic uncertainty scenario, 2010–2060. Refer to Figure 16 for area delineations.

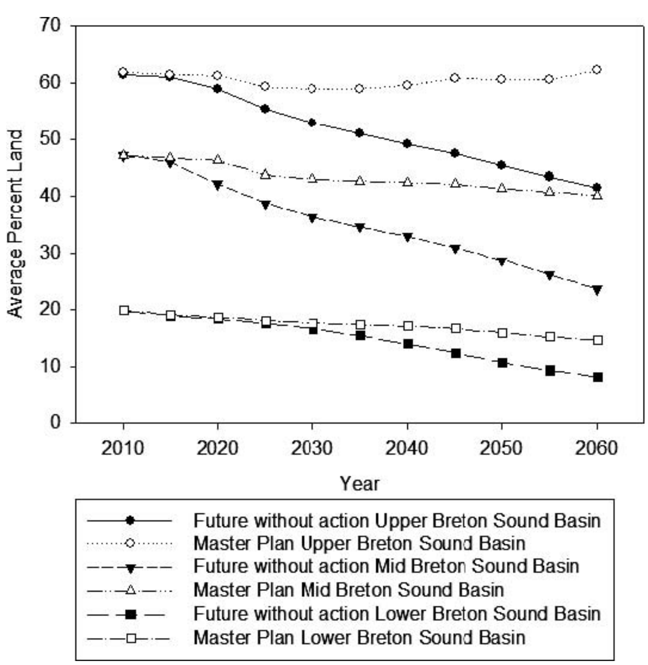

Figure 18. Average percent land projections in upper, mid and lower Breton Sound Basin for "Future-without-action" and Master Plan alternatives under less optimistic uncertainty scenario, 2010–2060. Refer to Figure 16 for area delineations.

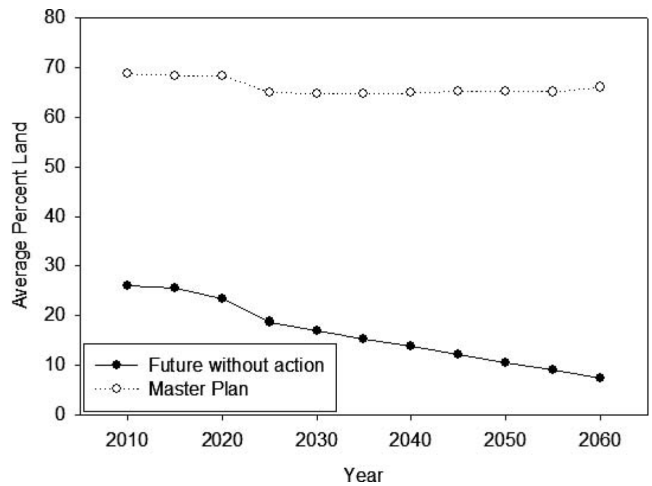

Figure 19. Average percent land projections in the South Lake Lery marsh creation project for "Future-without-action" and Master Plan alternatives under less optimistic uncertainty scenario, 2010–2060.

The spatial wetland morphology model predicted where land change might occur under given environmental uncertainty scenarios. This information is invaluable to the Coastal Protection and Restoration Authority when determining which restoration and protection projects could be most beneficial by comparing a Master Plan versus a FWOA situation. It is important to note that certain areas (*e.g.* the Mississippi River Delta Basin) are lost in model projections regardless of restoration investment, and as such, other strategies of adaptation may have to be utilized.

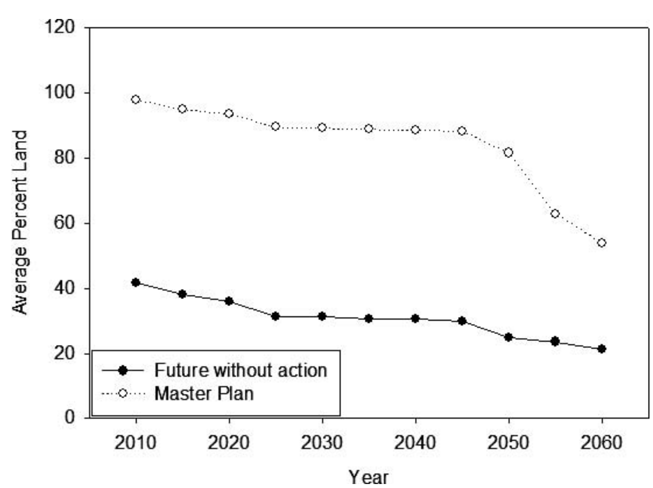

Figure 20. Average percent land projections in the East Pecan Island marsh creation project for "Future-without-action" and Master Plan alternatives under less optimistic uncertainty scenario, 2010–2060.

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