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Risk of Inundation to Coastal Wetlands and Soil Organic Carbon and Organic Nitrogen Accounting in Louisiana, USA

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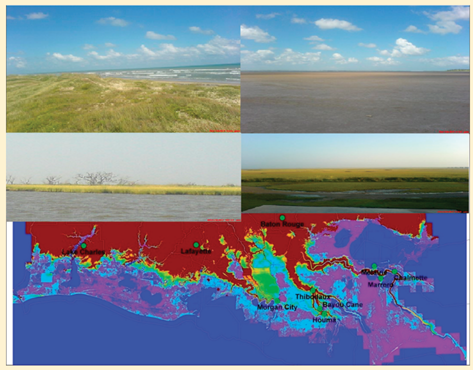
ABSTRACT: Exceeding 1.2 million acres (4856 km^2) since the 1930s, coastal wetland loss has been the most threatening environmental problem in Louisiana, United States. This study utilized high-resolution LiDAR (Light Detection and Ranging) and DEM (Digital Elevation Model) data sets to assess the risk of potential wetland loss due to future sea level rises, their spatial distribution, and the associated loss of soil organic carbon (SOC) and organic nitrogen (SON) estimated from the State Soil Geographic (STATSGO) Database and National Wetlands Inventory (NWI) digital data. Potential inundation areas were divided into five elevation scales: < 0 cm, 0−50 cm, 50−100 cm, 100−150 cm, and 150−200 cm above mean sea level. The study found that southeastern Louisiana on the Mississippi River Delta, specifically the Pontchartrain and Barataria Basins, are most vulnerable to sea-level rise induced inundation. Accordingly, approximately 42,264,600 t of SOC and 2,817,640 t of SON would be inundated by 2050 using an average wetland SOC density (203 t per hectare) for the inundation areas between 0 and 50 cm. The estimated annual SOC and SON loss from Louisiana's coast is 17% of annual organic carbon and 6−8% of annual organic nitrogen inputs from the Mississippi River.



INTRODUCTION

According to the 2007 report of the Intergovernmental Panel on Climate Change,[1] the global average sea level has been rising from 1961 to the present time at an average rate of 1.8 mm per year (ranging from 1.3 to 2.3). The rise rate was faster for the past 10 years from 1993 to 2003, averaging about 3.1 mm per year with a range between 2.4 and 3.8. Researchers[2] have found that the rate of sea-level rise increased from the 19th to the 20th century, and that the rise is likely to accelerate in the 21st century due to anthropogenic global climate change. For the full range of the Special Report on Emissions Scenarios (SRES), the IPCC[1] predicts that the global mean sea level will rise by 180 to 590 mm between the years 1990 and 2100.

Louisiana has experienced severe coastal wetland loss and barrier island erosion. Within the last 50 years land loss rates have exceeded over 60 km^2 per year, and in the 1990s the rate has been estimated to be between 40 and 56 km^2 each year.[3] This loss represents 80% of the coastal wetland loss annually in the entire continental United States. The highest relative sea-level rise (RSLR) is 17.7 mm per year at Calumet station in St. Mary's Parish of Louisiana according to the U.S. Army Corps of Engineers tide gauge stations[4] compared to 10.4 mm per year at Grand Isle, Louisiana, 6.3 mm per year at Galveston, Texas, 2.3 mm per year at Pensacola, Florida, 2.2 mm per year at Key West, Florida, 1.7 mm per year at Cedar Key, Florida, 1.5 mm per year at Biloxi, Mississippi, and 3.1 mm per year eustatic sea-level rise (SLR).

Wetlands are among the most valued ecosystems and play an important role in the global carbon cycle and adaption to global climate change.[5] Wetland soils can contain from a few percent of organic matter to 100% (peat). Wetland soils serve an important role in removing carbon dioxide from the atmosphere, building a carbon sink, and thereby being able to mitigate and adapt to global climate change. In Louisiana one-third of soil organic carbon (SOC) is buried in wetlands, the state's largest carbon sink. The Gulf of Mexico dead zone is one of the largest in the world. Hypoxic water areas were caused by nutrients enrichment, particularly nitrogen (N) and phosphorus.[6−9]

Besides the inputs to the Gulf of Mexico from the Mississippi River Basin,[10−13] Louisiana's coastal wetlands losses provide potential nutrients sources for the coastal microbial food web, which may further exacerbate oxygen depletion of the near-shore waters in the Gulf of Mexico.[14] The accurate projection of marsh-derived SOC and soil organic nitrogen (SON) sources to the Gulf of Mexico due to a future sea level rise has not been investigated.[15,16] A large part of the land SOC and SON loss by inundation will be consumed by marine ecosystems, while the others may remain in the sea floor for a long time. Because most readily usable organic matter is oxidized or consumed rapidly, little organic matter may accumulate in deep marine systems.[17] It is useful to quantify the potential SOC and SON inputs to the Gulf of Mexico from coastal wetlands due to future sea level rises.

Several programs are in place to restore Louisiana's coastal areas and wetlands including the federal Coastal Wetlands, Planning,

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Protection and Restoration Act (CWPPRA) of 1990, "Coast 2050—Toward a Sustainable Coastal Louisiana"[3] developed in 1998, and the Gulf of Mexico Energy Security Act signed into law in December 2006. These programs have given million of dollars, and are expected to give billions of dollars, to Louisiana per year for coastal restoration and protection. A major challenge of Louisiana's coastal restoration is to develop the most strategic, efficient, and timely strategies for science and science-based planning, while maximizing the synergies and minimizing the conflicts in achieving multiple social objectives.[18]

The objectives of this study were to (i) assess the spatial distribution of inundation areas in south Louisiana using Light Detection and Ranging (LiDAR) and 1:24k Digital Elevation Models (DEM) data sets and reclassifying these areas into five potential inundation elevation categories; (ii) quantify SOC storage using the State Soil Geographic (STATSGO) Database in these areas that may potentially be inundated; (iii) examine SOC storage and N contents within possible inundated elevation categories; (iv) estimate potential SOC and SON inputs to the Gulf of Mexico from the coastal wetland loss due to future sea level rises.

■ METHODS

Study Area and Data Sources. Louisiana coastal area extends from 89° W to 94° W in the longitude and from 29° N to 30.5° N in the latitude. Louisiana is a low-lying state with an average elevation of 30.5 m, ranging from 2.4 m below (New Orleans) to 163.0 m above (Driskill Mountain) sea level. Wetlands occur throughout the state with the largest percentage in the Gulf Coast marsh and alluvial plains. Louisiana, after Alaska and Florida, has the largest wetland acreage (35 612 km^2) in the United States.[19]

This study used the geographically referenced databases: U.S. Geological Survey (USGS) 1:24K Digital Elevation Models (DEM) data, Federal Emergency Management Agency (FEMA) Light Detection and Ranging (LiDAR) data (http://atlas.lsu.edu/lidar), United States Department of Agriculture—Natural Resources Conservation Service (USDA-NRCS), formerly the Soil Conservation Service (SCS), State Soil Geographic (STATSGO) Database, and National Wetlands Inventory (NWI) digital data (http://wetlandsfws.er.usgs.gov).

NWI digital data were developed by the U.S. Fish and Wildlife Service and represent the extent, approximate location, and type of wetlands. The classification system was adopted as a national classification standard in 1996 by the Federal Geographic Data Committee. These data delineate the areal extent of wetlands and surface waters as defined by Cowardin et al.[20]

LiDAR data were derived from LiDAR measurements performed in 1999, and are presented at an elevation posting a horizontal interval of 5 m and a vertical interval of 0.2 m. These data were produced for the Louisiana Federal Emergency Management Agency (FEMA) Project under the St. Louis District U.S. Army Corps of Engineers (USACE) by 3001 Inc. (a Northrop Grumman company). The entire mosaic LiDAR data in the Louisiana coastal area were merged by Computer Aided Design and Geographic Information Systems (CADGIS) Research Laboratory at Louisiana State University. The Louisiana 1:24K Digital Elevation Data set[21] was derived from the U.S. Geological Survey National Elevation Database (NED) by Louisiana Department of Environmental Quality (LDEQ) and Louisiana Oil Spill Coordinator's Office (LOSCO). The 1:24K DEM has a 30 m horizontal resolution and 0.3 m vertical precision.

Terrain Analysis. Inundation zones are the areas that are at risk to be flooded because of their flat and low elevation. This study classified elevation into five potential inundation scales: below 0 cm, 0−50 cm, 50−100 cm, 100−150 cm, and 150−200 cm above mean sea level. Areas above 200 cm in elevation were classified as referenced noninundation zone. The areas of each elevation category were summarized from the LiDAR and 1:24k DEM data sets by multiplying the total cell number and each cell size. All raster cells at certain elevations in the LiDAR data were flagged along Louisiana coast area. LiDAR data and 1:24k DEM data were reclassified with these five scales converted from feet units through reclassify, a function of Spatial Analyst Tools in ArcGIS 9.3.[22]

Estimation of Soil Organic Carbon. Soil organic carbon contents were estimated from the soil organic matter (SOM) content, soil layer depth, and bulk density in the STATSGO database[23−25] as follows:

$$C_s = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(\mathrm{BD}_{ij} \times D_{ij} \times \mathrm{SOM}_{ij}) \times \mathrm{COMP}_i}{1.724} \qquad (1)$$

where C_s is the SOC content (metric tons), SOM is the soil organic matter content (%), D is the depth of a soil horizon (m), BD is the soil bulk density (t m^{-3}), COMP is the area percent of the soil component within each map unit, and the subscripts i and j are the identifiers for soil horizons and components, respectively. The Van Bemmelen factor of 1.724 was used on the formula that soil organic matter contains 58% organic carbon.[26] The maximum measured soil horizon depth in STATSGO was 275 cm.

Spatial Analyses and SOC Storage and Potential Loss Estimation. SOC densities were calculated by the total SOC contents in each polygon of STATSGO data sets dividing the polygon area through the Visual Basic for Application (VBA) in ArcGIS 9.3[22] and the Structured Query Language (SQL) in Microsoft Access 2007. SOC estimates of each polygon and NWI vector polygons were converted to 10 m × 10 m raster data sets through a function of Conversion Tools in ArcGIS 9.3[22] for spatial analysis requirements. The elevation classification map was aggregated with SOC densities and NWI raster data sets within each elevation category. We conducted this procedure through a function of Spatial Analyst Tools in ArcGIS 9.3[22] named Zonal Statistics as Table, which was used to summarize the SOC values within each elevation scale (below 0 cm, 0−50 cm, 50−100 cm, 100−150 cm, 150−200 cm, and above 200 cm) or each wetland type (Freshwater Forested/Shrub Wetland, Estuarine and Marine Wetland, and Freshwater Emergent Wetland). We used the average SOC densities multiplying the projected 1990−2050 wetland loss—"best estimate"[3]—on the inundation zones between 0 and 50 cm to estimate the total potential SOC loss. The annual loss of soil organic carbon was estimated by dividing the total potential SOC loss by sixty.

Estimation of Soil Organic Nitrogen Storage and Potential Loss. We estimated SON contents based on the average C:N ratios, chemical analysis results of an investigation in the entire coastal marshlands of Louisiana. The mean C:N ratio of the peat and meadow soils was 17.83:1 in the Zoige plateau, southeast of the Qinghai−Tibet plateau of China.[27] Brupbacher et al.[28] conducted soil sampling, identification, and chemical analysis of soil samples collected from 366 sites in the coastal marshlands of Louisiana between August 7 and August 22 in 1968. The sampling

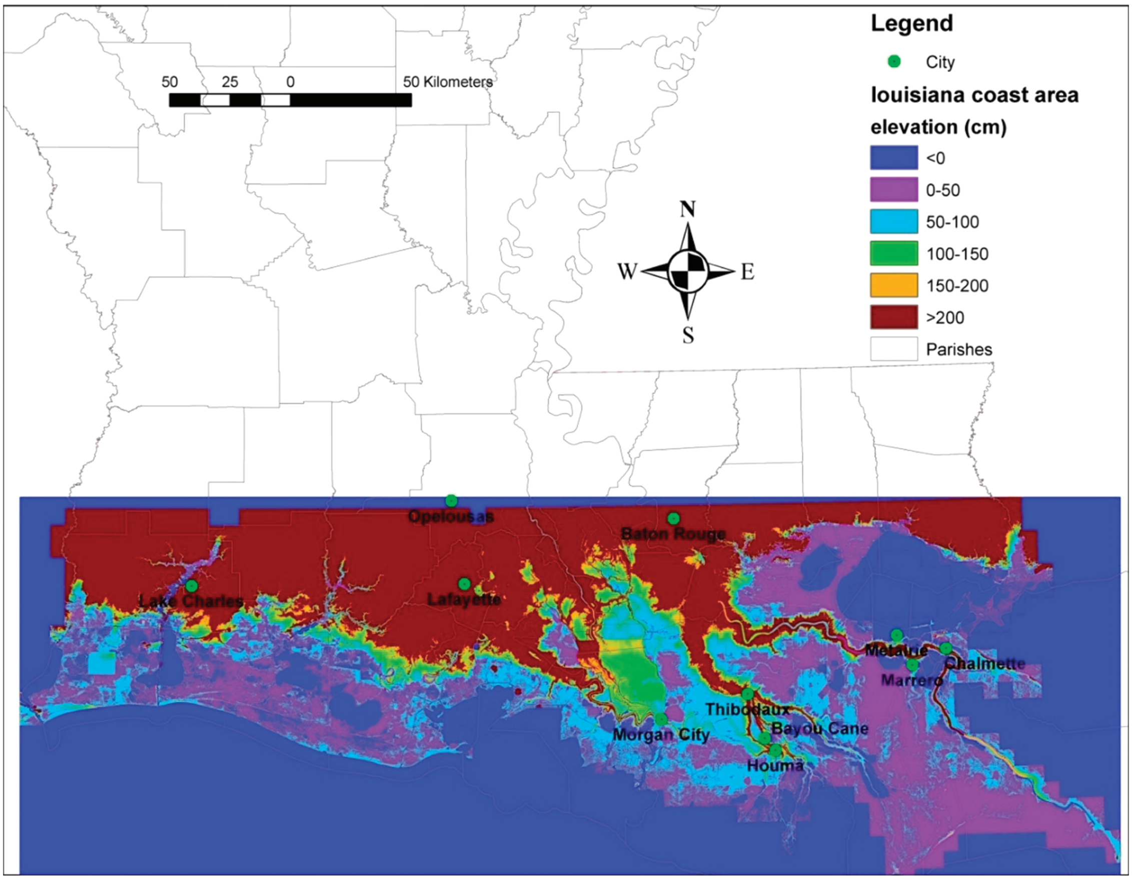

Figure 1. Louisiana coastal areas in LiDAR data.

sites stretched from the western boundary to eastern boundary of southern Louisiana. Two helicopters were used in collecting the samples, taken from the surface to a depth of about 20 cm. A 25-g subsample of air-dried soil materials was used for the determination of organic carbon (C), organic nitrogen (N), acid-extractable phosphorus (P), sodium (Na), magnesium (Mg), calcium (Ca), and potassium (K). The ranges of C:N ratios in mineral soil materials in freshwater marshes, brackish marshes, and saltwater marshes were 8.0−18.2, 9.9−23.4, and 11.7−26.0, respectively. The ranges of C:N ratios in organic soil materials in freshwater marshes, brackish marshes, and saltwater marshes were 10.3−28.2, 10.4−36.2, and 12.2−43.8, respectively. We used the median C:N ratio 15:1 to estimate the total SON loss from the coastal wetland ecosystems on the 0−50 cm inundation zones between 1990 and 2050. The annual loss of SON was estimated by dividing the total potential SON loss by sixty.

■ RESULTS AND DISCUSSION

Spatial Distribution of Elevation in Louisiana Coastal Area. Southeastern Louisiana coastal areas around the Mississippi River, parts of Pontchartrain and Barataria Basins, are in the most vulnerable inundation zones, between 0 and 50 cm elevation (Figure 1). The Mississippi River flows out to sea in the southeast area of the state. These areas are the historical and current Mississippi River deltaic lobes built during the last 5000−10 000 years, which have the highest SOC density in Louisiana.

Table 1 shows potential inundation areas, SOC storage, and percentages at six elevation classes using two different data sets. The total inundation zones between 0 and 50 cm in coastal Louisiana were 10 892.95 km^2 with the LiDAR data set, which is 30% more than that determined with the 1:24k USGS DEM data set (7378.32 km^2). The total inundation zones between 50 and 100 cm in LiDAR data sets were 6817.35 km^2, while the DEM data set found a total inundation area of 8572.69 km^2 for the same elevation category. However, LiDAR and 1:24k DEM data sets found a very similar land area at the elevation of more than 200 cm (15 839 km^2 vs 15 556 km^2, respectively).

Louisiana coast showed the highest SOC density in the areas with an elevation between 0 and 100 cm. The mean SOC densities in the maximum soil depths in LiDAR data sets between 0 and 50 cm, 50−100 cm, and 100−150 cm, were 197, 189, and 118 t per hectare, respectively.

The horizontal resolution of LiDAR data is 5 m , which is much higher than that of the 1:24k DEM data and Landsat Thematic Mapper (TM) multispectral imagery. The minimum detectable spatial resolution of TM multispectral imagery is 30 m for the current coastal Louisiana land loss research.[29] The boundaries of the mosaic LiDAR data do not cover all of the Louisiana areas, missing the active delta zone of southern-most Louisiana, the bird foot delta. The boundary of 1:24k DEM data is complete and covers the entire state. However, the 1:24k DEM data cannot differentiate between the zero meter land areas and water areas. It shows the same elevation for those zero meter land areas, lakes, and sea waters. In this regard, the LiDAR data provide clear resolution because of their better vertical precision.

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Table 1. Distribution of SOC Stock in Coastal Louisiana Lowlands

elevation(cm)	LiDAR					1:24,000 DEM				
	area (km^2)	area percentages	mean (t/ha)	SOC (10^6 t)	total SOC percentages	area (km^2)	area percentages	mean (t/ha)	SOC (10^6 t)	total SOC percentages
<0	6053.91		103	62.27						
0−50	10 892.95	28.75%	197	214.92	39.63%	7378.32	19.04%	203	149.70	24.93%
50−100	6817.35	17.99%	189	128.61	23.71%	8572.69	22.13%	223	191.60	31.90%
100−150	2610.40	6.89%	118	30.75	5.67%	1674.80	4.32%	188	31.47	5.24%
150−200	1731.84	4.57%	100	17.31	3.19%	5559.24	14.35%	136	75.44	12.56%
>200	15 839.45	41.80%	95	150.74	27.80%	15 556.91	40.16%	98	152.36	25.37%

Table 2. Size and Elevation of Different Coastal Wetlands As Determined with LiDAR Data Sets

elevation (cm)	freshwater forested/shrub wetland		estuarine and marine wetland		freshwater emergent wetland		total areas
	area (km^2)	percent	area (km^2)	percent	area (km^2)	percent	area (km^2)
water areas	9	0.1%	2031	29.3%	45	1.2%	2085
<0	342	3.8%	416	6.0%	294	7.7%	1052
0−50	2359	26.3%	2375	34.2%	1835	47.8%	6570
50−100	2099	23.4%	1909	27.5%	1458	38.0%	5466
100−150	1047	11.7%	177	2.6%	112	2.9%	1337
150−200	623	6.9%	10	0.2%	25	0.6%	659
>200	2498	27.8%	22	0.3%	68	1.8%	2589
total	45.4%		35.1%		19.4%		

Table 3. Size and Elevation of Different Coastal Wetlands As Determined with 1:24k DEM Data Sets

elevation (cm)	freshwater forested/shrub wetland (km^2)		estuarine and marine wetland		freshwater emergent wetland		total areas
	area (km^2)	percent	area (km^2)	percent	area (km^2)	percent	area (km^2)
<0	172	1.9%	573	8.1%	266	6.7%	1011
0−50	630	7.0%	3267	46.4%	1984	49.7%	5882
50−100	2681	29.8%	2835	40.3%	1227	30.7%	6743
100−150	691	7.7%	230	3.3%	219	5.5%	1140
150−200	2314	25.8%	120	1.7%	237	5.9%	2670
>200	2496	27.8%	14	0.2%	63	1.6%	2573

Thoms et al.[30] compared the LiDAR (resolution: 1 m; accuracy/precision: 8−11 cm/2−3 cm), ground-based differential GPS (DGPS) survey (resolution: 1−200 m; accuracy/precision: <1 cm), and 1:100K 9” DEM (resolution: 250 m; accuracy/precision: >3 m) in the Narran Lakes Ecosystem (5500 ha) of Australia. They found that the LiDAR could yield significantly more details than the DGPS survey, shown to be a highly accurate and robust technique for acquiring topographic data, even in locations that are unsuitable for ground surveying and where the overall landscape is of exceptionally low relief. They concluded that LiDAR has the potential for accurate determination of the topography of floodplain wetlands. Knight et al.[31] explored the use of LiDAR (vertical resolution: 5 cm) to map an approximately 92-ha area of mangrove, saltmarsh, and some terrestrial forest. Based on the simulation results for the tidal inundation and sea level scenarios, they concluded that the LiDAR data set may be a feasible method to inform research on changes in land use and ecosystems caused by future sea level rises. Hopkinson et al.[32] compared TRIM (Terrain Resource Information Management) 1:20k contour vectors, stereo aerial photography DEM, and airborne LiDAR, and found that the LiDAR data were clearly better for the detailed watershed attribute assessment with the continued reductions of LiDAR acquisition costs.

SOC and SON Storage and Potential Loss in Louisiana Coastal Wetlands. Large areas of freshwater forested/shrub wetlands, estuarine and marine wetlands, and freshwater emergent wetlands in Louisiana are at risk in the inundation zones between 0 and 100 cm in both LiDAR and 1:24k DEM data sets (Tables 2 and 3). Over 6000 km^2 of estuarine and marine wetlands, up to 3000 km^2 of freshwater forested/shrub wetlands, and at least 3000 km^2 of freshwater emergent wetlands are in the inundation zones below 100 cm in both the LiDAR and 1:24k DEM data sets. Total wetlands areas in the inundation zones below 100 cm are 15 173 km^2 in LiDAR data sets and 13 636 km^2 in 1:24k DEM data sets.

Estuarine and marine wetlands showed the highest SOC density and total carbon percentage, although freshwater forested/

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Table 4. SOC Storage of Three Major Coastal Wetlands in Louisiana

wetland type	area (km^2)	area percentages	mean SOC (t/ha)	total SOC (10^6 t)	total SOC percentages	SON density (t/ha)
freshwater forested/shrub wetland	8978	44.8%	184	165	42.0%	13.1
estuarine and marine wetland	7047	35.2%	243	171	43.5%	14.3
freshwater emergent wetland	3999	20.0%	144	57	14.6%	9.6

shrub wetlands had the largest areas in coastal Louisiana. The mean SOC densities of freshwater forested/shrub wetlands, estuarine and marine wetlands, and freshwater emergent wetlands in the maximum soil depths in Louisiana were 184, 243, and 144 tons per hectare, respectively. The SOC densities in these wetlands are much larger than the average SOC densities in agriculture and forests, which were 94 and 97 tons per hectare, respectively. SON densities of freshwater forested/shrub wetlands, estuarine and marine wetlands, and freshwater emergent wetlands were 13.1, 14.3, and 9.6 tons per hectare, respectively (Table 4).

Coastal land loss is among the most serious environmental problems in Louisiana. According to a recent GAO report, coastal Louisiana has lost over 1.2 million acres (4856 km^2) since the 1930s,[33] an area more than 25 times larger than Washington, DC. Based on the 1974−1990 marsh loss rate, Louisiana is projected to lose nearly 514 460 acres (2082 km^2) of marsh from 1990 to 2050 without restoration—21% of today's marsh as a "best estimate".[3] Nearly 115 000 acres (465 km^2) of that loss will be prevented if the benefits of coastal restoration projects are included.[3] Thus, with the current restoration efforts we will still lose nearly 400 000 (1619 km^2) net acres of marsh by 2050. Recently, Blum and Roberts[34] estimated that an additional area of 10 000−13 500 km^2 of the Mississippi Delta would be submerged by the year 2100 owing to subsidence and sea-level rise due to the absence of sediment inputs. They postulated that significant drowning would be inevitable, even if sediment loads would be restored, because sea level is now rising at least three times faster than the rate of the delta-plain development.

One assumption was made to estimate the potential SOC and SON loss: SOC and SON from those eroded wetlands will be eventually distributed to the Gulf of Mexico. SOC loss from the coastal terrestrial ecosystem will be approximately 42 264 600 tons using the average SOC density, 203 tons per hectare, for the inundation areas between 0 and 50 cm and the "best estimate," 514 460 acres (2082 km^2) from 1990 to 2050 without restoration.[3] The SON loss from the coastal terrestrial ecosystem from 1990 to 2050 without restoration will be approximately 2 817 640 tons using a median C:N ratio of 15:1.

The annual loss of land soil organic carbon and organic nitrogen for 1990−2050 was 704 410 tons of SOC per year and 46 960 tons of SON per year. Bianchi and others[35,36] estimated that the dissolved organic carbon (DOC) and particulate organic carbon (POC) loading are 3 100 000 and 930 000 tons per year from the Mississippi River to the Gulf of Mexico. Therefore, our estimated annual land SOC loss to the sea in coastal Louisiana is 17% of annual organic carbon inputs from the Mississippi River. Goolsby[10] estimated that mean annul total N (61% nitrate N, 37% organic N, and 2% ammonium N) and organic N flux to the Gulf of Mexico was 1 568 000 and 580 160 tons per year from the Mississippi River Basin. Dagg and Breed[12] estimated that the Mississippi River currently delivers approximately 1 820 000 tons total N (53% nitrate, 43% organic nitrogen, and 4% ammonium) and 782 600 tons organic N each year to the northern Gulf of Mexico. Therefore, our estimated annual SON loss from coastal Louisiana to the sea is only 6% or 8% of annual organic N inputs from the Mississippi River. These low nitrogen percentages are in agreement with the argument of Turner and other scientists:[37] wetland loss is not likely to be a significant contribution to the carbon-loading hypoxic zone offshore.

Louisiana's coast is generally divided into four regions based on hydrologic basins for planning purposes: Region 1, Pontchartrain; Region 2, Breton, Barataria, and Mississippi River; Region 3, Terrebonne, Atchafalaya, and Teche/Vermilion; and Region 4, Calcasieu/Sabine and Mermentau.[3] Each region is further divided into mapping units. Coastal wetlands have to accrete vertically to survive and keep pace with RSLR and SLR. The process of coastal wetlands vertical accretion can be explained as organic matter accumulation and mineral sedimentation accumulation.[38] One question is the importance and restoration order of regions or spatial parts of region. Louisiana's current restoration program has many objectives. Carbon and nitrogen sequestration potential should be included to determine the importance and/or restoration priority of wetlands. The spatial areas, which have higher carbon and nitrogen densities, should receive high priorities of restoration and protection. Considering carbon sequestration in the processing of wetland restoration or protection can bring carbon credit to those projects and gain more support.

Google Earth provides a number of high-resolution satellite images at both geospatial and temporal scales. Google Earth was used to present the fossil fuel CO_2 emissions in data product (the "Vulcan" inventory) at both high-resolution spatial and temporal scales.[39] The U.S. Fish and Wildlife Service created a Keyhole Markup Language file to view the National Wetlands Inventory data under Google Earth platform (http://www.fws.gov/wetlands/Data/GoogleEarth.html). Google Earth platform and those high-resolution satellite images can be utilized in the future soil carbon and nitrogen accounting and coastal wetlands inundation research.

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