Limnol. Oceanogr., 57(1), 2012, 18–28

doi:10.4319/lo.2012.57.1.0018

Watershed land use and river engineering drive wetland formation and loss in the Mississippi River birdfoot delta

Andrew W. Tweel* and R. Eugene Turner

Department of Oceanography and Coastal Sciences, School of the Coast and Environment, Louisiana State University, Baton Rouge, Louisiana

Abstract

The Mississippi River basin was developed for agriculture at an unprecedented scale and intensity within the last 200 yr. These changes favored erosion and sediment transport, which were subsequently reduced by soil conservation practices, the trapping of sediment behind large reservoirs, and channel engineering. We discuss the relationship between sediment loading and the growth, loss, and stability of wetlands in the Mississippi River birdfoot delta (MRBD). We report an anthropogenically driven increase in mean suspended sediment concentrations in the Mississippi River below New Orleans, from a modeled 350 mg L^{-1} (174×10^9 kg yr^{-1}) at the end of the 18th century to a measured maximum of 675 mg L^{-1} (348×10^9 kg yr^{-1}) in the late 19th century, followed by a sharp reduction, and then a period of stabilization at 157 mg L^{-1} (91×10^9 kg yr^{-1}) after 1962. Changes in wetland area of the MRBD over the past two centuries reflect variations in sediment supply during periods of increasing, decreasing, and stable sediment loading, and are distinct from wetland loss patterns in other areas of coastal Louisiana. The rapid growth of the MRBD until the 1930s, which has been used as a reference for one of the world's largest wetland restoration efforts, may not be a suitable archetype for the majority of the coast. Additionally, future variation in sediment supply to the MRBD would likely change the total wetland area of the MRBD.

Intensive agricultural practices are typically associated with increased soil erosion (Walling 1999; Dearing and Jones 2003) that can result in riverine suspended sediment concentrations increasing up to an order of magnitude (Meade 1969; Douglas 1997). This increased sediment flux has muddied rivers, shoaled ports, and accelerated delta progradation from Greco-Roman and medieval times to at least 19th-century America. The Mediterranean's easily erodible soils and low tidal energy made ports especially vulnerable to siltation from rivers carrying eroded soils from the deforested and farmed lands of the ancient Greeks and Romans (Brückner 1986; Hughes 1996). Centuries later, as intensive agriculture spread westward, crops such as tobacco gave birth to a booming export industry in Chesapeake Bay settlements, but heavy soil erosion from those fields often formed new wetlands and shoals, rendering the ports inaccessible (Gottschalk 1945; Hilgartner and Brush 2006). The Plum Island estuary in Massachusetts also experienced rapid marsh formation in the 18th and 19th centuries as a consequence of increased sediment delivery following land clearing and agricultural development (Kirwan et al. 2011).

The effect of intensive cultivation on erosion and subsequent suspended sediment transport is more readily observed in smaller watersheds because much of the increased sediment load accumulates locally (Trimble 1999). By contrast, much of the soil eroded in large, continental watersheds is redeposited before reaching the main stem, dampening the downstream effects of increased erosion upstream (Costa 1975; Walling 1999). Variations in the suspended sediment load of large, sediment-laden rivers, such as the Yellow River in China, however, have been attributed to changes in agricultural land use (hereafter land use) over many centuries, if not millennia (Xu 1998; Wang et al. 2010).

The Mississippi River basin (MRB; Fig. 1) is unique among the world's large watersheds in that agriculture was introduced more recently and at an unprecedented scale and intensity than other rivers of comparable discharge. Severe erosion was commonplace as intensive European-style agriculture expanded into the MRB, and was significant enough to necessitate the formation of the Soil Conservation Service in 1935 (Turner and Rabalais 2003). Increasingly intensive river engineering, especially reservoir construction, greatly reduced sediment transport within the basin beginning in the early 20th century (Meade and Moody 2010). Other factors that may have also altered 19th-century sediment transport include bank clearing and channel dredging, as well as engineering to regulate flow near the river mouth (Winkley 1977; Wells and Coleman 1987; Kesel 1988), but changes in land use are considered to be the greatest effect, at least until reservoir construction (Keown et al. 1981; Dardeau and Causey 1990; Saucier 1994).

The earliest maps of the Mississippi River birdfoot delta (MRBD) depict channels bounded by marshes slightly wider than the channels. Later surveys documented a period of rapid subdeltaic land formation that began in the mid-1800s, resulting in 560 km^2 of new land (> 3× the area of Washington, DC) in < 100 yr (Wells and Coleman 1987). These areas of rapid land formation resulted from breaches in the river's natural levees, referred to as crevasses, which allowed direct sediment input into coastal bays, eventually filling them in. Maps of the 1930s delta depict this enlarged wetland landscape, much of which has since eroded. This recent erosion accounted for 10.1% of all

---

* Corresponding author: atweel1@lsu.edu

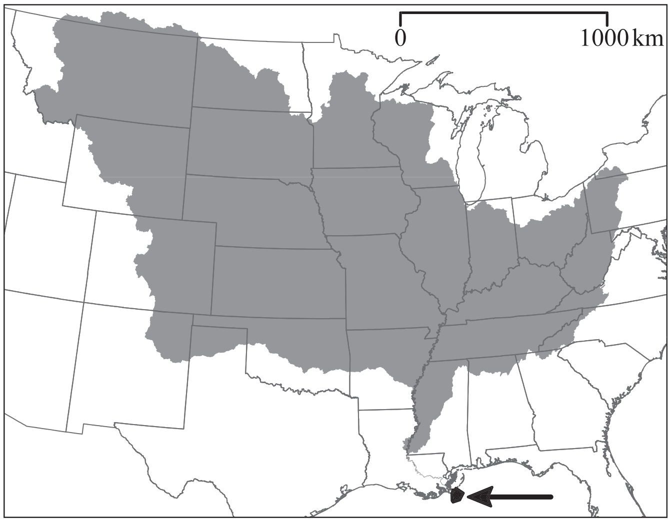

Fig. 1. The MRB (gray) and the study area used for delta land area analysis (black) indicated by arrow.

Louisiana coastal land lost between 1932 and 1990, and accounted for the two highest rates of land loss between 1932 and 1958 (West and East Delta 15-min quadrangles) (Dunbar et al. 1992). The growth and retreat of these four subdeltas of the MRBD over the past two centuries has provided a framework for understanding the subdelta life cycle and has also served as a smaller-scale model of the six delta lobes formed by the Mississippi River over the past several millennia (Fisk et al. 1954; Coleman and Gagliano 1964; Wells and Coleman 1987). The re-creation of these subdelta processes has been incorporated into restoration plans for one of the largest ecosystem restoration efforts in history (LDNR 1998; Kemp et al. 2004).

Here we quantify the relationship between soil erosion in the MRB, Mississippi River suspended sediment concentrations, and variations in land area in the MRBD. We test the hypothesis that the timing and amount of land gain and loss in the MRBD is proportional to changes in the suspended sediment load carried by the river. We analyzed 10 maps from 1778 to 2002 and compiled suspended sediment records from 1838 to 2002. Additionally, we compared these records to a model designed to assess predisturbance sediment load and evaluated the results in the context of land use, population growth, and surrogates of land disturbance.

Methods

Spatial data compilation and accuracy—We collected maps and spatial data for the MRBD for 1778 to 2002 from the Louisiana State University Cartographic Information Center and various public data servers. We only used maps with a published survey date for the entire study area. Privately published maps from before the 1800s were typically stylized, copied from earlier maps, or, in some cases, not updated from survey data for several decades. National Oceanic and Atmospheric Administration (NOAA) nautical charts were not suitable for this analysis because they are produced for navigational purposes and do not necessarily contain uniformly updated topographic information.

George Gauld compiled several surveys of the Louisiana coast that included depth soundings and published them in a 1778 map entitled *A Plan of the Coast of Part of West Florida and Louisiana: Including the River Yazous*. This map was based on surveys from 1764 to 1771 conducted for the Admiralty in Florida, and its accuracy and background have been previously discussed (Gauld 1969; Morgan 1973). We did not consider this map entirely suitable for quantitative analysis because of the surveying technology used, although we referred to it as the most accurate depiction of the delta from that period (Morgan 1955).

The first reliable surveys of the region are the topographic sheets (T-sheets) produced by A. Talcott for the United States Coast and Geodetic Survey (USC and GS) in 1838. An 1890 Mississippi River Commission map of West Bay, based on surveys completed between 1839 and 1845, complements a missing portion of the 1838 survey (Morgan 1973). Subsequent surveys for individual subdeltas were performed between 1859 and 1887 by the USC and GS and combined into one data set for the overall analysis, but were kept separate for interpreting changes in the individual subdeltas. The first photographic surveys were carried out in 1922 by the Naval Air Service, and were compiled as T-sheets by the USC and GS. A follow-up survey was completed in 1932, yielding an entirely new set of T-sheets.

We obtained six of the 10 data layers used for this analysis in a usable digital format. The remaining data were digitized using the same procedure used to develop the layers created by NOAA. Five data sets were obtained digitally in vector format from NOAA (1870s, 1932, and 1959) and the Louisiana Oil Spill Coordinator's Office (1992 and 2002). The 1978 data were acquired digitally as a bi-level raster from the United States Geological Survey, who developed it from United States Fish and Wildlife Service data (Barras et al. 2004). Data from 1838, 1922, and 1971 were obtained from maps that were scanned and georeferenced to a minimum of four control points and had a maximum root mean square error of 0.002 degrees. Specific map projection information was not available for digitization of the 1778 survey, and so we used the Bonne projection—a popular projection for surveys prior to 1853 (Daniels and Huxford 2001). Area measurements from Airy, Bessel, and Bonne projections were compared to account for possible errors caused by using a different projection, and only negligible differences in area were observed. The 1838 and 1922 surveys were on-screen digitized at an average scale of 1 : 7500. The 1971 USGS maps, originally printed as photographic quadrangles, were scanned and converted to a bi-level image in Adobe Photoshop before being vectorized using ArcScan, which is an extension of ArcGIS software (Environmental Systems Research Institute). All data were re-projected in ArcGIS to the North American Datum 1983 Universal Transverse Mercator zone 16-north to measure land area. All polygons smaller than 0.02 km^2 were omitted to compensate for potential differences in mapping scale. The change in total area resulting from this filtering was recorded for each map, and calculated as a percent loss due to processing. This loss was generally $< 1\%$, but was up to 6% in maps surveyed during periods of marsh breakup, and was considered inconsequential to our goal of identifying periods of increasing, maximum, decreasing, and stable land area.

The study area included all land downstream of a line drawn between Bay Tambour and Grand Coquille Bay, approximately equal to all land downstream of St. Phillips Bend in the Mississippi River located 32 km above Head of Passes. All polygons were clipped to the study area, and their areas were recalculated in the final projection. Initially, the study area was divided into smaller hydrologic units, but we determined that changes in one area were not independent of changes in another unit. For example, if river discharge increases in one area, it comes at the expense of river discharge to another area. The study area was, therefore, examined as a single system changing with time.

We also compared wetland soil type in the MRBD to other areas of the coast. The percent mineral matter for the top 24 cm of soil at Coastwide Reference Monitoring System (www.ocpr.louisiana.gov/crm/coastres/monitoring.asp) sites was analyzed in ArcGIS. The data were highly spatially autocorrelated (n = 716, Moran's I: 0.96) and were, therefore, appropriate for kriging to interpolate between sites. The final output was clipped to National Wetlands Inventory data (www.fws.gov/wetlands/Data/DataDownload.html).

Suspended sediments—Suspended sediment concentration data for the Mississippi River at New Orleans were compiled from a variety of sources dating back to 1838; portions of this data set have been discussed previously (Turner and Rabalais 2003; Thorne 2008). Data before 1877 are sparse, and there were various methods used in their collection (Humphreys and Abbot 1876; Vogel 1930; Keown et al. 1981). Two full years of suspended sediment data were collected at Carrollton, Louisiana, starting in February 1851, and ending February 1853 (Humphreys and Abbot 1876). The first year of these data was comprised of daily mass ratio observations (except Sunday) at three depths and three distances from the riverbank, and the second year consisted of only surface readings, under the assumption that the relationship between first-year depths could be used to estimate the mass ratios in the second year. One additional full year of concentration data exists for 1850 (Vogel 1930), but was collected at Fulton, Tennessee. The Fulton station location was about 275 river kilometers below Cairo, Illinois (Winkley 1977), and downstream from both the largest sediment and water inputs to the river (Keown et al. 1981). To test for differences between sampling location or methods, overlapping monthly data from 1879 and 1880 were compared to observations from Carrollton, Port Eads, and Fulton. These were also used to establish a ratio that was used to estimate the sediment concentration at Carrollton, using the Fulton data. Mean monthly sediment concentrations at Fulton were more dampened than at Carrollton, and tended to be higher during low discharge flows, but were lower in high-flow months, and averaged 7% greater than the concentrations measured at Carrollton.

Suspended sediment concentrations in 1838 and 1846 were estimated based on sampling during the three and four spring months, respectively, thus capturing the period of the highest and most variable sediment discharge (Keown et al. 1981). The concentration data for 1838 were collected at South Pass by A. Talcott for the Army Corps of Engineers and included surface and subsurface samples. The 1846 sediment concentration data were derived from surface water collected at New Orleans by Professor Riddell, Tulane University (Humphreys and Abbot 1876). The mean annual suspended sediment concentrations for 1838 and 1846 were estimated by prorating the missing monthly values using observations for 1851–1853 and forming a sediment concentration ratio for each month. These estimated concentrations are probably the least accurate of all of the data used, but their variation and discharge-to-concentration ratios were comparable to that of the two consecutive years of data collected at Carrollton. Five other sampling occasions between 1838 and 1867 consisted of insufficient records or sampling information to include in this analysis. The Army Corps of Engineers maintained a continuous record of suspended sediments between 1877 and 1895 at Port Eads (Turtle 1884; Quinn 1894, 1896), and the New Orleans Water and Sewerage Board has the longest continuous record of suspended sediment concentrations, which began in 1910. Suspended sediment data were calculated as a 3-yr moving average because of our objective of summarizing long-term trends in the data.

We compared annual loads and mean annual suspended sediment concentrations for the 33 yr ranging from 1851 to 1988 when detailed discharge data were available. A simple linear regression of suspended sediment concentration and discharge confirmed the suitability of using mean annual suspended sediment concentration as a proxy for annual load (mg $\text{L}^{-1} = 0.0439 \times Q_s + 107.73$, $r^2 = 0.85$, $F_{1,31} = 169.08$, $p < 0.0001$ [Q_s = annual sediment load in kg s^{-1}]). We also estimated annual load based on annual discharge (Poore et al. 2001), but since detailed discharge data were not available before 1933, we could not pair daily sediment observations to discharge data. We kept this calculation consistent throughout the study period.

We used the Area Relief Temperature (ART) model to estimate the suspended sediment concentrations before the 1800s (Syvitski et al. 2003). The ART model was calibrated using a database of 340 watersheds worldwide. This model is based on the physical characteristics of the basin at four latitude divisions, with specific constants for each division, and estimates the pre-disturbance annual load (Q_s in kg s^{-1}) using this equation:

$$Q_s = \alpha_3 A^{\alpha 4} R^{\alpha 5} e^{kT} \tag{1}$$

We used constants specific to temperate Northern Hemisphere river basins ($\alpha_3 = 6.1 \times 10^{-5}$, $\alpha_4 = 0.55$, $\alpha_5 = 1.12$, $k = 0.07$) and three input parameters specific to the MRB (A: basin area = 3.22×10^6 km^2, R: maximum basin relief = 4402 m, and T: average basin temperature =

9.77°C). The average temperature was based on a 29-yr record from the NOAA Earth System Research Laboratory (www.esrl.noaa.gov/psd/data/usclimate/tmp.state.19712000.climo), and was weighted for the area of each state that lies within the watershed, assuming equal temperatures inside and outside. The annual suspended sediment load was converted to a mean annual concentration using the linear regression of annual load against the sediment concentration noted above. Most of the uncertainty in the ART model output arises from rivers with smaller sediment loads, or watersheds that are greatly affected by reservoir construction (Syvitski et al. 2003). The ART model predicts sediment load within a factor of 2 for 75% of the 340 rivers included, but error is less than a factor of 2 for all of the 15 largest loads reported, and the model may underpredict for the largest basins (Syvitski et al. 2003). While there is inherently no observed sediment load to test the model estimate for the period before European settlement, we examined the results in the context of other indicators of disturbance as well as sediment observations collected at various points during watershed development.

We investigated the relationship between suspended sediment concentration and the percentage of the Mississippi River watershed under cultivation to see how well the ART model estimate (zero cultivation) compared. The United States Census Bureau collected data on the area of land improved for agriculture starting in 1850 (Historical Census Data Browser, mapserver.lib.virginia.edu). We prorated these data for the percent of each state that lies in the watershed, assuming a homogenous distribution of farmland inside and outside the watershed for each state. Population data are available for the period beginning in 1790 and were prorated amongst the watershed boundaries as was done for the agricultural data. To estimate land improvements prior to the 1850 census, the percent of improved land for the years 1850 to 1920 was linearly regressed against population size ($r^2 = 0.99$, $F_{1,6} = 721.6$, $p < 0.0001$) to estimate land use for the period between 1790 and 1850. We compared watershed land use to the observed suspended sediment concentrations and to the pre-disturbance estimate from the ART model. We also included MRBD subdelta volume (Wells and Coleman 1987) in this analysis.

Bed load, the component of sediment transport that travels along the bottom of a river, is not included in this analysis. A recent estimate of bed load in the Mississippi River is 2.5% of the total sediment load (Nittrouer et al. 2008). We did not correct for Mississippi River discharge entering the Atchafalaya River, which was about 10% in 1900 and increased to 30% by the 1960s (Turner et al. 2007).

Data analysis—We conducted a simple linear regression analysis of land area vs. 10-yr means of suspended sediment concentration. Data from the rapid land building period (1838 to 1867) were excluded because of the delay between subaqueous land building and when subaerial land appears (Wells and Coleman 1987). We also examined how the relationship between sediment concentration and various 5–20-yr lags in land area changed for when suspended sediment concentrations were rising, declining, or stable (PROC REG, Statistical Analysis System 9.1; SAS Institute). We expected to find threshold effects for wetland colonization and loss at different stages of development that were dependent on the net sediment accretion, hence elevation (McKee and Patrick 1988).

Results

Land area in the MRBD closely followed the changes in suspended sediment concentrations, with a longer response lag after periods of suspended sediment increase than when the suspended load was in decline (Fig. 2). Both land area and suspended sediment concentrations increased to a maximum, declined rapidly, then stabilized and remained relatively stable with only minor fluctuations since 1971. The peak in land area (692 km^2 in 1932, compared to 314 km^2 in 1838; Fig. 3a) occurred about 47 yr following the peak in suspended sediments, but the relative stabilization of land area (358 ± 13 km^2; $\mu \pm 1$ standard error [SE] for the four data sets from 1971 to 2002) occurred 5 yr after the suspended sediment concentrations stabilized at a level that was much lower than the peak in the 1890. Land area closely followed sediment concentration at uniform lags ranging from 0 to 15 yr (Fig. 4, $p < 0.05$, $n = 6$). The relationship between annual load and land area was similarly significant, and the intercepts for the two regressions averaged 226 km^2.

The suspended sediment concentrations averaged 563 ± 79 mg L^{-1} (338 ± 23 × 10^9 kg yr^{-1}, $\mu \pm 1$ SE) for the three full years of sampling that started in 1850 (Fig. 2b). If the estimated concentrations for the earliest two sampling periods are included, then the mean concentration for 1838 to 1853 is 611 ± 53 mg L^{-1} (324 ± 15 × 10^9 kg yr^{-1}). The peak suspended sediment concentrations occurred between the 1870s and 1890s, averaging 675 ± 38 mg L^{-1} (348 ± 27 × 10^9 kg yr^{-1}) for 19 yr. The decline in suspended sediments began gradually, but accelerated until significant reductions occurred around 1955. Following another sharp drop in the early 1960s, the suspended sediment concentrations at Carrollton, Louisiana, remained fairly stable at 157 ± 7 mg L^{-1} (91 ± 7 × 10^9 kg yr^{-1}). Overlapping suspended sediment concentrations for 1880 at Carrollton and Fulton were within the error of suspended sediment concentration for samples collected at Port Eads (Fig. 2b). The relationship between mean annual suspended sediment concentration and annual load was constant throughout the study period, but periods of increasing, peak, and diminished sediment loads are distinct from one another (Fig. 5).

There is no overall trend in discharge for the study period (Fig. 2a). The high discharge during the 1927, 1949–1951, and 1973–1974 flood years, however, corresponds to spikes in sediment concentration, and the abnormally low discharge years are co-related to lows in sediment concentration around 1895 and 1954. Despite this relationship, however, the mean discharge for the five years around 1850 was 5% greater than between 1870 and 1890, even though the sediment concentration was 10% lower.

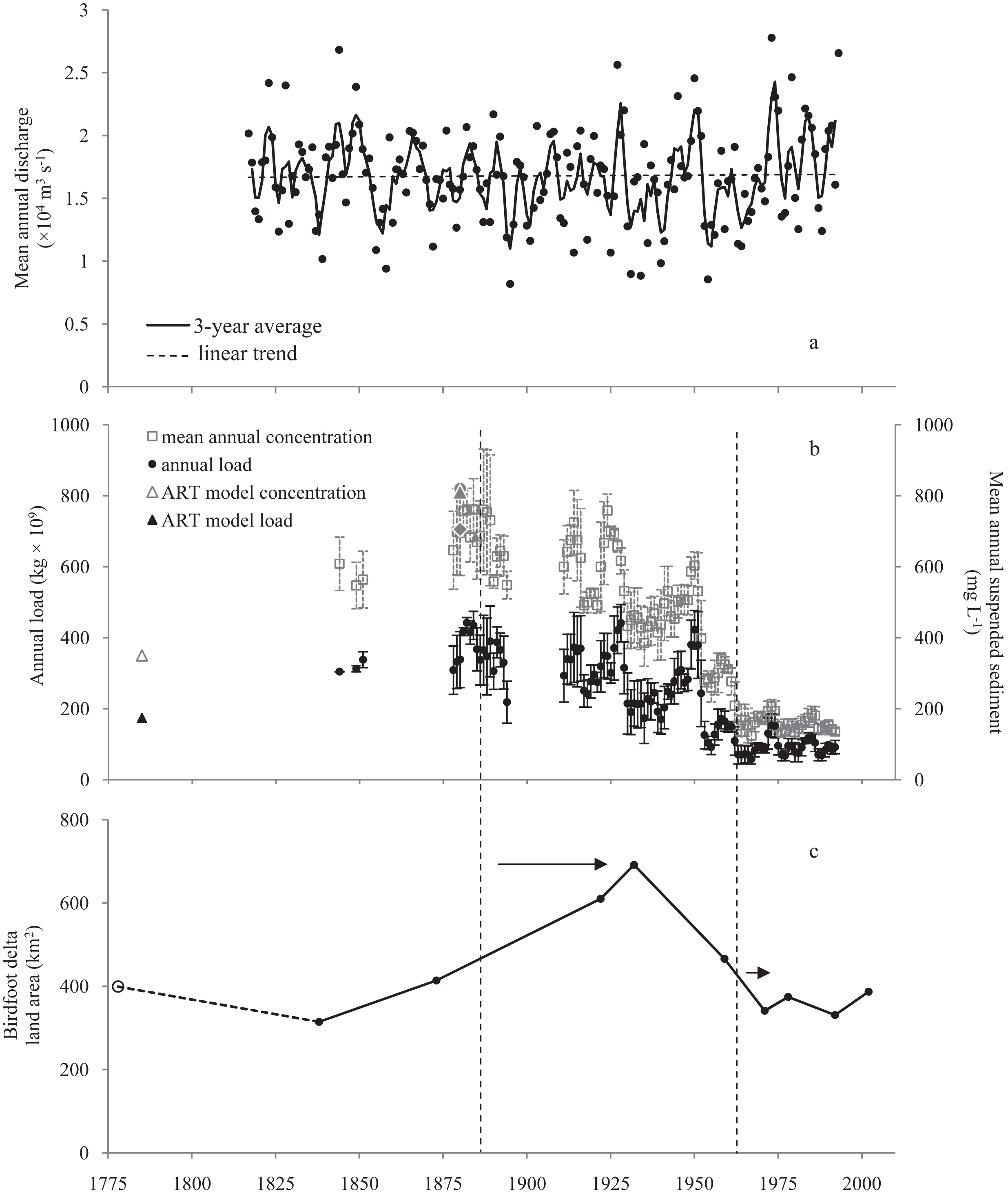

Fig. 2. Changes in suspended sediment concentrations in the lower river (principally New Orleans) and land area of the MRBD. (a) Mean annual discharge at Vicksburg, Mississippi, and 3-yr moving average (Poore et al. 2001). (b) Three-year averages of mean annual suspended sediment concentration (gray) and annual load (black) at New Orleans ($\mu \pm 1$ SE). Triangles show the predicted pre-disturbance suspended sediment concentration (open triangle) and annual load (solid triangle) determined using the ART model (Syvitski et al. 2003). Also plotted are 1880 observations from Carrollton (gray diamond), Fulton (gray triangle), and Port Eads (gray circle, partly obscured by Fulton). (c) The area of subaerial land in the MRBD. The solid lines link accurate surveys, and dashed line connects data from a 1778 survey. The arrows indicate differing lags between peaks in sediment transport and land area.

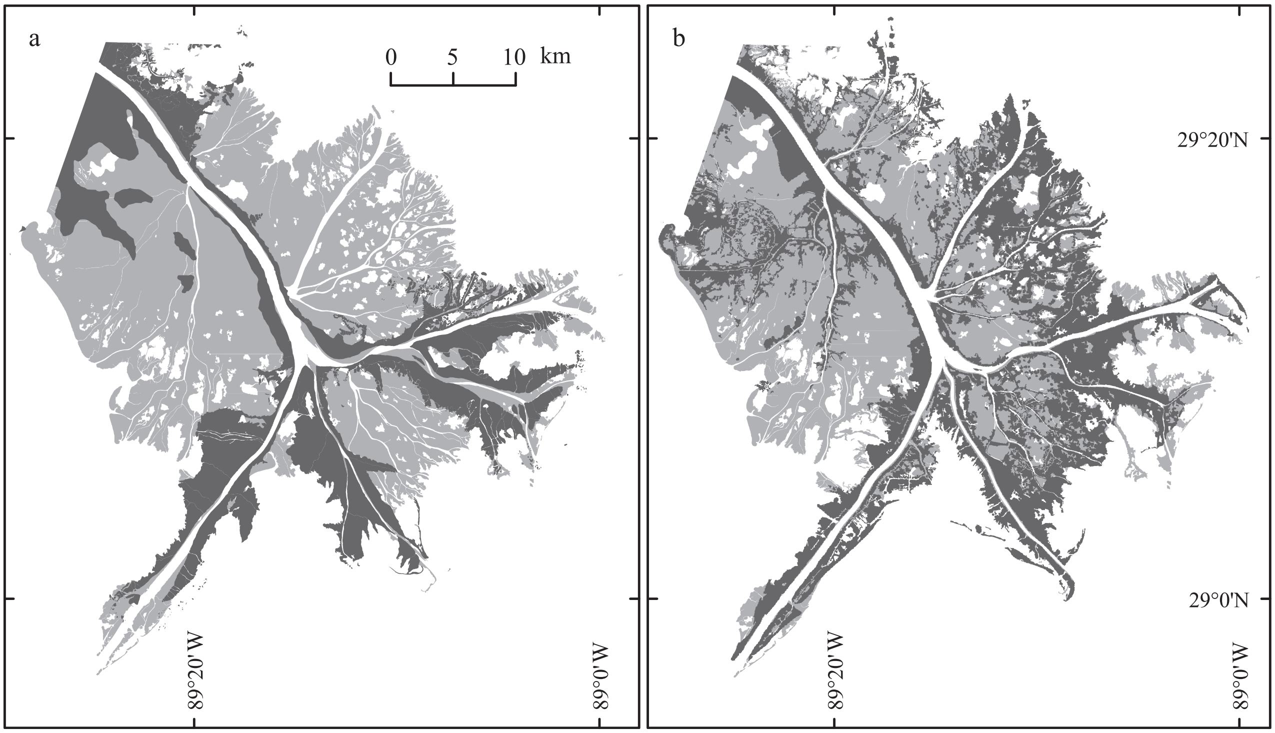

Fig. 3. The study area. (a) MRBD in 1838 (dark) and near its maximum size in 1932 (light) showing areas of wetland formation. (b) MRBD in 2002 (dark) and near its maximum size in 1932 (light), showing areas of wetland loss.

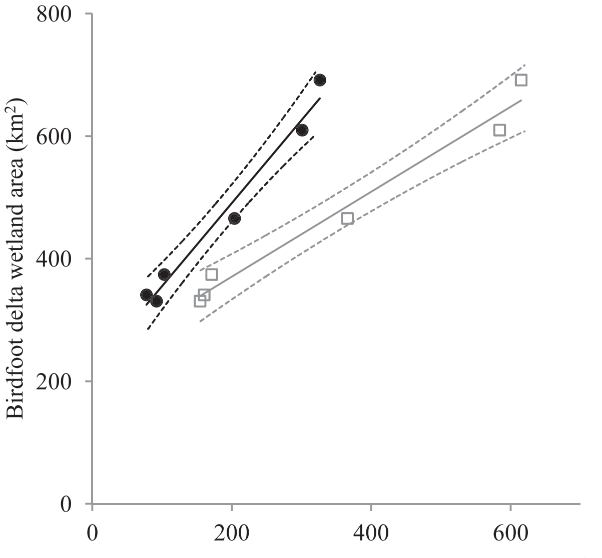

Fig. 4. Ten-year mean suspended sediment concentrations (gray) and annual loads (black) vs. land area of the MRBD since 1922 (concentration: $r^2 = 0.98$, $F_{1,4} = 155.22$, $p < 0.001$; load: $r^2 = 0.98$, $F_{1,4} = 160.67$, $p < 0.001$). The linear regression is significant for response intervals from 0 (shown) to 15 yr; earlier points are omitted due to a lag between bay infilling and wetland formation (*see* text for explanation). The dotted lines show the 95% confidence intervals.

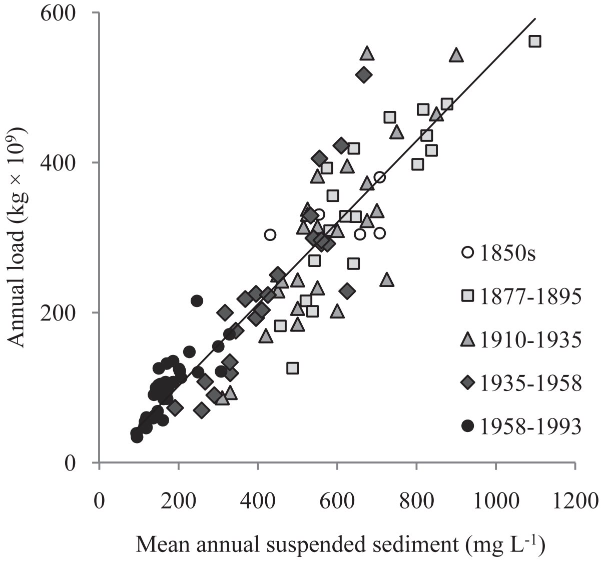

Fig. 5. Mean annual suspended sediment concentration vs. annual load at the following time intervals: increasing sediment transport (1850s), peak sediment transport (1880s), early reservoir construction (1910–1935), rapid reservoir construction (1935–1958), and decreased reservoir construction (after 1958).

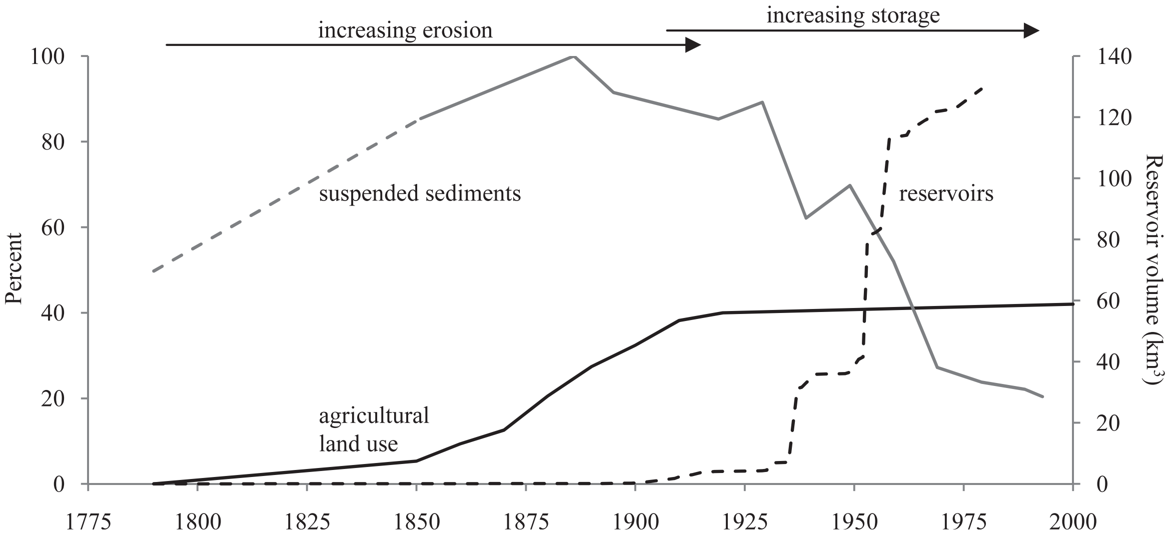

Fig. 6. Comparison of watershed agricultural land use (solid), cumulative reservoir volume (dashed), and 10-yr means of suspended sediment concentration (gray). Land use is presented as the percent of the whole basin area, reservoir volume is cubic kilometers of storage within the Missouri River basin (Keown et al. 1981), and sediments are the percentage of maximum observed for the interval. Other factors that may have influenced sediment transport are not shown (Kesel 1988).

Additionally, the drastic sediment reductions after 1962 do not correspond to a reduction in discharge. These differences indicate that there is a changing relationship between sediment concentration and discharge throughout the study period that is independent of the variations in discharge.

Agricultural land use increased in a sigmoidal fashion between 1800 and 1920, and has remained relatively stable, at around 40% of the basin, until today (Fig. 6; Raymond et al. 2008). The period of most rapid land-use change was between 1870 and 1900 for both the whole basin and also for only the subbasin states of Kansas, Missouri, Iowa, and Nebraska, which contain the highly erosive Missouri River basin soils (up to 2×10^6 kg km^{-2} yr^{-1} with modern land use; Keown et al. 1981). The reservoir volume in the Missouri River basin increased in two large increments. Nineteen percent of the total 1979 reservoir volume was constructed between 1935 and 1937, and an additional 55% was constructed between 1952 and 1958. Reservoir construction between 1958 and 1979 was 12% of the 1979 capacity. The decline in sediment concentration was coincidental with the increase in reservoir volume (Fig. 6).

The ART model estimate of the pre-disturbance annual sediment load for the Mississippi River was 174×10^9 kg yr^{-1}, equal to an estimated mean concentration of 350 ± 37 mg L^{-1} ($\mu \pm$ 95% CI for the regression of suspended sediment concentration and load).

The land area of the MRBD grew at an average rate of 4.1 km^2 yr^{-1} from 1838 (315 km^2) to its peak in 1932 (692 km^2), when it was 220% of the area present in 1838 (Fig. 2c). Land loss following this peak was rapid, and occurred at an average rate of 9.0 km^2 yr^{-1} between 1932 and 1971. The size of the MRBD in 1971 (341 km^2) was 110% its size in 1838, although the distribution of wetlands following subdelta decay was much more fragmented and covered a larger area (Fig. 3). There were relatively small gains and losses of land after 1971, and in 2002 the land area (387 km^2) was 120% the area present in 1838.

Wetland soil inorganic content varied widely, ranging from 97.1% in the MRBD to as low as 8.3% in the upper reaches of Barataria and Terrebonne basins (Fig. 7). Mean inorganic content for the whole coast was $58.3 \pm 19.1\%$ ($\mu \pm 1\ \sigma$).

Discussion

The conversion of prairie and forest to an agricultural landscape following European settlement in the Mississippi River watershed is mirrored in several large-scale changes in the river system, including the timing and rate of enlargement of the MRBD. Additional changes that were synchronous with 19th-century land-use change in the MRB include increases in offshore nutrient concentrations (Turner and Rabalais 1994), suspended sediment and nutrient deposition along the Upper Mississippi River (Engstrom et al. 2009), and overbank sedimentation in the Upper Mississippi Valley (Knox 1987). These analyses confirm that the change in land use had consequences extending well beyond the area of direct erosion effects, and are consistent with the results from the ART sediment load model that identifies a pre-disturbance load lower than the peak concentrations observed in the late 19th century. Because of the direct connection of the MRBD wetlands to fluvial input, which differs from the deltaic and chenier plains, wetland area in the MRBD would be expected to vary with sediment input (Blum and Roberts 2009).

The rapid increase in MRBD size between 1838 and 1932 is consistent with similar observations of land building resulting from changes in land use, including at least nine Mediterranean deltas and ports (Brückner 1986; Hughes

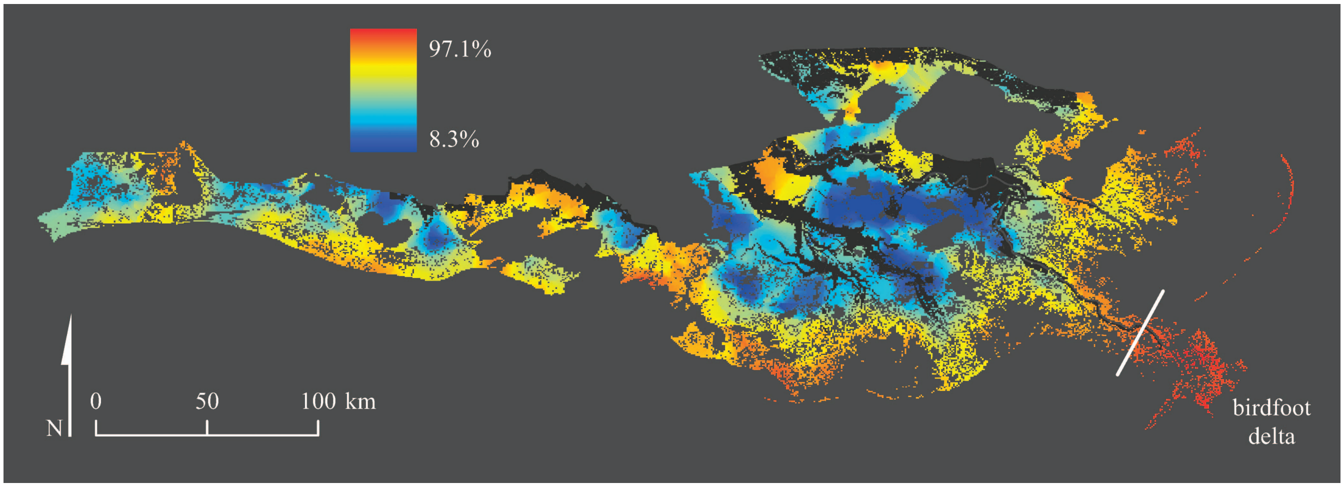

Fig. 7. The percent soil inorganic matter (0–24 cm) across the Louisiana coast. There is highly inorganic soil in the birdfoot delta compared to more organic soil in the deltaic plain. The area used for this analysis lies southeast of the white line; the dark gray denotes upland areas.

1996; Vella et al. 2005), two northern European river deltas (Hoffmann 1996), and eight deltas and upper estuaries in eastern North America (Cronon 1983; Bierman et al. 1997; Hilgartner and Brush 2006). This example at the mouth of the Mississippi River represents the largest and most recently developed watershed where this link has been quantified.

Wetland formation lagged 47 yr behind the peak in sediment discharge, whereas the reversion back to open water lagged 5 yr following the decline in sediment loading, indicating a hysteretic relationship between sediment loading and wetland area. The difference in lag times between growth and decline is expected because sediments filled shallow bays ranging from 2 to 9 m deep before wetlands "capped" the sediment accumulation in the final stages of land building. Wetland loss, however, is much more sensitive to changes in elevation because plants are adapted to a narrow range (a few centimeters) of tidal variation on this coast (McKee and Patrick 1988). The area of all four of the subdeltas peaked around 1930, even though these subdeltas were initiated over a span of 50 yr, indicating that the land formation and loss were influenced by a process operating at a larger scale than the growth and decay of a single subdelta. The areal decline in the Baptiste Collette subdelta was slightly more delayed than the other three subdeltas, possibly because deltaic subsidence rates decline with distance from the continental shelf (Roberts et al. 1994). The increasing proportion of Mississippi River discharge entering the Atchafalaya River starting around 1900 likely exacerbated this land loss.

The total volume of sediments in the four MRBD subdeltas increased by 0.15 $km^3\ yr^{-1}$ between 1875 and 1895, which is twice the rate of increase for the whole growth period (0.07 $km^3\ yr^{-1}$; Wells and Coleman 1987). The rate of land-use change was also greatest during this period for both the whole basin and the states containing the highly erosive soils of the Missouri River basin (up to 2×10^6 kg $km^{-2}\ yr^{-1}$ after land-use change), and increases in MRBD volume and land use both slowed in the early 20th century (Keown et al. 1981). Changes in Missouri River reservoir capacity and suspended sediments followed similar trends, and the rapid increases in reservoir capacity correspond to sediment concentration reductions. Reservoir construction slowed after 1958, and was mirrored by a decline of suspended sediment concentrations (Fig. 6).

There may have been several periods of subdelta lobe growth and decay before the 19th-century growth period (Coleman 1976). An earlier study (Coleman and Gagliano 1964) surmised that there was an intermediate delta north of the modern delta and south of the Plaquemine delta below present-day New Orleans. The marsh fragments interpreted as indicators of previous subdelta cycles (Coleman 1976) could be remnants of this intermediate delta, or portions of the modern delta as it prograded away from the former Plaquemine delta. Knowing the number of subdelta cycles, however, does not inform us about the areal extent or timing of processes for the entire MRBD. Additionally, the complex relationship between the two processes of changing sediment supply and land area serves as a reminder that such land change processes are rarely a consequence of purely geological or purely anthropogenic processes, but rather are a result of the interaction between the two (Brookfield 1999).

The difference between the ART model estimate of annual sediment loads, peak loads (1890s), and for the earliest records (1850s) is proportional to changes in the MRB occurring then, which included land use and perhaps bank clearing and channel dredging (Winkley 1977), and is similar to changes observed in other watersheds. The ART model parameters are based on physical features of the basin (*bottom-up*), and the comparison to agricultural development represents a different approach (*top-down*), yet both analyses support a pre-disturbance sediment concentration that is lower than the maximum observed (late 19th century) mean annual suspended sediment concentrations in the Mississippi River. This pre-disturbance value also falls within the range of historical background to maximum disturbance concentration ratios previously reported (Dearing and Jones 2003), of up to 1 : 3 for a basin of this size. Although this estimate may be improved by future research, it represents our best estimate based on all available data and models.

The present-day sediment load of 115 × 10^9 kg yr^{-1} (1987–2006) reaching the MRBD is 66% of the pre-disturbance load estimated by the ART model (Meade and Moody 2010). The estimated current sediment load for the whole river system, including discharge into the Atchafalaya River, is 83% of the ART model estimate of pre-disturbance sediment load. We report a lower post-dam sediment load than Meade and Moody (2010) that may be an artifact of different sampling procedures or deposition between the Tarbert Landing and Carrollton stations (Winkley 1977; Kesel 1988). While our analysis confirms that there has been a significant reduction in Mississippi River sediment transport since the 1890s, the pre-disturbance estimate by Meade and Moody (2010) is based on data collected after basin-wide changes had already occurred, and does not account for effects from changing land use or river dredging that favor sediment transport. Sediment transport analyses for the Mississippi River basin have concluded that changes in land use had a significant, if not the greatest, historical effect on sediment transport (Keown et al. 1981; Dardeau and Causey 1990; Saucier 1994).

The two highest land loss rates on this coast between the 1930s and the 1950s occurred in the 15-min quadrangles covering the MRBD. The beginning, peak, and reduction of wetland loss rates in other coastal areas are not synchronous with the changes observed in the MRBD (Dunbar et al. 1992) and are not correlated with the changing suspended sediment concentration or load in the river. The highly inorganic wetland soils of the MRBD are distinct from the highly organic wetlands that occupy most of the deltaic plain (Fig. 7). These differences in soil type and wetland loss rates indicate that processes regulating wetland loss and gain in the MRBD are distinct from the deltaic plain. The MRBD, therefore, may not be a suitable archetype for most of this coast.

The results from this study are consistent with the hypothesis that the rapid growth, decline, and stabilization of mineral-rich wetland area in the MRBD are driven by the fluctuations in Mississippi River sediment load. These observations are consistent with the anticipated consequences of land-use changes in the MRB and elsewhere in the world. Anthropogenic reductions in sediment transport have become the dominant factor determining whether relative sea-level rise is positive or negative in many deltas (Syvitski and Kettner 2011). The MRBD is one of the most dramatic of such deltas and an indicator of what may occur in other developing watersheds around the world. Because of the positive relationship between suspended sediments and land area in the MRBD, we predict that future variation in suspended sediments delivered to the mouth of the river, higher or lower, would likely lead to proportional land area changes in the MRBD, but not necessarily in the more organic soils of the deltaic plain.

Acknowledgments

The cartographic research was greatly facilitated by John Anderson, Louisiana State University Cartographic Information Center; Dave Morgan, The Cartographic Acquisition, Research, Teaching & Exhibition (CARTE) Museum, Baton Rouge, Louisiana; and Hampton Peele, Louisiana Geological Survey. Comments from two anonymous reviewers improved this manuscript. Support was provided to A.W.T. by a Louisiana Board of Regents Graduate Student Fellowship.

References

Barras, J., S. Beville, D. Britsch, S. Hartley, S. Hawes, J. Johnston, P. Kemp, Q. Kinler, A. Martucci, and J. Porthouse. 2004. Historical and projected coastal Louisiana land changes: 1978–2050. USGS Open File Report 03-334. U.S. Geological Survey. Available online at http://www.nwrc.usgs.gov/special/NewHistoricalland.pdf

Bierman, P., A. Lini, P. Zehfuss, A. Church, P. T. Davis, J. Southon, and L. Baldwin. 1997. Postglacial ponds and alluvial fans: Recorders of Holocene landscape history. GSA Today **7:** 1–8.

Blum, M. D., and H. H. Roberts. 2009. Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nat. Geosci. **2:** 488–491, doi:10.1038/ngeo553

Brookfield, H. 1999. Environmental damage: Distinguishing human from geophysical causes. Global Environ. Change B: Environ. Hazards **1:** 3–11.

Brückner, H. 1986. Man's impact on the evolution of the physical environment in the Mediterranean region in historical times. GeoJournal **13:** 7–17, doi:10.1007/BF00190684

Coleman, J. M. 1976. Deltas; processes of deposition and models for exploration. Burgess.

———, and S. M. Gagliano. 1964. Cyclic sedimentation in the Mississippi River deltaic plain. Trans. Gulf Coast Assoc. Geol. Soc. **14:** 67–80.

Costa, J. E. 1975. Effects of agriculture on erosion and sedimentation in the Piedmont Province, Maryland. Bull. Geol. Soc. Am. **86:** 1281–1286, doi:10.1130/0016-7606(1975)86<1281:EOAOEA>2.0.CO;2

Cronon, W. 1983. Changes in the land: Indians, colonists, and the ecology of New England. Farrara, Straus and Girous.

Daniels, R. C., and R. H. Huxford. 2001. An error assessment of vector data derived from scanned National Ocean Service topographic sheets. J. Coast. Res. **17:** 611–619.

Dardeau, E. A., and E. M. Causey. 1990. Downward trend in Mississippi River sediment loads. Potamology Program (P-1) Report 5, Environmental Laboratory. U.S. Army Engineer Waterways Experiment Station.

Dearing, J. A., and R. T. Jones. 2003. Coupling temporal and spatial dimensions of global sediment flux through lake and marine sediment records. Global Planet. Change **39:** 147–168, doi:10.1016/S0921-8181(03)00022-5

Douglas, I. 1997. Sediment transfer and siltation, p. 215–234. *In* B. L. Turner, W. C. Clark, R. W. Kates, J. F. Richards, J. T. Mathews, and W. B. Meyer [eds.], The earth as transformed by human action. Cambridge Univ. Press.

Dunbar, J. B., L. D. Britsch, and E. B. Kemp. 1992. Land loss rates. Report 3, Louisiana Coastal Plain. U.S. Army Engineer Waterways Experiment Station.

Engstrom, D. R., J. E. Almendinger, and J. A. Wolin. 2009. Historical changes in sediment and phosphorus loading to the upper Mississippi River: Mass-balance reconstructions from the sediments of Lake Pepin. J. Paleolimnol. **41:** 563–588, doi:10.1007/s10933-008-9292-5

Fisk, H. N., C. R. Kolb, E. McFarlan, and L. J. Wilbert. 1954. Sedimentary framework of the modern Mississippi delta. J. Sediment. Res. **24:** 76–99.

Gauld, C. A. 1969. A Scottish view of west Florida in 1769. Tequesta **29:** 61–66.

Gottschalk, L. C. 1945. Effects of soil erosion on navigation in upper Chesapeake Bay. Geogr. Rev. **35:** 219–238, doi:10.2307/211476

Hilgartner, W. B., and G. S. Brush. 2006. Prehistoric habitat stability and post-settlement habitat change in a Chesapeake Bay freshwater tidal wetland, USA. Holocene **16:** 479–494, doi:10.1191/0959683606hl938rp

Hoffmann, R. C. 1996. Economic development and aquatic ecosystems in medieval Europe. Am. Hist. Rev. **101:** 631–669, doi:10.2307/2169418

Hughes, J. D. 1996. Pan's travail: Environmental problems of the ancient Greeks and Romans. Johns Hopkins Univ. Press.

Humphreys, A. A., and H. L. Abbot. 1876. Report upon the physics and hydraulics of the Mississippi River. U.S. Government Printing Office.

Kemp, G. P., D. J. Reed, H. Mashriqui, W. McAnally, E. Reyes, C. Sasser, J. Suhayda, J. Visser, J. Wells, and C. Willson. 2004. Predicting land building in the Mississippi Delta Plain: Knowledge and uncertainty, Chapter 20. *In* R. R. Twilley [ed.], Coastal Louisiana ecosystem assessment and restoration (CLEAR) model of Louisiana coastal area (LCA) comprehensive ecosystem restoration plan. Louisiana Department of Natural Resources.

Keown, M. P., E. A. Dardeau, Jr., and E. M. Causey. 1981. Characterization of the suspended sediment regime and bed-material gradation of the Mississippi River basin. Potamology Program (P-1) Report 1. Accession No. ADA111236. U.S. Army Engineer Waterways Experiment Station.

Kesel, R. H. 1988. The decline in the suspended load of the lower Mississippi River and its influence on adjacent wetlands. Environ. Geol. **11:** 271–281.

Kirwan, M. L., A. B. Murray, J. P. Donnelly, and D. R. Corbett. 2011. Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. Geology **39:** 507–510.doi:10.1130/G31789.1

Knox, J. C. 1987. Historical valley floor sedimentation in the Upper Mississippi Valley. Ann. Assoc. Am. Geogr. **77:** 224–244, doi:10.1111/j.1467-8306.1987.tb00155.x

Louisiana Department of Natural Resources (LDNR). 1998. Louisiana coastal wetlands conservation and restoration task force and the wetlands conservation and restoration authority: Coast 2050 [Internet]. Baton Rouge, Louisiana: Louisiana Department of Natural Resources [accessed 2011 April 15]. p. 161. Available from www.coast2050.gov/2050reports.htm

McKee, K. L., and W. H. Patrick. 1988. The relationship of smooth cordgrass (*Spartina alterniflora*) to tidal datums: A review. Estuaries Coasts **11:** 143–151, doi:10.2307/1351966

Meade, R. H. 1969. Errors in using modern stream-load data to estimate natural rates of denudation. Geol. Soc. Am. Bull. **80:** 1265, doi:10.1130/0016-7606(1969)80[1265:EIUMSD]2.0.CO;2

———, and J. A. Moody. 2010. Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007. Hydrol. Processes **24:** 35–49.

Morgan, D. J. 1973. The Mississippi River Delta—legal geomorphic evaluation of shoreline changes. M.S. thesis. Louisiana State Univ.

Morgan, J. P. 1955. A geographical and geological study of the Louisiana coast. Coastal Studies Institute, Louisiana State Univ.

Nittrouer, J. A., M. A. Allison, and R. Campanella. 2008. Bedform transport rates for the lowermost Mississippi River. J. Geophys. Res. **113:** F03004, doi:10.1029/2007JF000795

Poore, R. Z., J. Darling, H. J. Dowsett, and L. Wright. 2001. Variations in river flow to the Gulf of Mexico: Implications for paleoenvironmental studies of Gulf of Mexico marine sediments. U.S. Geological Survey Bulletin 2187. U.S. Geological Survey.

Quinn, J. B. 1894. Report of the Chief of Engineers. *In* House of Representatives Executive Documents. 53rd Cong., 3d Sess., V. 2, Part 2.

———. 1896. Report of the Chief of Engineers. *In* House of Representatives Executive Documents. 54th Cong., 2d Sess., V. 2, Part 4.

Raymond, P. A., N. H. Oh, R. E. Turner, and W. Broussard. 2008. Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. Nature **451:** 449–452, doi:10.1038/nature06505

Roberts, H. H., A. Bailey, and G. J. Kuecher. 1994. Subsidence in the Mississippi River Delta; important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis. Trans. Gulf Coast Assoc. Geol. Soc. **44:** 619–629.

Saucier, R. T. 1994. Geomorphology and quarternary geologic history of the lower Mississippi Valley [Internet]. Vicksburg, Mississippi: U.S. Army Engineer Waterways Experiment Station [accessed 2011 April 15]. p. 364. Available from lmvmapping.erdc.usace.army.mil/.

Syvitski, J. P. M., and A. J. Kettner. 2011. Sediment flux and the Anthropocene. Phil. Trans. R. Soc. A **369:** 957–975, doi:10.1098/rsta.2010.0329

———, S. D. Peckham, R. Hilberman, and T. Mulder. 2003. Predicting the terrestrial flux of sediment to the global ocean: A planetary perspective. Sediment. Geol. **162:** 5–24, doi:10.1016/S0037-0738(03)00232-X

Thorne, C., O. Harmar, N. Clifford, R. Measures, C. Watson, and D. Biedenharn. 2008. Current and historical sediment loads in the lower Mississippi River [Internet]. London, England: U.S. Army European Research Office [accessed 2011 April 15]. p. 146. Available from handle.dtic.mil/100.2/ADA486343

Trimble, S. W. 1999. Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin, 1975–93. Science **285:** 1244–1246, doi:10.1126/science.285.5431.1244

Turner, R. E., and N. N. Rabalais. 1994. Coastal eutrophication near the Mississippi river delta. Nature **368:** 619–621, doi:10.1038/368619a0

———, and ———. 2003. Linking landscape and water quality in the Mississippi River basin for 200 years. BioScience **53:** 563–572, doi:10.1641/0006-3568(2003)053[0563:LLAWQI]2.0.CO;2

———, E. M. Swenson, C. S. Milan, and J. M. Lee. 2007. Hurricane signals in salt marsh sediments: Inorganic sources and soil volume. Limnol. Oceanogr. **52:** 1231–1238, doi:10.4319/lo.2007.52.3.1231

Turtle, T. 1884. Report of the Chief of Engineers. *In* House of Representatives Executive Documents. 48th Cong., 2d Sess., V. 2, Part 2.

Vella, C., T. J. Fleury, G. Raccasi, M. Provansal, F. Sabatier, and M. Bourcier. 2005. Evolution of the Rhône delta plain in the Holocene. Mar. Geol. **222:** 235–265, doi:10.1016/j.margeo.2005.06.028

Vogel, H. D. 1930. Sediment investigations on the lower Mississippi River and its tributaries prior to 1930. Paper H. U.S. Army Engineer Waterways Experiment Station.

Walling, D. E. 1999. Linking land use, erosion and sediment yields in river basins. Hydrobiologia **410:** 223–240, doi:10.1023/A:1003825813091

WANG, H., N. BI, Y. SAITO, Y. WANG, X. SUN, J. ZHANG, AND Z. YANG. 2010. Recent changes in sediment delivery by the Huanghe (Yellow River) to the sea: Causes and environmental implications in its estuary. J. Hydrol. **391:** 302–313, doi:10.1016/j.jhydrol.2010.07.030

WELLS, J. T., AND J. M. COLEMAN. 1987. Wetland loss and the subdelta life cycle. Estuar. Coast. Shelf Sci. **25:** 111–125, doi:10.1016/0272-7714(87)90029-1

WINKLEY, B. R. 1977. Man-made cutoffs on the Lower Mississippi River, conception, construction, and river response. Potamology Investigation Report 330-2. Accession No. ADA116595. U.S. Army Engineer Vicksburg District.

XU, J. 1998. Naturally and anthropogenically accelerated sedimentation in the Lower Yellow River, China, over the past 13,000 years. Geogr. Ann. Phys. Geogr. **80:** 67–78, doi:10.1111/j.0435-3676.1998.00027.x

Associate editor: Anthony W. D. Larkum

Received: 19 April 2011
Accepted: 08 September 2011
Amended: 15 September 2011