or perhaps a good Cajun story “down on the Bayou…”

Hypoxia on the Louisiana Shelf: A Tale of Muddy Waters and Politics

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Seminar Outline

1. The Mississippi-Atchafalaya River System and Louisiana Shelf: A River-Dominated Margin (RiOMar)

2. The Hypoxia "Problem"

3. Characteristics of River-Dominated Margins (RiOMar): Inherently Different From Semi-Enclosed Estuaries

4. Problems with the Management Plan for Hypoxia on the Louisiana Shelf: "Truth or Consequences"

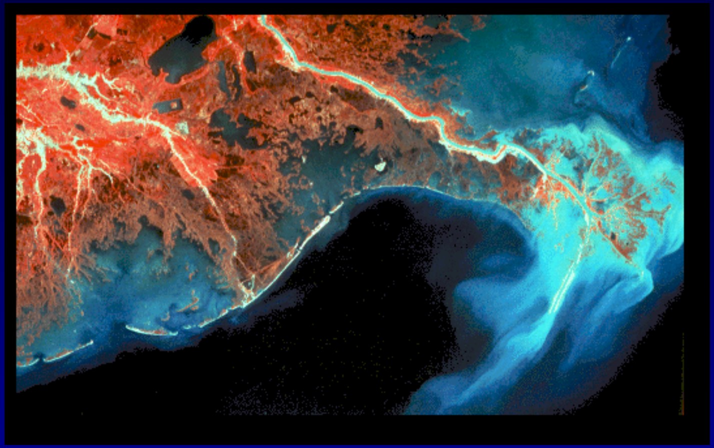
Collaborators

- Brent McKee (UNC) – radionuclides
- Mead Allison (UT) - seismic analysis and sedimentology
- Martha Sutula and Rebecca Green (ONR) – nutrients and carbon cycling
- Sid Mitra (ECU) - organics
- Nianhong Chen (postdoc at ODU), Shuiwang Duan (potsdoc at TAMUG), Bryan Grace, Troy Sampere, Laura Wysocki, - (Tulane, EES, graduate students) - chemical biomarkers (pigments, lignin), and bulk C, N, measurements

The Mississippi-Atchafalaya River System and Louisiana Shelf: A River-Dominated Margin (RiOMar)

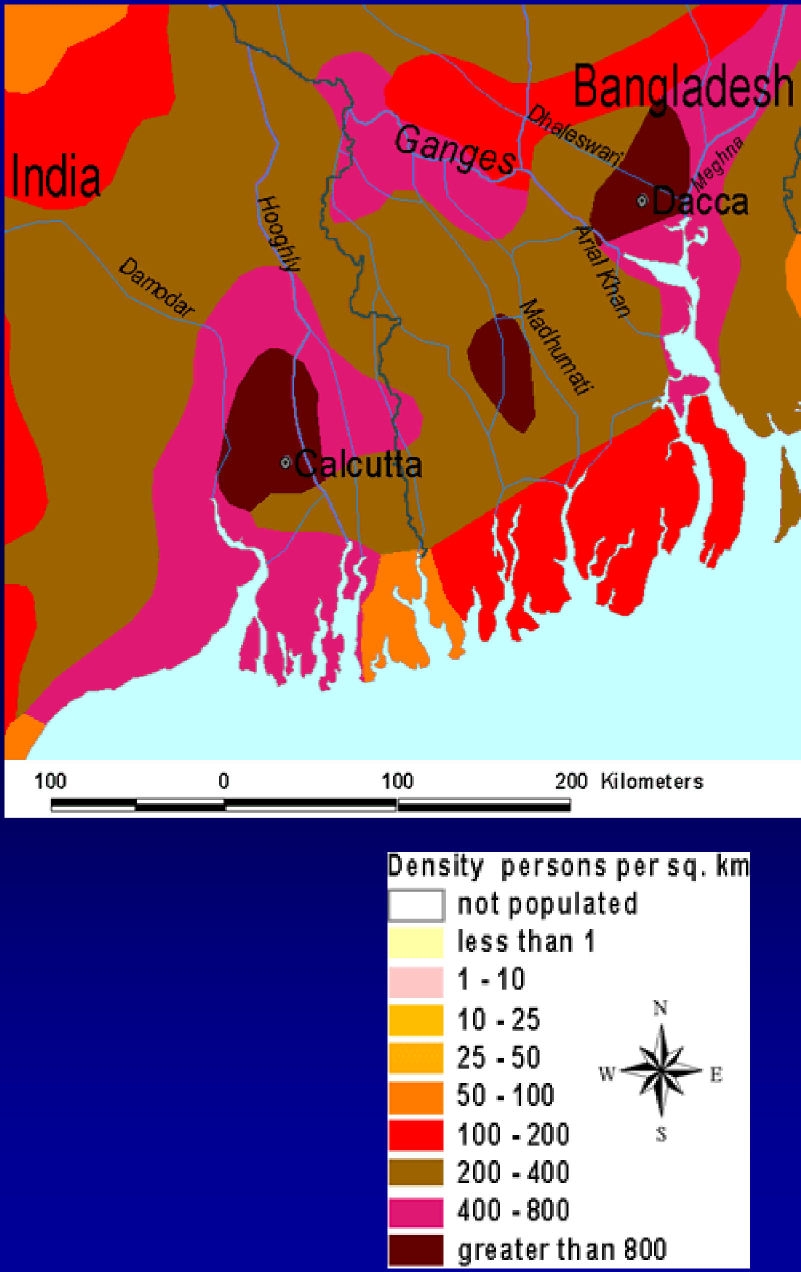
River-Dominated Ocean Margins (RiOMars)

Most of the terrestrial materials (organic carbon, macronutrients, micronutrients, major/minor elements, mineral matter) transported to the oceans enter via these margin environments

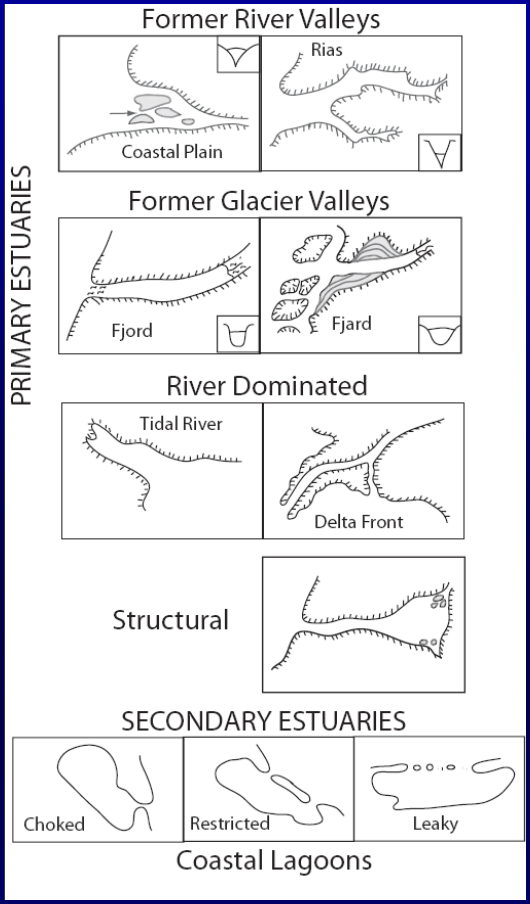


Rivers and Coasts are regions of high population density

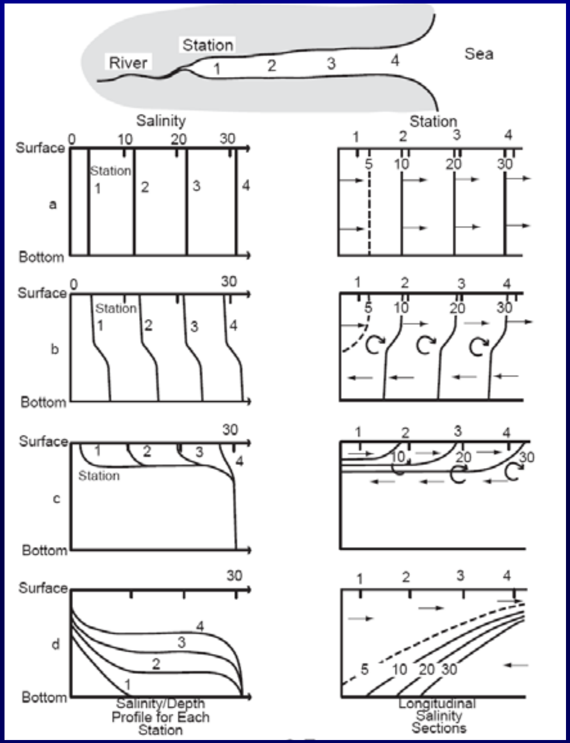
- By 2025, ~ 75% of world's population will live in the coastal zone
- Most of the remaining 25% will live near a major river



Estuarine Typology and Gradients



Modified from Perillo (1995)



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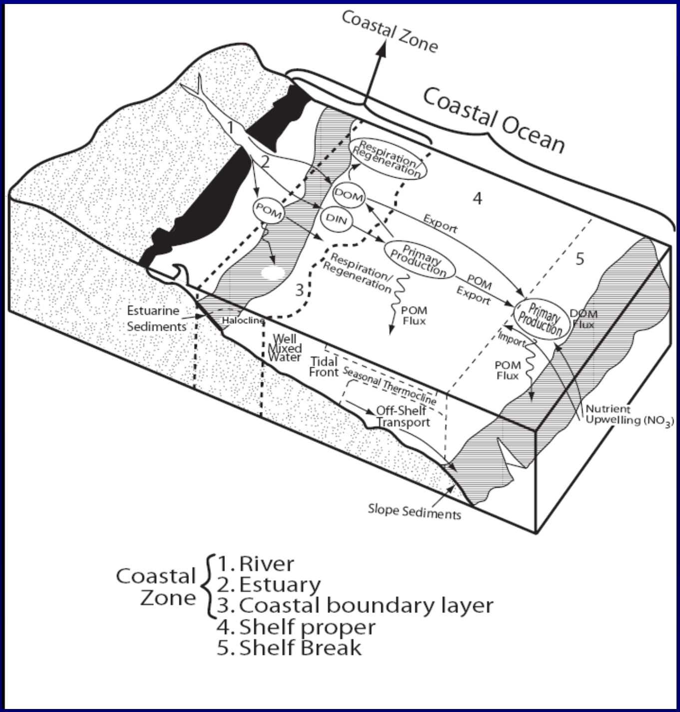
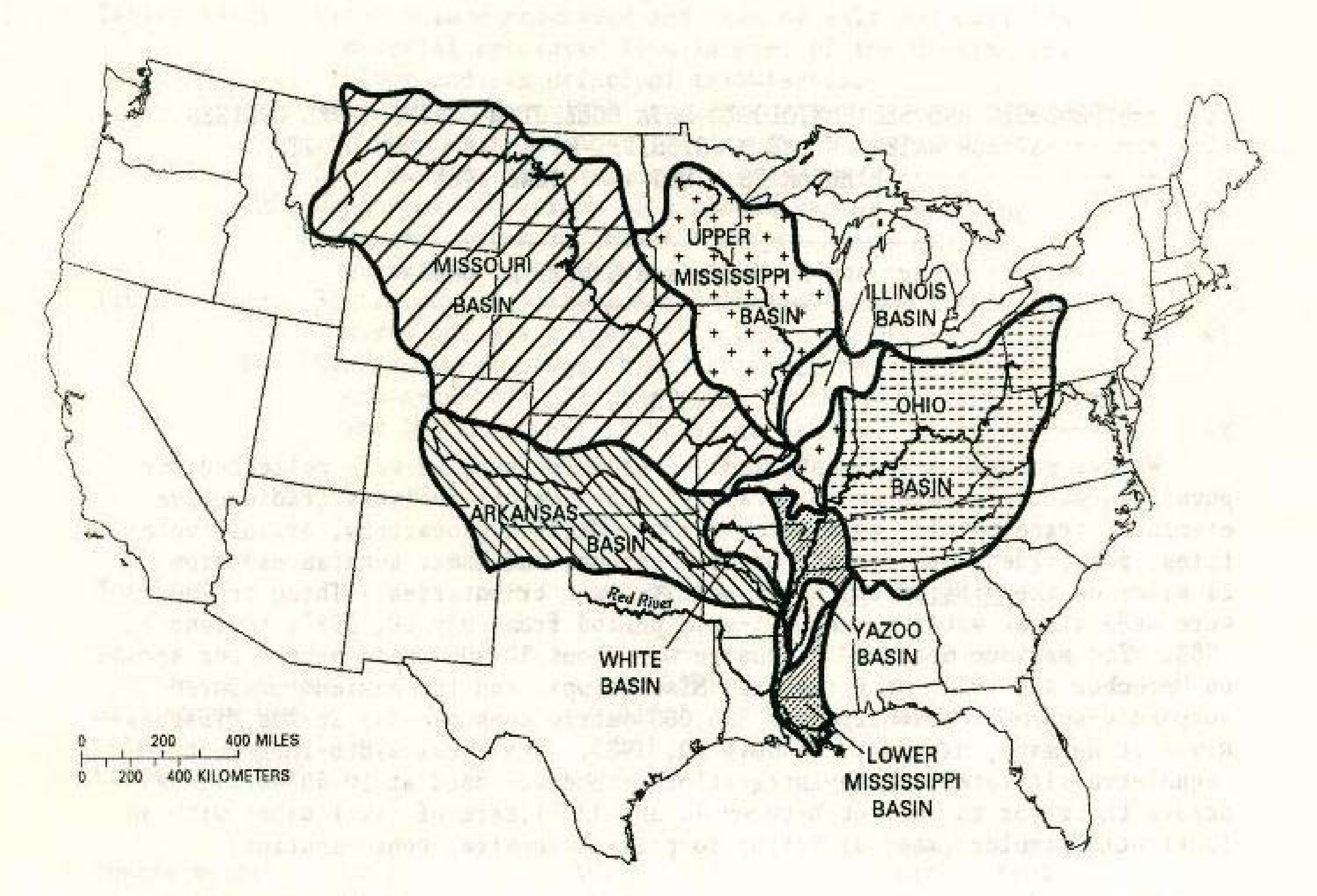
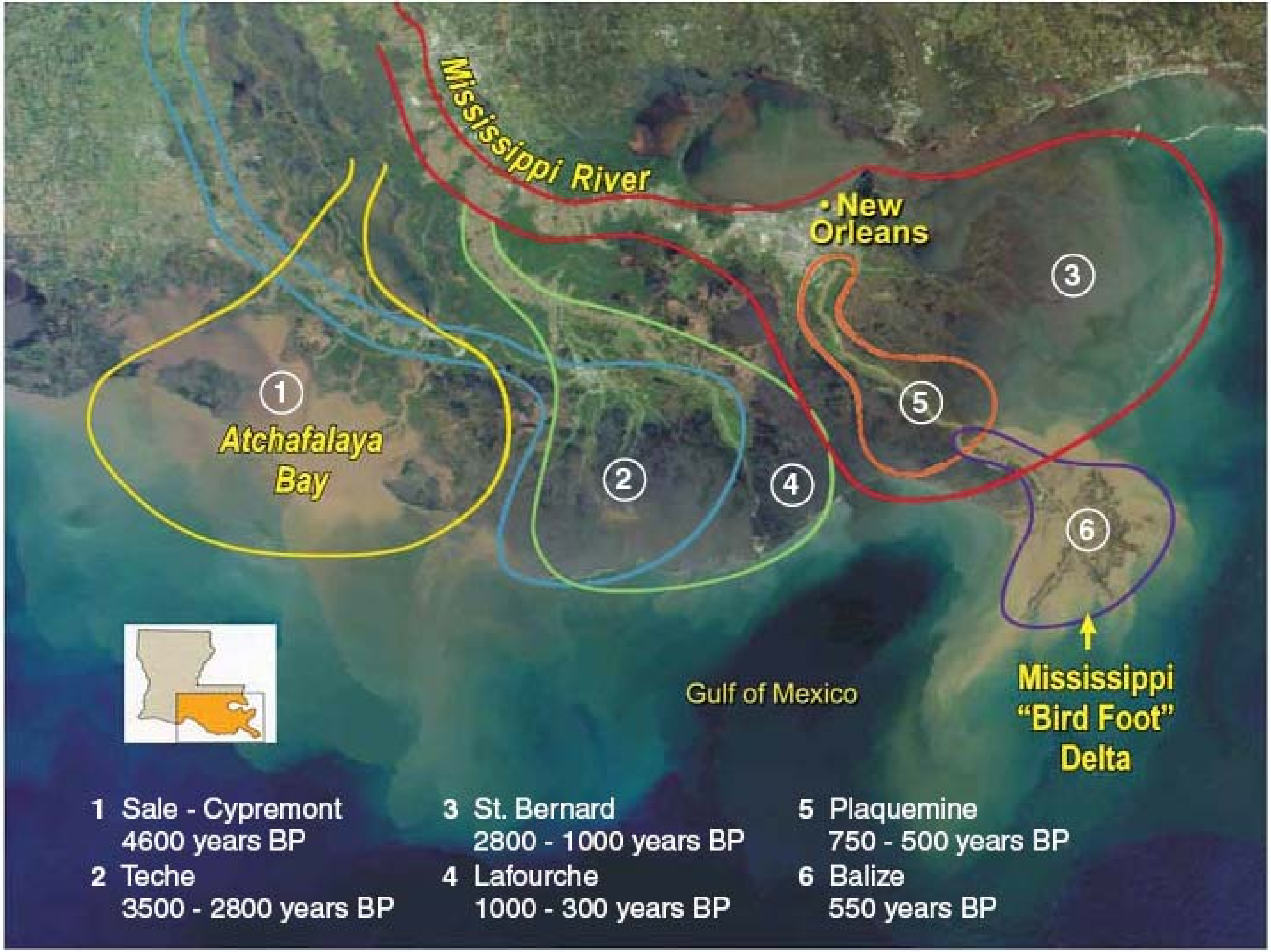


Modified from Alongi (1998)

Bianchi (2007) Biogeochemistry of Estuaries, Oxford Univ. Press

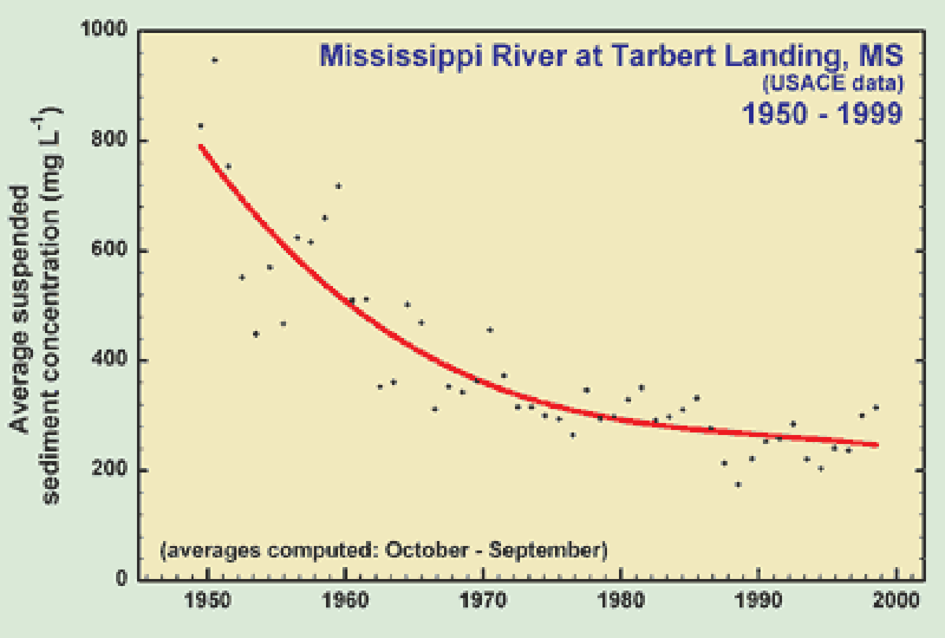
The Mississippi River and its Tributary Drainage Basins

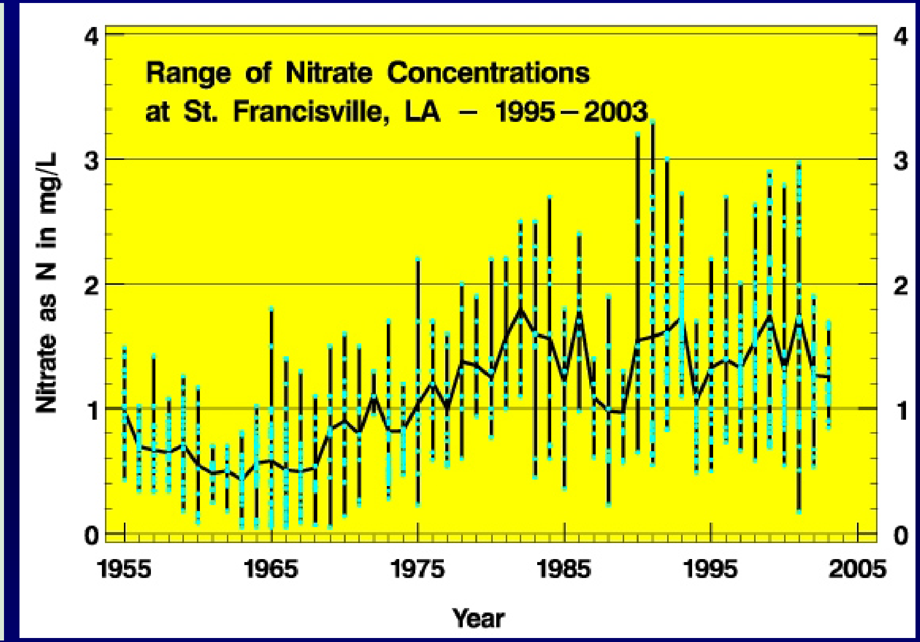




Day et al. (2007), as modified from Boyd and Penland (1988)

Historical Changes in the Suspended Particulate Matter and Nitrate Concentration in the Lower MR

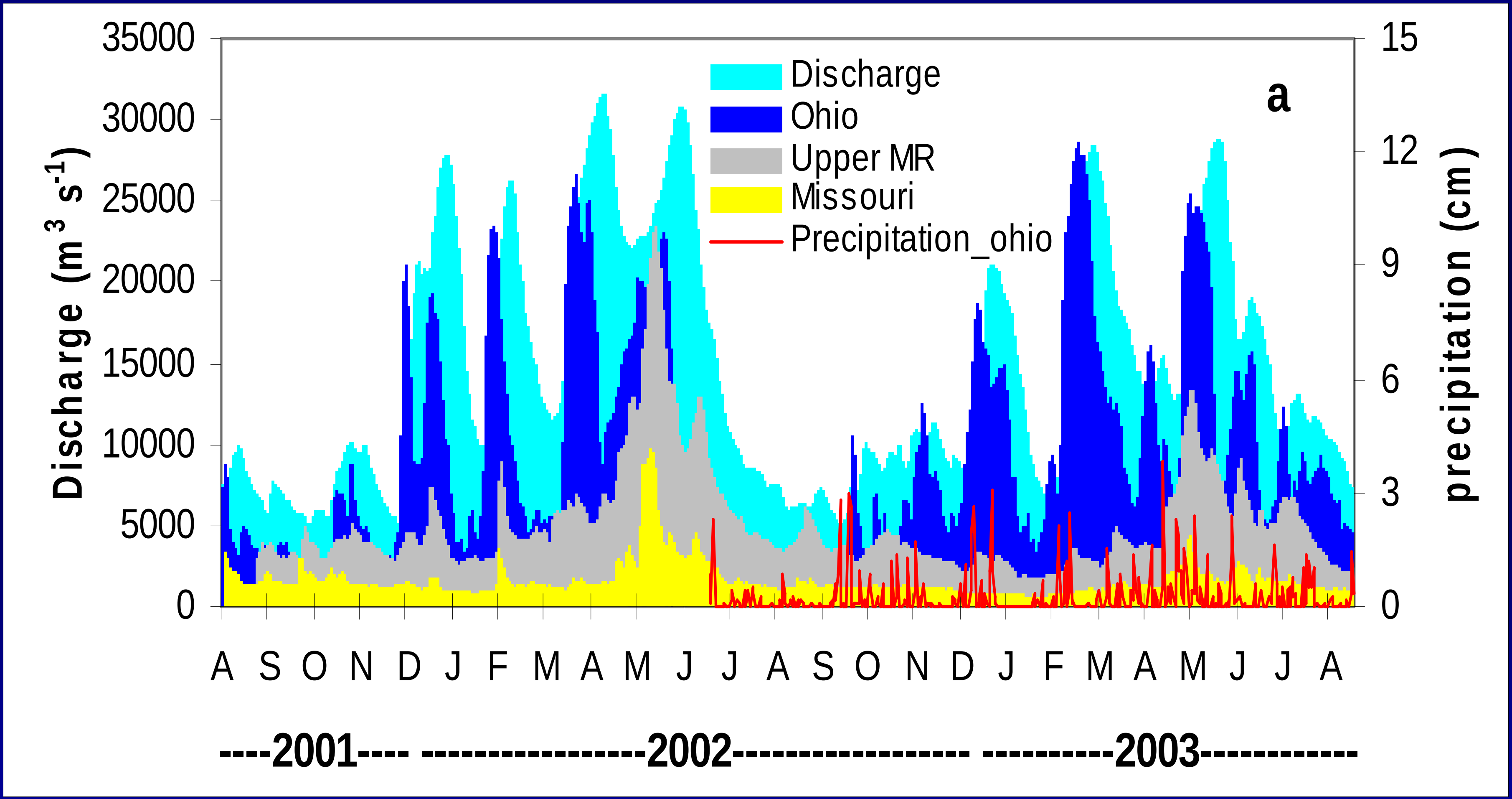




SPM concentrations decreased from 800 mg L^{-1} in 1950s to 250 mg L^{-1} in 1990s due to dam construction in the upper river.

Average nitrate concentrations increased from 0.6 to 0.7 mg L^{-1} in 1950s to the present level of about 1.5 mg L^{-1} because of utilization of chemical fertilizers.

Discharge Patterns of Mississippi, Ohio, and Missouri Rivers



USGS data from Duan and Bianchi (2006)

High Chlorophyll-a in Mississippi River

Table 1 Comparation of Chl-a concentration in MR, PR with other aquatic systems

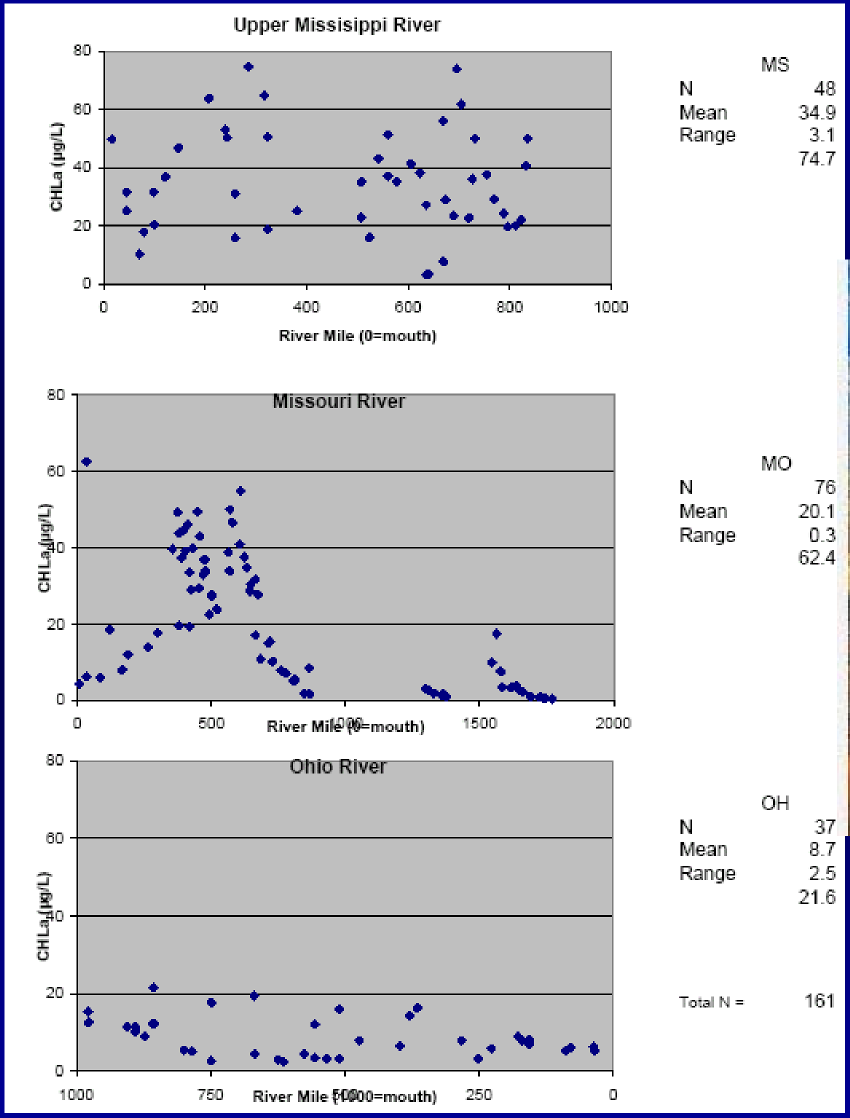
	Range (uM)	Average(uM)	Source
Lower Mississippi	0.8 - 23.6	7.1	Duan and Bianchi (2006)
Pearl (USA)	0.8 - 10.7	3.4	Duan and Bianchi (2006)
Columbia (USA)	1.1 - 22.2		Sullivan et al. 2001
Ohio (USA)	1.1 - 17.7		Sellers and Bukaveckas, 2003
MR Plume	0.44 - 31.1	3.2/6.9	Wysocki, et al., 2005
Lake Pontchartrain (U	0.3 - 7.7	2.6	Bianchi and Argyrou, 1997
Plumes in Baltic Sea		6.5-13.1	Wasmund et al., 1999
Suwannee (USA)	< 0.1		
Amazon	0.17-2.38		Saliot et al., 2001

Duan and Bianchi (2006)

Phytoplankton Abundance in Primary Tributaries of the MR

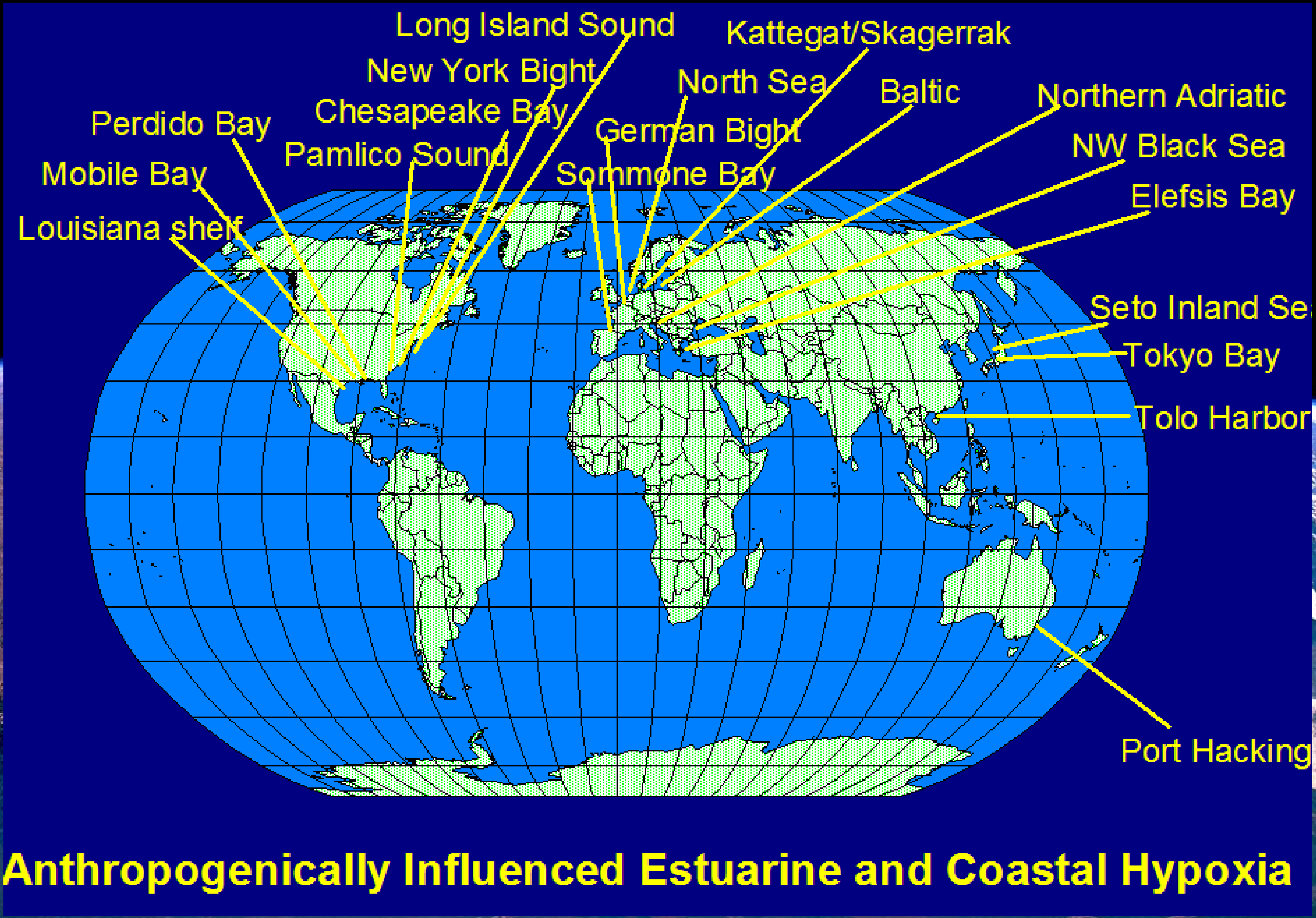
(EPA-EMAP, 2004)

Likely due to export of phytoplankton biomass from backwater reservoirs, navigation locks, and wetlands of tributaries during high-flow periods. Duan and Bianchi (2006)

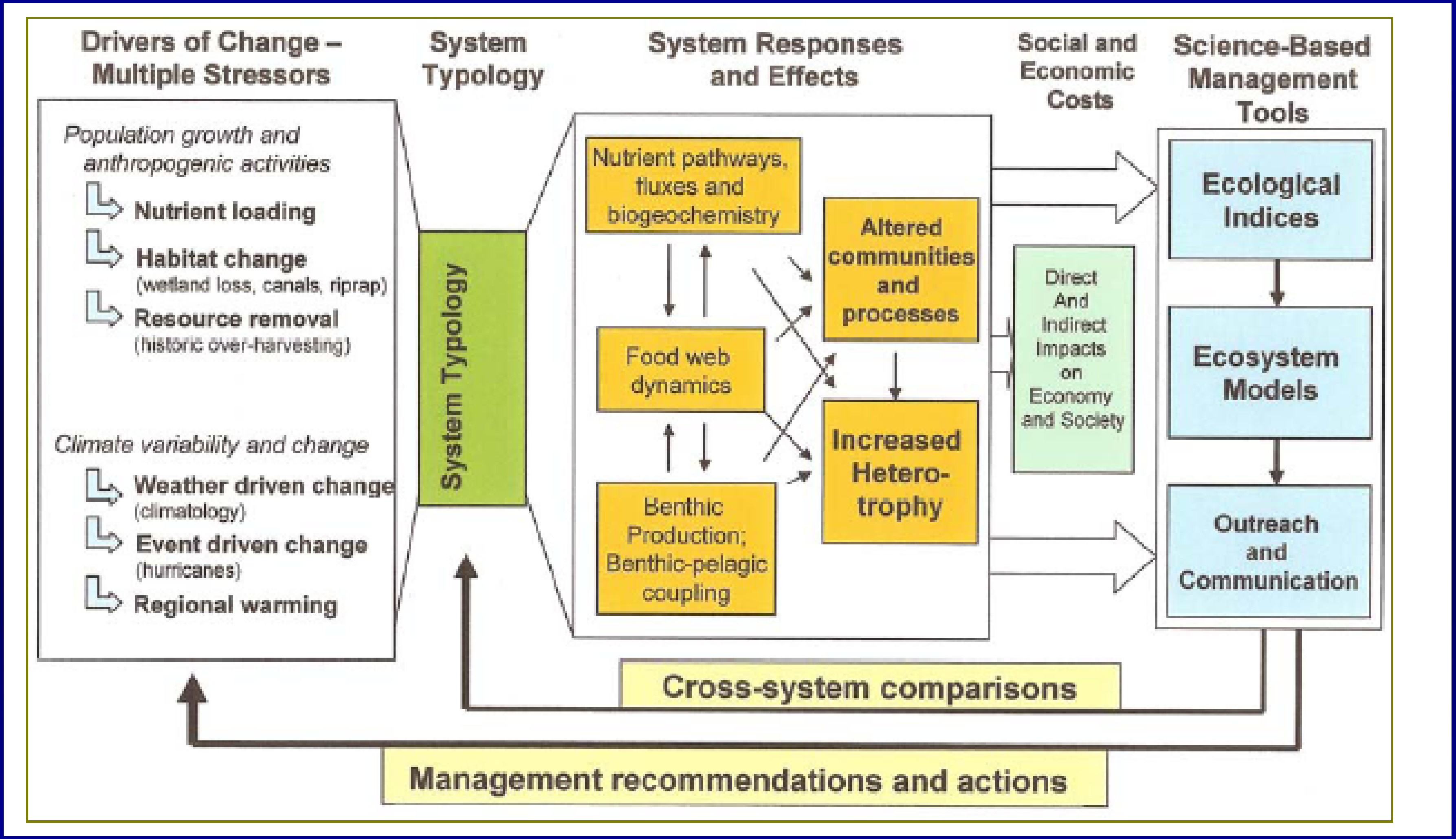


The Hypoxia “Problem”

The Globalization of Eutrophication and Hypoxia



Conceptual Model of Eutrophication



Cloern (2001)

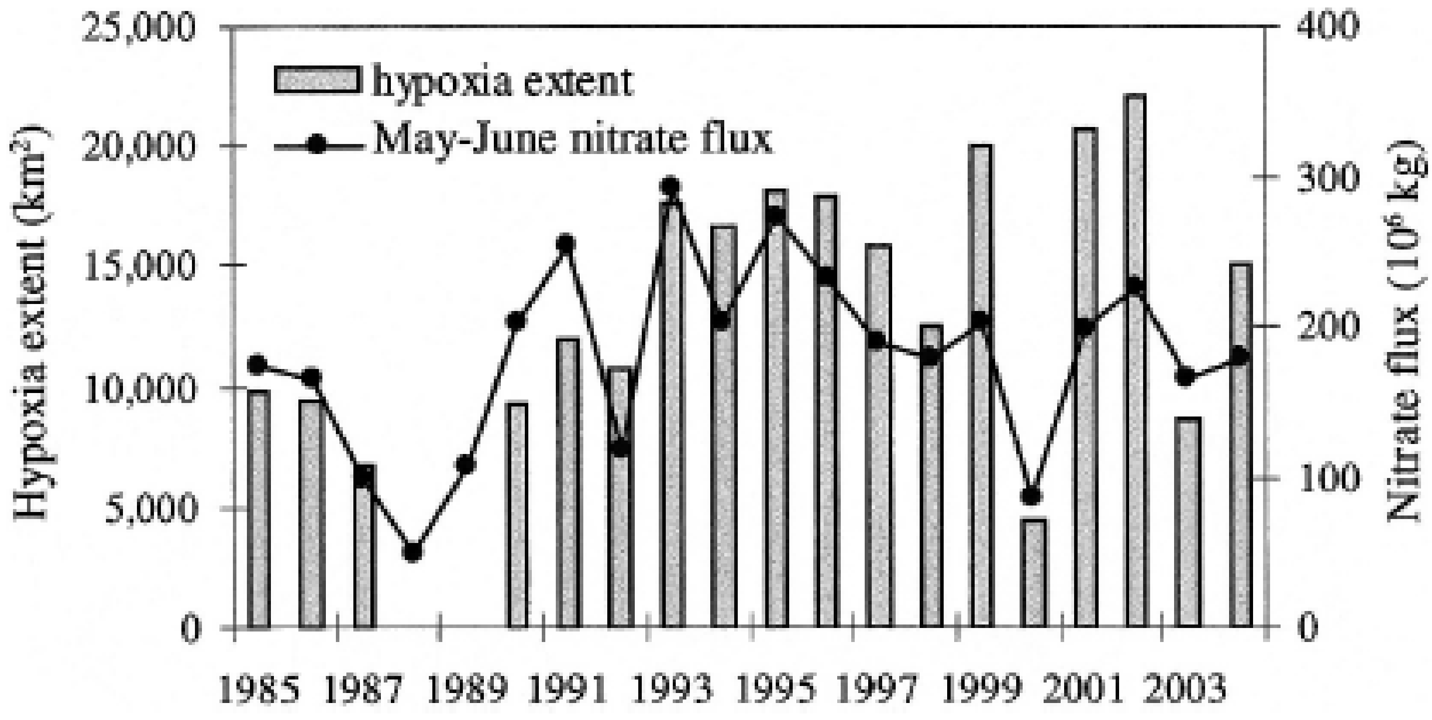
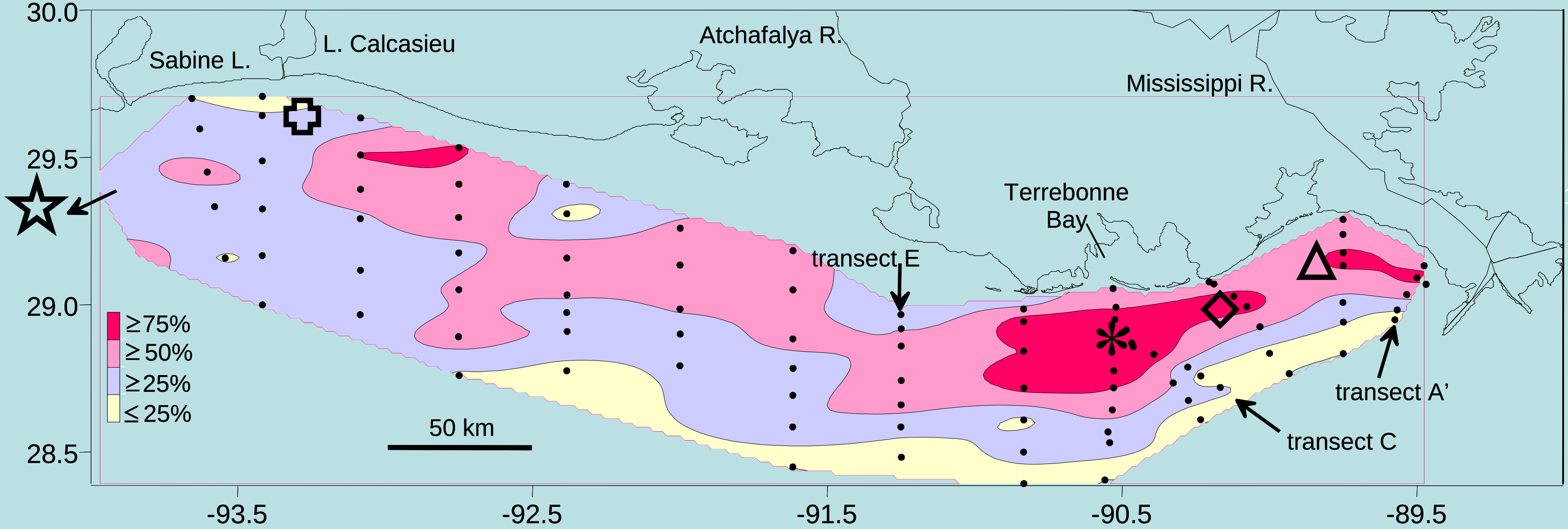


Fig. 1. M–J nitrate flux by the Mississippi River (at St. Francisville, Louisiana) and extent of seasonal hypoxia in the Gulf of Mexico between 1985 and the present. The hypoxic zone reached 40 km² in 1988; no data is available for 1989.

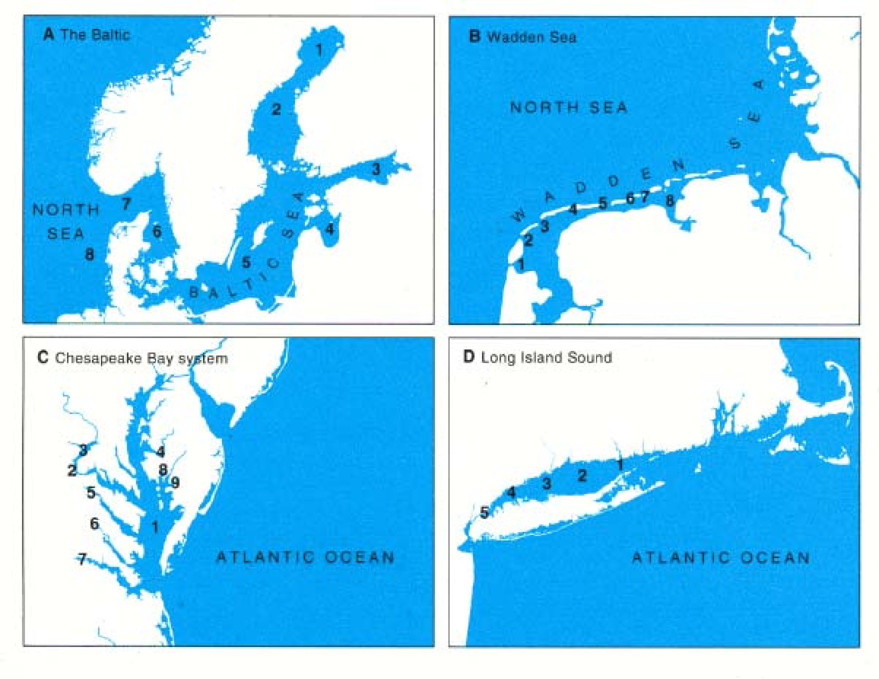
Donner and Scavia (2007)

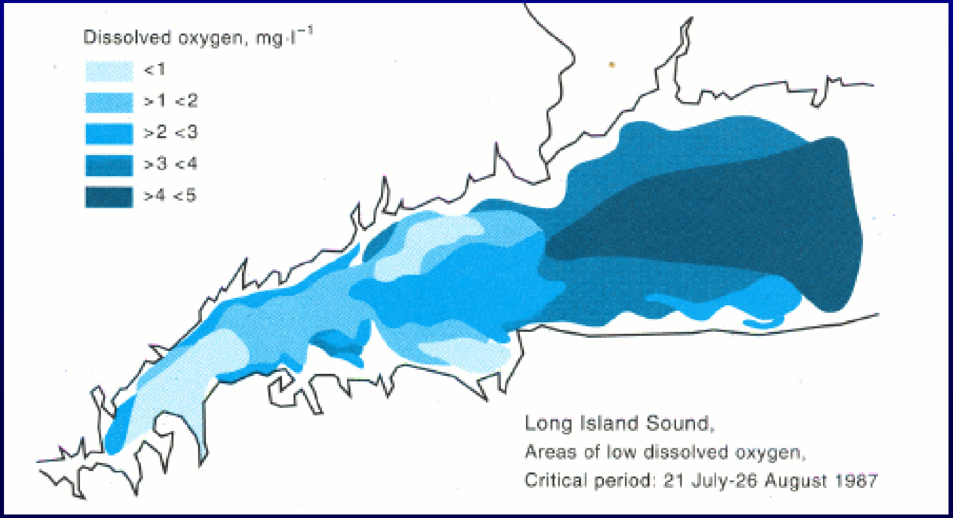


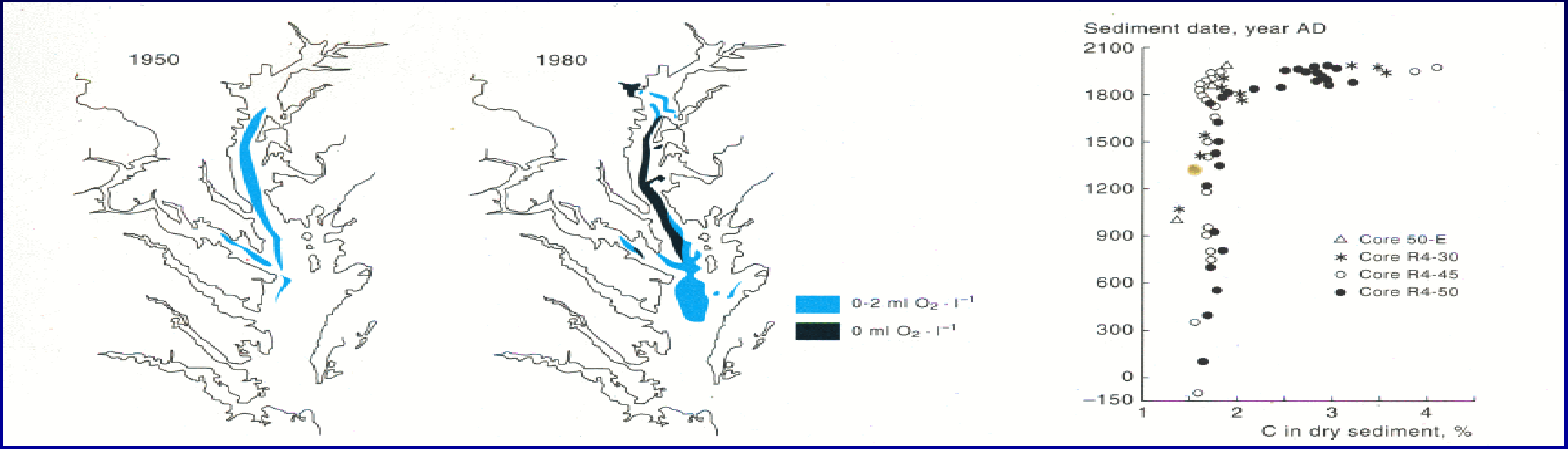
Contours are distribution of frequency of occurrence of mid-summer bottom-water hypoxia from 1985-2002 (Rabalais et al. 2002).

Historical Hypoxia Events in Estuarine Systems

de Jonge et al. (1994)







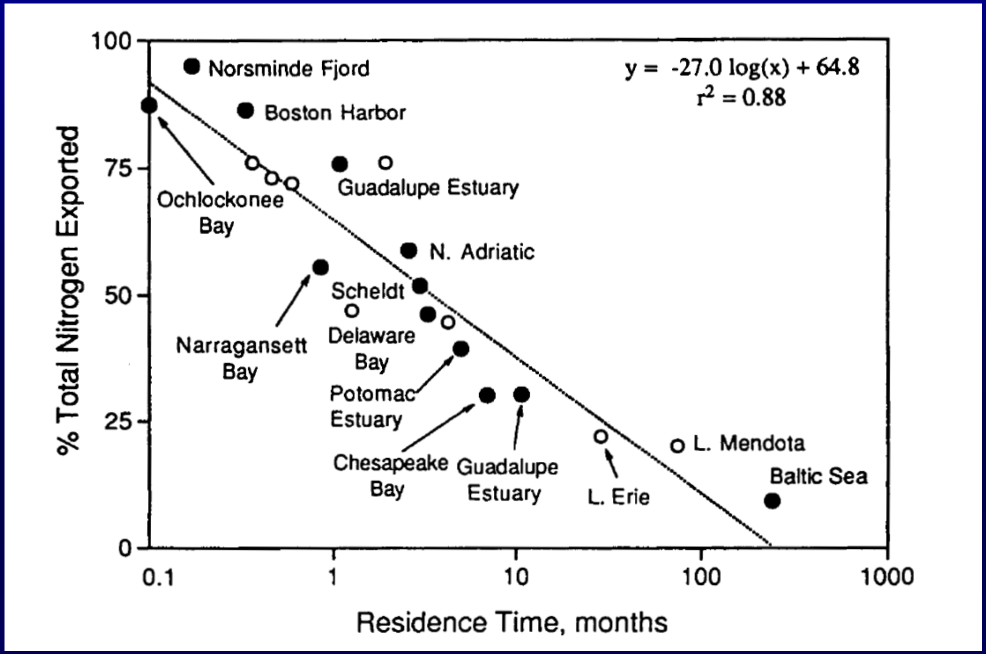
Regime Shifts in Baltic

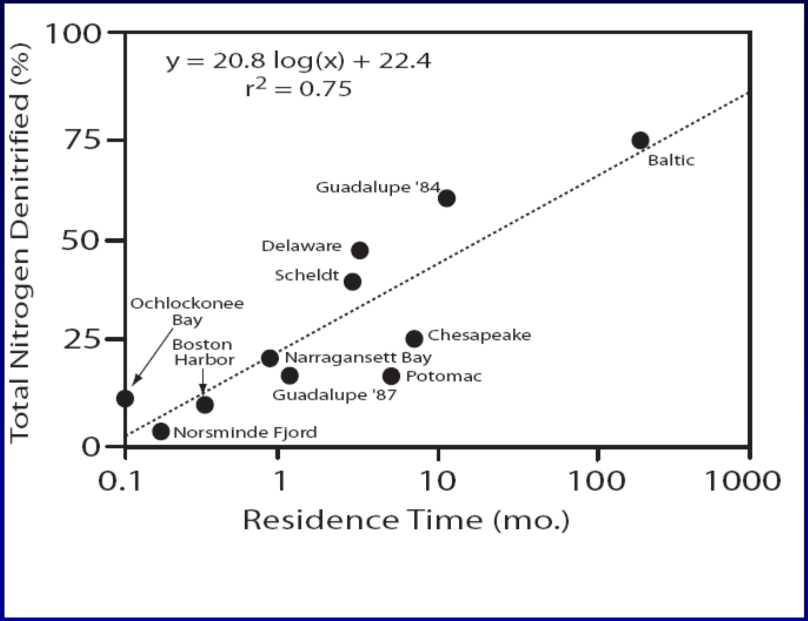
Table 2. Summary of Proposed Trophic Cascades, Regime Shifts and Stabilizing Mechanisms

Ecosystem change	Timing	Geographical extent	Character	Maintained by
The shift from seals to cod	After the 1930s	Entire Baltic (ICES SD 22–32)	Rapid transition in upper trophic levels: cod main predator	Hunting before1960. By the 1970s seal populations were kept low by reproduction impairment caused by toxic pollutants
The shift to a eutrophicated sea	1951 to ~1970	Basin scale change (ICES SD 23–29)	Shift to widespread hypoxia in deep waters and frequent algal blooms	External N and P inputs, boosted by internal P recycling, which stimulates nitrogen fixation (stabilizing new state)
The shift from cod to clupeids	~1989	Entire Baltic (ICES SD 22–32)	Rapid transition in upper trophic levels: reduced top-down control	Overfishing and bad conditions for reproduction of cod, clupeids also eat cod eggs and larvae, and compete with young cod for zooplankton (possibly stabilizing new state)

de Jonge et al. (1994)

The Effects of Residence Time



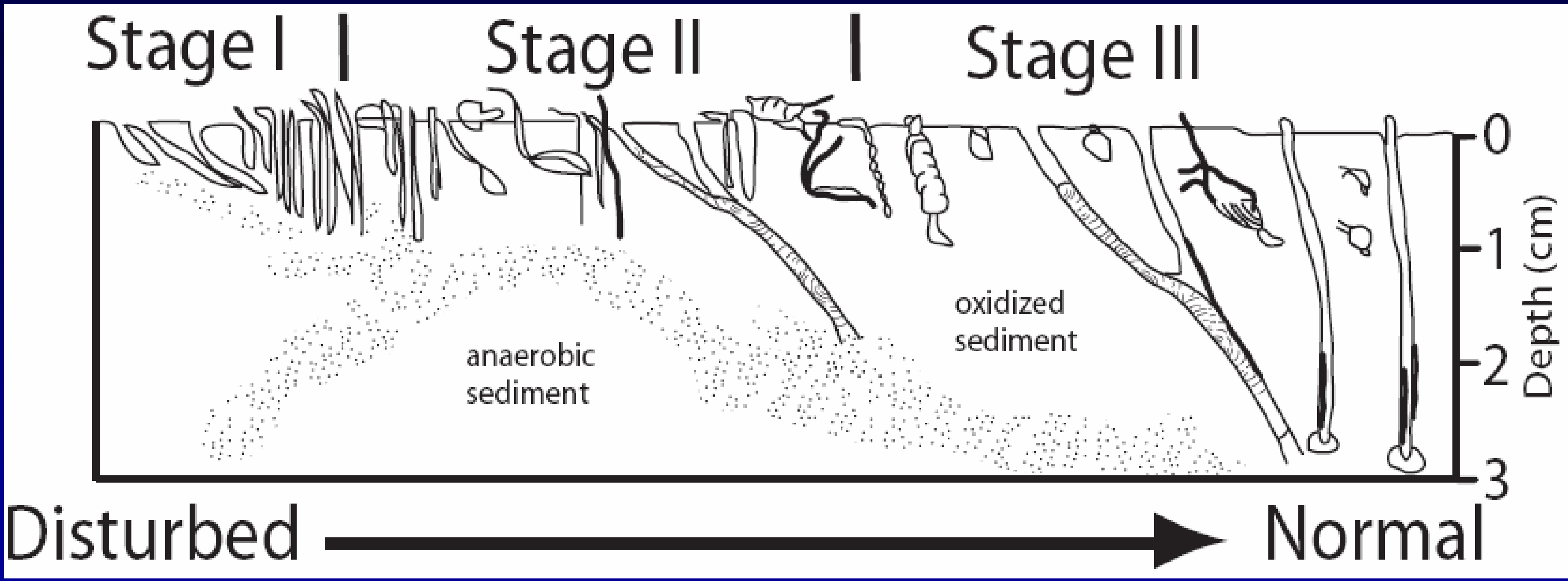


Nixon et al. (1996)

Effects of Hypoxia on Louisiana Shelf Benthic Communities

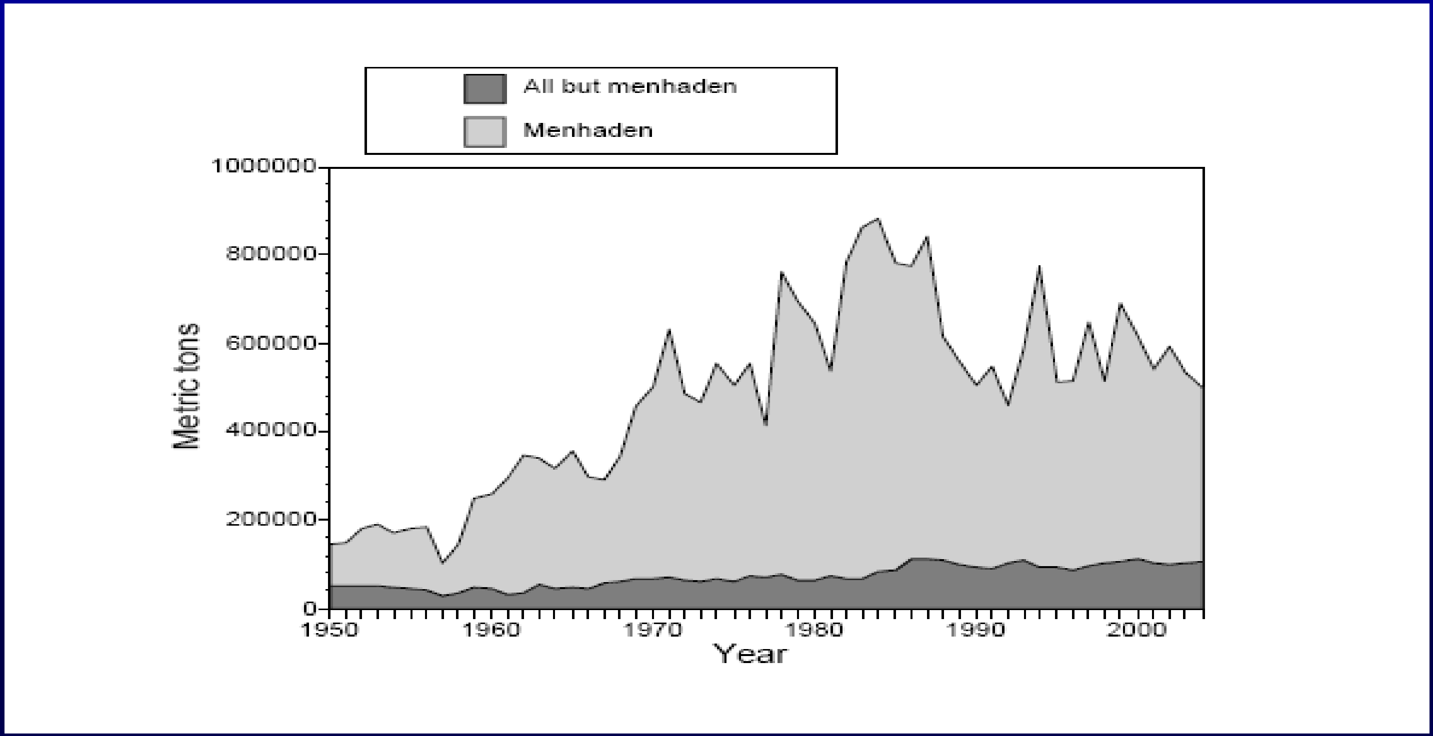
Louisiana hypoxic region sediments dominated by small polychaetes (e.g., *Paraprionospio pinnata*, *Amparete sp.*, *Magelona sp.*, *and Mediomastus ambiseta*) (Gaston, 1985; Rabalais et al., 2001). Other work has suggested that recovery from seasonal hypoxia is "meager" with individual size and biomass low (Boesch and Rabalais, 1991).

Benthic Macrofaunal Succession



Zajac (2001)

Fisheries on the Louisiana shelf



Cowan (2008)

Preliminary NOAA data on northern Gulf of Mexico commercial landings from off Louisiana during the hypoxia monitoring period (1985-2007) show that fisheries production (assuming that landings data reflect production) has increased over the period of record for combined catches of all species excluding Gulf menhaden (*Brevoortia patronus)*.

Louisiana alone accounts for ~75% of the fishery landings in the U.S. Gulf of Mexico.

To date, there are no clear linkages of negative hypoxia effects on the Louisiana shelf ecosystem (e.g., losses of benthic fauna, fishes), as was clearly demonstrated in earlier studies on more "traditional" estuarine systems, such as the Chesapeake, Baltic, and Narragansett

(Bianchi et al., 2008, EOS, In Press)

So, what is it about this river-dominated margin that makes it so resilient to hypoxic conditions?

Have other potential controls on hypoxia in this region, outside the prevailing river nutrient-centric view, been overlooked?

Missing Data?

In a recent assessment of the hypoxic literature by the EPA Action Plan (2007), it was discovered that, despite 20+ years of NOAA funding for hypoxia work on the Louisiana shelf, very little is know about rates of nitrification/dentrification, sediment nutrient fluxes, biogeochemical budgets (e.g., N, P, S, and C).

Why?

One of the problems…

Mapping of Dead Zone Completed
PRESS RELEASE, JULY 29, 2005

The coast wide extent of the Louisiana "dead zone" mapped this week is 11,840 km^2, slightly smaller than

the size of Connecticut,

reported Dr. Nancy Rabalais, Chief Scientist for Northern Gulf of Mexico Hypoxia Studies. The low oxygen waters extended from near the Mississippi River to the Louisiana/Texas border. The long-term average since mapping began in 1985 is 12,700 km^2 (or 4,800 square miles).

The following 4 natural and anthropogenically-derived characteristics within this RiOMar system (different from other semi-enclosed estuaries) may in part, answer for the aforementioned discrepancies in hypoxia effects (Bianchi et al., 2008):

- 1) Spatial/Temporal Variability and Magnitude of Freshwater Inputs and Wind-Driven/Coastal Current Mixing Events
- 2) Diversity and Magnitude of Organic Matter Sources and Loading
- 3) Rates and Efficiency Organic Matter Diagenesis in Mobile Muds
- 4) Rapid Transport of Labile Shelf-Derived Organic Matter to the Mississippi River Canyon

Spatial/Temporal Variability and Magnitude of Freshwater Inputs

Regional Distinctions within the Hypoxic Zone

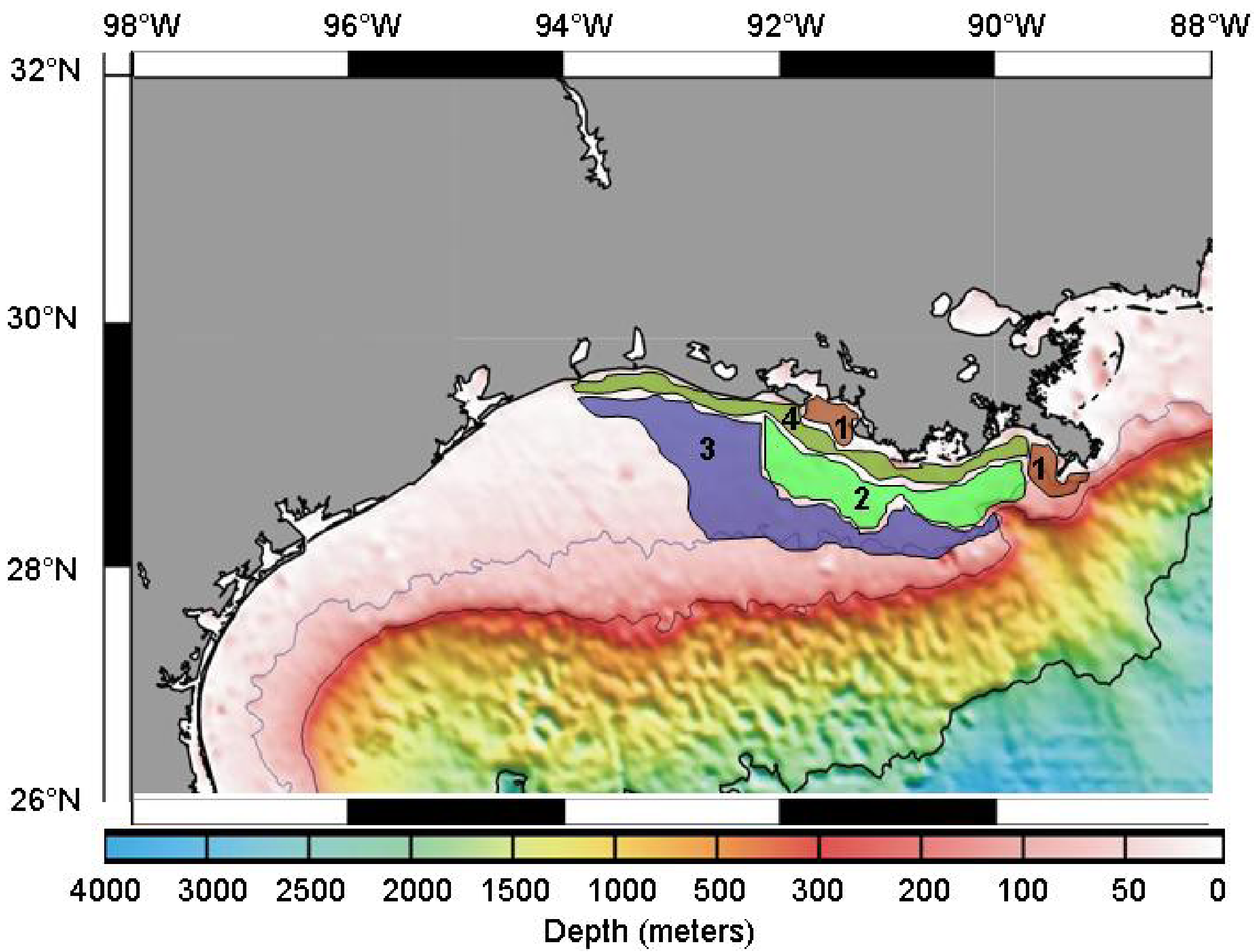


Figure 7: An illustration depicting different zones (Zones 1-4, numbered above) in the NGOM during the period when hypoxia can occur. These zones are controlled by differing physical, chemical, and biological processes, are variable in size, and move temporally and spatially. Diagram created by D. Gilbert.

Modified from Rowe and Chapman (2002)

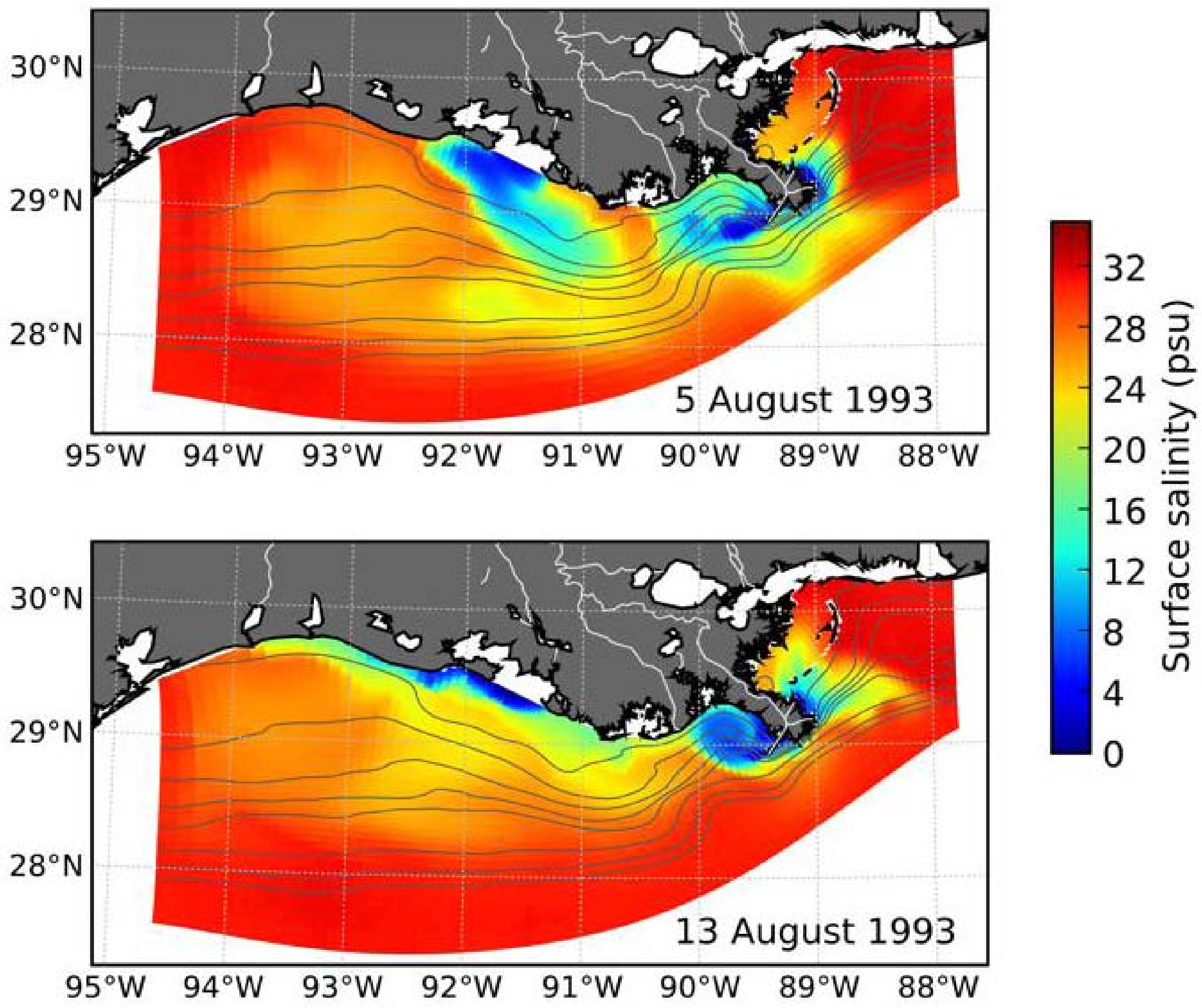


Figure 5: Modelled surface salinity showing the freshwater plumes from the Atchafalaya and Mississippi Rivers during upwelling favorable winds (top panel) and during downwelling favorable winds 8 days later (bottom panel). Adapted from Hetland and DiMarco (2007).

Hetland and DiMarco (2008)

Diversity and Magnitude of Organic Matter Sources and Loading

Mean Global Fluvial Loadings of Organic Carbon to the Oceans

Reference	DOC	POC	TOC
Smith and Hollibaugh (1993)	**164**	**197**	**386**

Units = 10^{11} mol C yr^{-1}

Mean Annual Fluvial Loadings of Organic Carbon from the Mississippi River

	DOC	POC	TOC
(**July** 1998 - June 1999)	3.0 (62%)	1.8 (38%)	4.8
This Study- Global Percent:	**1.8**	0.9	1.2

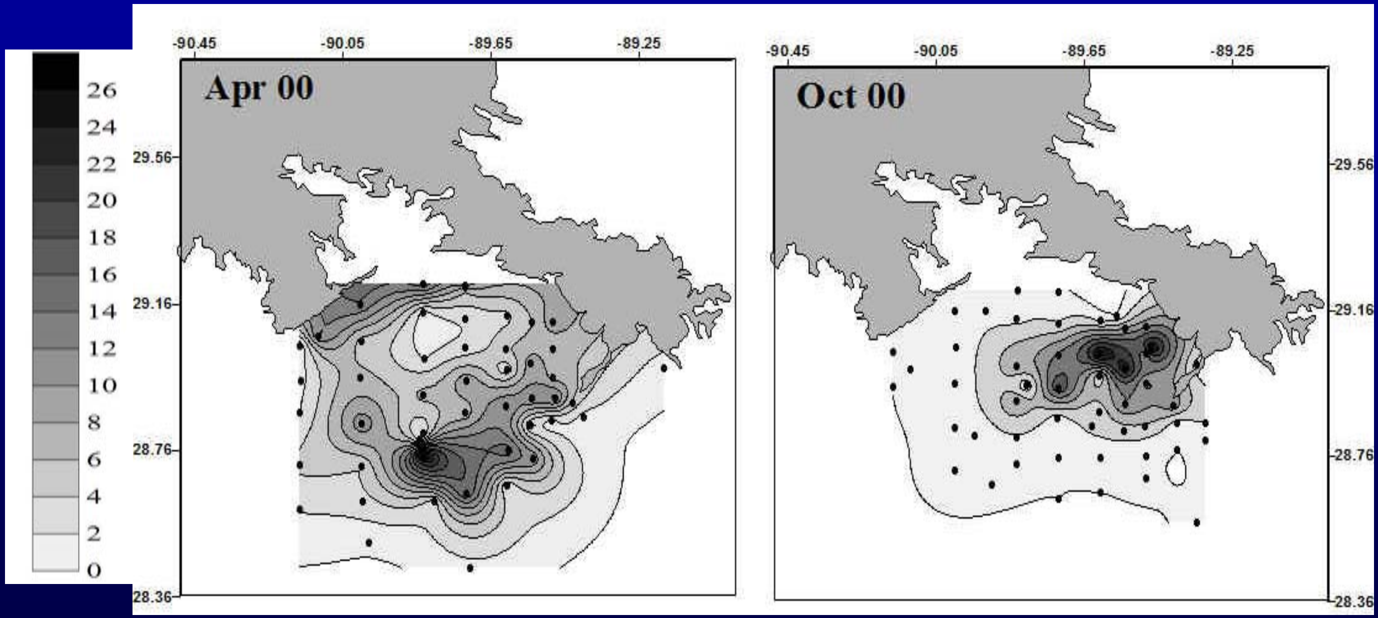
Units = 10^{11} mol C yr^{-1}

Bianchi et al. (2004, 2007)

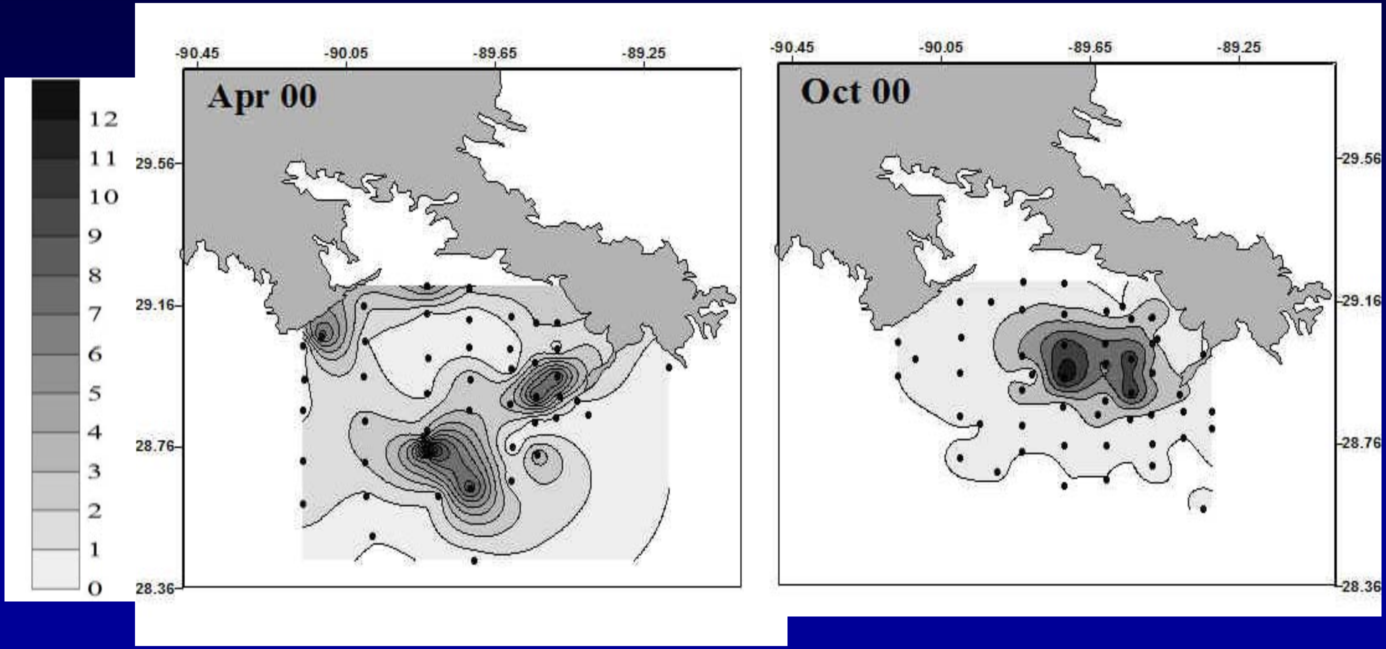
Nearshore diatom sources?

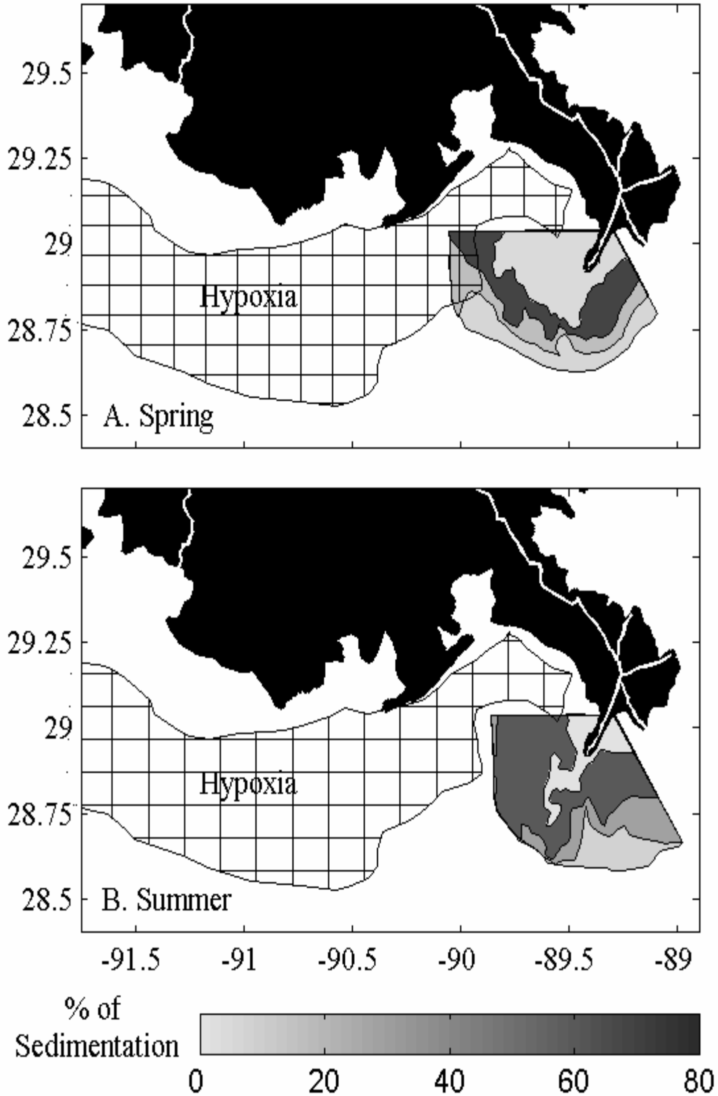
Wysocki et al. (2006)

Chlorophyll-a



Fucoxanthin

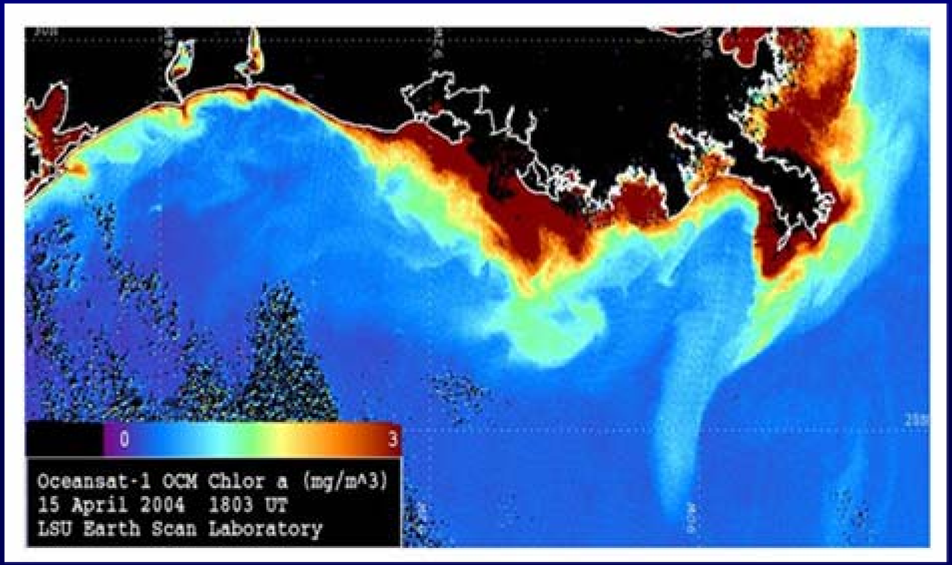


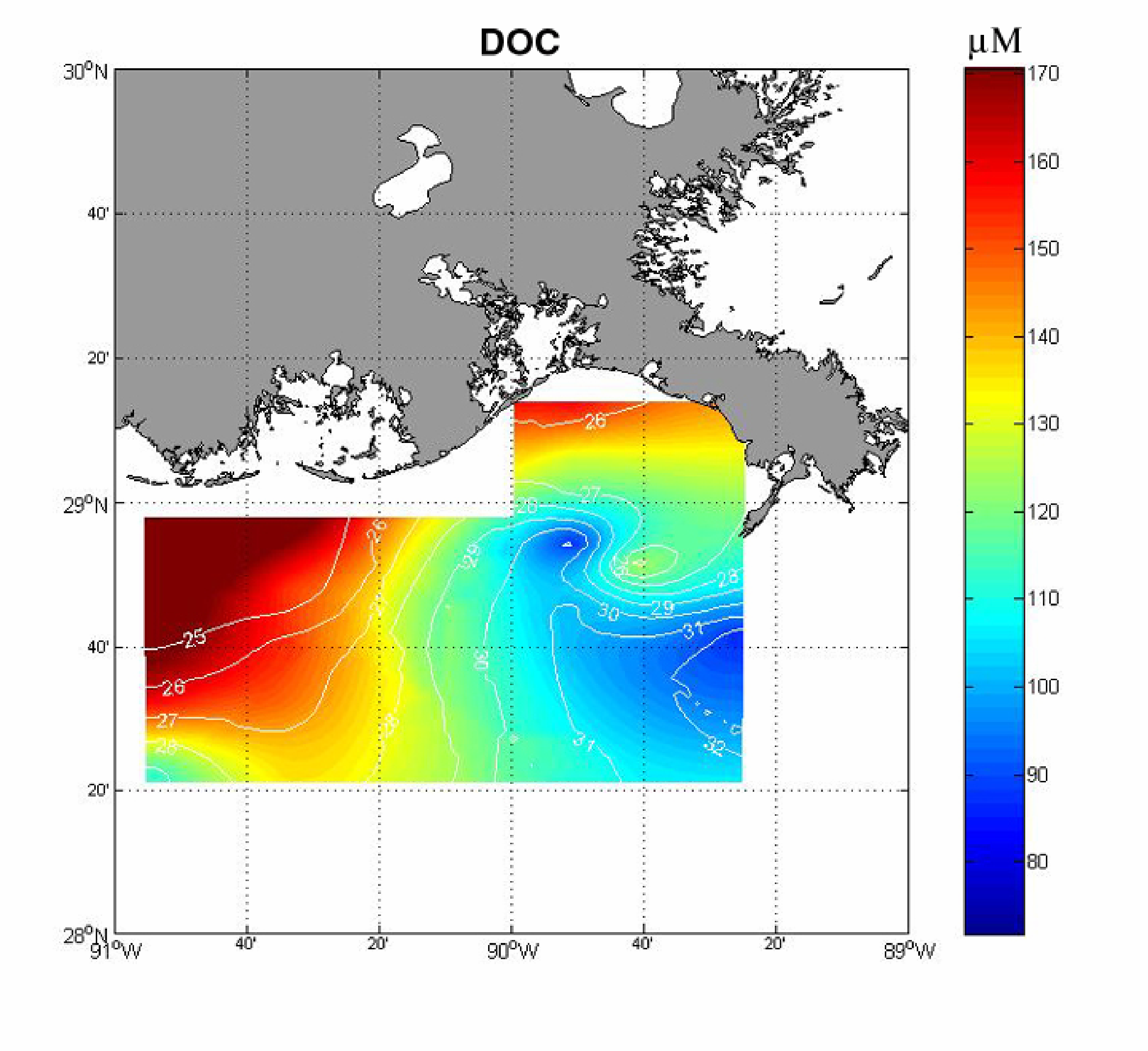


Seasonal variability in organic carbon (OC) budgets was investigated using a physical-biological model for the Mississippi River turbidity plume (MRTP).

Sedimentation of autochthonous OC from the immediate plume contributed ~23% of the O_2 demand necessary for establishment of hypoxia in the region (Green et al ., 2006)

Therefore, other organic matter sources are clearly contributing to hypoxia that have been largely ignored by the majority of research published on this region (Dagg et al., 2007, 2008; Bianchi et al., 2008).

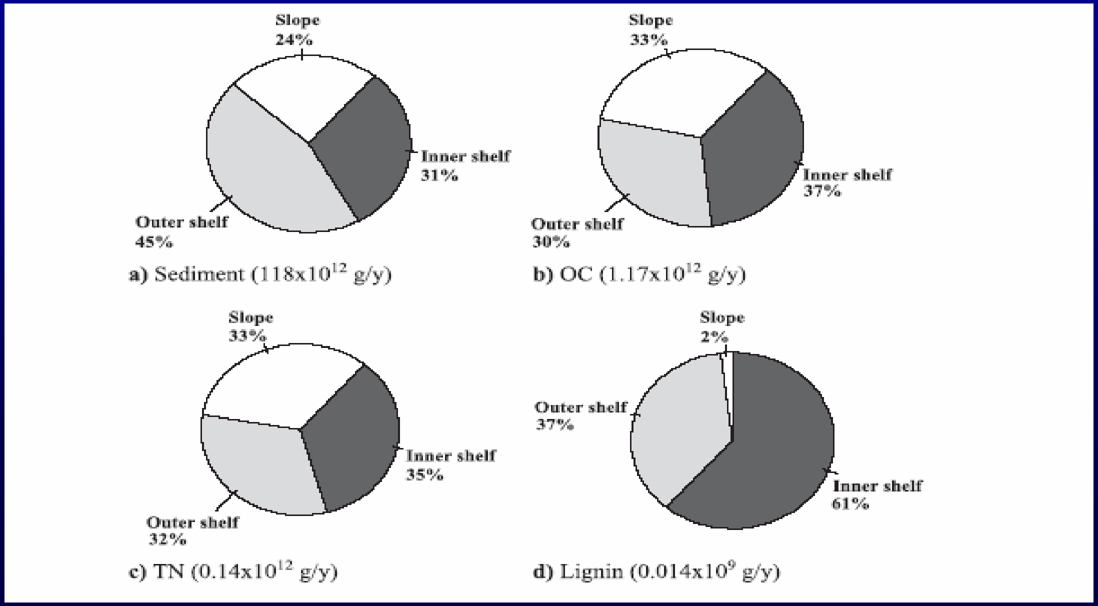




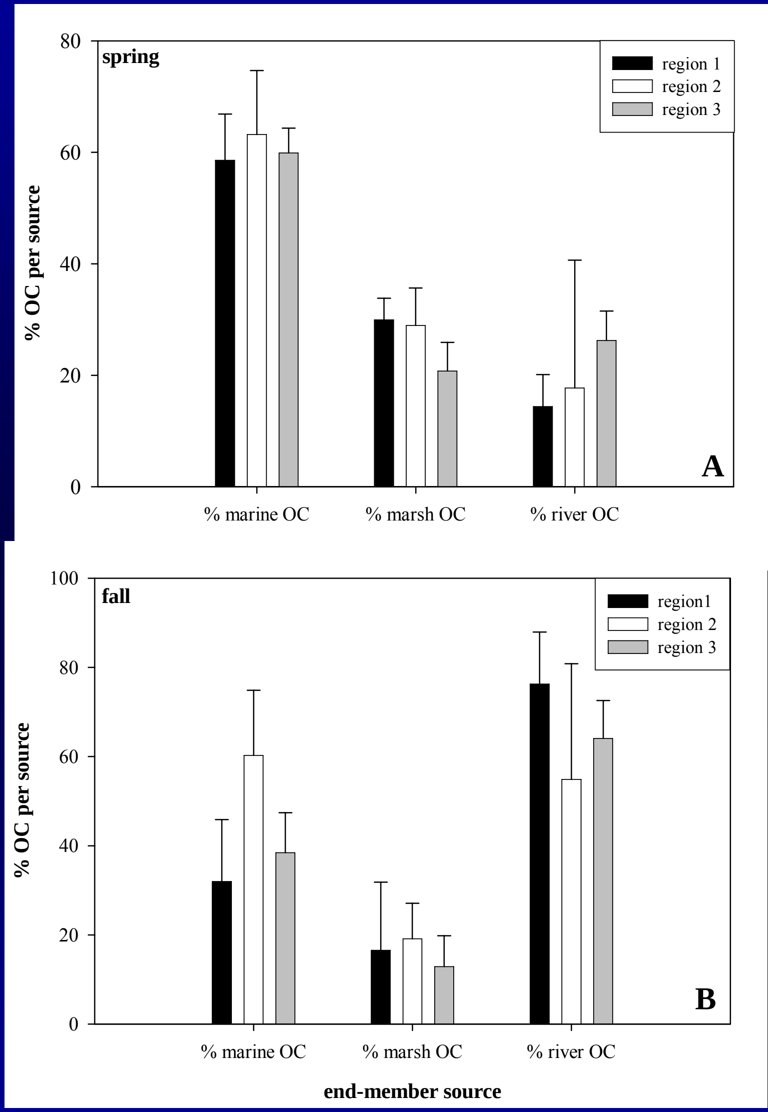
The association of high DOC with lowest salinity (< 25) suggests either the Atchafalaya River or coastal estuaries were sources for this material (Dagg and Bianchi, unpublished).

Chen and Gardner (2004) also reported significant outwelling of chromophoric dissolved organic matter (CDOM) from wetlands.

Sources of Terrestrial Carbon Inputs



Gordon and Goni (2004)



Wysocki et al., submitted to Mar. Chem.

Historical Changes in Hypoxia

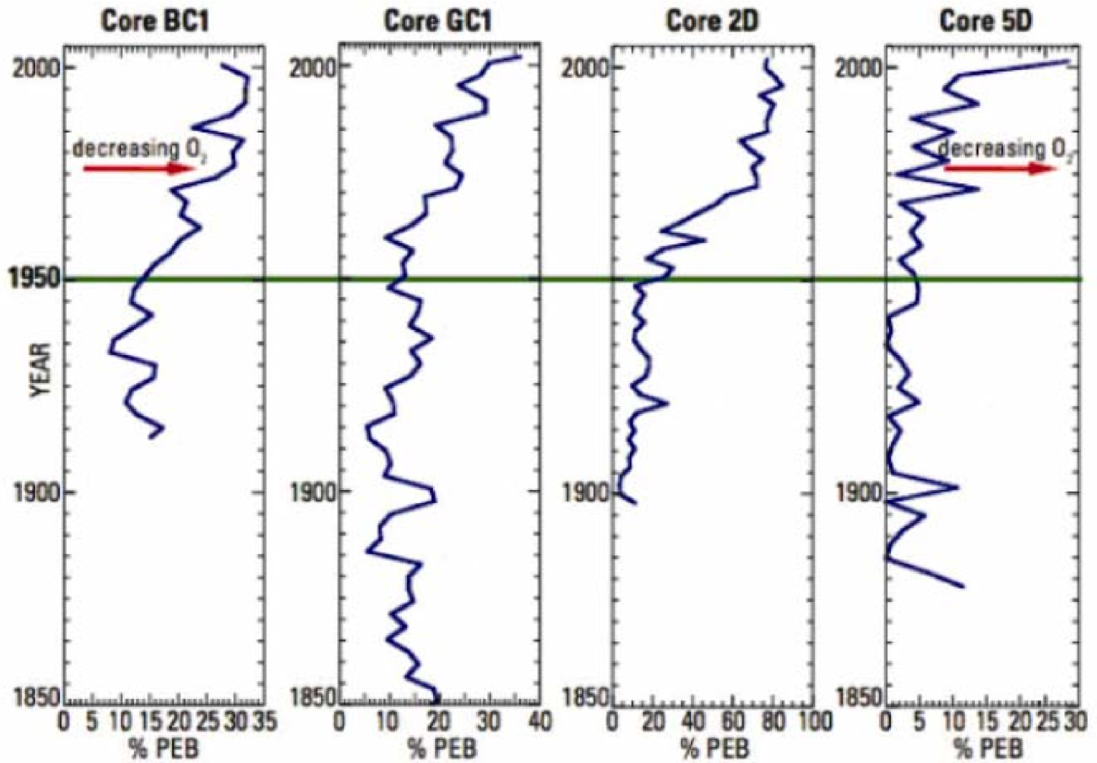


Figure 3: Plots of the PEB index (%PEB) in sediment cores from the Louisiana shelf. Higher values of the PEB index indicate lower dissolved oxygen contents in bottom waters. Taken from Osterman et al. (2005).

***Pseudononion atlanticum*, *Epistominella vitrea*, and *Buliminella morgani (PEB*) Index (Osterman et al (2005)**

Linkages with the Onset of Hypoxia

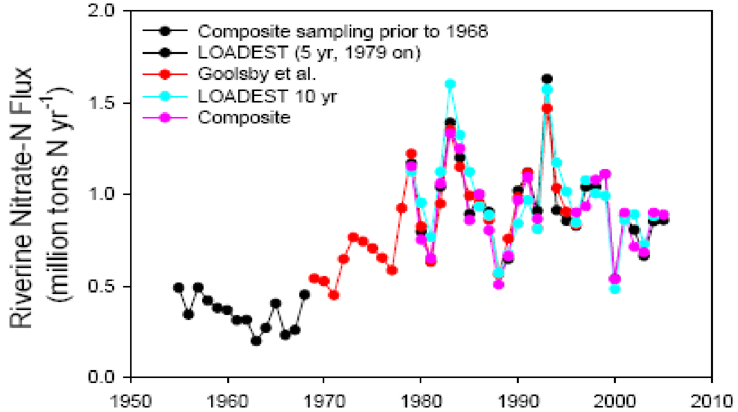


Figure 14: MARB nitrate-N fluxes for 1955 through 2005 water years comparing estimates from various methods for 1979 to 2005. Based on USGS data from Battaglin (2006) and Aulenbach et al. (2007).

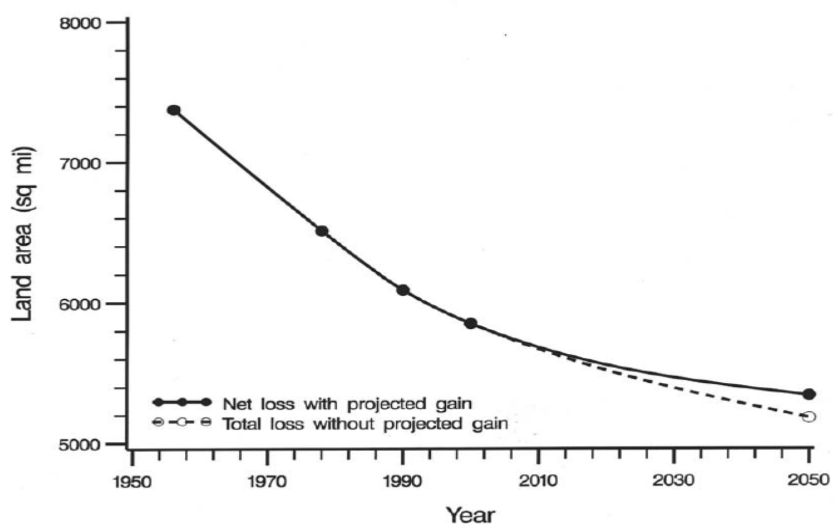
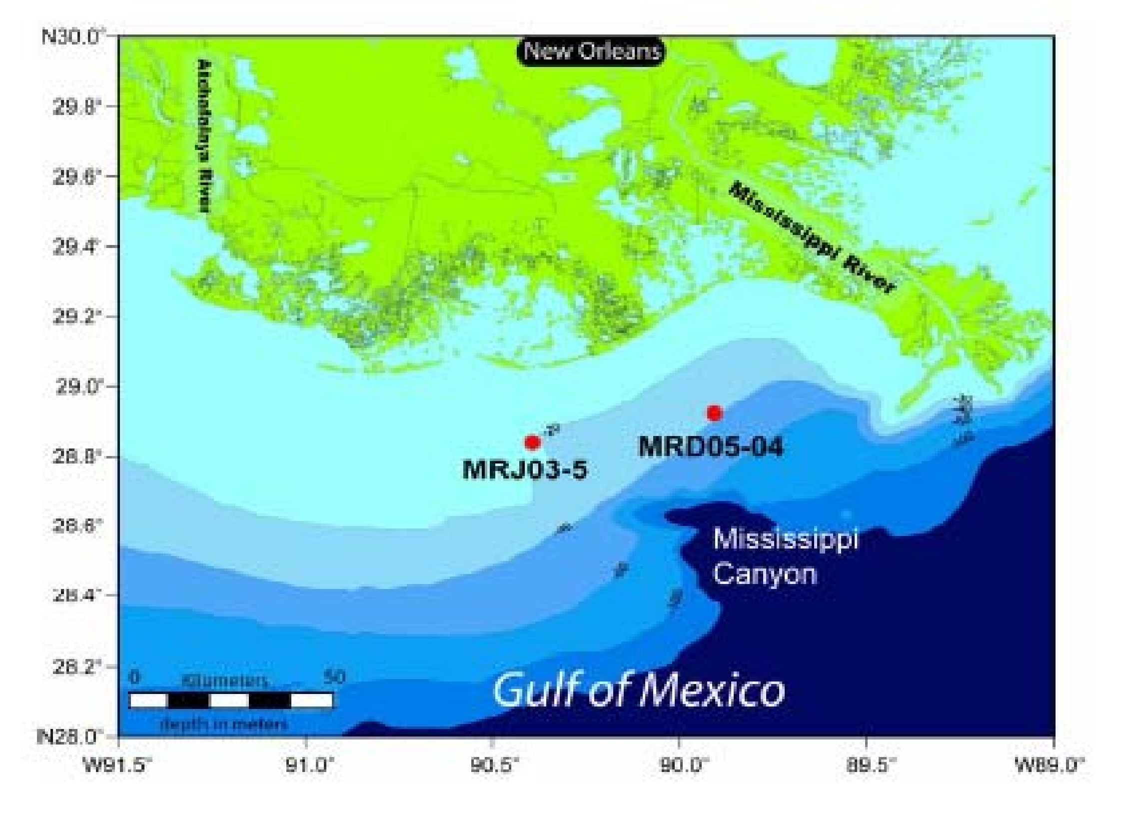


Figure 19. Projected coastal Louisiana land loss from 1956 to 2050.

Note: With the projected gain, the net loss from year 1956 to 2050 is estimated to be 2,038 sq mi (5,278 sq km) whereas without the projected gain, the estimated total loss amounts to 2,199 sq mi (5,695 sq km).

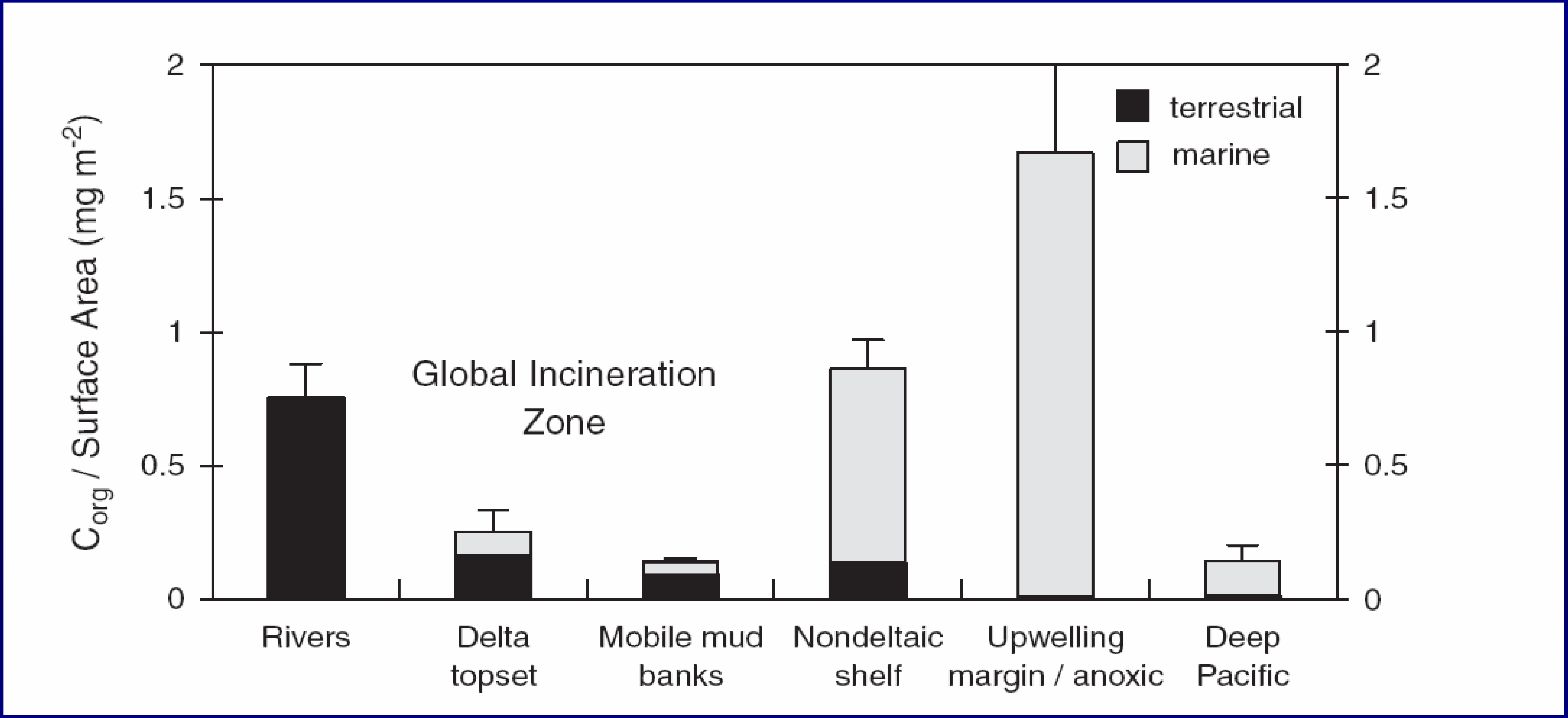
Barras et al. (2003)

Hypoxia events have occurred for at least the last 1000 yrs. BP on the Louisiana coast. Swarzenski et al. (2008)



Rates and Efficiency Organic Matter Diagenesis in Mobile Muds

Diagenesis in Mobile Muds



Aller and Blair (2006)

Transport of Mobile Muds

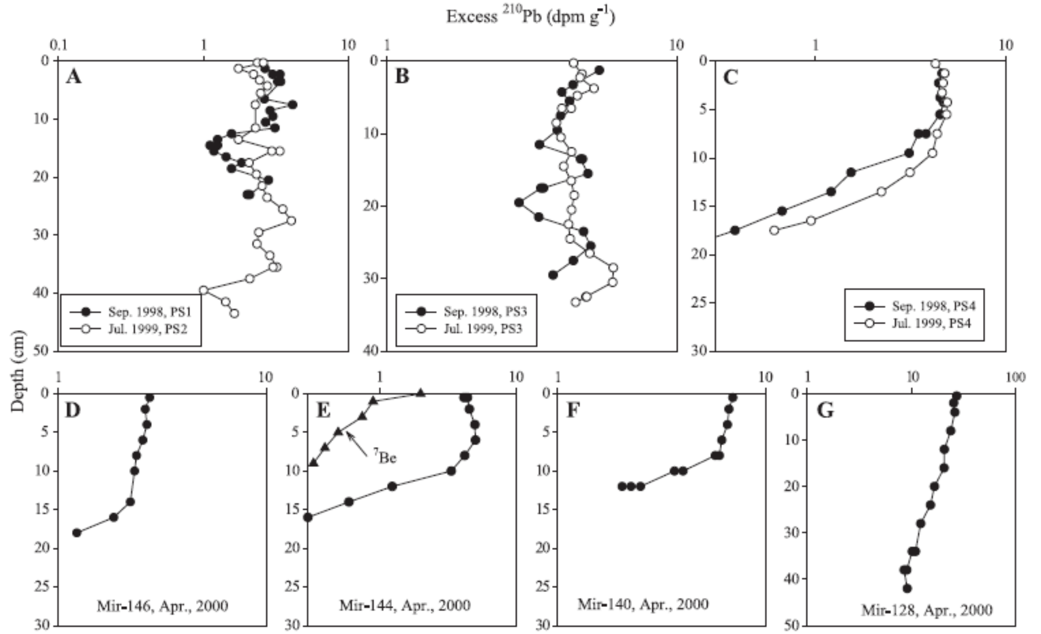


Fig. 2. Excess ^{210}Pb concentrations (dpm g^{-1}) in sediments from the river and shelf sites collected in September 1998 and July 1999, and from a cross-shelf transect collected in April 2000.

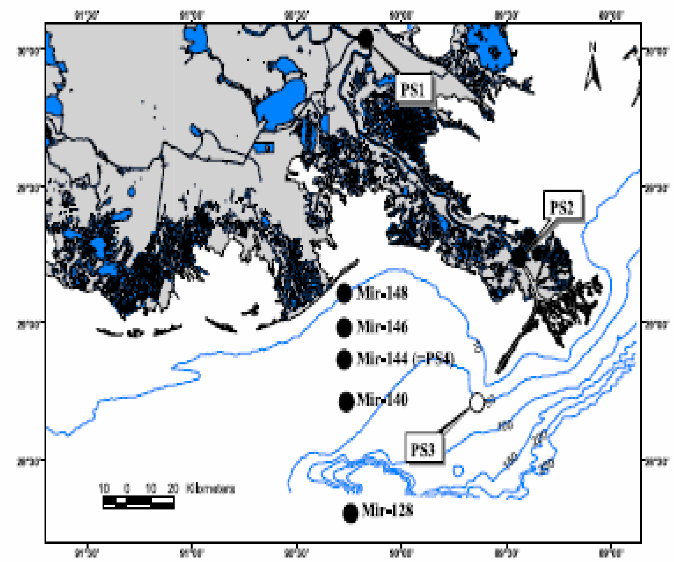
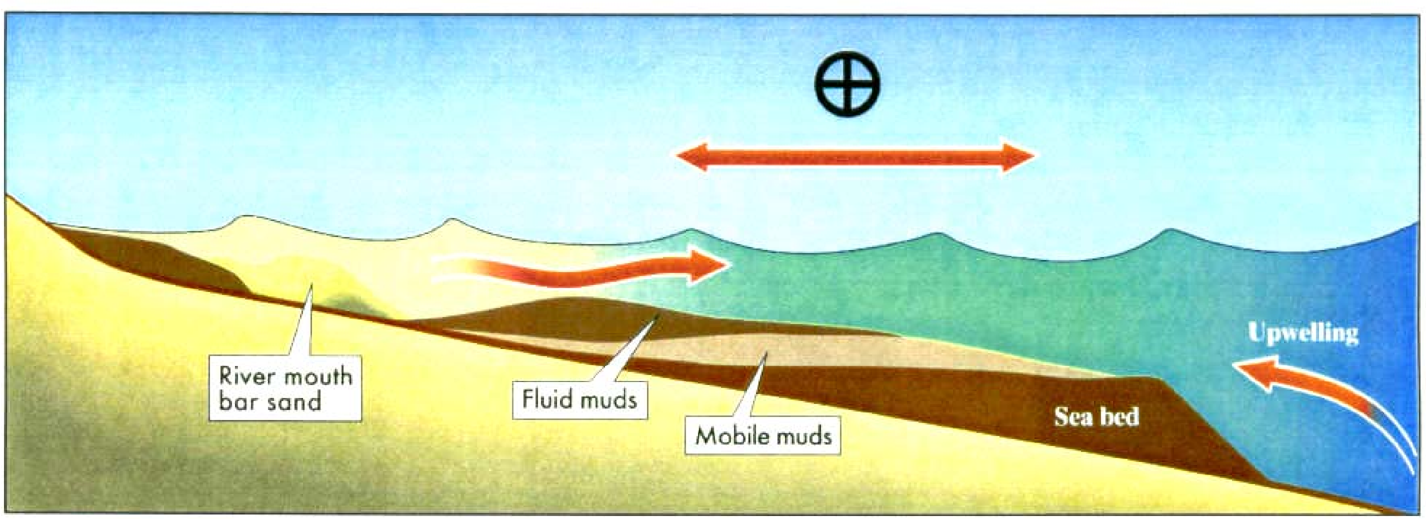


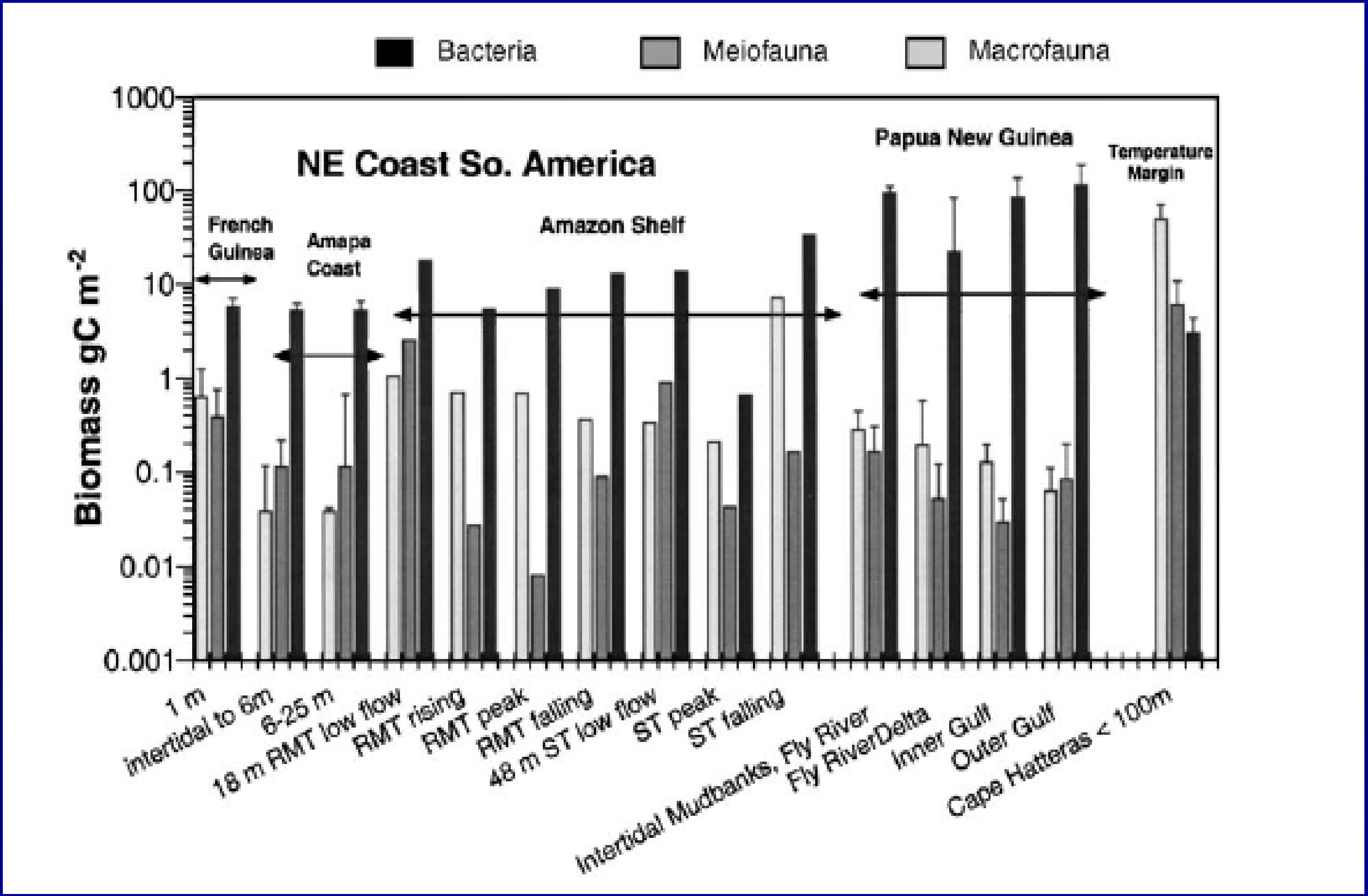
Fig. 1. Map showing the sampling sites in lower Mississippi River and the Louisiana shelf.

Chen et al. (2005)



(Bianchi, 2007)

Heterotrophy in Mobile Muds



Aller and Aller (1994, 2006)

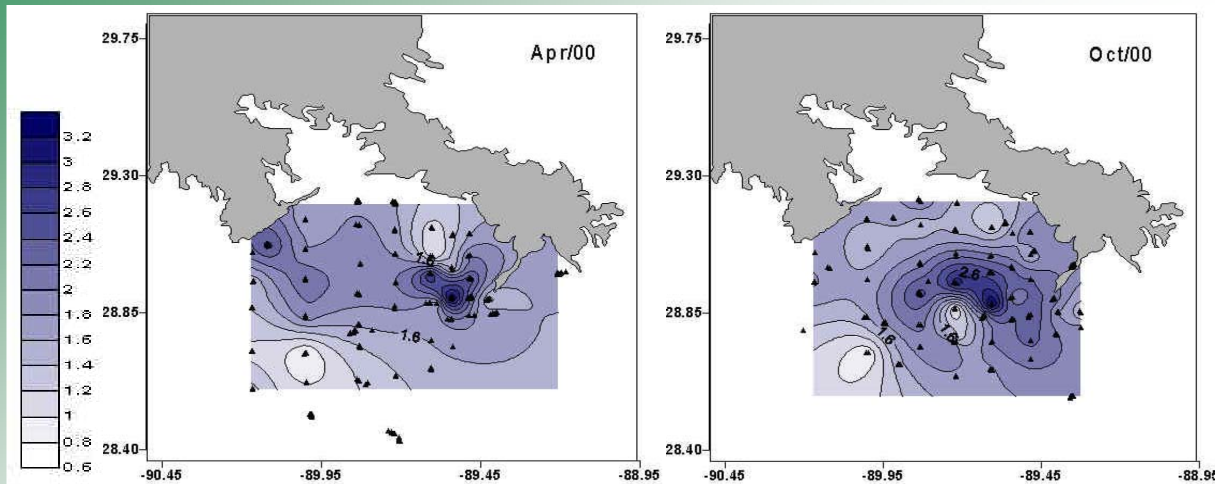
Louisiana Shelf Benthos

TABLE 2. Community biomass at the location studied (Fig. 1). Number of replicates are in parentheses.

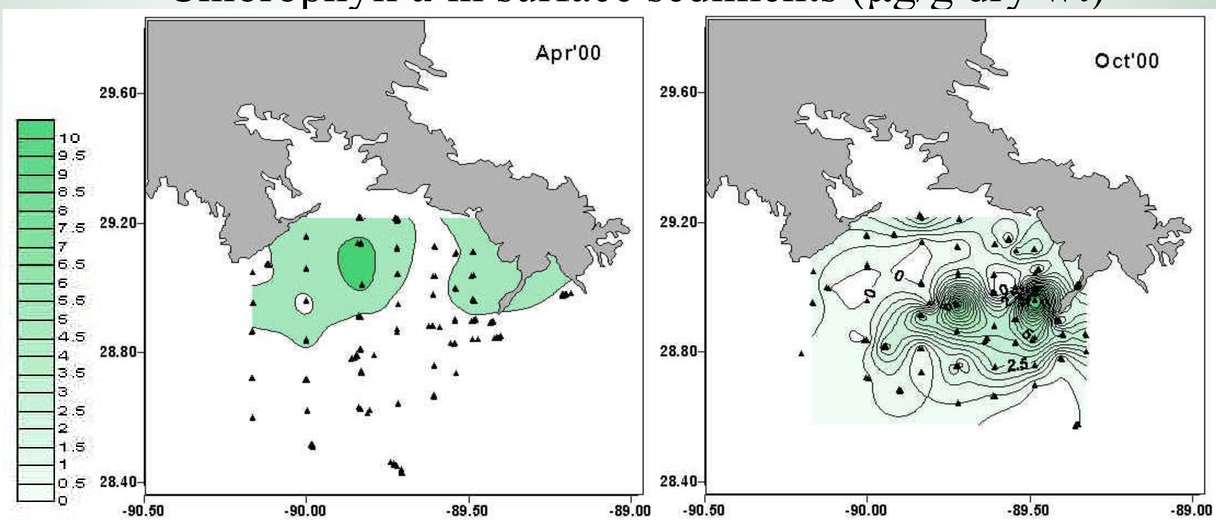
Sites and Dates	Macrofauna ($g\ C\ m^{-2}$)	Meiofauna ($g\ C\ m^{-2}$)	Bacteria ($g\ C\ m^{-2}$ 8 cm depth)	Total Biomass ($g\ C\ m^{-2}$)
July 1991				
C6A (1)	0.68	1.1	2.67	4.45
C6B (1)	0.16	0.43	7.12	7.71
C7 (1)	0.56	0.76	30.49	31.81
D2 (1)	0.11	0.21	22.22	22.54
Mean biomass	0.38 ± 0.29	0.66 ± 0.34	15.6 ± 12.9	16.7 ± 12.9
April 1991				
GC1	0.23 ± 0.62 (4)	0.37 ± 0.08 (2)	1.67	2.3
4	0.01 ± 0.01 (3)	0.55 ± 0.51 (2)	4.18	4.7
C6A	1.24 ± 0.7 (3)	0.55 ± 0.3 (2)	1.72	3.5
D2	0.49 (1)	0.07 ± 0.03 (2)	1.85	2.4
Mean biomass	0.49 ± 0.54	0.38 ± 0.23	2.36 ± 1.22	2.81 ± 0.99
August 1994				
1	0.19 ± 0.18 (3)	—	2.81 ± 1.1 (3)	3.4
2	0.20 ± 0.18 (3)	—	3.41 ± 1.1 (3)	3.7
3	0.11 ± 0.07 (3)	—	3.8 ± 1.1 (8)	4.0
4	0.12 ± 0.1 (3)	—	2.6 ± 1.3 (8)	2.8
C6B	0.04 ± 0.01 (3)	—	1.7 (1)	1.8
Mean biomass	0.15 ± 0.1	0.09 ± 0.1	3.1 ± 0.9	3.1 ± 0.9

Rowe et al. (2002)

Ad/Al ratios in surface sediments



Chlorophyll *a* in surface sediments (μg/g dry wt)



April
range: 0 – 2 μg/g
mean: 0.44 ± 0.09

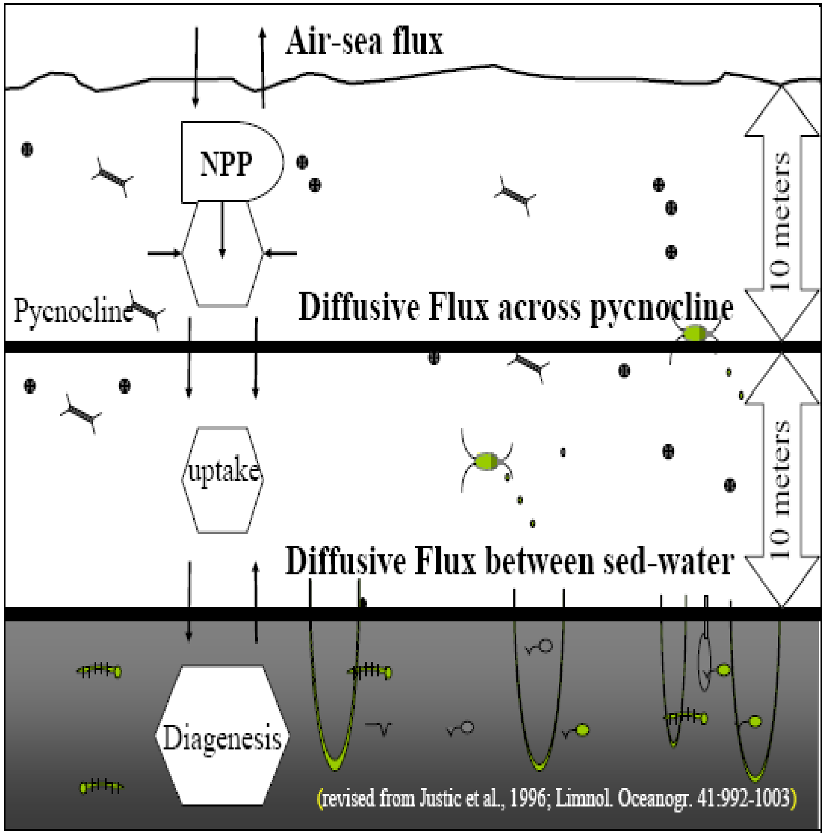
October
range: 0– 12 μg/g
mean: 1.75 ± 0.67

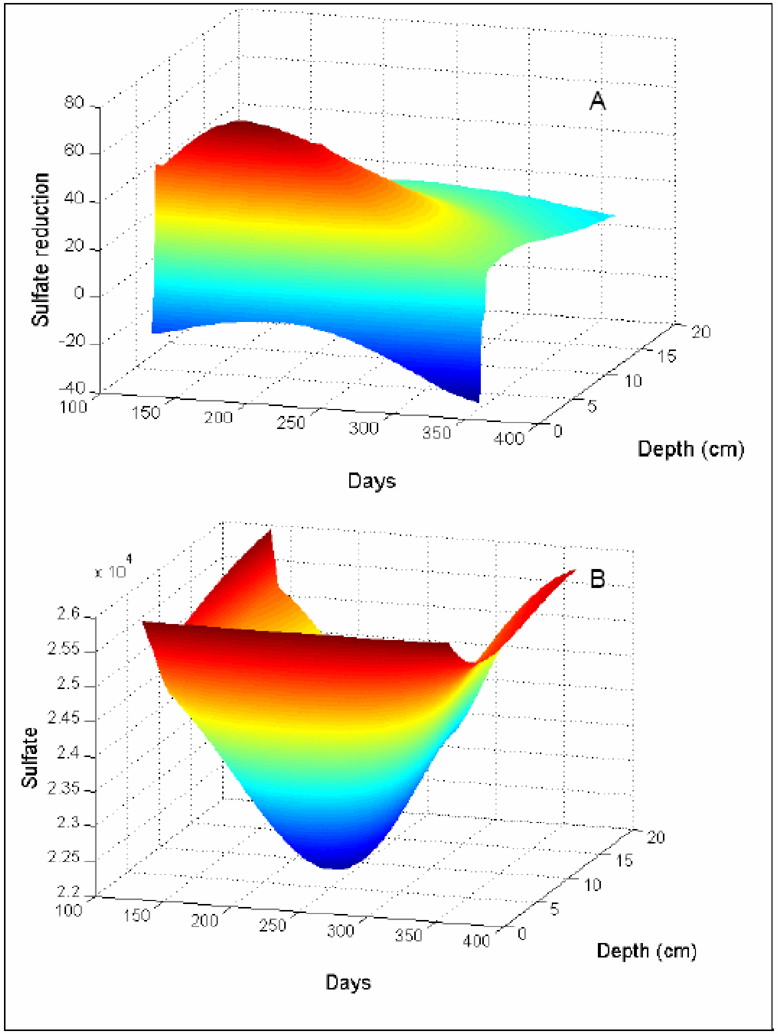
Wysocki et al. (2006)

Co-metabolism: the set of processes whereby refractory organic material (e.g. terrestrial OC) is broken down more efficiently when mixed with labile material (e.g. marine OC),via higher microbial turnover rates

Lohnis (1926); Canfield (1993); Aller (1998)

Benthic Respiration in the Hypoxic Zone





Eldridge and Morse (2008)

Low concentrations and/or absence of H_2S in the Louisiana Shelf waters?

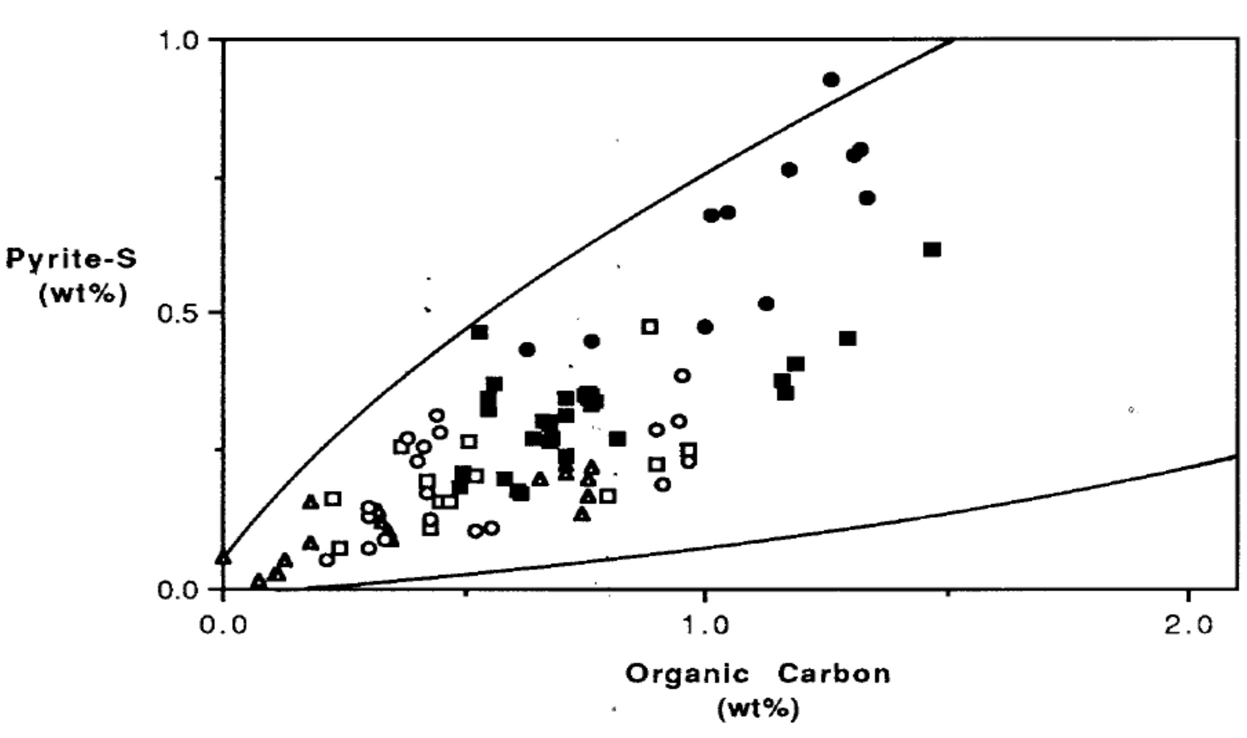


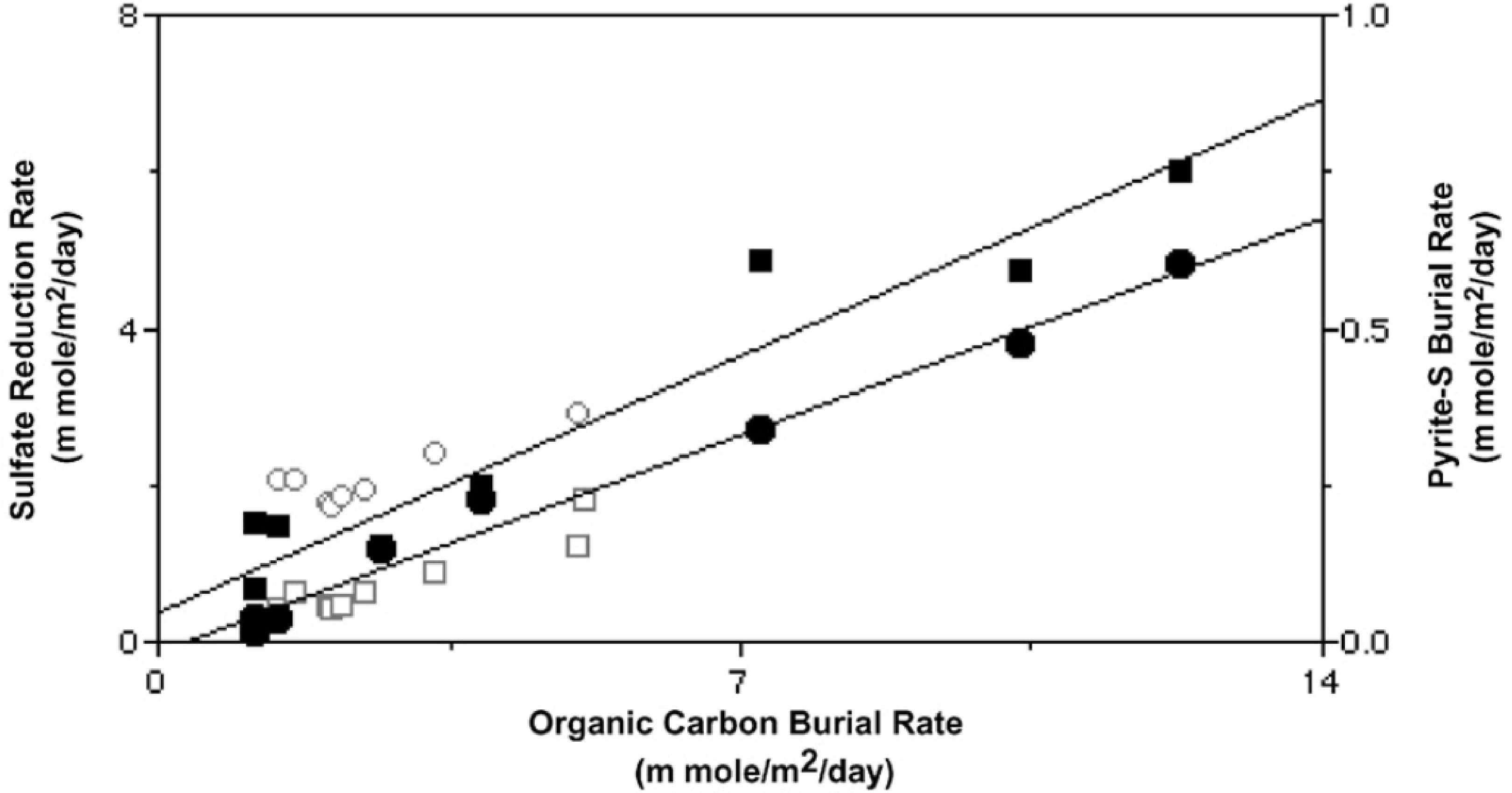
Fig. 11. Relationship between pyrite-S and organic carbon in sediments (Mississippi River delta-shelf-slope (●), Texas-Louisiana continental shelf-slope (■), western (○), south-western (▲), and southern (□) Gulf of Mexico sediments. The dashed lines represent a C/S ratio envelope of 2.8 ± 0.8.

Lin and Morse (1991)

High rates of pyritization expected in RiOMars, due to high sediment/metal (Fe) loading, where H_2S in pore waters reacts with Fe minerals to produce pyrite (FeS_2).

Of the total pyrite deposition in Gulf of Mexico sediments (ca. 6 x 10^{11} g y^{-1}), about 81% is deposited in Texas-Louisiana continental shelf sediments and about 15% in the Mississippi River delta sediments.

Other RiOMar systems like the East China Sea also have high rates of pyrite-S burial (Lin et al., 2002)



Rapid Transport of Labile Shelf-Derived Organic Matter to the Mississippi River Canyon

Spatial Variability of Surface Depositional Processes

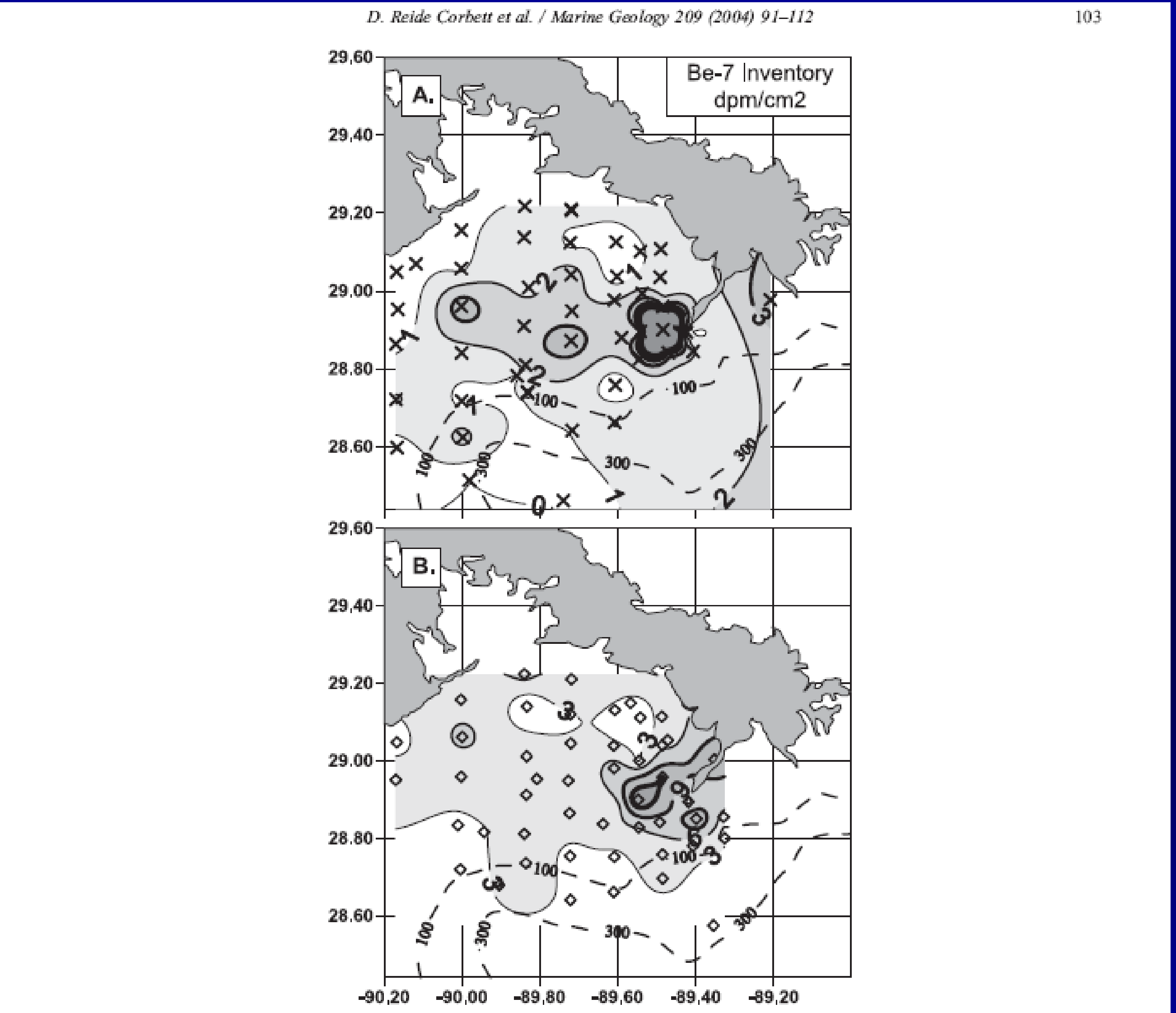
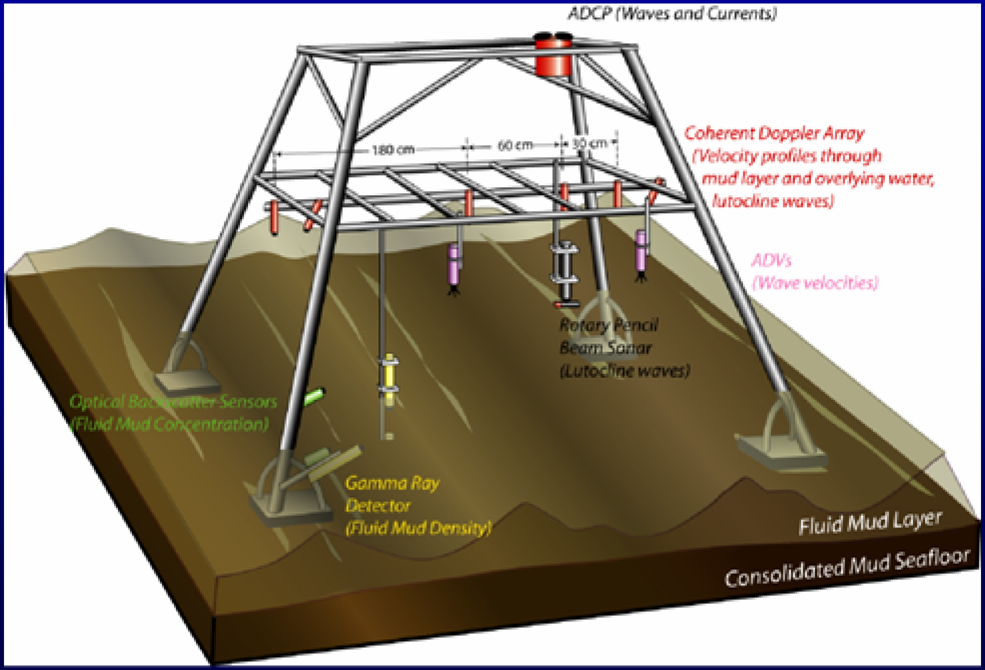


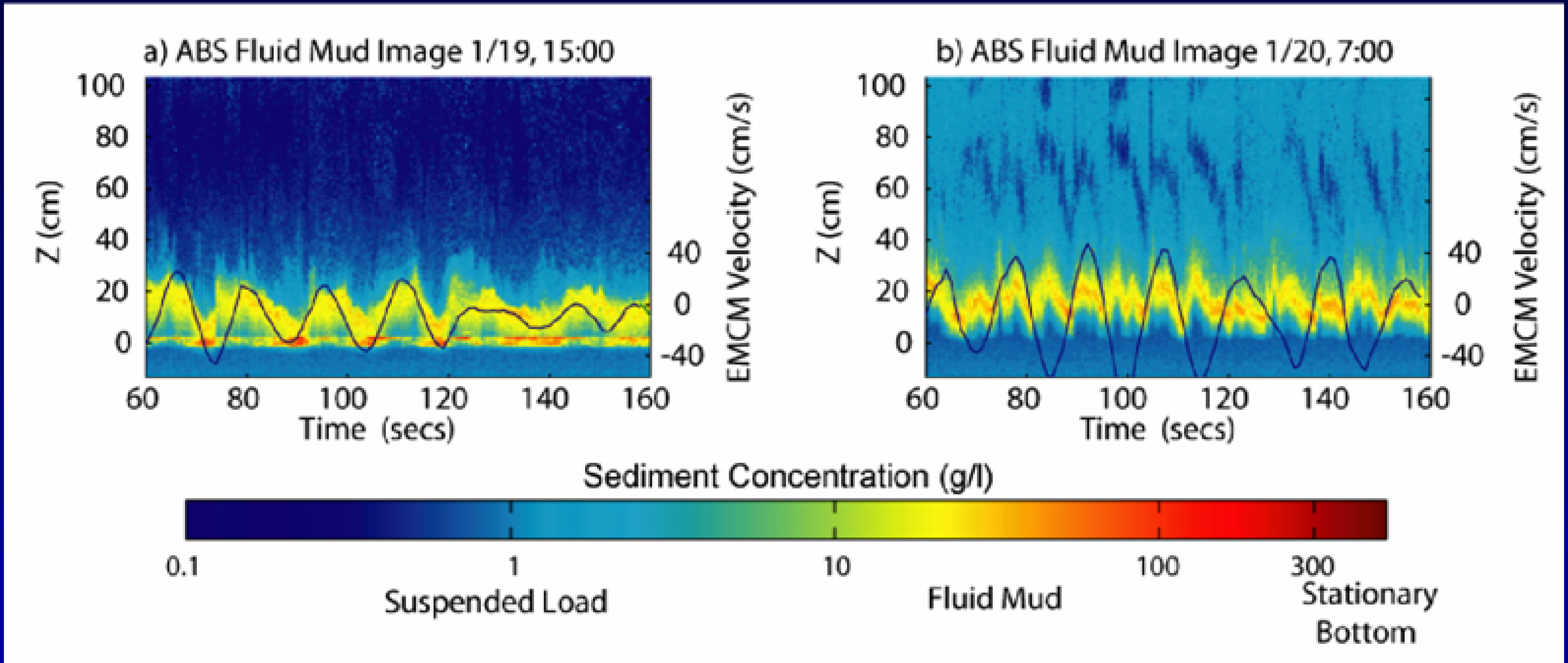
Fig. 6. Spatial distribution of the ^{7}Be inventory demonstrates the importance of the river as its source and the potential of sediment remobilization during the winter. Inventories are shown for MiRIR I (A) and II (B) in dpm cm^{-2}. The apparent bull's eye in the near river contour during both cruises is due to exceedingly high inventories (>10 dpm cm^{-2}) in several near river stations.

Corbett et al. (2004)

Mobile/Fluid Muds

(Traykovski, 2000)

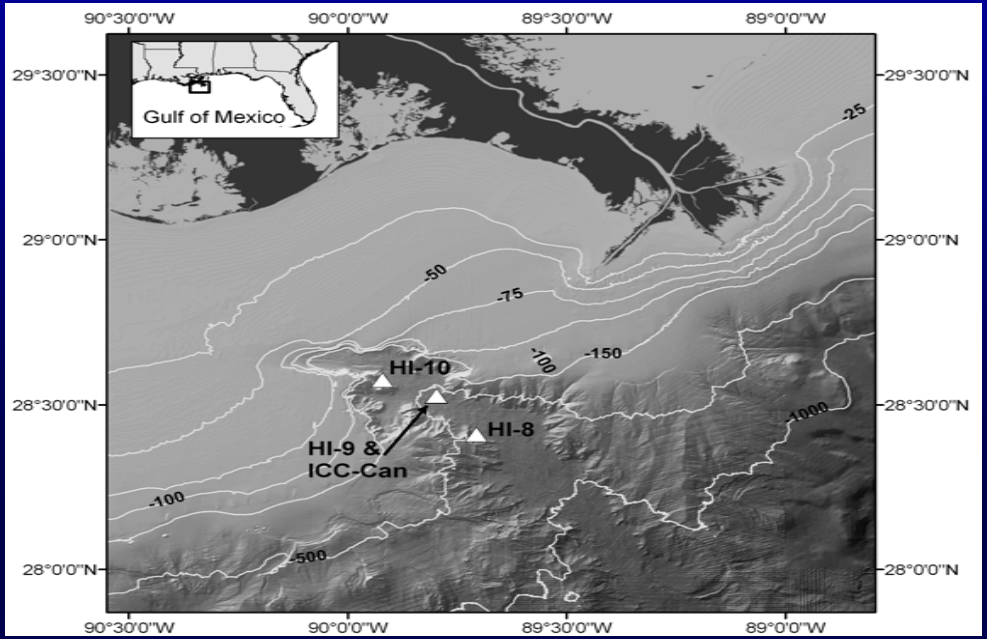


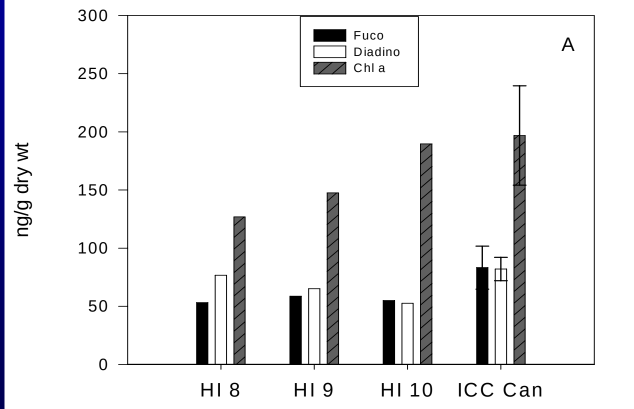


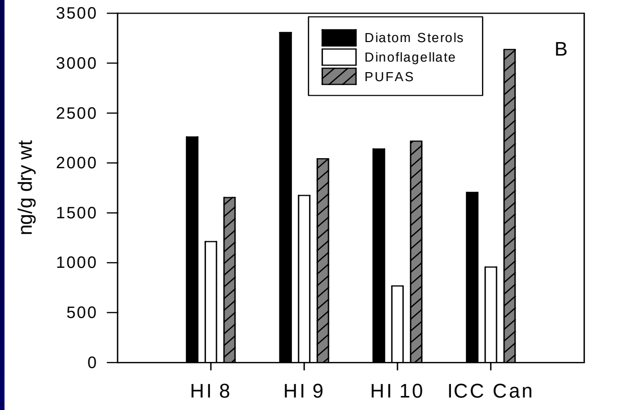
Gulf of Mexico Basin

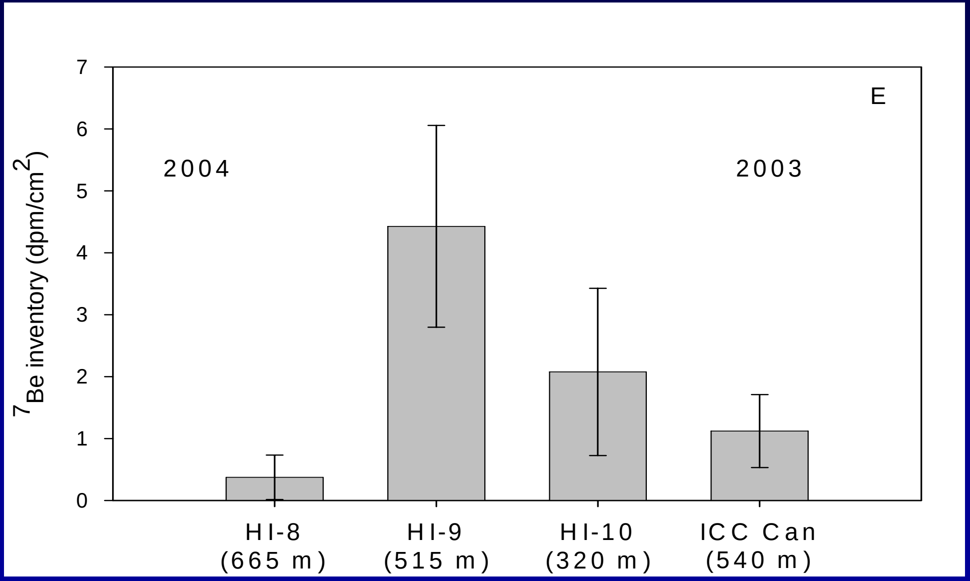
Rapid Export of Organic Matter from the shelf to the Mississippi Canyon

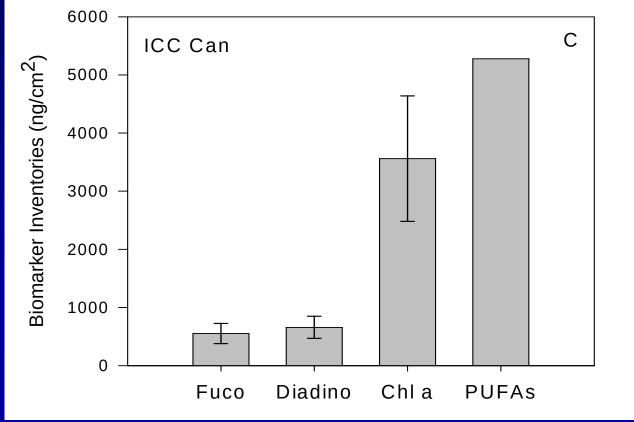
Bianchi et al. (2006)



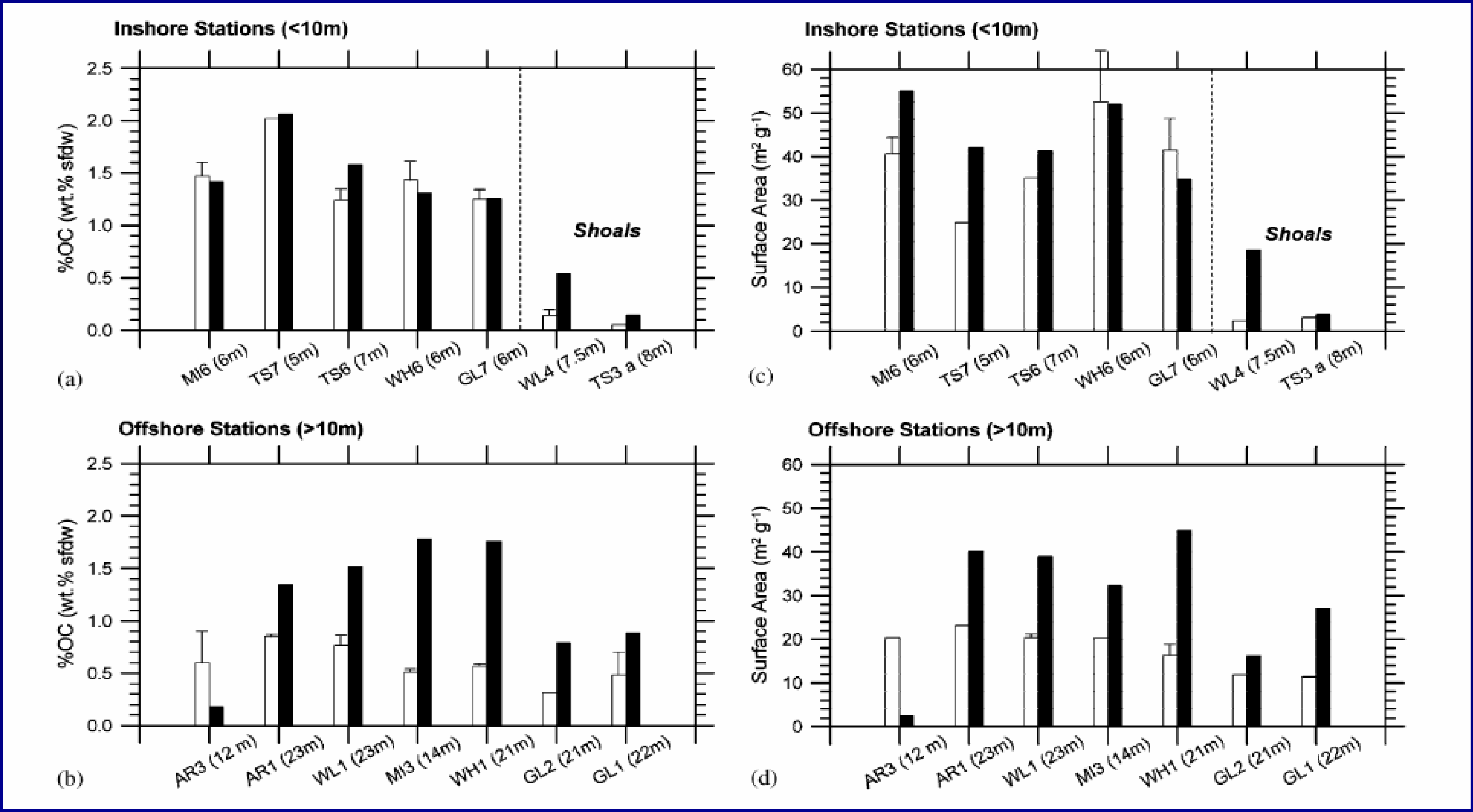








Effects Hurricane Lili on Organic Matter Distribution



Goni et al. (2006)

The Proposed Management Plan

Ecological Response from Nutrient Reductions in a “Well-Studied” Estuary

- *Published Monday, December 17, 2007 7:13 AM*

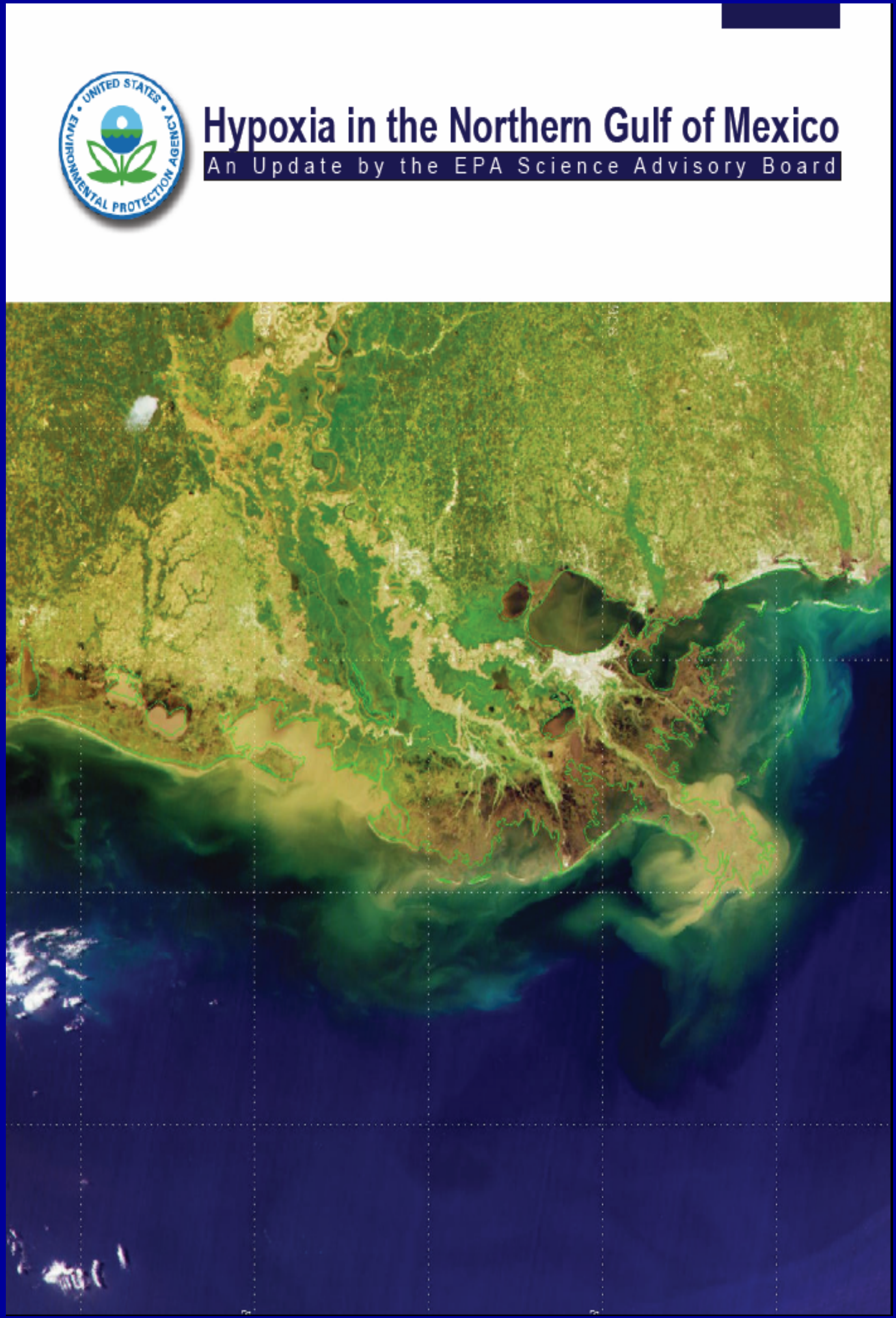
- ***'Save the Bay' effort fails in Chesapeake***
- *Wire Report*

- *ANNAPOLIS, Md. -- Billions of dollars have been spent to restore the polluted Chesapeake Bay since the rallying cry "Save The Bay" was plastered on a popular blue-and-white bumper sticker 30 years ago.*

- *The Bay foundation has given the bay a "D" grade for the ninth consecutive year.*

In 2001, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force Action Plan (Action Plan) for Reducing, Mitigating, and Controlling Hypoxia in the northern Gulf of Mexico (GOM), used a five-year running average to suggest a projected environmental goal of 5,000 km^2 be reached by 2015, whereby a 30% reduction in total riverine nitrate flux.

More recently, the Science Advisory Board (SAB) of the U.S. Environmental Protection Agency Advisory plan for hypoxia in the Northern Gulf of Mexico (2007) also agreed that proposed a 5,000 km^2 be reached, but that a 45% reduction in riverine total N and P fluxes be made as incremental annual reductions over time.



Recent estimates have shown that a 30% reduction in riverine nitrate flux would only result a 19% average reduction in plume primary productivity and 16% in sedimentation rate (Green et al., 2008)

Predicting Hypoxia in the GOM

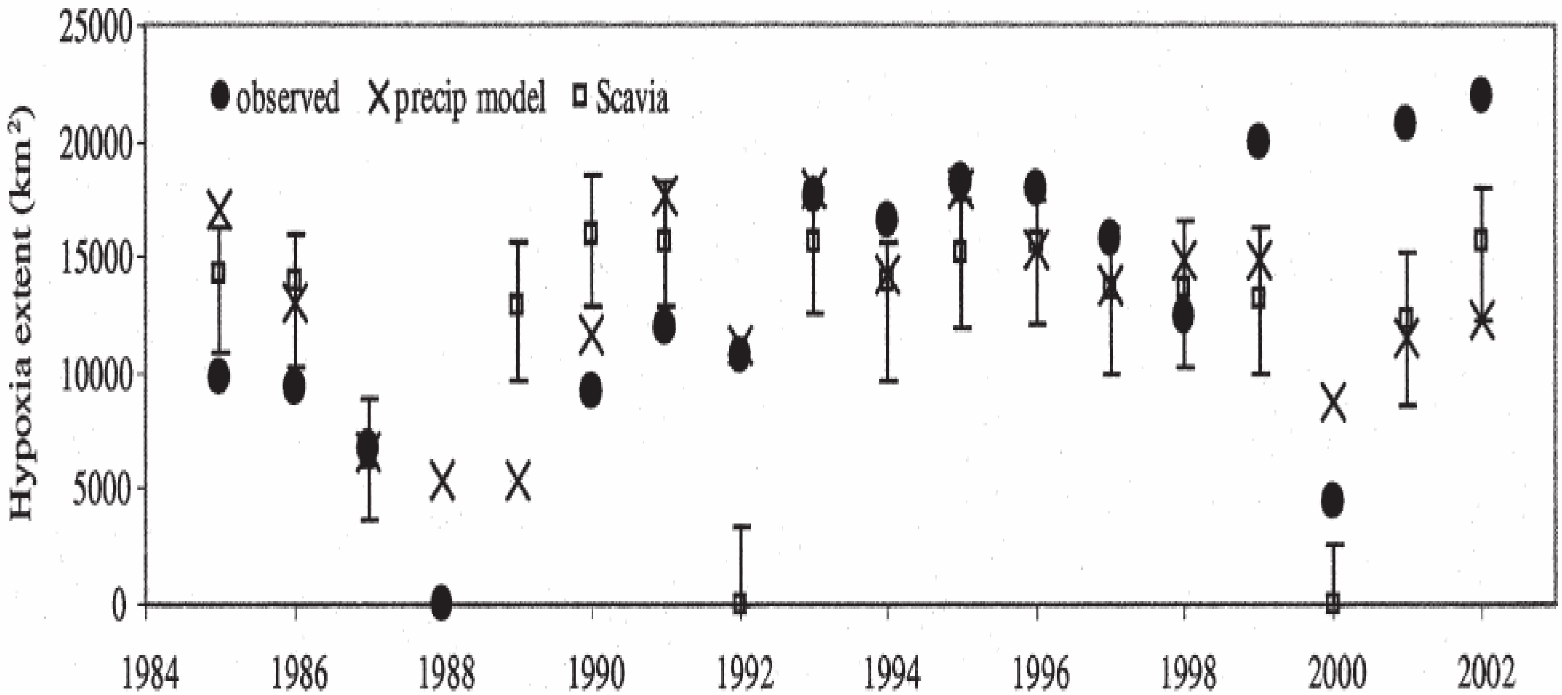
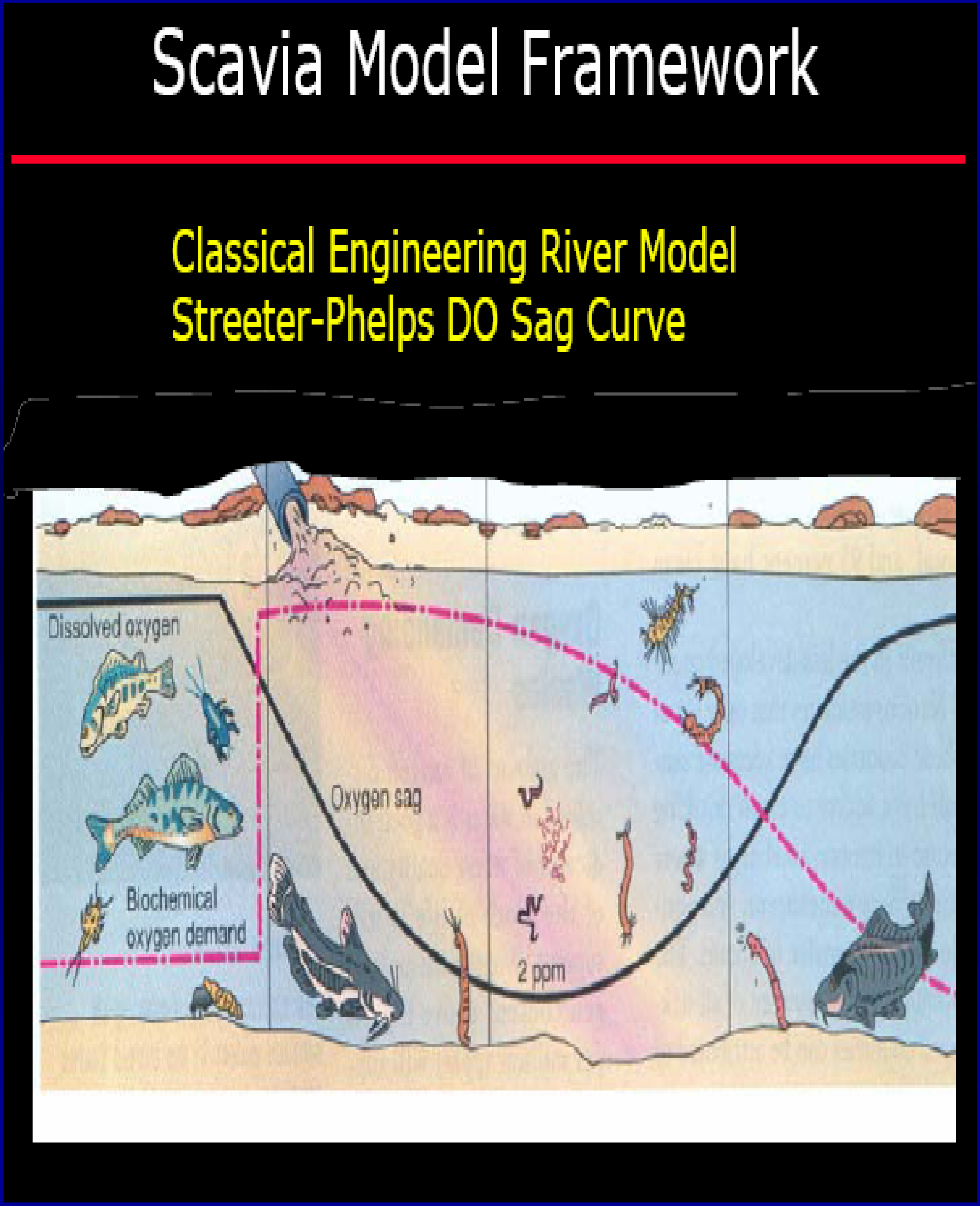


Fig. 4. Predicted and observed extent of seasonal hypoxia from 1985 to 2002. Scavia refers to the result from Scavia et al. (1993); error bars represent the range between the results for first and third quartiles. The model predicts no hypoxic zone in 1988 and 1994. The precipitation model is based on the N–D precipitation, the M–M precipitation, and the previous year's May–August nitrate flux.

Donner and Scavia (2007), as modified from Scavia et al. (1993) – Simple model, essentially based on nitrate flux and an "advective drift term," to predict hypoxic zone size.



Serious Flaws with this Simple Model

1. Uses "advective" term, for westward drift along Louisiana coast from DiMarco et al (1997), that is essentially zero, because of high seasonal variability.

2. Changes "advective" term each year to "fit" the size the hypoxic area each, essentially "tuning" the model good.

3. Assumes a "river-like" westward flow along the coast – based on simple 1D steady-state.

4. Using such a small advective term it would take a year to move the water the full extent of the hypoxic zone.

Are the simple river-centric nutrient models that predict hypoxia on the Louisiana shelf an example of Occam's razor being too sharp?

Saving wetlands or reducing the hypoxic zone: Truth or Consequences?

Figure 6: Proposed diversions of Mississippi effluents for coastal protection. From Coastal Protection and Restoration Authority (CPRA) of Louisiana, 2007 Integrated Ecosystem Restoration and Hurricane Protection: Louisiana's Comprehensive Master Plan for a Sustainable Coast. CPRA, Office of the Governor (La) 117 pp.

Based on sediment cores, it was concluded that "additional nutrient loading from river diversion projects for the lower Mississippi River, may exacerbate eutrophication already in the marsh environment." Parson et al. (2006)

General Conclusions

- Are N and P reductions needed in the Mississippi River?
- Has hypoxia worsened over the past 2 decades?
- Are there unequivocal results showing the negative effects of hypoxia and regime shifts in the northern GOM?
- Are nutrient management issues in RiOMars different from traditional semi-enclosed estuaries?
- Are all shelf environments less vulnerable to hypoxia?
- Has the emphasis on "simple models" in nutrient reduction estimates suffered from the general principle of Occam's Razor?
- Have political issues obfuscated our objective knowledge of research on hypoxia in the northern GOM?

Using three parameters to define each end-member – total lignin as Λ (mg lignin 100mg OC^{-1}), N/C ratio, and $\delta^{13}C$ – the proportional contributions were calculated as follows:

$$\delta^{13}C\ sample = (\delta^{13}C_{mar} * OC_{mar}) + (\delta^{13}C_{marsh} * OC_{marsh}) + (\delta^{13}C_{river} * OC_{river}) \qquad (Eq.\ 1)$$

$$\Lambda\ sample = (\Lambda_{mar} * OC_{mar}) + (\Lambda_{marsh} * OC_{marsh}) + (\Lambda_{river} * OC_{river}) \qquad (Eq.\ 2)$$

$$N/C\ sample = (N/C_{mar} * OC_{mar}) + (N/C_{marsh} * OC_{marsh}) + (0.033 * OC_{river}) \qquad (Eq.\ 3)$$

	$\delta^{13}C$	Λ	N/C
marine	-19.50‰ [1]	0.00	0.15[2]
marsh	-17.89‰ [3]	4.30[4]	0.06[4]
mean river	-24.78‰ [5]	1.35[5]	0.10[5]
spring river	-25.13‰ [5]	1.40[5]	0.10[5]
fall river	-24.06‰ [5]	1.19[5]	0.11[5]

[1] *Eadie et al, 1994*
[2] *Redfield values; C/N = 6.6*
[3] *J. Willis, LSU; personal communiction*
[4] *samples analyzed for this study*
[5] *Bianchi et al, 2007b*

Wysocki et al. (submitted)

where,
OC_{mar} is the proportion of OC that is derived from marine organic matter, OC_{marsh} is the proportion derived from marsh OM, and OC_{river} is the proportion that is derived from riverine OM.