FINAL DRAFT

RECOMMENDATIONS

ON FUTURE

MONITORING, MODELING, AND RESEARCH NEEDS

TO ADDRESS

HYPOXIA IN THE NORTHERN GULF OF MEXICO

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ABSTRACT

Scientific investigations in the Gulf of Mexico have documented a large area of the Louisiana-Texas continental shelf with seasonally-depleted oxygen levels (hypoxia). Nutrient over-enrichment from the Mississippi and Atchafalaya River Basins and stratification in coastal waters are believed to be the major factors contributing to over-production of phytoplankton in the Gulf and the resulting hypoxia. In January 2001, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force adopted the *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (*Action Plan*) to address this phenomenon. The Environmental Protection Agency (EPA) has reviewed previous studies supporting conclusions in the *Action Plan* in order to determine more effective ways to target efforts to reduce nutrient loads into the Mississippi River and Gulf of Mexico. The available Gulf hypoxia data and related scientific literature support the hypothesis that, for waters subjected to nitrogen and phosphorus loads significantly above historic background levels, there may be considerable benefit to reducing both nutrients in order to restore water quality in the northern Gulf of Mexico. While the *Action Plan* calls for appropriate voluntary action to address nitrogen loading, additional emphasis should be placed on reducing phosphorus loads as well. A balanced approach to reducing both nutrients will support achieving the second goal of the *Action Plan* – to restore water quality throughout the Mississippi River Basin. In addition, reducing phosphorus may significantly contribute to reducing the areal extent of the hypoxic zone by reducing initial biomass production in the early regions of mixing between the freshwaters of the Mississippi River and the marine waters of the Gulf. In order to better support management decisions in the future and to elucidate the relative importance of the various nutrients in contributing to the formation and extent of hypoxia in the northern Gulf, EPA provides specific recommendations on critical monitoring, modeling, and research needs that should be considered as a key element in the five year reassessment called for in the *Action Plan.*

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INTRODUCTION

Scientific investigations in the Gulf of Mexico have documented a large area of the Louisiana-Texas continental shelf with seasonally-depleted oxygen levels (hypoxia). Nutrient over-enrichment from the Mississippi and Atchafalaya River Basins and stratification in coastal waters are believed to be the major factors contributing to over-production of phytoplankton in the Gulf and the resulting hypoxia. In January 2001, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force adopted the *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (*Action Plan*) to address this phenomenon. The Environmental Protection Agency (EPA) has reviewed previous studies supporting conclusions in the *Action Plan* in order to determine more effective ways to target efforts to reduce nutrient loads into the Mississippi River and Gulf of Mexico.

One of the conclusions of this review was that a significant quantity of primary productivity (algal growth) in the Gulf that contributes to hypoxia occurs in the spring and that the Northern Gulf of Mexico has experienced significant increases in nitrogen and phosphorous concentrations since 1960. An analysis of the data available suggests that *in addition to controlling nitrogen*, opportunities may exist to address phosphorus loadings as a cost-effective means of reducing the areal extent of the hypoxic zone. This view is based on a conclusion that the lower Mississippi River has high dissolved inorganic nitrogen to dissolved inorganic phosphorus (DIN/DIP) ratios during high spring flows and is, therefore, not in "Redfield Ratio" balance.

APPROACH

Available information was reviewed, including relevant hypoxia literature, analyses of U.S. Geological Survey (USGS) data for the Lower Mississippi River and the Lower Atchafalaya River, analysis of data that had been collected under the Nutrient Enhanced Coastal Ocean Productivity (NECOP) Program; and review of the existing model used for predicting hypoxia reductions in the Gulf.

Data were analyzed from four key monitoring stations (Figure 1):

(1) The USGS Belle Chasse water quality station is located at River Mile 76, approximately 10 miles below New Orleans. The USGS Belle Chasse water quality station is located below all the major cities on the river and below all the major point source discharges. There are useful water quality nutrient records at Belle Chasse starting in 1981. Unfortunately, this station was partially terminated in the early 1990s and water quality records subsequent to that time are sporadic. Due to the paucity of other reliable water quality data from below New Orleans in recent years, the recent USGS Belle Chasse data was included in the analyses.

(2) The Tarbert Landing water flow monitoring station located at river mile 306 just below the Old River Outlet. There are no major streams entering the Mississippi River below this station and the recorded flows are a reasonable approximation of the flows in the Lower Mississippi River from St. Francisville to Head of Passes.

(3) The USGS station at Morgan City, LA provided water quality data for the lower Atchafalaya River at a point near where the river discharges into the coastal waters of the Gulf, approximately 80 miles southwest of New Orleans River.

(4) The Army Corps of Engineers (ACOE) water flow monitoring station at Simmesport, LA provided flow records for the Atchafalaya River.

Waters flowing past the Belle Chasse and Morgan City stations transport essentially all the suspended and dissolved constituents from the entire Mississippi River Basin. EPA then calculated the nutrient loads for DIN and DIP, and the resultant DIN:DIP elemental ratios for the Lower Mississippi River and the Atchafalaya River.

River loadings were calculated using FLUX. FLUX is an interactive program designed for use in estimating the loadings of nutrients or other water quality components passing a tributary sampling station over a given period of time. These estimates can be used in formulating reservoir nutrient balances over annual or seasonal averaging periods appropriate for application of empirical eutrophication models. Data requirements include (a) grab-sample nutrient concentrations, typically measured at a weekly to monthly frequency for a period of at least 1 year, (b) corresponding flow measurements (instantaneous or daily mean values), and (c) a complete flow record (mean daily flows) for the period of interest. Using six calculation techniques, FLUX maps the flow/concentration relationship developed from the sample record onto the entire flow record to calculate total mass discharge and associated error statistics. An option to stratify the data into groups based upon flow, date, and/or season is also included. In many cases, stratifying the data increases the accuracy and precision of loading estimates. Uncertainty is characterized by error variances of the loading estimates (Walker, 1999).

Figure 1. Lower Mississippi River and the Lower Atchafalaya River Basin

RESULTS

The annual average FLUX-calculated mass transport loads for DIN and DIP at Belle Chasse are 2,017 and 114 metric tons per day (mt/d), respectively. The average measured DIN concentration at Belle Chasse during the period 1980 to 1999 was approximately 1.6 mg/L (Table 1), which is equivalent to 114 µM DIN. Dortch, et al. (1994), indicated that 1.0 µM DIN was the lowest DIN concentration that phytoplankton were capable of extracting from seawater. Therefore, the LMR is providing DIN to the Gulf at a concentration approximately 114 times the minimal concentration necessary to sustain the growth of phytoplankton in a coastal environment. This assumes that light and other nutrients are not limiting the phytoplankton growth.

Table 1. Mean Chemical Concentrations at Belle Chasse USGS Monitoring Station 1980 - 1999

Parameter Name	Units	Mean
DIN	mg/L	1.53
P_ORTHO	mg/L	0.09

The average DIP concentration at Belle Chasse during the period 1980 to 1999 was approximately 0.09 mg/L. (Table 1). This is equal to approximately 2.9 µM DIP. Dortch, et al. (1994), stated that 0.2 µM was the lowest concentration that phytoplankton were capable of extracting DIP from seawater. Therefore, the LMR is providing DIP at a concentration approximately 15 times the concentration necessary to sustain the minimal growth of phytoplankton in a coastal environment.

The annual average FLUX calculated mass transport loads for DIN and DIP at Morgan City are 612 mt/d and 28 mt/d, respectively. The average DIN concentration during the period 1992 to 1999 was approximately 1.0 mg/L or 71 µM (Table 2). Therefore, the ARB is transporting DIN at approximately 71 times the concentration necessary to sustain the minimal growth of phytoplankton in a coastal environment. The annual average phosphate concentration during the period 1980 to 1999 was approximately 0.06 mg/L or approximately 1.8 µM. The ARB is transporting phosphate to the Gulf at approximately nine times the concentration necessary to sustain the minimal growth of phytoplankton in a coastal environment.

Table 2. Mean Chemical Concentrations at Morgan City USGS Monitoring Station 1980 - 1999

Parameter Name	Units	Mean
DIN	mg/L	1.00
P_ORTHO	mg/L	0.06

DIN and DIP Elemental Ratios in the LMR and ARB

DIN and DIP average concentrations were calculated using the FLUX program for the period of 1980 to 1999. The average elemental ratios for DIN/DIP are especially high at Belle Chasse and Morgan City during the spring (February to June) when the river flows are high (Figure 2). The high ratios indicate that large quantities of bio-available nitrogen relative to bio-available phosphorus are transported to the Gulf during the high spring river flows. The elemental ratios during the spring deviate from the Redfield proportions (16:1) by a factor of approximately 3 (Table 3). Lohrenz et al. (1999), also reported very high elemental ratios in the LMR and found that the high ratios were strongly correlated with high flows.

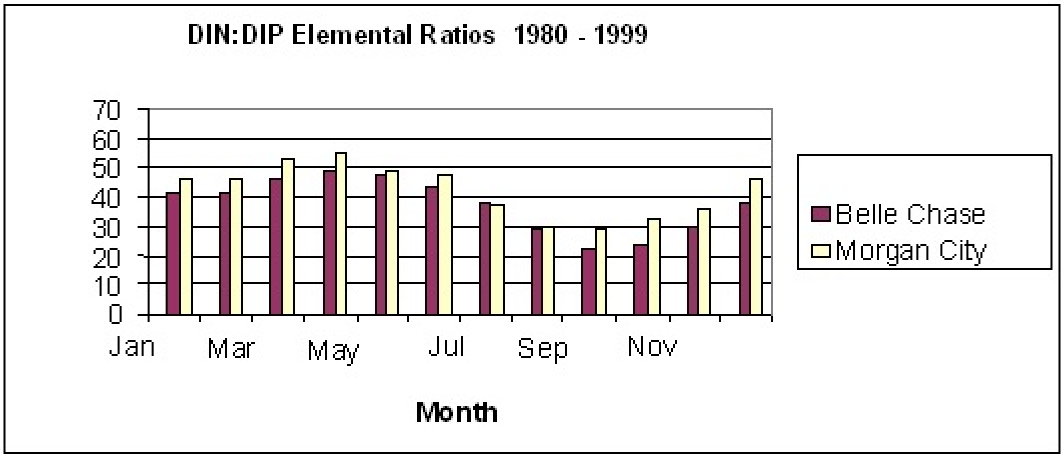

Figure 2. Average Monthly DIN/DIP ratios for Belle Chasse and Morgan City 1980 to 1999

Table 3. Annual Average and Spring Time DIN:DIP Elemental Ratios

	Belle Chasse	Morgan City	Average
Annual Average DIN:DIP Elemental Ratio	37	42	39.5
Spring Average DIN:DIP Elemental Ratio	47	52	49.5

DISCUSSION

The Lower Mississippi/Atchafalaya River system (MARS) discharges an average of 952,700 metric tons of nitrogen as nitrate each year (CENR Report 3) Goolsby, et al., 1999). Nitrate concentrations and mass flow are generally highest during the spring and early summer. Dortch and Whitledge (1992) considered that concentrations equal to or less than 1.0 micro-molar dissolved inorganic nitrogen were potentially limiting for phytoplankton growth. The MARS discharges an average of 41,770 metric tons annually of phosphorus as orthophosphate (Goolsby et al. 1999). Dortch and Whitledge (1992) determined a 0.2 micro-molar phosphorus concentration as a threshold for potential limitation of phytoplankton growth by phosphorus. EPA shipboard surveys (R. Greene, unpublished data) of nutrient concentrations near the mouth of the Mississippi River (Figure 3), revealed near surface DIN and DIP concentrations during June 2003 in excess of the above threshold values.

Figure 3. Surface DIN and DIP monitoring stations for the EPA survey conducted during June 2003.

Both nitrogen and phosphorous concentrations have increased significantly in the Lower Mississippi River and Northern Gulf of Mexico from 1960 to 1987 (Table 4)(Rabalais (1996) and Justic(1995)). The Mississippi River and the Northern Gulf of Mexico are both over-enriched with respect to nitrogen and phosphorous. Such over-enriched waters will likely require reductions in both nitrogen and phosphorous loads to achieve the desired levels of biomass production.

It is readily apparent that these rivers, during the spring and early summer, provide large nitrogen and phosphorus loads to the Gulf of Mexico. Uptake and elemental composition of nitrogen and phosphorus in phytoplankton in the open ocean are usually near the Redfield ratio of 16:1 measured as DIN: DIP (Redfield, 1958). Correll (1998) discusses conditions where DIN/DIP ratios can deviate significantly from the Redfield ratio.

During the spring and early summer in waters influenced by the Mississippi River, ratios of ambient concentrations of DIN: DIP have often been found to be much higher than the Redfield ratio (Lohrenz et al. 1999, Ammerman, et al. 1992, Chen, 2000, Smith and Hitchcock, 1994, Dortch et al. 1992, Nelson 2003, (personal communication), and Dortch 2003 (personal communication).

Table 4. Comparison of nutrient concentration changes in the Mississippi River and Northern Gulf of Mexico. Data from Table 5.1 of the Hypoxia Characterization report (1999).

Nutrient Concentrations and Average A		**Mississippi River**		**Northern Gulf of Mexico**	
		1960–62[4]	***1981–87***	***1960***[5]	***1981–87***
Nutrient Concentrations (μM) tomic Ratios					
Nitrogen[1]	Mean	36.5	114	2.23	8.13
	No. of Data	72	200	219	219
	Standard Error	2.9	6.0 ($p < 0.001$)	0.16	0.60
Phosphorus[2]	Mean	3.9	7.7	0.14	0.34
	No. of Data	-	234	231	231
	Standard Error	-	0.4 ($p < 0.001$)	0.01	0.02
Silica[3]	Mean	155.1	108	8.97	5.34
	No. of Data	72	71	235	235
	Standard Error	7.5	4.3 ($p < 0.001$)	0.55	0.33
Average Atomic Ratios				4.0	0.7
Silica:Nitrogen		4.2	0.9		
Nitrogen:Phosphorus		9	15	16	24
Silica:Phosphorus		39.8	14	64	16

[1] $N\text{-}NO_3$ for the Mississippi River, dissolved inorganic nitrogen ($DIN = NO_3 + NH_4 + NO_2$) for the northern Gulf.

[2] Total P for the Mississippi River, reactive P for the northern Gulf of Mexico.

[3] Reactive Si.

[4] Turner and Rabalais 1991 for N and Si, reconstructed for P.

[5] Reconstructed data.

In order to determine the relative nutrient load reductions necessary to achieve a desired level of biomass production in the Hypoxic Zone a more in depth understanding of the hydrodynamic flow regime and nutrient cycling in the Gulf Hypoxic Zone is necessary. The Hypoxic Zone appears to behave more like a stream due to the prevailing Gulf currents and influence of the large Mississippi River and Atchafalaya River freshwater discharges. The stratification of the fresh and salt water downstream of the river discharges coupled with the enriched nutrient loadings at the eastern edge produce the longitudinal hypoxic zone profile. This system cannot be simplified as a completely mixed “bathtub” typically used to assess nutrient impacts on fresh water lakes. A more realistic hydrodynamic model would treat the Hypoxic Zone as a plug flow system. Such a system accounts for the concentration gradients in nutrients and biomass as the bulk water flow moves east to west. The biomass production, decay, and nutrient re-mineralization kinetics are concentration dependant and, therefore, will vary spatially in a plug flow system.

To illustrate this point, the following data from the July 1994 LATEX study (Figures 5-7) indicates that the Hypoxic Zone is initially phosphorous limited and the algal production is greatest in the eastern portion of the Hypoxic Zone, West longitude 89-90. The July 1994 LATEX data in Figure 6 clearly indicates that there is a pronounced east-west gradient in surface water algal biomass during this sampling period. This trend positively correlates with the nutrient concentration gradients presented in Figure 5. In addition, the ratio of surface-to-bottom algal pigment concentrations indicate that the eastern portion of the hypoxic zone is dominated by active surface algae and the western portion is dominated by decaying bottom algae (Figure 7).

Interestingly, the reactive ortho-phosphate concentrations appear to be relatively constant in the Hypoxic Zone downstream of the initial algal production zone (Figure 5).

From this data set it is not obvious what would happen under various nutrient load reduction scenarios. For example, if phosphate concentrations were reduced, there would likely be a reduction in the initial biomass production. However, it is likely that the excess nitrogen would be transported further downstream and would be available to produce more algae with the apparently recycled and “replenished” phosphates. Likewise reducing nitrogen alone would not have much of an impact on the initial algal production unless the reduction was sufficient to create a nitrogen-limited condition. However, reducing the nitrogen load would reduce the amount of excess nitrogen compounds transported downstream in the hypoxic zone that would be readily available to produce algal biomass. The net result of a 20-30% reduction in nitrogen loads would be a reduction in the total algal biomass produced in the Hypoxic Zone.

Unfortunately there is limited data both spatially and temporally for the entire Hypoxic Zone. It would be instructive to assess how the system biomass and nutrient gradients respond to seasonal variations. Most of the data collected seasonally in the Hypoxic Zone is focused in a particular zone and is summarized below.

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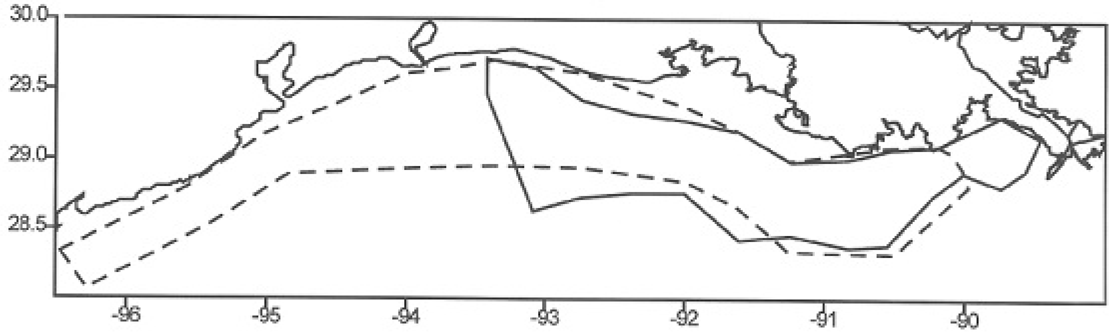
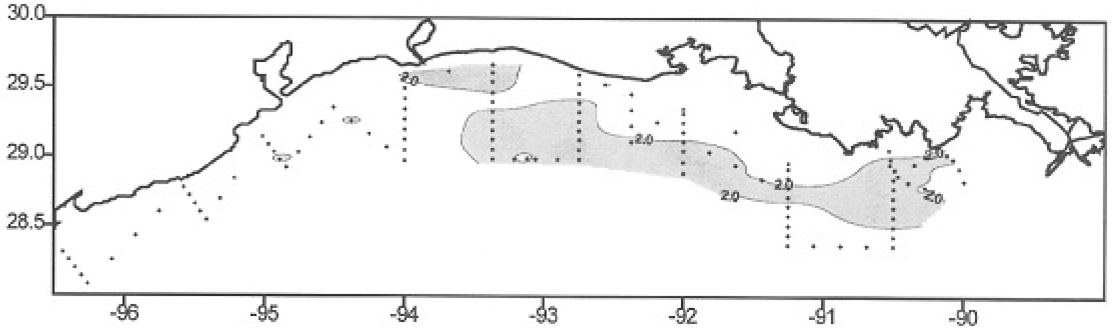


LATEX July 1994



NECOP July 1994

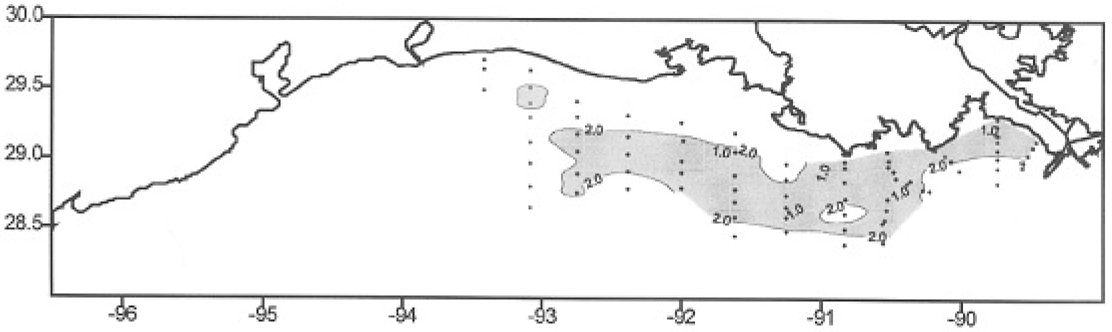


Figure 4. Location of the Sampling Points for the July 1994 LATEX Study and July 1994 NECOP Study.

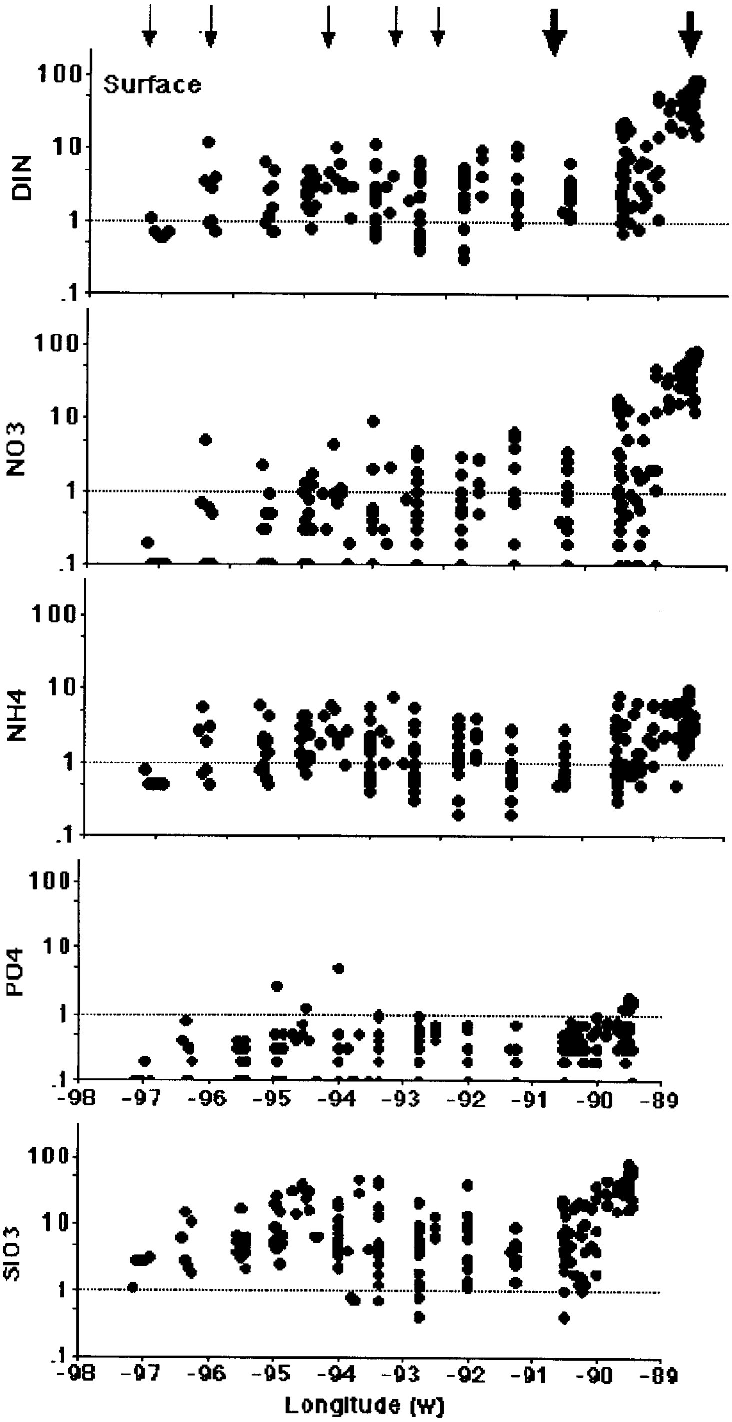


Figure 5. Concentration of dissolved inorganic nutrients (M) in surface waters at the LATEX sampling stations (Figure 4). Note: Total depth at these stations was 10-100 m. The arrows indicate the source and relative contributions of freshwater inputs. (From Rabalais and Turner 1998.)

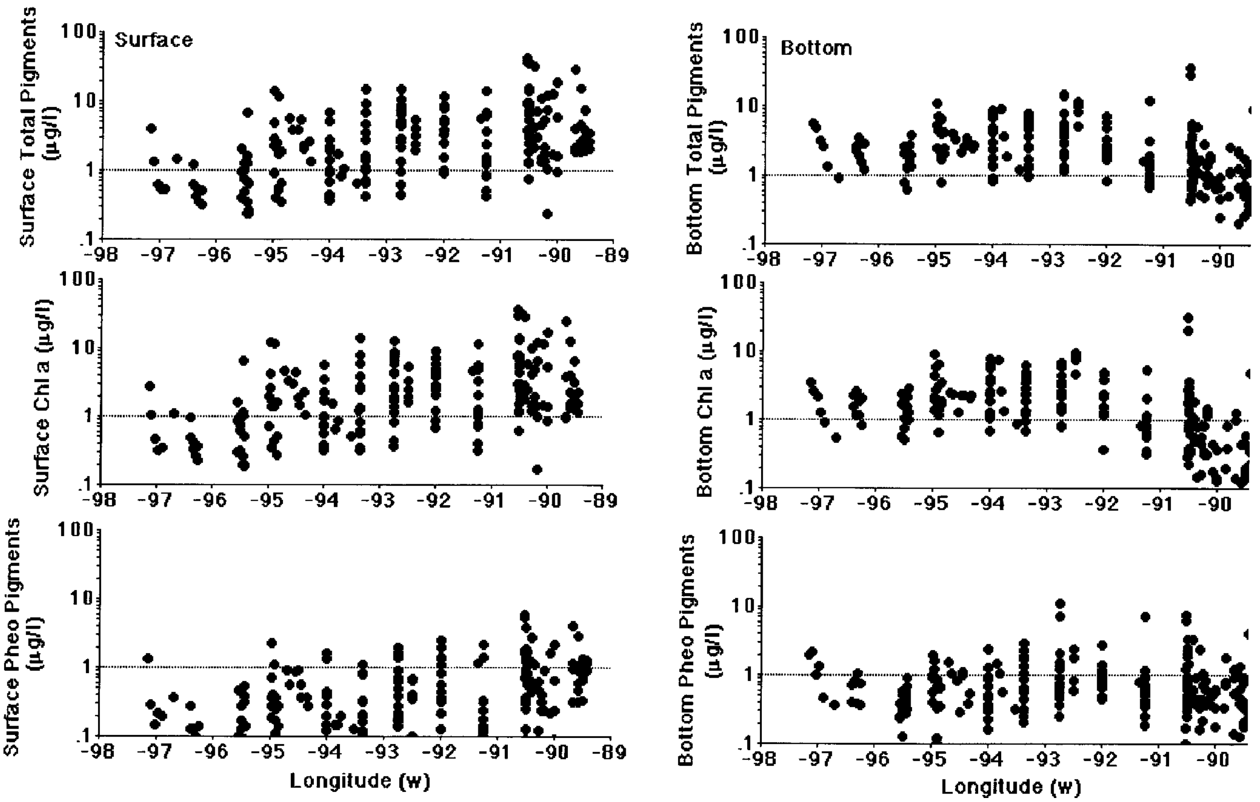


Figure 6. Relationship between the concentration of phytoplankton pigments (total, chlorophyll a, and phaeopigments (ug/l)) and longitude in surface and bottom waters at the LATEX sampling stations (Figure 3)). Note: Total depth at these stations was 10-100 m. (From Rabalais and Turner 1998.)

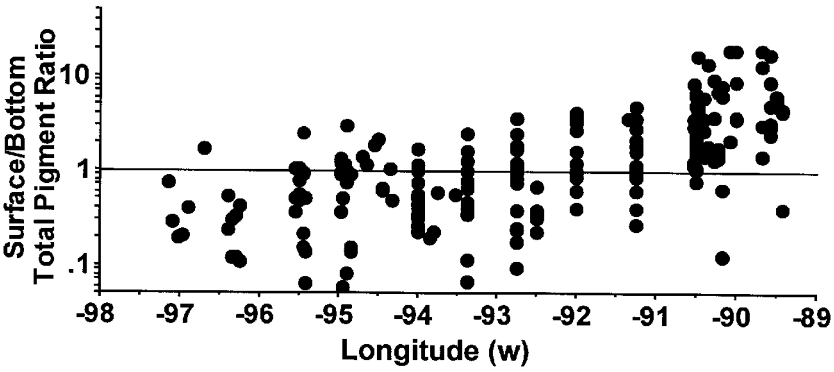


Figure 7. Relationship between the ratio of the concentration of total phytoplankton pigments (ug/l) in surface and bottom waters with the longitude at the LATEX sampling stations (Figure3). Note: Total depth at these stations was 10-100 m. (From Rabalais and Turner 1998.)

Scientists have been studying the growth of phytoplankton in the Gulf of Mexico for many years. Riley (1937) provided one of the first reports on phytoplankton concentrations off the Louisiana coast. He found that the quantity of phytoplankton appeared to be correlated with the concentration of orthophosphate. In the early 1990s, considerable effort was focused on determining what environmental factors in the Gulf regulated phytoplankton growth and primary production. Dortch and Whitledge (1992) conducted studies in summer 1987 and spring 1988 off of Southwest Pass. This area was characterized by sharp gradients in salinity, turbidity, and nutrients as river water from Southwest Pass mixed with Gulf of Mexico water. As the turbidity decreased, the corresponding increased penetration of sunlight into the nutrient-enriched water stimulated high levels of phytoplankton growth and production. At stations further offshore, nutrient concentrations were reduced to very low levels due to the combination of phytoplankton growth and dilution with high salinity Gulf of Mexico water having very low nutrient concentrations. Using two different approaches to assess nutrient limitation, Dortch and Whitledge (1992) found that the ratio of intracellular free amino acids to protein, an index of nitrogen limitation, did not support the view that nitrogen limitation was widespread. They also used an indirect method to infer which nutrients were limiting, based on concentrations and ratios of inorganic nutrients. This latter approach indicated that potential limitation by phosphorus was more likely than nitrogen limitation in areas of low salinity, especially during spring. The potential for nitrogen limitation was more prevalent in higher salinity waters further offshore, especially during the late summer.

The potential importance of phosphorus as a limiting nutrient has been reported by other studies and this was reviewed in CENR Report 1. Lohrenz et al. (1999) used an indirect approach similar to that of Dortch and Whitledge (1992) to infer which nutrients were limiting in the northern Gulf of Mexico. They also found evidence for potential phosphorus limitation in lower salinity waters, particularly in spring. Lohrenz et al. (1999) recommended phosphorus reduction in the Mississippi River as a potentially effective measure to control the excess phytoplankton production, especially during the spring and early summer. Smith and Hitchcock (1994) conducted nutrient enrichment bioassays in the Gulf of Mexico during March and September 1991 and May 1992. Their findings were consistent with phosphorus limitation during the spring, especially in the lower salinity waters, and nitrogen limitation in the fall. Other evidence for phosphorus limitation in Mississippi River plume waters comes from reported high rates of phosphorus turnover during July and August 1990 and September 1991, particularly in low salinity waters (Ammerman, 1992). Ammerman (1992) also found high activities of alkaline phosphatase, an enzyme that is induced in some phytoplankton under low phosphorus conditions.

Data were acquired from NOAA (http://www.aoml.noaa.gov/ocd/necop/) for three years, 1994, 1995, and 1997, which was part of an extensive data set on nutrient concentrations in the Gulf of Mexico spanning many years (Hendee (1994) and Hendee, personal communication, 2003). Dr. Nancy Rabalais, (Louisiana University Marine Consortium), Dr. R. Eugene Turner, (Louisiana State University), and Dr. William W. Wiseman (Louisiana State University) compiled these data through funding provided by NOAA. The data were from Transect C, which starts in the inshore waters (water depth 5.4 meters) off Terrebonne Bay, near Chauvin, Louisiana, West Longitude 90.5, and runs southeastward for approximately 50 miles to an offshore location where the water depth is approximately 45 meters (Figure4).

The DIN and DIP surface data from 1994 to 1997 were used to determine DIN/DIP elemental ratios for each month that data were collected. The results, depicted in Figure 8, show high DIN: DIP ratios during the spring and early summer and lower ratios during the late summer and fall. The DIN: DIP ratios during the spring and early summer were often well above the Redfield ratio of 16:1, indicative of the potential for phosphorus limitation. The lower DIN: DIP ratios during the late summer and fall are closer to the Redfield ratio, and this would be consistent with either phosphorus or nitrogen limitation, or co-limitation by both. More sampling is needed across the hypoxic area of the northern Gulf to better characterize the spatial and temporal variations in nutrient concentrations.

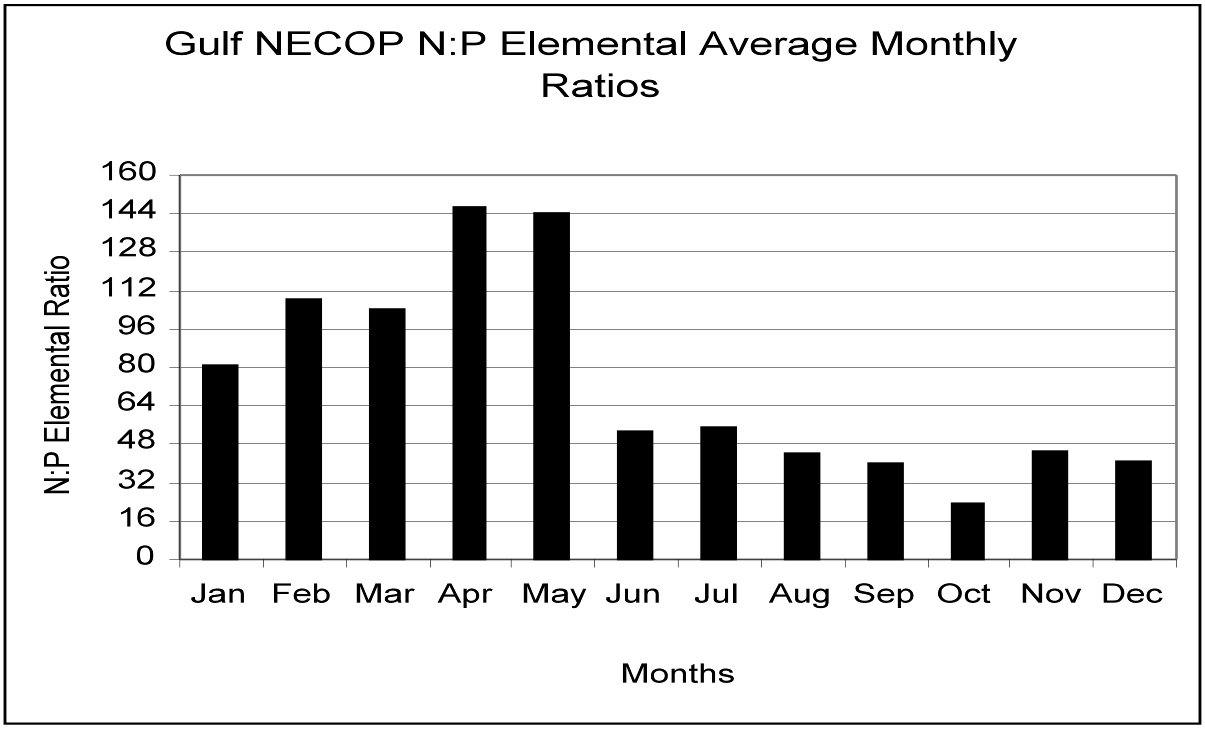


Figure 8. Average monthly DIN/DIP Elemental Ratios from Transect C Sampling, 1994, 1995 and 1997. (Figure 3)

Highest chlorophyll concentrations along Transect C in the eastern portion of the Hypoxic Zone were observed during the spring and early summer of 1997(Figure 9). This would be expected to coincide with the period of highest productivity. Consistent with this view, in an analysis of monthly composite chlorophyll data for Transect C stations C6, C6A, and C6B for the years 1985-1997, Rabalais and Turner (2001) reported that chlorophyll concentrations were generally highest during April and May and lower in the late summer months. This would suggest that, at these stations along Transect C, a large portion of the annual primary productivity occurs during the spring and early summer. Rabalais and Turner (2001) also refer to several studies showing relatively high abundance of copepod zooplankton, and the production of copepod fecal pellets during the spring and early summer.

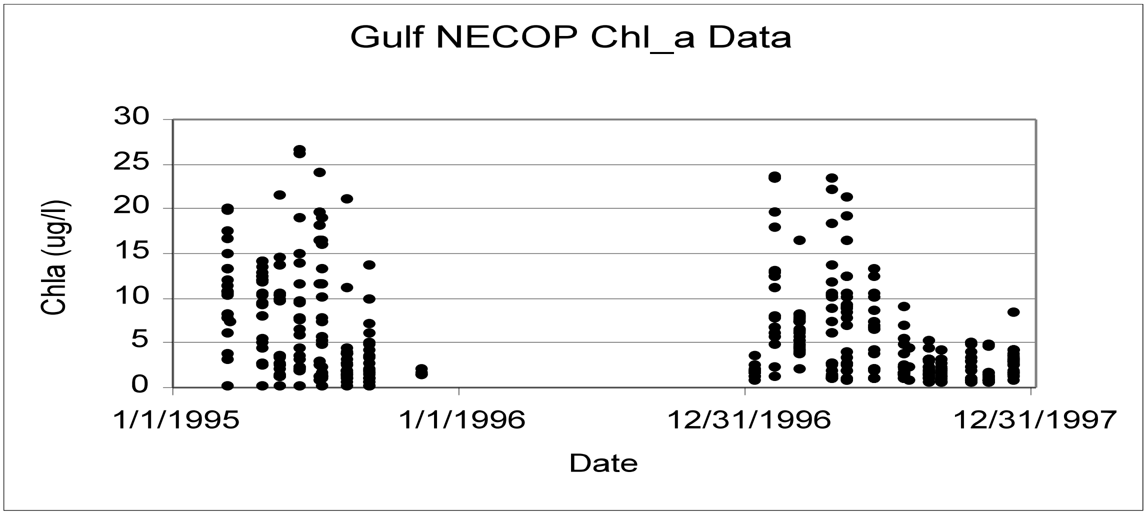


Figure 9. Chl_a Concentrations along Transect C, 1995 and 1997.

CENR Report 1 (Section 6.5, pages 75-77) concluded that the phytoplankton, copepod zooplankton, and copepod fecal pellets were produced in quantity during the spring and early summer growing season; that this productivity was the likely source of organic matter that sinks to the lower water strata and decays; and that the organic matter produced during the spring and early summer consumes dissolved oxygen and is a major factor contributing to hypoxia.

The available evidence indicates a potential for phosphorus limitation in the lower salinity waters of the northern Gulf of Mexico during the spring and early summer – an area that accounts for a substantial portion of the primary productivity causing hypoxia. Nitrogen limitation appears to be confined to the higher salinity areas, especially during the late summer and fall. The higher salinity areas usually have low nutrient concentrations due to nutrient depletion by phytoplankton and dilution with low nutrient offshore waters. These high salinity areas normally exhibit low primary productivity.

The pattern of phosphorus limitation during the spring and early summer and nitrogen limitation during the late summer and fall is not unique to the Mississippi and Atchafalaya river system. Fisher et al. (1992) described such a pattern for the Chesapeake Bay, based on comprehensive water quality sampling and nutrient loading studies. Fisher et al. (1999) also conducted comprehensive and very sophisticated nutrient addition studies for the Chesapeake Bay. These studies confirmed extensive phosphorus limitation in the Chesapeake Bay during the spring and early summer and nitrogen limitation during the late summer and fall. Accordingly, decreasing phosphorus and nitrogen loading to the Chesapeake Bay, to control excess phytoplankton production during the spring and early summer, is an integral part of the control strategy for the Bay.

FUTURE MONITORING, MODELING, AND RESEARCH NEEDS

The available Gulf hypoxia data and related scientific literature support the hypothesis that, for waters subjected to nitrogen and phosphorus loads significantly above historic background levels, there may be considerable benefit to reducing both nutrients in order to restore water quality in the northern Gulf of Mexico. While the *Action Plan* calls for appropriate voluntary action to address nitrogen loading, additional emphasis should be placed on reducing phosphorus loads as well. A balanced approach to reducing both nutrients will support achieving the second goal of the *Action Plan* – to restore water quality throughout the Mississippi River Basin. In addition, reducing phosphorus may significantly contribute to reducing the areal extent of the hypoxic zone by reducing initial biomass production in the early regions of mixing between the freshwaters of the Mississippi River and the marine waters of the Gulf. In order to better support management decisions in the future and to elucidate the relative importance of the various nutrients in contributing to the formation and extent of hypoxia in the northern Gulf, EPA recommends that the five year reassessment called for in the *Action Plan* focus immediate research, monitoring and modeling on the following critical needs.

Monitoring and Data Analyses

In the more marine segment of the plume, N reductions could possibly have a significant impact in reducing primary production. However, the relative importance to Gulf hypoxia of primary productivity in the higher salinity areas, especially during the summer and fall, relative to the much higher primary productivity that occurs in the lower salinity areas during the late winter and spring have not been adequately considered. Stable C and N isotope studies examining the formation of new production could help address this knowledge gap.

Routine shelf-wide monitoring should be conducted every month of the year and with monitoring every two weeks during the critical months (February through July). In addition to having adequate modeling to characterize phytoplankton and zooplankton population dynamics and hypoxia, these monitoring programs should incorporate adequate data collection necessary to support required physical modeling.

The initial priority for river water quality studies should be toward understanding nutrient bio-availability in the lower basins and the Gulf. Comprehensive bio-availability studies on nutrients in the lower Mississippi and Atchafalaya Rivers should be conducted. EPA published procedures for bio-availability studies (Algal Growth Potential) should be utilized. Nutrient addition protocols developed at the University of North Carolina by Dr. Hans Paerl and utilized in the Chesapeake Bay studies should be considered. At a minimum, monthly samples should be taken at St. Francisville, Belle Chasse, Venice, and in the Gulf of Mexico off Southwest Pass. Enough additional stations should be established in the Gulf sufficient to resolve nutrient bio-availability issues. The studies in the Gulf should be designed to build upon the information derived from the recently completed nutrient addition studies conducted by Drs. David Nelson and Quay Dortch (personal communication).

Algal growth potential studies adequate to evaluate the sources and fates of bio-available nutrients should eventually be conducted in the mid- and upper-MRB. When these studies are conducted, particular emphasis should be placed on the fate of dissolved inorganic phosphorus entering the rivers. There is a substantial body of literature that suggests that much of the dissolved inorganic phosphorus entering streams with high silt and clay content become bound to the sediment particles. The extent to which bound phosphorus is regenerated/recycled in the Gulf is apparently unknown. The very high DIN/DIP ratios reported in the high productivity portions of the plume by numerous researchers would suggest that bound phosphorus entering the Gulf from the rivers is probably not an important source of bio-available phosphorus for phytoplankton. However, this issue needs to be resolved.

Model Development

A 3-dimensional (3-D) hydrodynamic and water quality model should be developed for the near shore area or the inner shelf of the Gulf where the hypoxia problems occur and where the loadings from the rivers are delivered to the Gulf. The Gulf water quality model must have a detailed eutrophication structure. The kinetic structure should include biochemical processes and rate equations which describe the interrelationships between phytoplankton biomasses, primary productivity, nutrients and nutrient cycling, carbon and dissolved oxygen. The model should calculate the time varying distribution of the various chemicals necessary to perform the phytoplankton and dissolved oxygen balance within the Inner Louisiana Shelf. The role of stratification needs to be clarified and the boundary conditions for the model should consider the possible role of upwelling.

The model must also contain a sediment nutrient cycling component that accounts for nitrogen, phosphorus, carbon, oxygen and other fluxes between the water column and the bottom sediments on the inner shelf. An important aspect of nutrient dynamics and more specifically, meeting nutrient demands of primary producers, is the relative importance of sediment-water column exchange and regeneration of N and P (internal nutrient cycling). It is well known that there are significant differences between N and P recycling and hence re-supply rates within freshwater and marine ecosystems, especially shallow ones where sediment-water column exchange is greatly facilitated. This aspect of nutrient cycling dynamics needs to be incorporated in the overall scheme of nutrient supply, availability and limitation. In shallow systems like the Mississippi River plume and Northern Gulf of Mexico it is highly artificial to consider nutrient concentration and supply ratios based only on what is found in the water column at any point in time and space. Nitrogen and phosphorus regeneration rates need to be established and incorporated into the overall nutrient cycling and availability schemes.

Research Needs

During periods of maximum primary production, internal nitrogen and phosphorus cycling dynamics should be taken into consideration as these can affect and alter nutrient availability and limitation. Therefore, the additional issue of light limitation interacting with nutrient limitation in this region should be evaluated. How important light limitation is relative to P or N limitation on a seasonal basis appears yet to be resolved. Studies in other areas have indicated that algal blooms are occurring closer inshore in nutrient rich river plumes as sediment load and associated turbidity have decreased in the near-shore areas. Millions of acres of conventional row crop agriculture have been converted to no-till and conservation till in the Mississippi-Atchafalaya Basin. The millions of tons of reductions per year in soil loss may have already impacted phytoplankton population dynamics in the Gulf.

While nitrate (NO3) may be the most important externally-loaded nitrogen source, it is by no means the only available source, as nitrogen recycling in both the freshwater and marine portions of the Mississippi River plume likely supply ammonium to phytoplankton as well. The relative impacts of nitrate and/or ammonium (or even organic nitrogen) on structuring phytoplankton communities need to be investigated, as this can play an important role in establishing and promoting the types and fates of phytoplankton species and functional groups (i.e. diatoms, flagellates, cyanobacteria, dinoflagellates, etc.) supporting the base of the food web.

The critical issue of denitrification under low oxygen conditions in the bottom waters of the Gulf needs substantial examination. Denitrification is apparently the mechanism responsible for the dissipation of very large quantities of nitrogen to the atmosphere. Denitrification may be an important factor in what appears to be an annual shift of substantial areas of the inshore northern Gulf from potential phosphorus limitation to potential nitrogen-phosphorus and nitrogen limitation.

The role of nitrogen fixation by cyanobacteria in the Gulf needs substantial evaluation. If cyanobacteria produce nitrogen in sufficient quantities such that this nitrogen contributes to the production of substantial quantities of carbon that contributes to late season hypoxia, this could impact the effectiveness of various nitrogen reduction strategies. There is a substantial body of recent literature that suggests that nitrogen fixation is efficient enough to ensure that marine waters are not likely to be nitrogen-limited when there is an adequate supply of available iron (Kustka (2002), Moore (2001), and Capone (2001)).

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