The Dead Zone:
Ecology and Oceanography in the Gulf of Mexico

by

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The Problem

Bill sat at the kitchen table, adding up last month's expenses from running his fishing boat. With his trawler he fishes for bottom fish from his home base in Terrebone Bay, Louisiana—snapper and grouper mostly. But for the last few summers he has had to boat further and further out from the Louisiana shore to get to decent fishing grounds. The additional fuel costs were killing him. He rubbed his tired eyes and tried running the numbers through his calculator again.

"Hi Dad," said his daughter Sue, walking into the kitchen. "How does it look this month?"

"Not so good," said Bill, tossing his pencil onto the table. "The fuel bills were higher than ever this summer. It's going to be tight for our finances. I wish I knew why the fish disappear near shore in the summer."

He privately worried about how he was going to be able to afford Sue's college tuition this fall. Maybe it was time to get out of the fishing business, except fishing was all he knew. Plus, all his money was tied up in his fishing boat and gear. Who would buy it now that fishing in the Gulf was so problematic?

Sue sat down at the table and toyed with the pencil. She knew about her dad's worries. "You know, Dad," she said, "I've been thinking. Let me talk with some of my professors at the university. Maybe I can get some information from them about what causes the fish to disappear, and whether anyone is working on a solution. Someone at school ought to know something."

Bill smiled at his daughter, even though he wasn't hopeful. "Good idea, kiddo," he said. "Maybe more people are working on this than we know. See what the professors can tell you."

Sue hurried across campus. She had an appointment with Professor Gracia in the biology department, and she was late. She rushed up the stairs of the biology building and knocked at his door.

"Come in," Professor Gracia called out. "You must be Sue. I'm glad you could make it before I had to leave. You are right in thinking that a number of scientists must be working on the problem you described," he said as he handed her a map of the United States.

"Look here," he said, pointing to a region of the Gulf of Mexico just below Louisiana and eastern Texas. "See that shaded area? We call that the Dead Zone. During the summer there is very little in the way of marine macro-organisms there."

"Wow, I had no idea it was so big!" said Sue. "Do the fish actually die there?"

Professor Gracia started gathering up materials for his next class. "Some fish may die. Most of the fish and crustaceans that can leave the Dead Zone do so. It's called the Dead Zone because the dissolved oxygen levels in the water get so depleted the water can't support life."

Sue could see that the far edge of the Dead Zone corresponded with the distance her dad had to boat to get to good fishing grounds. "Is anyone working on why the Dead Zone forms?" she asked.

"A lot of people are very concerned and are actively collecting data to help get to the bottom of the cause," said Professor Gracia. "I've got to get to class right now, but let's meet again. I have more information and data to share with you."

"That's sounds great," said Sue. "I'll talk to you soon."

Figure 1a. Map of the U.S. showing area of the Dead Zone in the Gulf coastal waters of Louisiana and Texas (Goolsby et al., 2000).

Figure 1. Mississippi River drainage basin, major tributaries, and areal extent of 1999 midsummer hypoxic zone.

 Figure 1b. Detail of the Dead Zone (shaded) in the Gulf of Mexico. (Rabalais et al., 2002. Copyright, American Institute of Biological Sciences. Used with permission.)

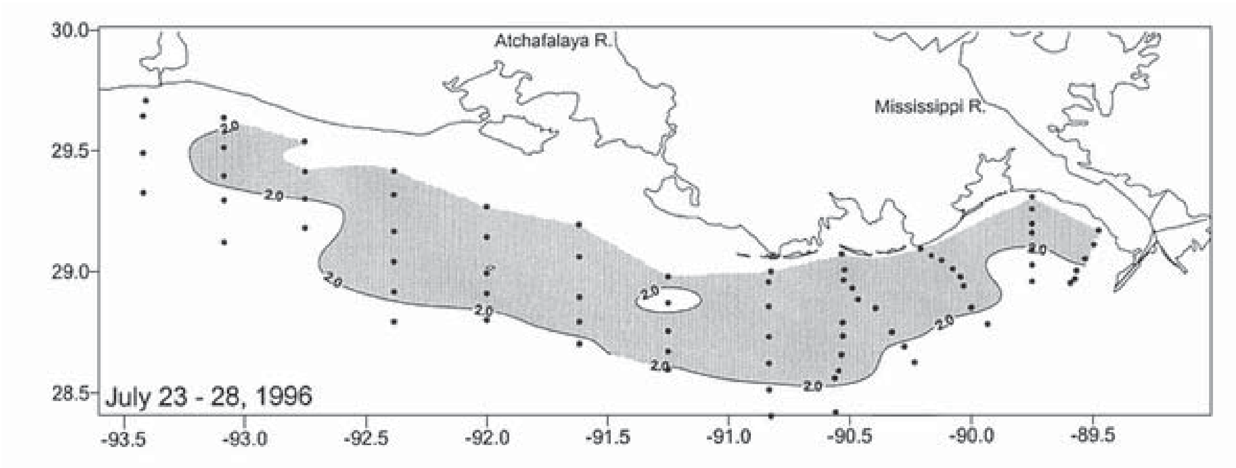


Figure References

Goolsby, D.A., and W.A. Battaglin. 2000. Nitrogen in the Mississippi Basin—Estimating sources and predicting flux to the Gulf of Mexico. *USGS Fact Sheet 135-00*. **http://ks.water.usgs.gov/pubs/fact-sheets/fs.135-00.html** Last accessed: May 22, 2009.

Rabalais, N.N., R.E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience* 52: 129–142.

Part II – What Affects the Dissolved Oxygen Content of Water?

"Hey guys, look at these maps of the Dead Zone I got from Professor Gracia," said Sue, walking up to her friends sitting at the lunch table in the student cafeteria. "What I don't get is why this particular area should have such low dissolved oxygen concentrations."

Sue handed the maps to her friend Paula, a physics major. Paula stopped eating her sandwich long enough to give them a look.

"There must be some physical cause," Paula said. "I can't imagine anything else that could affect the dissolved oxygen content of water so dramatically."

"Oh, come on," said Sue's friend Zack. "Living organisms should have a huge impact—aren't all the fish busy consuming oxygen in the water?"

"Well, of course you would think of that, you're a biology major," said Sue. "But let's be systematic. What are all the physical and biological influences we can think of that could affect how much oxygen is dissolved in the water?"

Questions

1. What physical forces or conditions affect the dissolved oxygen content of water?
2. What are the biological processes that can affect dissolved oxygen concentration?
3. What might cause each identified condition to fluctuate over the seasons?
4. If you had to choose, which of the conditions you've identified seem most likely to be the primary cause of hypoxia in the Gulf? Why?

Part III – How Do the Gulf Waters Change with the Seasons?

"Thanks for meeting with me again," said Sue, shaking hands with Professor Gracia. "I'm hoping you can help me understand what's going on in the Gulf, what people think causes the low oxygen levels."

"I can sure get you started," replied Professor Gracia, pulling out some papers from the pile on his desk. "You know, the Gulf waters are very dynamic, changing dramatically with the seasons, and from the surface to the bottom. For example, the Atchafalaya and Mississippi Rivers carry enormous amounts of fresh water into the Gulf and the volume fluctuates with the season. Because the river water is fresh, it's less dense than the seawater, and tends to stay on the surface. The prevailing current near shore in the Dead Zone is from east to west, so the river water is carried from where the river empties towards western Louisiana and Texas.

"Here are some data that will be useful for you to look at showing some of the seasonal changes in temperature, salinity, and dissolved oxygen concentration. Scientists measure the temperature, salinity, and dissolved oxygen concentration of water by using a probe. The probe continuously measures these properties as it is lowered to the sea floor. The data are presented in graphs called station profiles. Here are some taken at different times from a station just off Terrebonne Bay."

Professor Gracia handed several station profiles and a water discharge graph to Sue, then glanced at his watch. "I'm afraid I've got to head off to a meeting, but why don't you take these profiles and spend some time with them. See what you can glean from the data."

"Thanks," said Sue. "I will."

Figure 2. Salinity (triangles), temperature (squares), and dissolved oxygen concentration (circles) at various depths, in meters (0 = surface). A station off Terrebonne Bay, Gulf of Mexico. (Modified from N.N. Rabalais et al., 2002.)

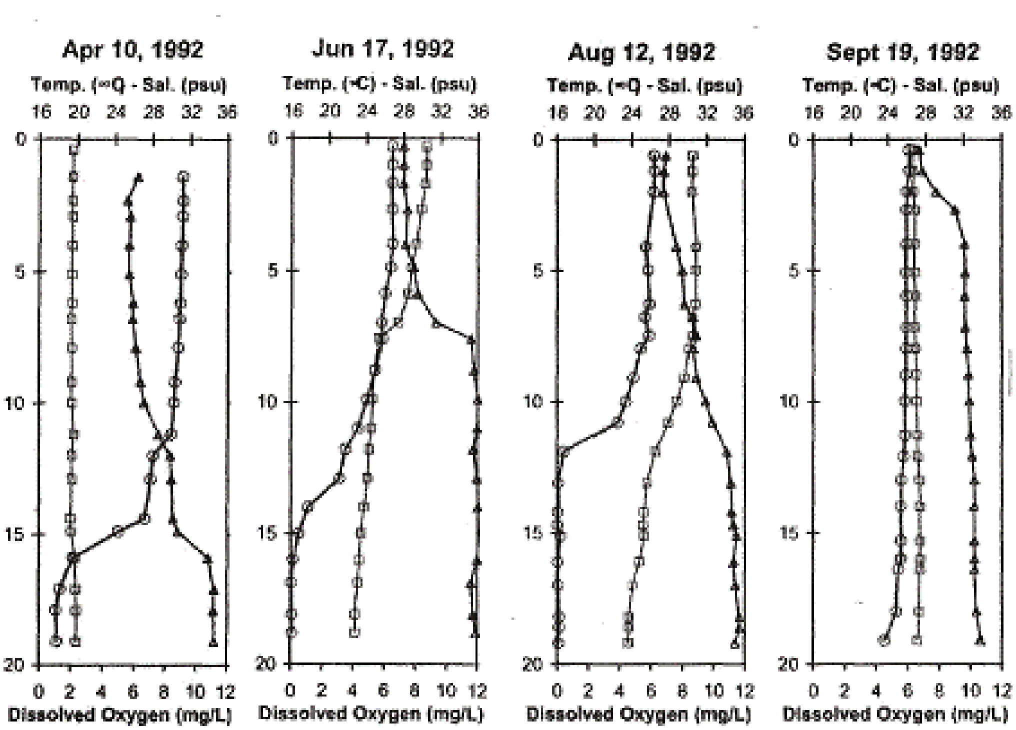
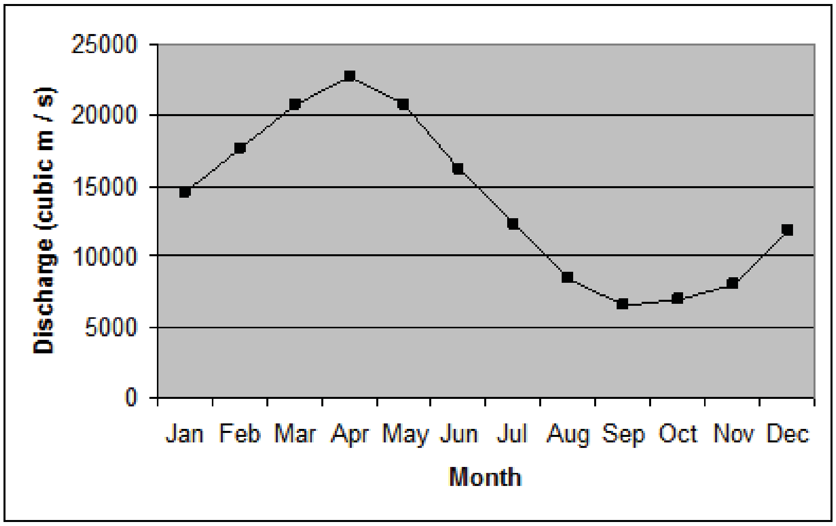


Figure 3. Average monthly water discharge from the Mississippi River for the years 1930–1992. (Modified from Walker, 1994.)



Questions

1. What is the average temperature of water in the top 5 meters in April? In August? How do those values compare to the average temperatures at 15–20 meters for those months?
2. Typical seawater has a salinity of 35 psu (practical salinity units). In which month is the difference in salinity of surface and bottom waters the greatest? Why do you think the difference is the greatest at this time of year?
3. In which month is the salinity difference between surface and bottom waters the least? What reasons can you think of to explain why the surface and bottom water salinities become more uniform at that time?
4. Water that contains 2 mg oxygen per liter or less is termed hypoxic, since at that concentration many aquatic aerobic organisms are unable to survive. How does the depth at which hypoxia is observed change over time?

Figure References

Rabalais, N.N., R.E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience* 52: 129–142.

Walker, N.D. 1994. Satellite-based assessment of the Mississippi River discharge plume's spatial structure and temporal variability. *OCS Study MMS 94-0053.* U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, La., 56 pp.

Part IV – How Do the Organisms Affect Dissolved Oxygen Concentration?

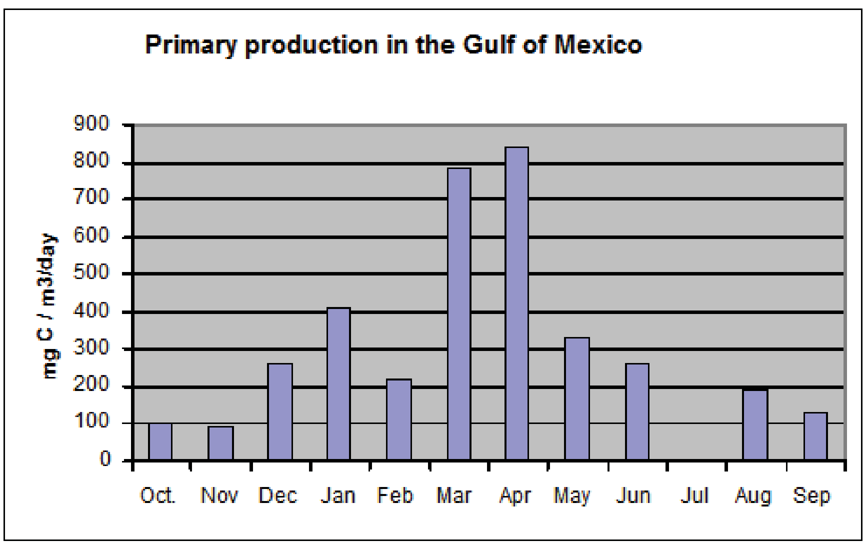
After spending time looking over Professor Gracia's station profiles, Sue felt like she had a much better sense of the seasonal changes in the Gulf and the effects of freshwater on the salinity at different depths. Her friend Zack's comments about fish using up oxygen made her wonder just how much living organisms can affect the oxygen concentration in such a large body of water. She wondered about what organisms are present besides fish, shrimp, and seaweeds—organisms she already knew about. Sue had learned about food webs in her introductory biology course, so she was comfortable with the idea of primary producers, primary consumers, and predators. But what organisms were playing these roles in the Gulf, and could they realistically affect the oxygen concentration in the water?

She decided to do some legwork to figure out who the key players are, where they reside in the water column, and how much respiration they carry out using the basic ideas of a generalized food web to guide her. She listed these questions for herself:

Questions

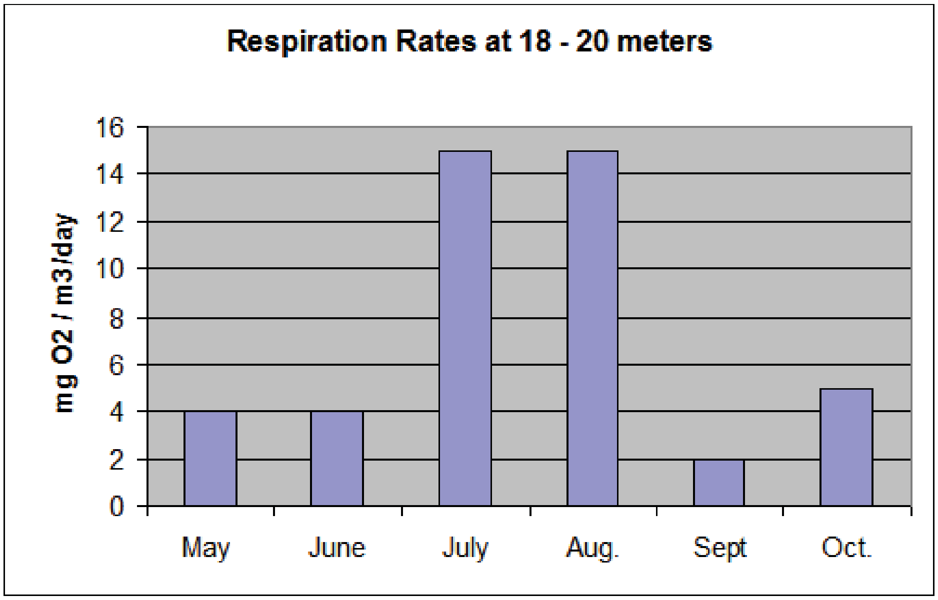
1. What group of organisms are the most important primary producers in the marine aquatic food web? How deep down in the water column can they be found?
2. What factors are the most important for controlling the growth of these organisms? That is, what limits their growth?
3. Why does the primary productivity in the Gulf of Mexico fluctuate over the year (see Figure 4 below)?

Figure 4. Primary production in the Gulf of Mexico in mg carbon assimilated per cubic meter per day. No data were collected for July. (Modified from Sklar & Turner, 1981.)



4. What are the major consumers in the Gulf of Mexico food web?
5. What are the remaining components of the food web in this area?
6. What groups are responsible for the greatest total amount of respiration (consumption of oxygen)?
7. At what time of the year does respiration rate peak (see Figure 5 below)? How does that compare to peak times of primary production? Why is there a lag between these two?

Figure 5. Respiration rates in the Gulf of Mexico at 18–20 m, transect C6b. (Modified from Dortch et al., 1994.)



Useful Resources

Lalli, C.M., and T.R. Parsons. 1993. *Biological Oceanography, An Introduction.* New York: Pergamon Press.

The Habitable Planet. Available online at http://www.learner.org/channel/courses/envsci/unit/.

Cycling Through the Food Web. Available online at http://www.bigelow.org/bacteria/. The Bigelow Laboratory for Ocean Sciences.

Our Ocean Planet—Oceanography in the 21st Century. Robert Stewart. Available online at http://oceanworld.tamu.edu/resources/oceanography-book/contents2.htm.

Figure References

Dortch, Q., N.N. Rabalais, R.E. Turner, and G.T. Rowe. 1994. Respiration rates and hypoxia on the Louisiana shelf. *Estuaries* 17(4): 862–872.

Sklar, F.H., and R.E. Turner. 1981. Characteristics of phytoplankton production off Bataria Bay in an area influenced by the Mississippi River. *Contributions in Marine Science* 24:93–106.

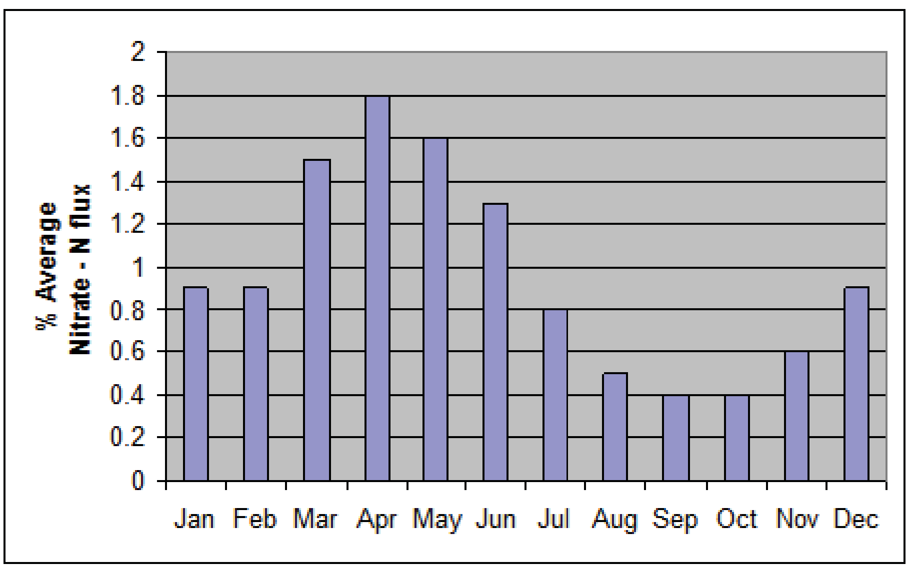
Part V – Why Does the Phytoplankton Population Increase?

Sue could see that photosynthesis by the phytoplankton population increased sharply in the spring months, suggesting their populations had soared. Following the spring peak, photosynthetic rates declined as the population members died and respiration rates in the water rose dramatically. It made sense to Sue that the organic matter from dead phytoplankton was sinking, providing a rich food source for marine bacteria populations at the base of the water column. As the bacterial populations climbed, they depleted the oxygen available in the water, especially at the bottom of the water column.

But why did the phytoplankton population explode in the first place? Sue knew that light and nutrients were the things most likely to limit growth. Day length was increasing in April and May when the populations climbed, but since the population crashed when day length continued to increase in June, light did not seem to be the cause. Nutrients seemed more likely to be the culprit, carried into the Gulf by the Mississippi River. This also made sense knowing that the prevailing current would carry nutrient-rich water from the river to the west of the Mississippi's mouth, exactly where the Dead Zone was located.

Nitrogen is commonly the limiting nutrient so Sue decided to confirm her suspicions by tracking down data on the monthly change in the nitrogen concentration of the Mississippi River (Figure 6).

Figure 6. Monthly discharge of nitrate and nitrogen from the Mississippi River into the Gulf of Mexico. Values are normalized for the average annual value from 1978 to 1995. (Modified from Turner, et al., 2005.)



Questions

1. What are the peak months for nitrate-nitrogen discharge from the Mississippi River into the Gulf?
2. How do the peak months for nitrate-nitrogen discharge compare to the peak months for phytoplankton primary production?

Figure Reference

Turner, R.E., N.N. Rabalais, E.M. Swenson, M. Kasprzak, and T. Romaire. 2005. Summer hypoxia in the northern Gulf of Mexico and its prediction from 1978 to 1995. *Marine Environmental Research* 59(1): 65–77.

Part VI – Why Is the Dead Zone a Seasonal Phenomenon?

"Hey Sue, can I join you?" asked Paula. Sue was sitting in the cafeteria, digging into her lunch.

"Sure, Paula. I'm excited—I actually have made some headway on my project to figure out what's happening in the Dead Zone," said Sue. "It looks like the Mississippi River water is carrying nutrients like nitrogen into the Gulf, and that in turn promotes a population explosion of photosynthetic plankton. Excretion of organic compounds from the phytoplankton, plus their dead cells when they die, sink down, providing a rich source of food for heterotrophic aerobic bacteria. It's the bacteria that use up the oxygen in the water."

Paula picked at her salad. "Um, ok. But the Mississippi River flows constantly—why does the Dead Zone occur only in the summer? Your dad is able to fish much closer to shore in the late fall and into the winter. What makes the Dead Zone disappear then; what restores oxygen to the water?"

"Ah, Paula, you always manage to get right to the part I haven't figured out yet," said Sue. "I understand why the oxygen depletion happens, but I really don't know what restores the oxygen levels once they are low."

Sue thought back on the ways that dissolved oxygen enters the ocean. One or more of these processes must re-oxygenate the water for the Dead Zone to disappear.

Questions

1. Does it seem likely that any of the seasonal changes noted in Part II, Question 3, re-oxygenate the bottom waters of the Dead Zone in the autumn and winter?
2. Recall that in the summer the water column in the zone of hypoxia is layered. Figure 2 in Part III shows that the river plume occupied the upper water column. This resulted in a low salinity surface layer, made warm by solar irradiance. Beneath the river plume was the Gulf water. This water had a higher salinity and was cooler. How does temperature and salinity affect the density of water? How does this affect the stability of the water?
3. Let's check your answers with a demonstration. Your instructor will queue up a film clip. Predict what will happen to the water when the barrier is removed from the tank, and explain why.
4. Observe the film clip. Did it confirm your prediction? If not, what did happen and why?
5. To mix a stable water column requires kinetic energy. Can you think of any processes that might supply this energy? Do any of these processes change in intensity with the seasons?
6. What makes the hypoxia disappear in the fall and winter?

Useful Resources

Ocean World, Ch. 6 Temperature, salinity and density.
At **http://oceanworld.tamu.edu/resources/ocng_textbook/chapter06/chapter06_04.htm**.

Chamberlin, W.S., and T.D. Dickey. *Exploring the World Ocean*. 2008. New York: McGraw-Hill.

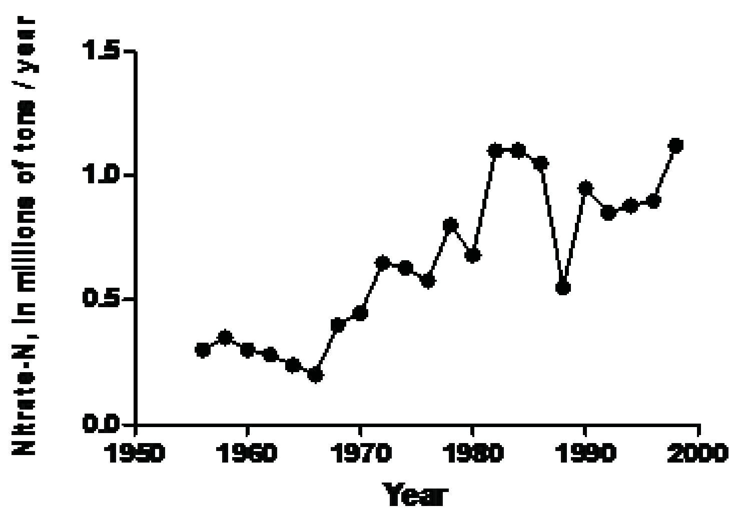
Part VII – Where Does the Nitrogen Come From?

"I'm impressed—you've put together most of the pieces of the Dead Zone puzzle," said Professor Gracia. Sue blushed, but nodded, as they walked together towards his office.

"Well, it really matters to my family, so I had a pretty strong motivation," she said. "I think I understand now why the Dead Zone is temporary, getting flushed out by the turbulence of fall and winter storms. The data on nitrogen carried in by the Mississippi show a sizeable increase in early spring when the river discharge rate is at its peak. That supports the bloom of phytoplankton, and the eventual population explosion of marine aerobic bacteria. They deplete the oxygen available in deeper waters, and form the Dead Zone in early summer. The one thing I haven't figured out is where the nutrients in the Mississippi river water are coming from, and why the Dead Zone was not a problem many years ago."

"I think your second concern, why hypoxia is a relatively recent phenomena, is explained by this graph" said Professor Gracia. "What do you notice about nitrogen discharge in the sixties versus the last decade?"

Figure 7. Nitrate and nitrogen (in millions of tons per year) discharged into the Gulf of Mexico from the Mississippi River. (Modified from Goolsby, 2001.)



"I can see that nitrogen has increased, but what is the source of the nitrogen?" said Sue.

"That's probably the most controversial part of this whole problem," said Professor Gracia, opening his office door. He pushed some books off a chair and motioned towards it. "Here, have a seat. Most researchers, such as Nancy Rabalais and Don Goolsby, have argued that the most important source of nitrogen comes from the fertilization of farms on the land that drains into the Mississippi River. Nutrients not used by crops are washed into the river system and are carried downstream. The farming interests argue that you can't rule out the possibility that it comes from other sources. Here, take a look at this letter to the editor of the journal *Science* by Clifford Snyder, the Midsouth Director of the Potash and Phosphate Institute." Professor Gracia pulled out a folder from his filing cabinet, and handed Sue a sheet.

> "There are also no conclusive data that identify the sources of the nitrate and nitrogen that enter the Mississippi River and ultimately reach the Gulf. In the White House Committee on the Environment and Natural Resources (CENR) Topic 3 report, Don Goolsby and others used a statistical model to conclude that agriculture was the major source of nitrogen to the Mississippi River basin. Their conclusion was not surprising, since inputs to the model were based on the

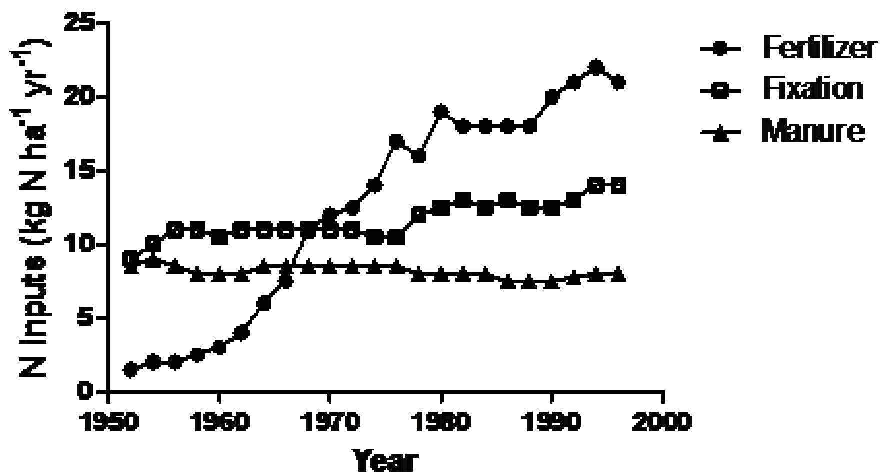
assumption that many non-agricultural sources (for example, urban runoff and geological nitrate) were insignificant. Their estimates of discharge are simply proportionate to the tonnage of each input source in sub-basins of the Mississippi River basin. River monitoring clearly indicates that major nitrogen loads come from the geographic area of the Corn Belt, but the sources remain unclear. This geographic area contains naturally rich soils of the prairies, as well as agriculture. The proportion of the nitrogen that comes from agriculture and the proportion of the agricultural nitrogen that arises from fertilizer use remain uncertain." (Snyder, 2001)

Sue read the letter quickly.

"Snyder seems to be saying that while it's true the nitrogen is coming from the Corn Belt, it could be originating from the prairie soils, that we can't know how much is coming from the natural soil and how much is coming from added fertilizer. I guess it would be hard to tell exactly where a nitrogen molecule came from," Sue said.

"Ok," said Professor Gracia. "Now take a look at this data from Don Goolsby and his colleagues, and see what you think."

Figure 8. Nitrogen inputs to the 20-state region of the Mississippi River basin, in kilograms of nitrogen per hectare per year. Fixation refers to the nitrogen fixation that occurs in legume crops. (Modified from McIsaac et al., 2002.)



Questions

1. Which nitrogen source has added the greatest amount of nitrogen to the land in the Mississippi River basin in the years since 1970?
2. Refer to Figure 7, which shows the increase in nitrogen carried by the Mississippi into the Gulf, and to Figure 8 above. Are the data in these graphs consistent with the idea that nitrogen naturally present in rich prairie soils is the source of nitrogen carried into the Gulf of Mexico? Why, or why not?

Figure References

Goolsby, D.A., and Battaglin, W.A. 2001. Long-term changes in concentrations and flux of nitrogen in the Mississippi River Basin, USA. *Hydroogical Processes* 15:1209–1226.

McIsaac, G.F., David, M.B., Gertner, G.Z, and Goolsby, D.A. 2002. Relating net nitrogen input in the Mississippi River basin to nitrate flux in the lower Mississippi River: A comparison of approaches. *Journal of Enviromental Quality* 31: 1610–1622.

Part VIII – Conclusion

When important scientific claims are made there is typically a flurry of research and experiments, and a welter of different conclusions and interpretations. As data from different sources accumulates, however, it becomes clearer which interpretations are consistently supported, and which are not. Although a small minority of scientists continue to argue that the source of the nitrogen increase has not been proven, most scientists examining the data from numerous studies have concluded that fertilizer application in farms of the Mississippi River basin are the source of nitrogen that leads to the Dead Zone. The problem has moved slowly from scientific debate, to scientific consensus and into the arena of public policy and government action. The United States Geologic Survey released a report in January, 2008. Here is an excerpt from the accompanying news release which states unequivocally:

> "Nine states in the Mississippi River Basin contribute the majority of nutrients to the Northern Gulf of Mexico, threatening the economic and ecological health of one of the nation's largest and most productive fisheries.
>
> "Excessive nutrients have resulted in a zone of low dissolved oxygen or hypoxia, caused by the growth of large amounts of algae. This can stress and cause death in bottom-dwelling organisms in the Gulf." (Alexander, et al., 2008)

Now that the cause of the Dead Zone has been determined, state and federal agencies are looking for ways to reduce nutrient pollution from farmlands before it enters the Mississippi River system. Voluntary reduction in fertilizer application, restoring wetlands along waterways, and establishment of vegetated buffering zones to absorb nutrients before they enter rivers and streams are among the action strategies being pursued. The goal is to reduce the area of the Dead Zone to 5,000 square kilometers by 2015. This represents about 1/3 the average square area of the Dead zone between 2003–2007. Achieving this goal will require overcoming many challenges, including reluctance of farmers to alter farming practices. In the mean time, small fishing operations near the Dead Zone will continue their struggle to survive.

Figure References

Alexander, R.B., R.A. Smith, G.E. Schwarz, E.W. Boyer, J.V. Nolan, and J.W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River basin. U.S. Geological Survey. http://water.usgs.gov/nawqa/sparrow/gulf_findings/ Accessed: May 14, 2008.