Coastal Ecosystems

Robert Howarth – Environmental Defense

I have been asked to talk about the coastal effects associated with acid deposition. Last week, several of us met under Ellis Cowling's and Jim Galloway's direction in Woods Hole, and this is a direct outgrowth of that. The point I want to make here is partly to put the coastal nutrient pollution issue in context, and also to show what Jim Galloway calls the cascading effects of nitrogen in the landscape (Figure 1).

Nitrogen has a variety of potential environmental effects, both on human health and the functioning of ecosystems. Unlike many pollutants, nitrogen does not have a single effect, rather it has this huge range of effects as it moves through the environment.

The nitrogen can come either from fossil fuel combustion, NO_X, that we have heard mostly about, or ammonium, which is the growing problem we have heard a little bit about this afternoon.

The NO_X clearly contributes to ozone and smog and then goes on to contribute to fine particles and haze problems.

The ammonium waste also contributes to fine particles and haze problems. Both of those, when deposited onto forests, can have a variety of effects, some potentially beneficial such as increased growth, but all of the negative effects that Charlie Driscoll talks about.

As that leaves the forest or the upstream landscape, it contributes to lake acidification. Then the same nitrogen, as it reaches the coast, is contributing to the coastal nutrient pollution I will be talking about.

Now, there are losses along the way to the atmosphere as N_2O, which is a long lived gas with a residence time of 130 years in the atmosphere. That, too, has deleterious effects, in that it is a strong greenhouse gas, and it is a major and growing contributor to ozone depletion in the stratosphere, creating the ozone hole.

Today I will talk principally about what the consequences of nitrogen are in the coastal zone, and what the sources of this nitrogen pollution to the coast are.

The linkage to atmospheric deposition and acid rain is that we now believe that a very large percentage of the nitrogen pollution in the coastal zone originates through atmospheric transfer. Globally, an estimated two-thirds of the nitrogen that is created from human activity for agriculture and through fossil-fuel combustion is transferred through the atmosphere and some point. Some of this falls directly onto the surface of the oceans, while the rest is deposited onto the terrestrial landscape. A significant amount of this deposition onto land is then exported in streams and rivers to coastal marine ecosystems (Figure 2).

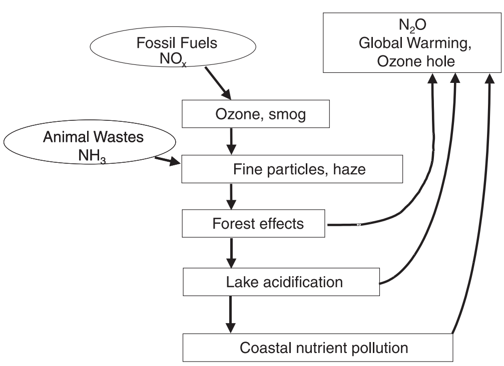


Figure 1. The cascading effect of nitrogen on human health and ecosystem functioning as a single atom moves through the environment.

Terrestrial systems (N deposition Tg/yr)	
NOy	25
NHx	40
	65

Oceans (N deposition Tg/yr)	
NOy	20
NHx	20
	40

Figure 2. Estimates for deposition of both NO_y and ammonia and ammonium globally, onto the terrestrial landscape and onto the oceans. NO_y is 55% from combustion sources. Agriculture contributes 45% of NO_y and 85% of NH_x. 67% of human-created N cycles through atmosphere. Data are courtesy of Jim Galloway.

Our best estimates are, in the United States, somewhat more than one third of the nitrogen reaching the coast comes through the atmosphere at some point in time.

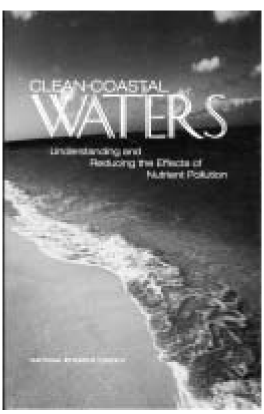
My talk is focused on nitrogen and not sulfur. Seawater systems have tremendous amounts of sulfur in them and adding sulfur makes no difference.

On the other hand, seawater systems are limited in their production by nitrogen. If we add more nitrogen, there is a very, very strong effect of increased algal and plant growth.

The concern in marine ecosystems is not with acid effects. Unlike the previous talk, I am not talking about the toxicity of acid rain, because seawater is very well buffered and handles the acidity fine. The concern is with the nitrogen itself.

Now, nitrogen is a nutrient, and nutrients are defined as things that nourish, so we think of them as a positive. The problem is simply having too much of a good thing. In the United States, and in fact much of the world, the coastal oceans now have too much of a good thing.

The consequences of this excessive nitrogen fertilization are summarized in this report, a report from the National Academy of Sciences that came out last summer. It is called Clean Coastal Waters: Understanding and Reducing the Effects of Coastal Nutrient Pollution. The report is the result of a three-year-long committee at the National Academy that I chaired, and we looked at all aspects of coastal nutrient pollution (Figure 3).



Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution

NRC 2000

Figure 3. A report from the National Academy of Sciences' Committee on Causes and Management of Coastal Eutrophication. Online: www.nap.edu/catalog/9812.html.

One of our major conclusions is that the atmospheric source of nitrogen to coastal rivers and bays, particularly the atmospheric deposition of nitrogen onto the terrestrial landscape with subsequent export to coastal rivers and bays, is very much underappreciated and under-regulated.

What happens when we add nitrogen to coastal waters? Well, nitrogen is usually the limiting nutrient in coastal marine ecosystems. You add nitrogen, you get more algal and plant growth. In moderation, this is not necessarily bad, and can in fact result in greater fish harvests. However, excessive nitrogen inputs lead to a series of deleterious ecological effects which are harmful to fish and other marine life.

One of these changes is a decrease in dissolved oxygen. Low levels of oxygen, which we call hypoxic conditions, are unable to support fish and other higher forms of life. We are seeing increased incidences of hypoxia and even anoxia – the complete absence of dissolved oxygen in seawater – globally in many parts of the coastal oceans, including waters in the United States. This figure (Figure 4) shows the largest example we have in the United States, an area off the plume of the Mississippi River in the Gulf of Mexico, the coastal waters of Louisiana, an area that has grown to be as large as 20,000 square kilometers in some recent summers. That is an area the size of the state of New Jersey with oxygen levels too low to support fish and other higher forms of life.

There is some evidence that these "dead zones," as they are called, have existed for quite some time in many regions. However, we are seeing more of these low-oxygen areas, and many such as the dead zone in the northern Gulf of

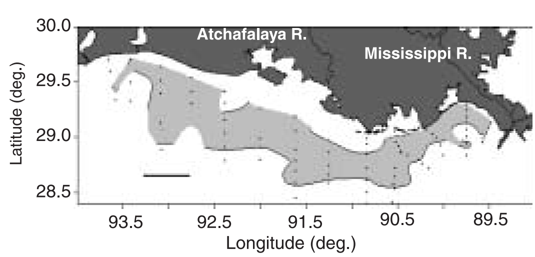


Figure 4. The extent of the hypoxic zone in the northern Gulf of Mexico in July of 1999. Bottom dissolved oxygen less than 2.0 mg/L. Figure is courtesy of Nancy Rabalais.

Mexico are clearly growing in size. This is the result of increased nitrogen flows to these waters.

I want to reiterate that this is not simply a problem of coastal Louisiana. These dead zones, areas of excessively low oxygen, are now common-place in the coastal oceans of the world. Here in the United States, they are prominent features in Chesapeake Bay, Long Island Sound, and several other systems.

Adding nitrogen to coastal waters also increases the incidence and duration of harmful algal blooms. Things like brown tides and red tides and physteria blooms can all be encouraged by adding nitrogen to coastal waters. Some such blooms are natural events. Harmful algal blooms have always occurred, but they are increasing greatly in their severity and length of duration, and that appears to be at least in part a consequence of putting more nitrogen into coastal waters.

Nitrogen also has a major influence on biodiversity. When we fertilize coastal rivers and bays with nitrogen, we lose biodiversity in a very, very obvious way.

One aspect of that is degrading sea grass habitat. This slide (Figure 5) shows a relatively pristine subtropical sea grass bed. If you have a good eye, that is an area of about one meter by one meter. If you have a good eye and you are a good botanist, you might be able to pick out something like 10 to 15 different species of plants, just visually, in this area of approximately 1 square meter.

If you add nitrogen to a system like that, the habitat quality is degraded (Figure 6). The productivity of the seagrasses increases, at least to a point, but the habitat value for nursery grounds for fish and shellfish is much less. You also lose biodiversity, and in this degraded seagrass bed, only two species are apparent. If the seagrass meadow receives even more nitrogen pollution, the seagrasses die out, further degrading the habitat quality.

Ecological changes among phytoplankton and zooplankton are harder to observe, but nitrogen pollution also alters the ecological structure of plankton communities, and lowers their biodiversity as well.

The first survey that was ever made in the United States to try to put a systematic estimate on the extent of the problem of coastal nitrogen pollution was done by NOAA just in the last few years. They released their report in December of 1999. It is an excellent study and I recommend it to anybody who is interested in this problem.

The NOAA study concluded that, although the data quality are variable, that there are sufficient data around to estimate the spatial extent of this problem of coastal nutrient pollution.

They concluded that something like two thirds of the coastal rivers and bays of the United States are moderately to severely degraded from this problem, roughly one third moderately degraded and one third severely degraded.

This slide (Figure 7) shows the geographic extent of the problem. Degradation from nitrogen pollution occurs in some of the coastal rivers and bays of each region in the United States. Our NAS committee concluded that nitrogen is the largest pollution problem in the coastal waters of the United States.

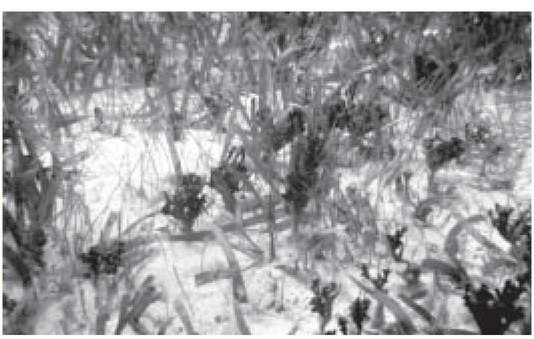


Figure 5. A seagrass meadow receiving only low amounts of nutrient inputs.

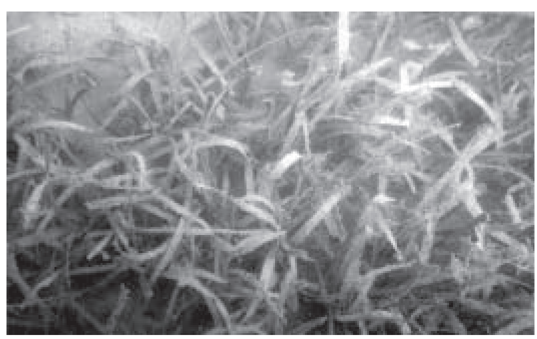


Figure 6. A seagrass meadow receiving elevated nutrient inputs.

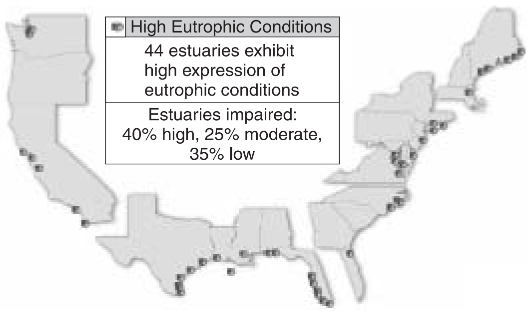


Figure 7. The geographic distribution of coastal rivers and bays in the United States that are highly degraded from nutrient pollution. Reprinted from the NOAA report of Bricker et al. (1999).

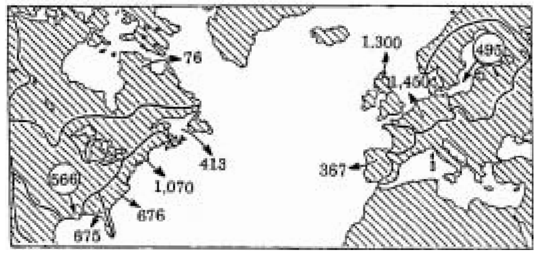


Figure 8. The flux of nitrogen to the coastal oceans from various regions surrounding the North Atlantic Ocean (riverine N export, kg/km²/yr). Reprinted from Howarth et al. (1996).

Where is the nitrogen coming from? I have already said a large part of it is from atmospheric deposition. Let me just give you a little bit of the background that has been pulled together to determine where nitrogen is coming from.

This slide (Figure 8) shows a large scale analysis to try to determine what the fluxes of nitrogen to coastal oceans are and where the nitrogen might be coming from. It shows the flux at the scale from the land to coastal oceans, at the scale of large regions, such as the entire Mississippi River Basin or the entire northeastern United States. The fluxes are per area of watershed (kilograms of nitrogen per square kilometer per year).

You see a lot of variation from as little as 76 kilograms per square kilometer per year up there in Hudson's Bay and Labrador, to a rather high number in the northeastern United States of over 1,000 kilograms per square kilometer per year, and higher fluxes yet in parts of Europe.

We can explain that variation very simply, by looking at what the inputs of nitrogen under human control are to the landscape. Those inputs are the NO_y deposition from fossil fuel combustion, inorganic fertilizer use, nitrogen fixation in agricultural systems, and the movement of nitrogen in and out of a region in food and animal feeds (Figure 9).

If we take these data and simply plot the sum of the total nitrogen inputs into a region from human activity, they are strongly correlated with the flux of nitrogen to the coast in rivers and from sewage treatment plants (Figure 10). The relationship is linear, and surprisingly strong. If humans burn more fossil fuel, or use more nitrogen in agriculture, or import more food into a region, more nitrogen will escape to the coast and pollute coastal ecosystems. Note that the slope of this line

	NOy deposition	Fertilizer	N fixation by crops	Net Import or export in foods	Total
North Canada rivers	70	160	30	-50	210
St. Lawrence basin	610	330	260	-30	1170
NE coast of US	1200	600	750	1000	3550
SE coast of US	1020	1170	370	450	3010
Eastern Gulf of Mexico	760	1260	250	580	2850
Mississippi River basin	620	1840	1060	-1300	2220
Baltic Sea drainages	480	1730	30	20	2220
North Sea drainages	1090	5960	5	-5	7050
NW European coast	1090	2870	50	-320	3700
SW European coast	460	3370	15	-65	3780

Figure 9. The sources of nitrogen to regions surrounding the North Atlantic Ocean. Reprinted from Howarth et al. (1996).

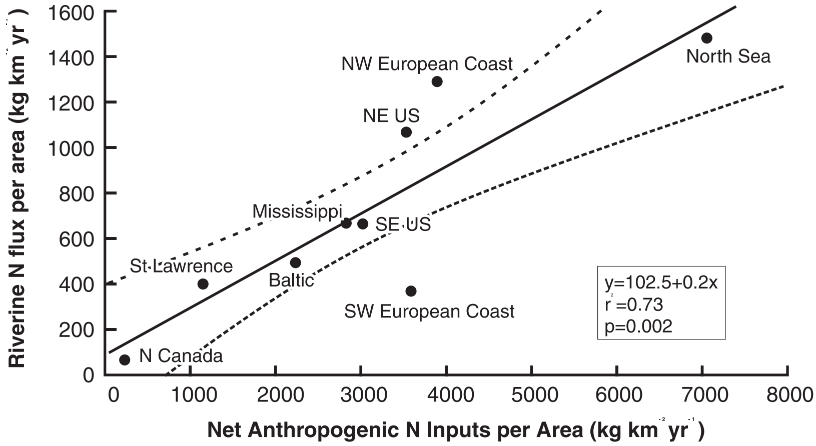


Figure 10. The relationship between nitrogen inputs to a region and the flux of nitrogen from a region to the coast for the temperate-zone regions surrounding the North Atlantic Ocean. Reprinted from Howarth et al. (1996).

is 0.20, that is, approximately 20% of the nitrogen mobilized by human activity reaches the coast, and the rest is retained in the landscape by various mechanisms.

Globally, fertilizer use is a bigger source of nitrogen use and pollution than is NO_y deposition from fossil fuel sources. However, as shown in Figure 2, much of the nitrogen from agricultural sources also flows through the atmosphere, both in oxidized forms, and as ammonium. I'll come back to the flux of ammonium in just a few minutes, but first I want to focus a little more on the issue of NO_y deposition in the northeastern United States. In the United States generally, most of the NO_y deposition comes from fossil fuel combustion, as opposed to some tropical areas where fluxes of NOx from agricultural fields are also significant sources for NO_y deposition. The regional importance of this NO_y deposition varies within the country, and is the largest single source of nitrogen pollution in the northeastern US, while being relatively unimportant in the Mississippi River basin (Figure 11).

Let's take a closer look at nitrogen sources in the northeastern United State, where deposition from fossil fuel sources is the major source of nitrogen under human control. A group led by my colleagues Beth Boyer and Nico van Breemen has made a careful analysis looking at the nitrogen flux out of a variety of watersheds in the northeastern United States, from Maine down to Virginia

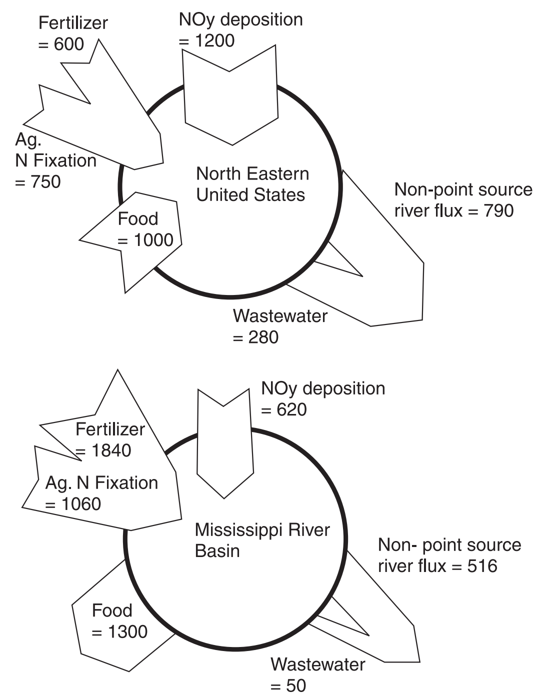


Figure 11. A comparison of nitrogen inputs and exports (in kg N km-2 year-1) for the northeastern United States and for the Mississippi River basin. Reprinted from the report of the National Academy of Sciences Committee on Causes and Management of Coastal Eutrophication.

(Figure 12). In some of these watersheds, NOy deposition is the major input, while other watersheds have significant use of nitrogen in agriculture and significant import of nitrogen in food (Figure 13). If you plot the sum of human-controlled nitrogen inputs to these watersheds, you again see that it is an excellent predictor of the flux of nitrogen out of the watershed in rivers (Figure 14), much as we saw earlier for the course regional-scale analysis.

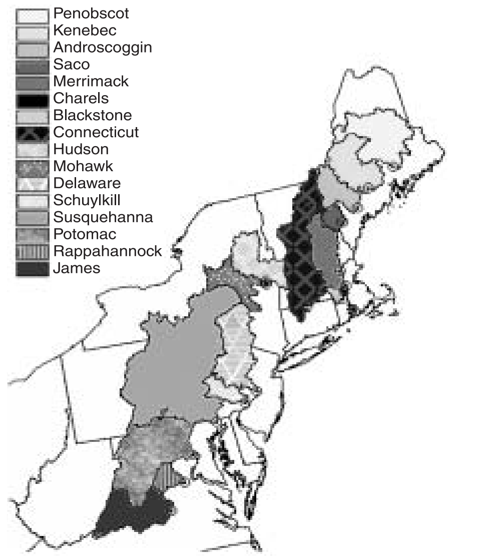


Figure 12. The major watersheds of the northeastern United States. Reprinted from Boyer et al. (2002).

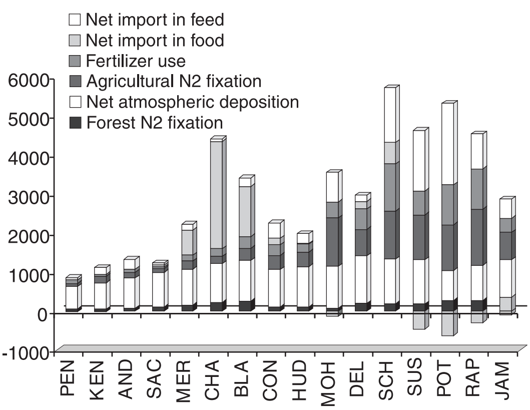


Figure 13. Inputs of nitrogen to the major watersheds of the northeastern United States (nitrogen inputs in kg/km²/yr). Reprinted from Boyer et al. (2002).

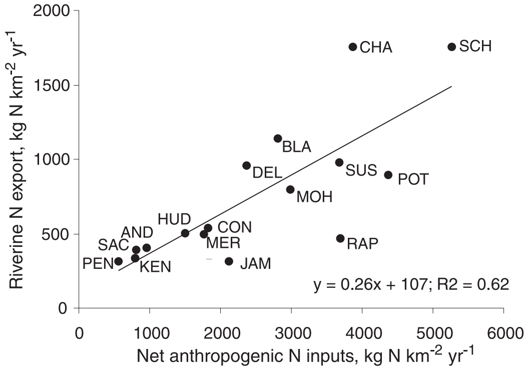


Figure 14. The relationship between nitrogen inputs per area and nitrogen flux in rivers for the major watersheds of the northeastern United States. Reprinted from Boyer et al. (2002).

One of the implications of this analysis is that a significant amount of the nitrogen deposition that falls onto the landscape, including onto forests, must be exported to rivers. This conclusion surprises a lot of scientists who have worked on the biogeochemistry of forests, because we have this paradigm, which is a reasonable paradigm, that forests do a good job of retaining nitrogen deposition until some point where they become saturated. If you add more and more nitrogen, the forest is able to retain it, since production of the forest is limited by nitrogen. This is the paradigm, until you add so much nitrogen, the forest is no longer limited by nitrogen and it starts to leach out as nitrate.

However, we now see that forests may be leakier of nitrogen even before they become nitrogen saturated. The analysis by Nico van Breemen and his group is that for the forested landscape of the northeastern United States as a whole, approximately one quarter of the nitrogen entering the forest is leached to streams and groundwater, with some of this leaving as dissolved organic nitrogen, but most probably leaving as nitrate (Figure 15).

I want to say a little bit about ammonia. While NOy deposition in the United States has been fairly steady over the past 15 years or so, the deposition of ammonia and ammonium is probably increasing. In our NAS committee report, we looked very carefully at what the fluxes of ammonium are through the atmosphere, what the deposition is and what the sources are. We

N balance for forests in northeastern U.S. (kg N $km^{-2} yr^{-1}$)

Inputs		
	Deposition	1070
	N fixation	240
		1310
Sinks and exports		
	Tree/plant storage	460
	Tree harvest	260
	Soil storage	100
	Denitrification	195
	Leaching (75% NO_3)	295
		1310

Figure 15. The inputs and fate of nitrogen to the forests of the northeastern United States, on average. The area considered are the watersheds shown in slide 12. Data are from van Breemen et al. (2002).

concluded that, for the United States, 92 percent of the ammonium flux comes from animal waste.

We are having a large-scale increase in industrial farm animal production in the United States, and that is what is contributing to the increased ammonium flux we are seeing. As I mentioned above, the deposition of ammonium globally is similar to or perhaps even larger than NOy deposition. In the United States, this is not true, and NOy deposition from fossil fuel combustion is probably some 4-fold greater than is ammonia and ammonium deposition. But the ammonia source is rapidly growing and deserves attention.

Our NAS committee, relying on the work of the International SCOPE Nitrogen Project, tried to estimate what the nature of the overall human alteration of the nitrogen cycle might be. We looked at what a pristine flux of nitrogen to coastal ecosystems might be, if there were no human activity in the landscape, no NOy deposition, and no agriculture. We concluded that for northern Canada, there has been relatively little human influence, but for the northeastern United States, humans have probably increased this nitrogen flux by at least 10-fold and, in parts of Europe, by even more than that.

Much of this change has been recent. Some of this has been going on since the start of the agricultural and industrial revolutions, but it has greatly accelerated over the last several decades, and we can see that in a variety of data sets. Fluxes in many rivers in the northeastern United States and the flux in the Mississippi River (Figure 16) have all increased as more nitrogen has been mobilized in their watersheds by human activity over the past many decades.

Let me just conclude with some of the major conclusions from our National Academy report. If any of you are interested in learning more about atmospheric deposition and coastal nitrogen pollution, I would urge you to take a look at our report.

First, the nitrogen cycle is being altered more rapidly than the cycle of any other major element globally.

As a result of that, something like two-thirds of the coastal rivers and bays of the United States are now moderately to severely degraded from nutrient pollution.

Our committee concluded, on that basis, that this is the largest pollution problem in the coastal waters of the United States.

The extent of the nitrogen alteration varies from region to region, in the United States and globally. There has probably been a 10-fold increase on average for the nitrogen flux to coastal ecosystems in the northeastern United States, and much of that increase has occurred over the last four decades.

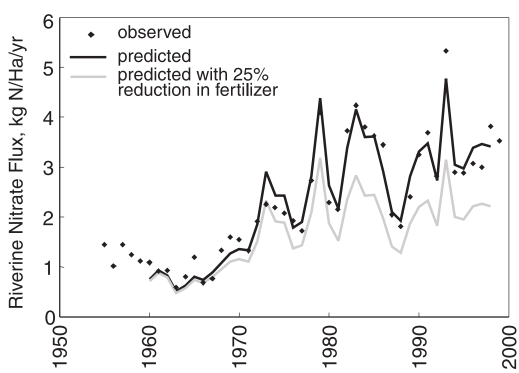


Figure 16. The flux of nitrate down the Mississippi River over time. The diamonds show actual data. The dark line shows model predictions, based on estimates of nitrogen input to the basin and variation in climate over time. The light line shows an estimate of what the nitrogen flux would have been had 25% less fertilizer been used in the basin. Modified from McIsaac et al. (2001).

Non-point sources are the dominant source of nitrogen in all regions of the world, at the scale of large regions. Non-point sources also dominate in many individual coastal ecosystems, including Chesapeake Bay and the dead zone in the northern Gulf of Mexico. However, sewage inputs are the dominant source of nitrogen to some coastal systems, such as Long Island Sound.

In some regions, the major source of nitrogen contributing to non-point fluxes is from fertilizer. Other agricultural sources are also major contributors. Animal waste from industrial-scale operations stand out in this regard, and are major contributors of nitrogen to the atmosphere as ammonia, as well as directly to coastal waters.

NO_y deposition from fossil fuel sources is the major nitrogen source in some regions, including the northeastern United States. Our committee report highlighted that many existing models and reports on the importance of NO_y deposition to coastal nutrient pollution, in the opinion of our academy study, have underestimated the extent, perhaps by a factor of up to two to three, for a variety of methodological issues.

It is a huge contributor, even more of a problem than one would have guessed, say, five or ten years ago. I will stop there and take questions, if there is time.

QUESTIONS

AUDIENCE: There is no reference to organic nitrogen. Could you identify some of the principal chemicals and what their sources might be?

MR. HOWARTH: The question is, what are the sources of the organic nitrogen and what are the chemical forms we are seeing.

The quick answer to that is I believe there is insufficient study. There are several people who have been looking at that over the last decade, but it has only been over the last decade, and it is a complex question.

In terms of the depositional sources, a lot of the material appears to be relatively low weight amine-like things, which may well have sources from these animal wastes and similar sorts of things as well.

Some of it is natural. For instance, pollen would be a contributor to the particulate phase of the organic flux.

In terms of breaking out how much of the organic deposition is natural versus from human sources, I don't think there is a strong enough consensus to say.

If we look at the landscape, what is moving, say, from forests, it would be a variety of higher weight molecular compounds, and those are very poorly characterized.

We do know, from mass balance, that once they hit larger rivers, some of this organic nitrogen is converted to nitrate and other inorganic forms, so some is labile on a time scale of days to weeks to months.

MR. BULGER: The American Fertilizer Institute thinks that most applications of nitrogen are five to 10 times what plants could actually use under those agricultural conditions. Do you think that is true? That is a huge amount of wasted nitrogen.

MR. HOWARTH: Our NAS committee took a fairly careful look at the fate of fertilizer, and concluded that over half of the nitrogen inputs to agricultural fields in the US is actually removed from the field in harvested crops. That indicates farmers are doing a pretty good job, and in fact are using fertilizer fairly efficiently.

There is room for improvement, though. Some evidence suggests that farmers in the mid-west fertilize on average at rates around 30% higher than necessary for the optimum economic return. They see little if any additional crop yield for this extra use of fertilizer, but it gives then some sense of security in knowing they are maximizing crop yield. They could probably reduce fertilizer use by 30% and see little loss of yield, while greatly reducing the loss of nitrogen to downstream ecosystems.

Clearly, we need some change in agricultural incentive policies to discourage over-fertilization.

MR. STOSS: Fertilizers in residential use, does the fertilizer data include recreational uses, such as on golf courses and residential like lawn care chemicals?

MR. HOWARTH: It does, and there we probably are seeing massive over-fertilization on golf courses and lawns. On a national scale, they are still relatively small users compared to agriculture, but locally they are going to do damage to coastal ponds. It is a big problem in some parts of the country.

MR. KNAUER: Doug Knauer with the Wisconsin Department of Natural Resources. [Question off microphone.]

MR. HOWARTH: There has been a 30 to 40-year tradition of looking at iron as a limiting nutrient as well as nitrogen and phosphorous and silicon and several other things.

Anything I say, I am sure, would be subject to some debate in some circles. Having qualified it in that way, let me say I think there is a pretty strong consensus that most of these coastal systems, certainly the ones in the temperate zones of the United States, are strongly nitrogen limited.

A couple of them are phosphorous limited. Some of them switch seasonally between nitrogen and phosphorous and there might be an additional slight effect of iron, but it isn't a major influence.

On the other hand, if you move to some of the oceanic areas of the world where iron is much lower, where there is a fair amount of iron coming from land sources, that iron becomes much more limiting, which is the basis for that argument. In these coastal systems, nitrogen really is the key.

MR. KRANOWITZ: Jeremy Kranowitz from the Izaak Walton League. At the CLEAR(?) network meeting at the end of the year, there was some discussion about nitrogen deposition and they were trying to identify power plants specifically as sources.

They said that in estuaries, by their best estimates, it was something like one to four or five percent. Do you have data that talks more about that the majority is from non-point sources, but do you have data specifically about power plants?

MR. HOWARTH: On average for the United States, the combustion of fossil fuels is contributing just over 25% of the input of nitrogen to coastal waters, from both direct deposition onto the waters and from deposition onto the terrestrial landscape with subsequent flux through rivers to the coast. As I mentioned, there is significant variation, so the NOy deposition term is more important than this in some regions such as the northeastern US and less important in others such as the Mississippi River. But on average, approximately one quarter of the nitrogen pollution is coming from fossil fuel combustion.

The US EPA estimates that power plants and other stationary sources of combustion are responsible for approximately 40% of the NO_x load to the atmosphere, and therefore for 40% of the NO_y deposition from fossil fuel sources.

If you combine these estimates, you conclude that approximately 10% of the nitrogen pollution in the coastal waters of the US, on average, come from power plants.

I think the estimates you heard of one to four percent are low, and are probably based on some of the older analyses.

It is a rapidly changing field. One of the problems is that the first estimates of what the contribution of atmospheric deposition would be to a nutrient polluted estuary are only 25 years or so old. They are good estimates, but they weren't based on a large amount of detailed monitoring data.

We still don't have good monitoring data in a lot of these coastal areas because the depositional networks were set up to look at the acid effects, not our coastal effects.

So, we don't have good handles on deposition in many areas, although people like Joe Scudlark and others are trying to improve that.

The other problem is that once the nitrogen hits the landscape, you need some sort of estimate of what its mobility gives off.

The older models – by older models I mean those that are more than four or five years old – are based on that model that nitrogen isn't going to leave the forest to any significant extent until we add so much that it saturates the needs of the forest.

The current evidence is that that is a wrong model, that nitrogen will be leaving at much, much lower levels of deposition. So, it is a much bigger problem than would have been estimated, even a few years ago.

MS. CHAN: Melissa Chan with the Department of Energy. I was wondering if you found that most of your nitrogen pollutants in the coastal areas were from U.S. sources, or whether nitrogen is a trans-boundary pollutant like mercury and can come over the oceans, or is very mobile in that way.

MR. HOWARTH: The United States produces plenty of nitrogen pollution. I think we are probably our major contributor.

Nitrogen is capable of moving through the atmosphere up to around 1,000 kilometers or so. The aerosol particle is an ammonium sulfate particle.

Most of the nitrogen in the atmosphere is being deposited fairly close to sources, and most of the things that are moving in streams and rivers are just moving at the scales of those rivers or coastal currents.

I think it is safe to say that the majority of nitrogen is coming down relatively close to home and we should clean up close to home.