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Science FINDINGS

INSIDE

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"Science affects the way we think together."
Lewis Thomas

UNDERCOVER ISOTOPES: TRACKING THE FATE OF NITROGEN IN STREAMS


Sherri Johnson

Researchers collect water samples from Amazon Creek in Eugene, Oregon, as part of a national study to understand the ways and rates at which streams process nitrogen.

"Water is the driver of Nature."
—Leonardo da Vinci

Nitrogen is an essential element for life. It's a key ingredient in amino acids, the building blocks of proteins in plants and animals. Globally and in the Pacific Northwest, naturally-occurring nitrogen has historically been a limiting factor in plant growth. That's why nitrogen-rich fertilizers were developed. Too much of a good thing, however, can quickly become a problem elsewhere in the ecosystem.

In the United States, nitrogen inputs to the landscape from human activities have doubled over the last 50 years. Nitrogen in fertilizer, emissions from fossil fuel combustion, sewage, and animal waste finds its way to streams, rivers, and ultimately the ocean.

Waterways with excessive amounts of nitrogen can experience noxious algae blooms, which in turn deplete the oxygen in the water making it uninhabitable for fish and other aquatic organisms. An extreme example of this is the dead zone in the Gulf of Mexico. Some years, this

IN SUMMARY

Excess nitrogen stemming from human activities is a common water pollutant. Fertilizer runoff, sewage, and fossil fuel emission all contain nitrogen that often ends in streams, rivers, and ultimately the ocean. Research has found that more nitrogen enters a river system than can be accounted for at its mouth, indicating that instream processing is occurring. A team of scientists conducted several experiments on streams across the country to better understand the fate of waterborne nitrogen.

Sherri Johnson from the Pacific Northwest Research Station and her collaborators from Oregon State University led the Oregon-based studies. They added small amounts of two forms of a naturally occurring nitrogen isotope to streams in forested, agricultural, and urban areas. These novel experiments enabled researchers to quantify the rate at which different forms of nitrogen are processed and removed by stream organisms. They found that small streams are particularly effective at processing ammonium, an easily altered form of nitrogen, but that uptake of nitrate, a common pollutant, was comparatively limited. They also found that land use influences the efficiency of a waterway's nitrogen processing abilities, and that stream systems are less efficient at processing and removing nitrogen when it's present in higher concentration. Management activities that increase channel complexity and maintain or enhance riparian vegetation can help reduce nitrogen loading and facilitate its processing.

zone of oxygen-depleted water stemming from the mouth of the Mississippi River has covered up to 7,000 square miles. Excessive nitrogen in drinking water also has adverse health effects for humans, leading to blue baby syndrome and possibly some forms of cancer. Because of this, nitrogen levels are regulated by the Environmental Protection Agency through the Clean Water Act.

But it's not all gloom and doom. Aquatic systems are natural filters for the landscape, removing and transforming pollutants that drain from their watersheds. "Studies have indicated that only about a quarter of nitrogen released in upstream watersheds ends up in the oceans, suggesting that nitrogen is being removed along the way," says Sherri Johnson, a research ecologist with the Pacific Northwest (PNW) Research Station in Corvallis, Oregon. The question is, what happens to the other 75 percent or so of waterborne nitrogen?

A team of aquatic scientists from across the United States has conducted several Lotic Intersite Nitrogen eXperiments (LINX) to find out. This research, funded by the National Science Foundation, examines the fate of nitrogen in water and ways that streams remove excess nitrogen stemming from human activities. Johnson and Stan Gregory, her colleague at Oregon State University, led the Oregon-based research for this national study.

STREAM CHEMISTRY

To understand the fate of nitrogen in streams requires a review of stream chemistry and the nitrogen cycle. Nitrogen gas composes 78 percent of the atmosphere, but neither plants nor animals can use it in that form. The atmospheric nitrogen must be "fixed" before it can be used, a service certain plants, bacteria, and algae perform to turn the nitrogen gas into ammonia (NH_3) or ammonium (NH_4^+), nitrite (NO_2^-), and then nitrate (NO_3^-). Once in this form, plants and algae can absorb it, and it's taken further into the food web when these are consumed by insects, fish, and other animals. The nitrogen cycle is completed during the denitrification process when different bacteria convert the nitrates back into nitrogen gas and it is released into the atmosphere.

Some nitrogen gas is harmless, but in other forms, it becomes a potent greenhouse gas. Life as we know it is balanced on these chemical processes, underscoring the importance of fully understanding how the balance may shift as environmental conditions change. For example, does the fate of nitrogen in streams change as the nitrogen concentration increases? Does the proportion of nitrogen that's processed in the upper reaches of the stream remain the same, or will more of it be processed downstream? Will more be converted to gas and released into the atmosphere?

To begin to answer these questions, the first LINX study measured how quickly nitrogen, in the form of ammonium, was taken up in streams and where it went. To do this, scientists used a novel technique. They added small amounts of a naturally occurring stable isotope of nitrogen (^{15}N ammonium) to 11 undisturbed forest streams. The isotope acted as a tracer, and researchers were able to track how far the nitrogen traveled downstream and which processes removed it from the water. Mack Creek in the H.J. Andrews Experimental Forest in Oregon was the representative site for the West Cascades. The study sites in Arizona, Kansas, Michigan, New Mexico, North Carolina, Puerto Rico, and Tennessee were selected to represent other biomes.

"The value of looking at streams in these different regions is that the streams have different physical and biological characteristics, which influence their ability to process nitrogen. The different biomes also have different amounts of naturally occurring nitrogen and different levels of input from human activities," explains Johnson.

In the first LINX study, a controlled, continuous amount of the isotope was dripped into the stream over 42 days. "We sampled everything that we could quantify, and we sampled them repeatedly," says Johnson. "Then we followed the reverse process of processing and decline of nitrogen out of biota over the next 6 weeks. This let us quantify the rates of uptake and release into different parts of the food web when we shut off the experiment."

Researchers tracked the fate of the added isotope by collecting water samples, insects, riparian vegetation, and different types of stream organic matter downstream from the addition point. The uptake of nitrogen is related to ecosystem photosynthesis, which

KEY FINDINGS

- Headwater streams in undisturbed landscapes are highly efficient at processing ammonium, an easily altered form of nitrogen. By using stable isotope enrichment techniques, scientists found that more than 50 percent of the available nitrogen was removed from the water column by aquatic biota and a small amount by terrestrial riparian vegetation.
- Uptake of nitrate, a common from of nitrogen pollution, was comparatively limited, leaving more of it to be transported downstream.
- Excessive nitrogen inputs can overwhelm a stream's capacity to handle these loads. Across a range of land use types (forest, agriculture, urban), the ability of small streams to process nitrate declined as ambient nitrate concentrations increased.

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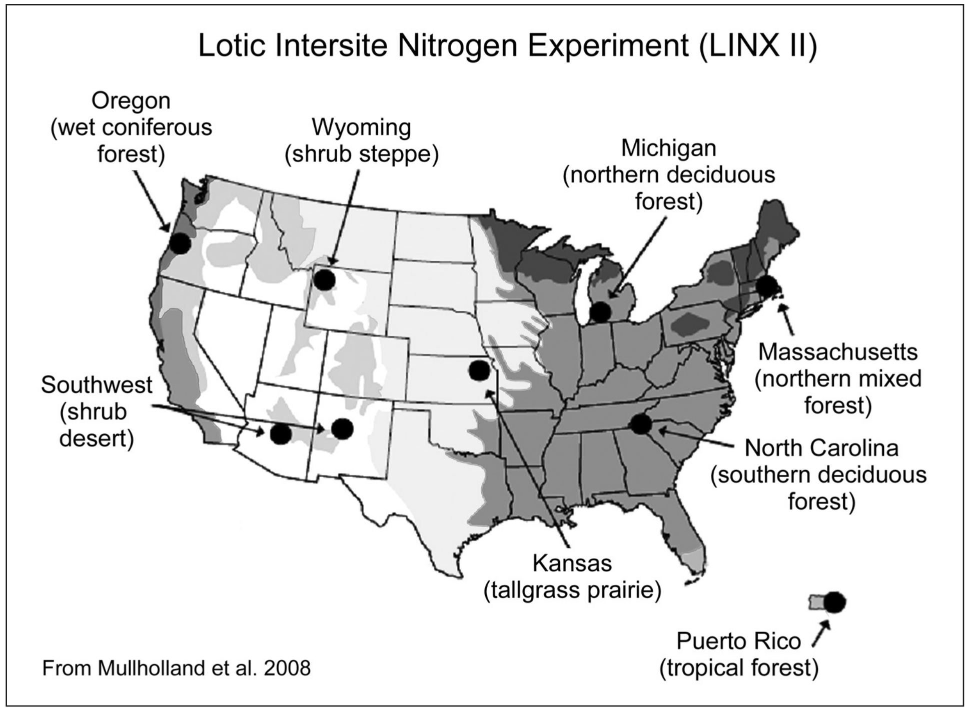
happens during the day, explains Johnson. “The primary producers in the steam really need that nutrient and suck it up. It’s a cellular process. The microbes and plants take it in from the water, and the bugs and fish are ‘labeled’ as they eat these lower-level organisms.”

Johnson points out that they weren’t fertilizing the stream. “We added such a small amount of the isotope that it didn’t raise the background, or ambient, concentration in the stream. And yet the tracer let us follow the nitrogen through the system. That was a unique aspect to this study. For years people have been trying to look at these processes, but the only way you could do it was to add more. Then you might bias the process because suddenly lots more food and nutrients are available.”

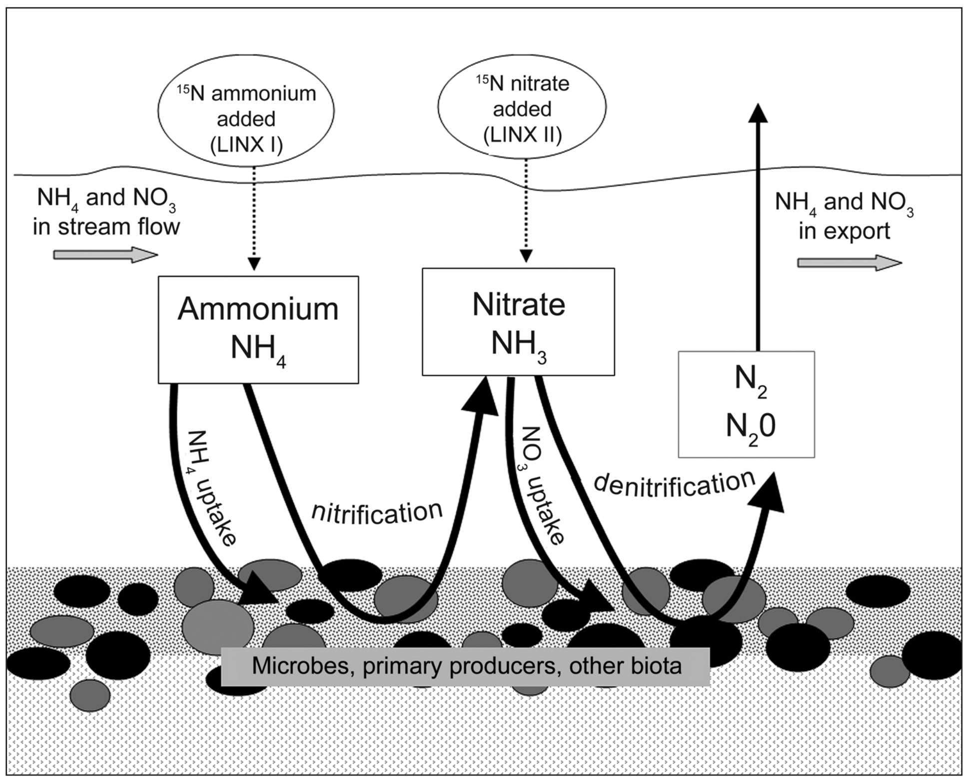
The surprising finding from this study was that up to 50 percent of the available nitrogen across study sites was removed from the stream by aquatic biota, and a small amount was removed by riparian vegetation. The scientists found that this removal happened quickly—within about 650 feet of where the tracer was introduced. This was true not only on streams lined by old forests like Mack Creek, but in many of the study streams.

The second LINX study focused on the fate of nitrate and quantified rates of denitrfication—the part of the nitrogen cycle where nitrogen is actually removed from the stream by another set of organisms, converted to gas, and released into the atmosphere. To do this, researchers dripped a different form of the isotope (^{15}N nitrate) into the streams to specifically follow nitrate through the system for 24 hours. This was a larger study, involving 72 streams across the country and included a land use component. Researchers wanted to know if urban or agricultural land uses affected a stream’s ability process nitrate, a common form of nitrogen pollution. In Oregon, the forested streams served as the reference conditions.

Johnson and her colleagues again focused their study sites in western Oregon, continuing to use Mack Creek but now including a stream on Weyerhaeuser forest land, and one on Oregon State University’s McDonald-Dunn Forest. In contrast, one of their urban streams runs through a concrete channel in downtown Eugene, another is in a park in Albany, and the third is in Corvallis. The other streams run through the agricultural Willamette Valley.



Locations of study streams in the second Lotic Intersite Nitrogen eXperiment (LINX).



A conceptual model of nitrogen processing in headwater stream ecosystems. The first LINX study focused on the nitrification process, whereas the second LINX study focused on the denitrification process.

This second LINX study found that regardless of biome, excess nitrogen inputs can eventually overwhelm stream capacity to handle these loads. “We found that land use influences stream communities,” says Johnson. “More developed land uses generally lead to more nitrogen in the local streams. At first, instream microbes and plants ramp up production to take advantage of the surplus nitrogen, but they become less efficient as nitrogen levels increase, resulting in changes to local stream communities, and ultimately, excess nitrogen is transported downstream and to estuaries.”

The cross-site analysis of all 72 streams also showed that small streams were particularly effective at efficiently removing nitrogen because they have a higher ratio of streambed to water volume compared to larger streams.

A SUM LESS THAN THE PARTS

"Before these studies, people didn't know about the fate of nitrogen or have data to quantify the rates of nitrogen processing and denitrification in streams," says Johnson. Data in hand, the next step was to develop a stream network model of nitrate removal. The model was designed to enable scaling across river basins to examine effects of land uses on nitrogen export in river networks—a useful feature given that it's not feasible to measure each and every stream. The model also takes into account different stream sizes and nitrogen removal rates that vary depending on the nitrate concentration.

Before the LINX studies, explains Johnson, "when we stood at the mouth of a stream and took a water sample, we thought that the levels of nitrogen in that sample were what was coming out of the hill slopes. The LINX studies indicate this isn't the case and quantified this across a range of sites. If there wasn't instream processing, you would see even more accumulation downstream, but because these streams are very active sites of uptake, we don't see all that nitrate downstream."

"Streams are more than simple delivery conduits linking terrestrial and marine ecosystems," says Johnson. "These studies demonstrate that streams actively retain and transform dissolved inorganic nitrogen. Granted, our numbers are from smaller streams, not the Mississippi, the Columbia, or even the main stem of the Willamette," says Johnson. "But we are able to help quantify some of these processes, and we are applying them to situations that we can't yet measure."

One question still to be answered is how long the nitrogen remains in the stream biota. Another broader question relates to the effects of forest management and climate change on instream concentrations and export. Johnson and another group of colleagues are beginning to address these in a study that uses the findings from the LINX experiments and combines them with 40 years' worth of biogeochemical and hydrologic data from H.J. Andrews and other experimental forests to track multiyear changes in nitrogen availability and export following disturbances such as timber harvest and drought.

Researchers process water samples.

LAND MANAGEMENT IMPLICATIONS

- Streams process and transform dissolved inorganic nitrogen (both ammonium and nitrate).
- Stream mosses, liverworts, micro-algae, and fungal and bacteria communities on wood are critical drivers of nitrogen processing. Their presence is vital to maintaining the clean water that salmon and other charismatic species need.
- The condition and ability of headwater streams to process nitrogen will be reflected in the condition of larger aquatic ecosystems downstream.
- Land use influences stream communities. The efficiency of denitrification, the only process that completely removes dissolved inorganic nitrogen from aquatic systems, is particularly affected by loss of channel complexity and increased nitrogen concentrations.
- Riparian vegetation serves as a filter, removing nitrogen from streamwater and groundwater.

AVOIDING SYSTEM OVERLOAD

"The ultimate goal of our research," says Johnson, "is to provide land managers and planners with a better understanding of the importance of streams in controlling the nitrogen loading to lakes and coastal ecosystems, and to show how land management activities can preserve or enhance the ecosystem services provided by streams."

Because streams become less efficient at processing and removing nitrogen when more is present, protecting stream ecosystems from excessive nitrogen loading in the first place is critical to maintaining water quality. One concern, explains Johnson is that policies that may lead to significant land conversion, such as the emerging demand for biofuel, may lead to increased nitrogen levels in the Nation's aquatic ecosystems as more fertilizer is used


Sherri Johnson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Streams with greater channel complexity and riparian vegetation more efficiently processed nitrogen than streams in simple channels and with little riparian vegetation. Pictured above are examples of the forest, agricultural, and urban streams sampled in Oregon as part of the national study on stream denitrification.

to grow the sources of biofuel. Another concern is residential development in forested areas that may lead to increased nitrogen inputs higher in the watershed with cascading effects downstream.

The contact opportunities between water and the organisms that process and remove nitrogen appears to be one critical factor in determining the amount of nitrogen that will be removed. "The small streams, which constitute the majority of any given watershed, are the most tightly coupled to terrestrial ecosystems," says Johnson. Consequently, headwater streams are particularly active sites for nitrogen processing. The condition of aquatic ecosystems downstream is tied to the condition and ability of headwater streams to process nitrogen. Groundwater from hill slopes and subsurface flows under the stream bottom are also important because the water percolates slowly through those systems, allowing more contact time with the organisms that process and remove nitrogen.

"Streams with a lot of channel complexity—boulders, fallen logs, braided channels, backwaters, and other obstructions—do a better job at nitrogen uptake than those with simpler, single-chute channels," says Johnson. Again, this is because the complexity provides more opportunities for the water to come into contact with the stream organisms. Restoring channel complexity to improve fish habitat likely will have the added benefit of improving water quality.

In the Pacific Northwest, where much of our attention focuses on fish when we talk about water quality, it is important to recognize the critical role of stream mosses, liverworts, micro-algae, and fungal and bacteria communities on wood. "Their presence is vital to maintaining the clean water that more charismatic species like salmon need," Johnson explains.

Streamside vegetation also is an influential factor in nitrogen uptake, so the condition and composition of the riparian vegetation is important. Combining channel restoration with management efforts that focus on enhancing riparian plant communities may also lead to reductions of nitrogen. "These types of restoration activities can go hand in hand," says Johnson.

"A river is the report card for its watershed."

—Alan Levere

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Rhonda Mazza is a science writer with the Pacific Northwest Research Station. Michael Feinstein, a science writer in Vashon, Washington, contributed to this issue.

FURTHER READING

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Local farm families who graciously gave us access to the streams on their lands