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PROFILE

Profile of Stephen R. Carpenter

Whether you are a fisherman, a kayaker, or just a lover of the outdoors, the sight—and smell—of a scummy, algae-covered lake may not be particularly appealing. For Stephen R. Carpenter, who is all of the above as well as a renowned lake ecologist, the problems associated with this algae buildup, or eutrophication, go far deeper than simple aesthetics. "Eutrophication is a significant environmental problem that can impact humans on a recreational, economic, and even public health level," says Carpenter, "and it's likely to intensify in the coming decades due to increases in human population, demand for more food, land conversion, and fertilizer use."

Carpenter, the S. A. Forbes Professor of Zoology and Halverson Professor of Limnology at the University of Wisconsin–Madison (Madison, WI), has studied freshwater ecology for over 30 years. His multitude of research interests include eutrophication, aquatic food webs, nutrient cycling, and ecological economics. Beyond his research and teaching, Carpenter also has, among other activities, served on numerous National Science Foundation (NSF) advisory panels, been President of the Ecological Society of America (2001–2002), and served as the Chair of the Beijer Institute of Ecological Economics Board of Directors (2003–2005). In addition, he works on the editorial board of multiple scientific journals, including PNAS. Carpenter was elected to the National Academy of Sciences in 2001.

Recently, Carpenter has become interested in the capabilities and limits of ecosystem forecasting. In his Inaugural Article published in this issue of PNAS (1), he forecasts the long-term impact of the primary human contributor to lake eutrophication: nonpoint phosphorus pollution. Using Wisconsin's Lake Mendota as a model, Carpenter projects the phosphorus concentrations in the water, sediment, and surrounding soils over the course of a millennium. The scenarios predict a need for dramatic change because moderate reductions in agricultural phosphorus will only delay, and not prevent, eutrophication. The results also demonstrate the persistence of eutrophication. "In theory, eutrophication is reversible," says Carpenter, "but from the perspective of a human lifetime, once you push a lake over that threshold, eutrophication is a one-way trip."

Stephen R. Carpenter and algae on Lake Mendota, WI.

From Streams to Lakes

Born in Kansas City, MO, in 1952, Carpenter was immersed in science and the outdoors at an early age. Carpenter spent most of his youth in Bethesda, MD. "It was a much smaller place back then," he says. "Bethesda was at the urban fringe of DC. Everything beyond that was rural." His father, Richard, was a chemist, so there was always a lot of science discussion in the household. After his father became a staff member on the National Academies' Board on Environmental Studies and Toxicology, ecology and the environment became a regular part of their conversations.

Growing up, Carpenter spent many summers on his grandfather's farm in Missouri. In between helping with the farm work, he and his cousins found time to enjoy the nearby wilderness, whether fishing, camping, or just frolicking: "Boys who are roaming free in a farm environment find all kinds of interesting things to do." Carpenter thinks his transition to an ecologist just stemmed naturally from his youth. "Hiking, camping, fishing, and hunting all come together in ecology," he says. "I was really excited when I discovered there was a way to get paid for being a scientist outdoors."

Carpenter's interest in ecology blossomed during his undergraduate education at Amherst College (Amherst, MA), where he met a pair of dynamic teachers: Stuart Fisher and Lincoln Brower. "Fisher and Brower . . . were very influential and made me think ecology was just a great thing to do," says Carpenter. "Fisher, in particular, was an aquatic systems ecologist, and that field really captured my imagination."

Carpenter performed undergraduate research for Fisher, who specialized in stream ecology, and Carpenter published his first paper on the primary production of macrophytes (rooted aquatic plants) in the Fort River of Massachusetts (2). Carpenter's work in Fisher's laboratory convinced him to further his ecological research in graduate school, and after receiving his B.A. in biology in 1974, Carpenter entered the graduate programs in Botany and Oceanography & Limnology at the University of Wisconsin–Madison. He joined Michael Adams' laboratory to study the role of macrophytes in the phosphorus cycle of lakes.

Graduate research gave Carpenter his first exposure to the three fields he would continue to study over the course of his career: lake science, phosphorus cycling, and the emerging field of ecosystems ecology. "My project was part of the follow-on grants to the International Biological Program," says Carpenter. "The [International Biological Program] was, I think it's fair to say, the first big ecosystem research program funded in the United States."

Graduate school also proved to be personally rewarding for Carpenter. He met fellow student Susan Moths, whom

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This is a Profile of a member of the National Academy of Sciences to accompany the member's Inaugural Article on page 10002.

he married in1979, the same year he defended his doctoral dissertation. Carpenter did not take much time to celebrate, though—soon after graduation, he drove from Wisconsin down to South Bend, IN, to begin teaching at Notre Dame University.

Untangling the Food Web

Carpenter did not leave Wisconsin completely behind, however. He continued to work on lake research at Notre Dame and carried out most of his studies at the university's field station near Land O' Lakes in Wisconsin. He shifted his research focus to include plants and animals, as he began studying how the food web structure controls lake ecosystems. In 1982, he began collaborating with Jim Hodgson and James Kitchell, two other scientists interested in the dynamics of lake ecosystems, on the Trophic Cascades Project.

The goal of this project was to understand the dynamics of food webs through large-scale manipulations of entire lakes. One of the early studies involved physically exchanging the bass and minnow populations between two lakes, creating altered environments with contrasting top predators. Through these manipulations, the researchers could test the theory that altering the biomass of the higher levels of a food web could regulate the biomass and productivity of the plankton community (3).

After 10 years at Notre Dame, Carpenter returned to Madison for a faculty position opening in the Department of Zoology. Carpenter was curious about the respective contributions of aquatic and terrestrial carbon in supporting a lake's food web. The prevailing theory, first proposed by Stephen Forbes in 1887, was that lakes were self-sufficient ecosystems. Many ecologists had begun to question that theory but could not actually test it because aquatic and terrestrial carbon are virtually identical in isotopic composition.

The Trophic Cascades experiments suggested that big fish can regulate carbon fixation and determine whether a lake acts as a source or a sink of atmospheric carbon (4). Together with Michael Pace, Jonathan Cole, and collaborators in Sweden, Carpenter and Kitchell tested the importance of terrestrial carbon for lake food webs (5, 6). As it turned out, lakes were not isolated communities and were in fact strongly linked to the surrounding environment.

"Our results showed that the conventional wisdom is inaccurate, and that the food web of a small lake is strongly dominated by the terrestrial ecosystem," says Carpenter. "Up to 50% of the organic carbon in the water comes from the land." The researchers found labeled C-13 throughout the food web—in bacteria, plankton, and even fish. These findings helped strengthen the concept that neighboring ecosystems are interconnected and dependent on each other.

The case may not be entirely closed, however. "One of the big questions in this study is whether the findings hold for bigger lakes," Carpenter points out. "These isotope experiments are very expensive, so the lake we studied is only about 2 hectares. We are now doing an experiment in a 30-hectare lake, which is about the largest we can afford."

Returning to His Roots

While Carpenter continued working on the Trophic Cascades Project after his return to the University of Wisconsin in 1989, Madison's location and strong limnology program allowed him to pursue other interests. Some of that research included examining the accumulation of polychlorinated biphenyls (PCBs) in fish and invertebrates in Lake Michigan (7), but a majority involved studying Madison's Lake Mendota, a 40-km^2 body of water that is one of the most extensively studied lakes in the world. One of Carpenter's many projects at Lake Mendota was a renewed interest in the phosphorus cycle and its role in eutrophication.

Carpenter particularly focused on nonpoint phosphorus pollution, or pollution that does not originate from a specific source, such as a factory. Most nonpoint pollution, Carpenter says, comes from agriculture. "In agricultural or dairy watersheds, there's a tendency to import a lot of phosphorus, mostly in the form of chemical fertilizers or animal feed," he explains. "While some phosphorus does leave the watershed, such as in the form of food, most of it builds up in the soils. And then a small amount runs off to surface water, but it doesn't take very much to cause a lot of damage."

> **"The food web of a small lake is strongly dominated by the terrestrial ecosystem."**

Carpenter studied how elevated phosphorus impacted the Lake Mendota ecosystem, including its effect on phytoplankton production, food web structure, and water clarity. Carpenter's investigations began to branch into devising strategies to manage the phosphorus cycle. This expansion brought him to the interdisciplinary field of ecological economics, which seeks to quantify the relative value of ecosystem services: "Ecosystem services can be defined broadly as the valuable things people get from nature." In terms of lakes, such services include irrigation, fishing, hunting, swimming, and drinking water. Carpenter thus began examining the economics of eutrophication. He compared the benefits lakes provide if they remain clean and clear versus the benefit factories or farms receive by causing eutrophication. The goal of this comparison is to find a level of phosphorus input that maximizes benefits to both sides (8).

Most recently, Carpenter has developed an interest in ecological forecasting, another interdisciplinary field that seeks to project ecosystem dynamics by building models based on past and future trends. "Many ecologists are getting interested in ecological forecasting because it's a really exciting research frontier," says Carpenter. "Ecologists have been talking about it since the late 1990s, but some of the new tools for statistical acquisition and modeling open up whole new opportunities to tackle forecasting-type problems."

"However, the most important challenge of ecological forecasting is not the projections themselves," Carpenter adds. "They are intellectually interesting, but they are only part of the job." Rather, he believes, accurate assessments of the uncertainties and limits of ecological forecasts are the critical challenges facing ecologists. "Many features of change are fundamentally unpredictable," he says, "so a big part of dealing with change is building resilience against the unpredictable and retaining the capacity to adapt when surprising things happen."

In his Inaugural Article (1), Carpenter projects the phosphorus levels in the water, sediment, and soil around Lake Mendota over 1,000 years and how these levels would affect eutrophication status of the lake. He then proposes two possible management plans that would reduce the input of soil phosphorus to potentially improve the lake's condition.

The first plan Carpenter puts forth involves balancing the phosphorus budget, such that no more phosphorus is introduced into fertilizer than leaves in the form of food products such as meat or grain. Although balancing the phosphorus budget may seem like a simple solution, "the simulation shows that so much phosphorus is stored in the upland soils that eventually the lake will be driven over a threshold," he explains. "This could take as long as 150 years, but once the lake is driven over the threshold, water quality is substantially worse and persistently so."

In his article, Carpenter also explores a second, more dramatic policy shift for effectively stopping phosphorus imports. "Under that more severe scenario [of stopping agricultural import]," says Carpenter, "the lake gets no worse and begins to make a smooth recovery, although it does take a long time."

Carpenter adds that his simulations only considered agricultural phosphorus input. In practice, humans could take other measures, such as installing buffer strips to absorb phosphorus or erecting structures to retard erosion, which could speed up the recovery process. Although he does not know how many of these measures are feasible, he says that at a minimum some change is needed: "We can't simply continue with the status quo. That basically writes off water quality."

A Call for Change

Although his Inaugural Article and other recent projects focus on Lake Mendota, Carpenter believes his models are applicable to lakes around the world: "I became quite active in studying eutrophication globally, and that sparked my interest in global phosphorus cycles and the ways that large-scale management of phosphorus is affecting lakes." In 1995, he had an opportunity to pursue this interest when he received a Pew Fellowship in Conservation and the Environment. "That fellowship allowed me to look very broadly at lake degradation and causes of environmental problems," he says, "and it was a real switch point in my career."

In the past decade since receiving the Pew Fellowship, Carpenter has lent his voice as a lake expert to bring attention to various ecological issues. In 2001, he helped author a viewpoint paper, along with James Clark of Duke University and other prominent scientists, addressing the role of ecological forecasting in the decision-making process (9). The same year, he and other international scientists coauthored another paper highlighting the dangerous losses of resilience that make ecosystems vulnerable to rapid and severe degradation (10). Carpenter points out that lakes often do not undergo a steady progression from clear to eutrophic, and instead they can exist in two stable states, clear or turbid, separated by an unstable intermediate. Currently, many lakes are stressed to levels near the unstable point. "A big runoff event, like an extremely wet summer or a big thunderstorm, could come along and quickly tip the balance," he says "It's essentially an accident waiting to happen."

In June 2001, Carpenter undertook his largest ecological forecasting project by taking part in the Millennium Ecosystem Assessment, an international, multipartner-funded program launched by the United Nations. "The goal of this program was to understand globally the status, trends, and plausible futures of ecosystem services," he says. Carpenter served as cochair for the Scenarios Working Group: "We were charged with looking up to 50 years in the future and projecting what the situation for ecosystem services might be under various assumptions about changes in global policy, demographics, [and] global governance."

After 5 years of information gathering and research, the Scenarios team produced a mixed bag of results; although they concluded that the environment on Earth was deteriorating, it was still treatable (11). "There are a number of policies that could improve ecosystem services," says Carpenter, "and all of them are being practiced somewhere at a large enough scale that you can tell that they work. Unfortunately none of the policies are being practiced at the scale needed to improve global ecosystem services by 2050."

Carpenter plans to do what he can to help implement some of those policies, and he also plans to remain active in ecosystem forecasting and ecosystem management. "I think that ecologists have a tremendous role in understanding change," he says. "We are on the brink of some very big changes in the way ecosystems function and in the way people relate to ecosystems." He notes that findings from the Millennium Ecosystem Assessment showed that recent environmental changes influenced by humans are some of the fastest seen in history, and future changes might be faster still. "While some of these changes may be beneficial, many others can be potentially threatening."

"We simply have to change the way we do business in managing ecosystems," he adds, "and in that regard ecosystem ecologists have an opportunity and responsibility to work with policymakers and scientists from other disciplines to make those changes as constructive as possible. We're either going to make changes on our own or get some hard ones forced on us by nature, and the former is much more preferable, in my opinion."

Nick Zagorski, *Science Writer*

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