Pacific salmon bring it all back home

Even in death, these fish fuel life in their natal streams

Jeff Cederholm has been spending a lot of his time with dead fish. During the past few years, he has studied hundreds of coho salmon carcasses in dozens of streams. He has tracked the bodies using radio telemetry and spent hours in blinds to see which creatures eat the carcasses. He has even used night-vision goggles to observe bobcats dining on deceased coho after dark.

He is not suffering from some morbid fish fixation. Cederholm, a salmon biologist for the Washington Department of Natural Resources, is studying the coho salmon's role in the ecology of the small headwater streams in which the fish spawns. He and his colleagues are finding that coho enrich the entire ecosystem of their spawning streams, sustaining algae, aquatic insects, streamside plants and wildlife, and the next generation of young fish.

Like other species of Pacific salmon, coho hatch out of eggs laid in streambed gravel; migrate out to sea, where they spend most of their adult life; and return to natal streams to spawn and die. "Salmon are the only animals that return nutrients to the land from the sea," says Cederholm.

By the mid-1980s, when Cederholm began his study of coho carcasses, it was clear that salmon runs throughout Washington, Oregon, and California were declining, but few researchers had addressed what the loss of the salmon might mean to the ecology of traditional spawning habitats. The prevailing belief maintained that salmon carcasses—particularly those of coho, which spawn in steep headwater streams—were quickly washed away after spawning and had little effect on the nutrient balance of freshwater habitats.

by Sharon Levy

Still, Cederholm was becoming curious about the importance of spawned-out salmon. "The healthiest spawning streams," he points out, "are loaded with salmon carcasses." He wondered if abundant carcasses actually improve fish habitat by bringing in nutrients.

To test the assumption that most dead coho were quickly washed out of headwater streams, Cederholm tagged coho carcasses obtained from hatcheries, planted them in streams, and tracked their fate. He found that streams containing plenty of logs and rootwads—called large organic debris, or LOD—from surrounding forest retained most of the carcasses, which accumulated in pools created by LOD. These pools also provide shelter for young salmon.

Logging and other human activities have decreased the amount of LOD in many Pacific Northwest streams. Early loggers used waterways to transport downed trees, a practice that scoured streambeds and ensured the disappearance of big, easily accessible trees from stream banks. Many streamsides are now dominated by second-growth hardwood forests. Unlike the rot-resistant conifers that once shadowed the streams, hardwood trees decay so quickly that they fail to provide long-term pools for fish. Moreover, past efforts to clear streams of barriers to salmon migration—although well intentioned—often went too far, removing LOD that is an essential part of salmon habitat.

Cederholm and his coworkers observed a surprising array of species feasting on dead coho, including otters, black bears, raccoons, and skunks. These larger animals often pulled carcasses onto streambanks, where leftovers were scavenged by wrens, shrews, mice, and other small creatures. Coho spawn in the fall, and their carcasses remain through the winter, the hungriest time of year for wildlife in Pacific Northwest forests. Perhaps most, if not all, woodland animals rely on salmon to help sustain them until spring. Even white-tailed deer sometimes feed on salmon carcasses.

Clues from Alaska

In 1890, Private Harry Fisher, a member of a US Army survey party exploring Washington State's Olympic Mountains, lost his way and became the first man to explore the whole length of the wild Queets River. Although at first he feared that he might starve, he feasted on salmon throughout his journey. Describing a September night on the Queets, he wrote: "Although warm and comfortable, I might as well have selected a camp in Barnum's Menagerie so far as sleep was concerned. Located near a shoal in the stream, great salmon threshed in the water all night long, in their effort to ascend the stream. Wild animals which I could not see snapped the bushes in all directions, traveling up and down in search of fish."

This kind of scene has faded into history on the Olympic Peninsula and much of the Pacific Northwest Coast. Many runs, and many thousands of salmon, have succumbed to dams, water diversions, overharvesting, and pollution from agricultural runoff, logging, and urban sewers. On the Olympic Peninsula, where Cederholm did his first carcass experiments, salmon have declined to less than half their former numbers, and many runs have vanished completely.

But in Alaska, where many rivers continue to flow undammed and human settlements are still dwarfed by the vast landscape, visitors can witness something resembling Harry Fisher's description of fish along the Queets a century ago. "Until you see it, you have no idea what the salmon are like, 20 fish going up the river abreast," says Thomas Kline, a research scientist at the Prince William Sound Science Center in Cordova, Alaska. "It's very awe inspiring to see these huge runs and then realize the effect they are having on freshwater ecosystems."

Kline did the research for his doctoral dissertation at Iliamna Lake in southwest Alaska. By applying known isotope-tracing techniques in a new way, he became the first researcher to show direct evidence of marine nutrients moving from salmon carcasses into a freshwater food web.

Previous researchers had tried to document the importance of massive migrations of pink and sockeye salmon to the nutrient balance of the fishes' freshwater habitats. Some biologists had tried to correlate the abundance of salmon carcasses with the density of algae or zooplankton. Others had used mass balance analysis—constructing a nutrient budget based on measurements of nutrients in individual salmon and estimates of the number of spawners and nutrient concentrations in lake water. An earlier study in Lake Iliamna had estimated that in years of peak sockeye runs, salmon contributed more phosphorus to the lake than all other sources combined.

Then Kline and his graduate advisor, John Goering, came up with the idea of adapting a stable-isotope tracing technique for their study of the lake's ecology. "Heavy" nitrogen and carbon—^{15}N and ^{13}C—are naturally occurring, stable isotopes that are found in much higher concentrations in the ocean than in freshwater or terrestrial environments. Goering was fascinated when he came across a study that used isotope signatures in human bones to assess the diets of prehistoric peoples. Coastal people who relied on marine food sources had higher levels of the heavy isotopes in their bones than did inland, agricultural people.

Biologist Jeff Cederholm, here with a chinook salmon on Donkey Creek, Washington, has made new discoveries about the importance of dead salmon to stream ecosystems. Photo: Jennifer Wilson.

In the same way, isotope signatures could identify salmon-derived nutrients in the diets of living organisms in Lake Iliamna. Because salmon do not feed during their spawning migration, their tissues retain high levels of marine nutrients. Kline was able to track individual atoms of carbon and nitrogen as they moved from the bodies of dead sockeye into the algae, aquatic insects, and fishes of the lake. His results, which he reported in 1993 in the *Canadian Journal of Fisheries and Aquatic Sciences*, were dramatic. Up to 90% of the nitrogen in benthic algae came from salmon, as did up to 70% of the nitrogen in net plankton and juvenile sockeye.

In a related study, Kline compared levels of heavy nitrogen and carbon in the biota of two sections of Sashin Creek, in southeast Alaska. A waterfall on Sashin Creek acts as an impassable barrier for salmon. Pink salmon spawn below the falls, but no anadromous fish occur upstream. In the salmon spawning area, Kline found that more than 90% of the nitrogen in algae was derived from salmon just after spawning, and nearly 50% at other times of year. Aquatic insects and nonmigratory rainbow trout in the spawning area had much higher levels of the heavy isotopes than did insects and trout from above the waterfall.

The coho connection

Sockeye and pink salmon love a crowd. Unlike coho and chinook, which disperse along spawning streams and stake out mating territories, sockeye and pinks migrate and spawn in dense groups. These differences in behavior may account for a difference in how fisheries biologists have responded to Kline's work. His results captured the attention of Alaskan fisheries biologists and limnologists working with sockeye and pinks. But in Washington, where coho and chinook are the principal species of concern, few experts seemed to think that Kline's findings would apply. "The question," explains Bob Bilby, aquatic ecologist for Weyerhauser Company, "is whether coho also make an important contribution to nutrient balance in their spawning streams."

The answer that Bilby has derived from his own research comparing Washington streams with and without coho is a resounding yes. Bilby measured levels of heavy nitrogen and carbon in organic slime from streambed rocks, riparian plants, aquatic invertebrates, and fish. Levels of ^{15}N in all of these life forms were significantly higher in spawning streams than in streams devoid of coho. In one such stream, amounts of marine-derived nitrogen ranged from 10.9% in invertebrate predators to 30.6% for juvenile coho.

Levels of ^{13}C also were higher in the biota of spawning streams, with the exceptions of streamside plants and of invertebrates that feed principally on fallen plant parts. These exceptions are not surprising, because the primary source of carbon for terrestrial plants is atmospheric carbon dioxide—a source unlikely to be affected by migrating salmon.

Some animals take up marine nutrients by the fairly obvious route of eating coho carcasses, eggs, or newly emerged fry that have been nourished by a yolk sac derived from parental tissues. But more subtle mechanisms also play an important role in incorporating marine nutrients into the food web of spawning streams. Bilby found that the mixture of algae, fungi, and bacteria that forms a slimy coating over submerged rocks acts as a sponge, taking up nutrients from decaying coho carcasses. Indeed, even the surface of gravel can absorb salmon nutrients from stream waters. Once absorbed by the gravel, the nutrients are taken up by aquatic insects and worms that feed by scraping organic matter from rocks or by gathering bits of detritus from the streambed. In coho spawning streams, these classes of invertebrates—known as grazers and gatherers—contain high levels of marine-derived nitrogen and carbon.

Washington State biologists add coho salmon carcasses from a hatchery to a stream to evaluate the response of the fish community in the system to enhanced availability of carcass material. Photo: Robert E. Bilby.

Within hours of a spawner's death, its carcass is invaded by invertebrates. In swift water, caddisfly larvae and other scavengers feed inside gill cavities or beneath carcasses for protection from the current. But in still water, carcasses may be almost completely covered by feeding insects. More than 1000 caddisfly larvae may crowd together on a single fish head. A 1976 study by biologist N. H. Anderson in the journal *Ecology* suggested that feeding on carcasses may be critical to the growth of some aquatic insect larvae.

Fish, in their turn, feed on both the invertebrates and the carcasses. For growing juvenile coho, fuel provided by dead spawners comes at a critical time. Coho fry emerge from the gravel in March or April and spend the following winter in their home streams before migrating to sea. The availability of nutrients during this first winter can make a vital difference to a whole cohort of fish.

The evolution of anadromy—the salmonid behavior of splitting the life cycle between sea and stream—may itself have been an adaptation to recurrent famine in nutrient-poor lakes and streams. Like the cold waters that cradle young sockeye in Alaska, Washington State's salmon streams provide little sustenance compared with the wealth of the ocean. In winter, deep forest shade and heavy rainfall lead to turbid, scouring flows that cause algae to die back and primary production to drop even lower.

Bilby's work, in the context of other research, provides strong evidence that coho carcasses form a crucial larder of nutrients in these streams during fall and winter. Juvenile fish feed heavily on carcasses, eggs, and scavenging insects. Up to 95% of the stomach contents of a rapidly growing young fish are likely to be spawner derived.

Bilby found that the growth rate of juvenile coho more than doubled with the arrival of adults. In one case, the average rate of growth of individual fish increased from 7 milligrams per day in summer to 16 milligrams per day during and after the spawning season. By contrast, young cutthroat trout in a tributary stream that is inaccessible to migrating coho showed a decline in growth rate during the winter, the period when juvenile coho were growing fastest. "Increased growth is very important, particularly for anadromous salmonids," says Bilby. "The larger they grow, the better they survive their inland winter and the better they survive in the ocean."

The carcass famine

The low productivity of streams in the Pacific Northwest means that no other nutrient sources are available to compensate for declining returns of adult coho. Bilby fears that coho may be caught in a kind of negative feedback loop. Fewer returning adults means a decline in juvenile growth and survival, leading to further declines in the number of returning adults and in the capacity of spawning streams to support fish.

The same process appears to be at work in some sockeye spawning areas in Alaska. Like coho, young sockeye overwinter in their home waters and rely on nutrients from adult spawners during a crucial growing period. In Kline's Lake Iliamna study area, sockeye abundance changes in a natural five-year cycle. Kline has demonstrated that the level of marine-derived nitrogen in young fish declines in years when the number of returning adults is low. And if salmon carcasses have a clear impact in Iliamna, Alaska's largest lake, their effect on smaller systems is even more pronounced. In some of the state's smaller sockeye lakes, declines in the salmon population may be due largely to nutrients lost as fewer adults return to spawn.

Bilby and Cederholm are collaborating on a study designed to determine how many coho spawners are needed to nourish the next generation of young fish. "We're looking at streams with varying levels of spawning populations and tracing levels of ocean nutrients in young of the year," explains Cederholm. As the number of returning adults in a stream rises, the proportion of marine isotopes also should go up.

The researchers want to determine if a saturation point occurs at which a population of growing juvenile coho cannot absorb more spawner-derived fuel. Based on preliminary studies, they believe that this kind of pattern does exist. They are now addressing the complex question of how many adult fish are needed to bring an entire watershed to this nutritional saturation point. "We need to allow as many adults as possible to return to spawn," says Bilby. "Over several generations, this will build up nutrient capital."

> "The whole riparian ecosystem depends on salmon carcasses"

The findings of this ongoing study may influence regulations governing commercial and sport fishing for coho. Already, fisheries managers in Washington and Oregon have begun to put spawned-out hatchery salmon into spawning streams, instead of dumping the fish in landfills. Although this tactic may help to increase nutrient availability over the short term, Bilby views it as a temporary fix, not the ultimate answer to the coho conservation dilemma.

That dilemma continues amid intense political wrangling. For more than four years, environmentalists and fishermen have been pushing to have coho in California, Oregon, and Washington listed as threatened under the federal Endangered Species Act. Listing has been strongly opposed by the timber and hydropower industries, ranchers, and others likely to be affected by environmental restrictions aimed at protecting coho habitat.

Nevertheless, during the past year the National Marine Fisheries Service (NMFS) listed some populations of the fish. Central California coho were listed late in 1996, but the agency delayed a decision on coho in northern California and Oregon, citing scientific disagreement over the status of these populations. Then, last April, NMFS listed coho in northern California and southern Oregon.

Because so many human activities have harmed Pacific salmon, a serious effort to save them will affect almost everyone in the northwest. But the salmon's loss would likely have equally profound effects on the region's streams and forests—effects that few would have imagined before Kline, Bilby, and Cederholm began to explore the vital importance of dead salmon.

For Cederholm, the connections between salmon and the life of northwestern forests were dramatized when he began finding tags from his study carcasses in piles of bear scat. "Although carcass numbers on our study streams were at one-tenth or one-fifteenth of historical levels, we noticed much more wildlife activity along streams when carcasses were present," he says. "The animals that eat carcasses poop along the streambanks and fertilize the soil. It's all tied together. The whole riparian ecosystem depends on salmon carcasses." ❑

Sharon Levy is an Arcata, California, freelance science writer who is developing a special interest in the biology of rot and decay. The sight of chinook salmon spawning in an undammed river stands out in her memory as one of the wildest events she has ever seen.