Food Chains: The Carbon Link

Borrowing a technique from geochemistry, ecologists move from guesses to numbers

By STEPHEN HART

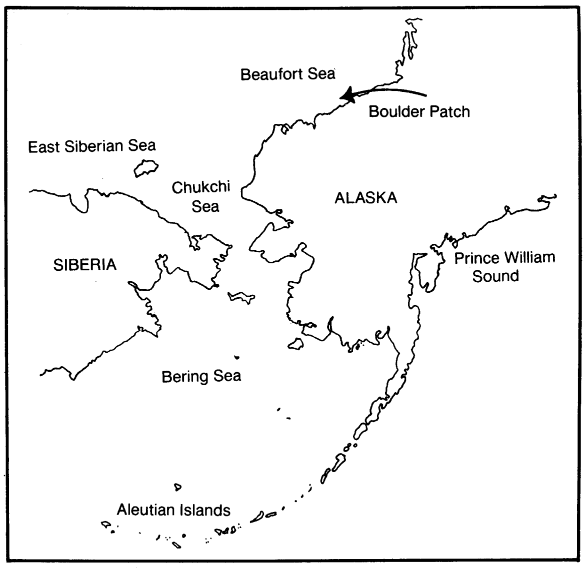
A polar bear kills and eats a ring seal, forging one link in an Arctic food chain. From this simple observation, ecologists can draw a conclusion: Atoms from the seal will become part of the bear. But to link the bear all the way down the food chain to the one-celled phytoplankton building sugar molecules from carbon dioxide, two scientists resort to a more exotic technique: trimming the bear's toenails.

Ecologists have strung together food chains for decades, tracing food backward from consumers to primary producers such as phytoplankton — microscopic algae thought to occupy the lower end of the chain in the oceans. Traditionally, such efforts have relied on observation and guesswork. But in recent years, a growing number of ecologists have added a quantitative technique, called stable isotope tracing, to their expanding kit of research tools. While geochemists have used the technique since the 1940s, ecologists have only recently recognized its potential in their field.

"In the past five years, it's taken off in terms of mapping carbon flow in food webs," says Charles A. Simenstad of the University of Washington in Seattle. "It certainly is changing a lot of our concepts of food webs." Before ecologists took up isotope tracing, he adds, "all we could do was sit down and play accountant. I don't think we considered it guesswork in those days, but in hindsight, it certainly was."

Scientists studying food webs can trace isotopes in bits of tissue — bear-claw parings, for example — to answer questions such as where a polar bear fed last winter, where a whale migrated last year, what kind of grass a bison grazed 10,000 years ago and whether phytoplankton supply most of the food in coastal marine food webs. Understanding where an animal spends its time and what it eats can help scientists protect fragile ecosystems from encroaching human habitation, manage hunting and assess the long-term environmental effects of pollution.

If ecologists could dye plankton with an indelible red food coloring, their jobs would be easier. As larger organisms devoured the plankton and the telltale red atoms made their way through the food chain, the red would remain, eventually tinting the polar bear's fur a delicate pink. Stable, or nonradioactive, isotopes have no color, but like the imaginary food coloring, they can serve as a label that persists through an ecosystem.



Ecologists exploit the relative simplicity of food chains in the frigid waters surrounding Alaska and Siberia.

All elements come in various forms called isotopes, each isotope carrying a different number of neutrons. The number of protons — the other type of particle in an atom's nucleus — remains constant from one isotope to the next. Extra neutrons affect an atom's chemical activity only slightly, so living things can use common isotopes as well as the rarer variants. Isotopes of nitrogen, sulfur, oxygen and carbon all figure into biological processes and all leave their mark in tissues. Increasingly, ecologists analyze isotopes of more than one element to untangle knotty food webs. But they used carbon first, and for many it remains the element of choice.

Nearly all of Earth's carbon atoms contain 12 neutrons; about 1 percent have 13 and a vanishingly small number are even heavier with 14. In carbon, one extra neutron adds weight but two add instability. Carbon-14, a radioactive isotope, decays slowly, while both carbon-12 and carbon-13 remain stable.

To measure the relative amounts of isotopes in tissue, scientists use a mass spectrometer designed specifically for the task. After scrupulously cleaning a small sample, they burn it until nothing remains but carbon dioxide gas that the spectrometer can read. Finally, they compare the ratio of carbon-13 to carbon-12 in the gas to an international standard. Variations from the standard amount to only a few parts per thousand.

Organisms that capture the sun's energy, such as green land plants and phytoplankton, serve as the base of a food pyramid for all other living things on Earth. These "primary producers" also carry the key to the value of carbon isotope tracing in ecology. When they photosynthesize, they use light energy to build food molecules of water and carbon dioxide. Because they differ in the way they take up carbon dioxide or in the way they use it, some photosynthesizers build food molecules with a slightly higher carbon-13:carbon-12 ratio than others.

Each organism has its own, measurable carbon isotope ratio, or signature, which remains recognizable through chewing, conversion to animal tissue and on up the food chain. The carbon-13 proportion increases slightly, and predictably, with each link up the chain.

Carbon isotope tracing works best in simple ecosystems, where scientists can avoid the complication of too many food (i.e., carbon) sources. Some marine communities fill this bill. Phytoplankton make most of the food on which the ocean food web rests — or so scientists have assumed. But in nearshore environments, kelp forests may rival phytoplankton in nutrient productivity.

So lush and fast-growing are these huge seaweeds that marine ecologists compare kelp beds to tropical rain forests. Reaching 120 feet in a single season, a kelp plant grows like hair, its tissue constantly sloughing off at the tips.

Sloughing and storm damage free clouds of nutritious debris, which eventually settles to the seafloor.

In considering kelp's nutrient contribution, "people have all along been saying, 'Well, here's all this plant biomass – it must be important,'" says David O. Duggins of the University of Washington's Friday Harbor Laboratories on San Juan Island. But beyond the observation that some animals, such as sea urchins, snails and chitons, munch away at the plant almost incessantly, researchers had no hard evidence to support that assumption.

Because kelp's carbon isotope signature differs enough from that of phytoplankton to distinguish the two, carbon isotope tracing could verify kelp's contribution to the food chain – if researchers could find a coastal study site with no land plants nearby to confuse the issue.

In the early 1980s, Kenneth H. Dunton of the University of Texas' Marine Science Institute in Port Aransas found a spot with only two sources of carbon – kelp and phytoplankton. The site, called the Boulder Patch, lies in the Beaufort Sea off the northern coast of Alaska. "This kelp bed community is completely isolated," Dunton says. "It doesn't have anything on either side of it for almost 1,000 kilometers."

Dunton measured carbon isotope ratios in kelp, phytoplankton and marine animals living in the Boulder Patch. As expected, snails and chitons dining on kelp retained a kelp-like isotope signature. But some predatory snails, sediment-eating worms and sea squirts that filter nutrients from the water also appeared to get more carbon from kelp than from phytoplankton, reported Dunton and Donald M. Schell of the University of Alaska in Fairbanks in the January 1987 MARINE BIOLOGY. Not all of the animals studied depended entirely on kelp carbon. But almost none lived entirely on phytoplankton. Carbon isotope tracing allowed Dunton to measure, rather than speculate on, kelp's nutritional importance to a large number of near-shore animals.

At the opposite end of Alaska, Duggins and Simenstad added another twist to the kelp story. In a sense, their "natural experiment" began in the 19th century, when fur traders decimated sea otter populations throughout the Aleutian Islands, eliminating otters from some islands. Legally protected since 1911, otters today flourish on some islands and remain absent from others. Islands where otters abound "are just packed with forests of kelp," Duggins says. Without otters, scant kelp survives.

Sea urchins form the link that explains these observations. Where urchins – the otter's favorite food – live free of predation, they graze kelp down to the rocks. The difference between islands, Duggins says, "is absolutely striking."

Working with James A. Estes of the U.S. Fish and Wildlife Service and the University of California, Santa Cruz, Duggins and Simenstad assessed the relative importance of kelp and phytoplankton by counting kelp, measuring the growth of filter-feeding animals and tracing stable carbon isotopes. When they experimentally "planted" barnacles and mussels – both filter feeders – at kelp-rich islands, these animals grew two to five times faster than their counterparts planted at kelp-poor islands. And even though the scientists measured the carbon isotope ratio in filter feeders such as mollusks and sea anemones during midsummer phytoplankton blooms, they found these animals derived an average of nearly 60 percent of their carbon from kelp, the group reports in the July 14 SCIENCE.

By quantifying kelp's role as a major "breadbasket" of coastal ecosystems, marine scientists have gained a new appreciation for the ecological importance of these forests of the sea. Both direct and indirect damage to kelp beds could cascade throughout a coastal ecosystem. Catastrophic storms and climate changes such as El Niño might destroy kelp beds directly; disease or pollution might damage them indirectly by killing off the predators of kelp-eating animals.

"It's known that oil spills, for example, affect sea otter populations," Duggins says. "We're certainly learning every day the degree to which that's true from [the *Exxon Valdez* spill in] Prince William Sound." If too many otters die, urchin populations may surge, he says, and that could be devastating to kelp.

Following food from grass to bones

Ecologists find fertile territory for isotope tracing on land as well as in the sea. Because photosynthetic processes vary from one species of land plant to another in terms of the enzymes used and the first carbon compounds made, scientists can divide the plants into groups based on their stable carbon isotope ratios. Plants following the "C3" photosynthetic pathway start out by linking three carbon atoms, whereas "C4" plants link four carbons and feature a slightly higher ratio of carbon-13 to carbon-12.

Larry L. Tieszen, a paleoecologist studying modern and ancient ecosystems, proved in 1979 that carbon isotope tracing distinguishes C3 from C4 material in half-digested food from herbivore stomachs as accurately as microscopic analysis, and with less time and effort. If the isotope ratio survives eating, he reasoned, it might also survive death, remaining in certain tissues to preserve an integrated record of the animal's lifetime diet.

"So presumably," he says, "we could take an individual's hair, fingernail or muscle and get a pretty good idea of the contribution of the C3 and C4 components to that individual's diet."

Tieszen's tissue of choice is collagen, the rubbery protein that forms cartilage, tendons and the matrix of bones. Muscle and hair disintegrate quickly after death, but some collagen remains in bone for thousands of years, and traces persist even in fossils.

Tieszen and his co-workers at Augustana College in Sioux City, S.D., have begun analyzing carbon isotope ratios in ancient bison bones to infer climate changes of the past. Bison eat grass, and grass forms the link between bison bones and climate. Both C3 and C4 grasses grow in North American prairies, their relative proportions determined partly by temperature: At warmer temperatures, more C4 grass grows. In preliminary analyses of bison bones about 10,000 years old, the researchers find the beginning of a trend toward a larger carbon-13:carbon-12 ratio. The increase, Tieszen says, implies more C4 grasses on the prairie – a shift possibly prompted by a warming climate.

But bison may not be indiscriminate lawn mowers, he notes. If they graze selectively, this could skew the isotope results. To find out, Tieszen collects bones from modern bison that died of natural causes and compares their carbon isotope ratios with those of the grasses in their grazing areas. If the results show that the animal does act as "a clipping machine that goes out there and just randomly clips the vegetation," he says, bison collagen could provide prairie paleoecologists with a powerful tool for exploring the past.

Scientists don't collect bone collagen from live animals, but they can collect another protein, keratin – the stuff of horns, hooves and claws. While collagen integrates all the nutrients it receives during bone growth, offering scientists a single, amalgamated picture of the animal's lifetime diet, keratin is laid down sequentially, yielding a continuous series of dietary "snapshots." Tieszen has seen seasonal carbon-13 changes in modern bison horn. And Donald M. Schell of the University of Alaska in Fairbanks finds evidence of seasonal diet shifts in the hooves of caribou and moose, as well as in the claws of ring seals and polar bears (see main story). Schell says such analyses offer a new way to follow food molecules in any animal that migrates or changes food sources seasonally. – *S. Hart*

Even when an animal dines on only one carbon source, ecologists can still wring out interesting information. Many birds, fish and whales survive mostly on tiny, phytoplankton-grazing marine animals called zooplankton, which vary in carbon isotope signature with latitude. The farther north the zooplankton live, the lower their ratio of carbon-13 to carbon-12. Animals eating zooplankton at opposite ends of such a gradient will incorporate different isotope signatures.

Dunton discovered another carbon ratio gradient in zooplankton while working in the Boulder Patch. But in this case the gradient changed from east to west. Serendipitously, Dunton's discovery solved a puzzle for Schell.

To gauge the possible effects of oil exploration on endangered bowhead whales, Schell had begun analyzing carbon isotopes in tissues of dead whales in an attempt to map their migration routes (SN: 1/3/87, p.6). Measuring carbon isotope ratios in baleen – the fingernail-like plates through which whales filter huge mouthfuls of plankton-rich water – he was surprised to find a regular variation in the ratio from one end of the baleen to the other. If whales were feeding at two ends of Dunton's zooplankton gradient, he surmised, they would incorporate carbon-13 in an annual pattern – and that's what the baleen showed.

Schell and his co-workers have continued sampling whale tissue, expanding what's known about the animals' migration route. Young bowhead whales appear to feed heavily in both their summer (eastern Beaufort Sea) and winter (Bering Sea) ranges. And because the carbon-13 patterns in baleen reflect a yearly migration, they also provide the first method for accurately determining the age of the huge mammals, Schell says. The patterns indicate young whales grow much more slowly than scientists thought, taking up to 20 years to reach sexual maturity.

Dunton, Schell and co-workers from Alaska, Texas and the Soviet Academy of Sciences in Leningrad have now extended the known zooplankton gradient – the range over which its carbon isotope ratio changes – from the eastern Beaufort Sea down to the Bering Sea and eastward into the Soviet East Siberian Sea. The just-completed plankton and whale studies are scheduled for publication later this year in Marine Biology and Marine Ecology Progress Series.

The solution to the whale puzzle convinced Schell that carbon isotope analysis could be valuable in tracking other migratory species. "The work we did with bowhead whales showed that we had a stable isotope gradient that goes across the Beaufort Sea, so we decided we'd try and apply that to polar bears," he says.

Because polar bears have an average population density of only one bear for every 100 square miles of ice in the Beaufort Sea, the International Union for Conservation of Nature and Natural Resources classifies them as "vulnerable." Legal restrictions protect the species from sport and commercial hunting, but traditional hunting by Native peoples in the Arctic is allowed in both Canada and Alaska. "In order to really know the bottom line on the yield that can be taken from a population, you first need to define the population," says Steven C. Amstrup, polar bear project leader for the U.S. Fish and Wildlife Service in Anchorage.

Oil exploration is more difficult to manage than hunting. Canada and the United States are developing oil and gas reserves in the Arctic, and the Soviet Union also plans oil exploration there. This poses potential threats to the polar bear habitat, Amstrup says, and makes it "even more important that we define the population and get a better estimate of population size and dynamics so that we can determine what each population can stand in the way of human influences."

Guessing that polar bears would take at least 12 months to grow their 1½-inch-long claws, Schell and Amstrup last year began collecting claw shavings from killed bears. Carbon isotope analysis on the parings looks promising, Schell reports, clearly distinguishing Beaufort bears from those originating farther west. "It does appear that if a bear moves from one environment to another, you see the change in the stable isotope patterns of the claw," he says.

But to match an isotope pattern to a migration pattern, they must observe bears migrating. Since 1981, Amstrup has radio-collared migrating polar bears. "We have a lot of bears that are old friends, and we know where they live," he says. Claw samples from those living bears may allow the researchers to establish the link between the carbon signature in the claw and the wanderings of the bear.

And how do they pedicure a live polar bear? First, they tranquilize the bear with a dart fired from the safety of a helicopter. Then, Schell says, "we just take a little knife and skive off a little piece of the claw – pare the fingernail, so to speak."

Many ecologists agree that stable carbon isotope tracing holds tremendous potential in their field. Ironically, that emerging consensus may mean the technique won't take center stage much longer in the titles of journal articles, notes paleoecologist Larry L. Tieszen of Augustana College in Sioux Falls, S.D. "I think the exploration of the technique as a technique is about finished," he says. "But the application of the technique is just getting started." □