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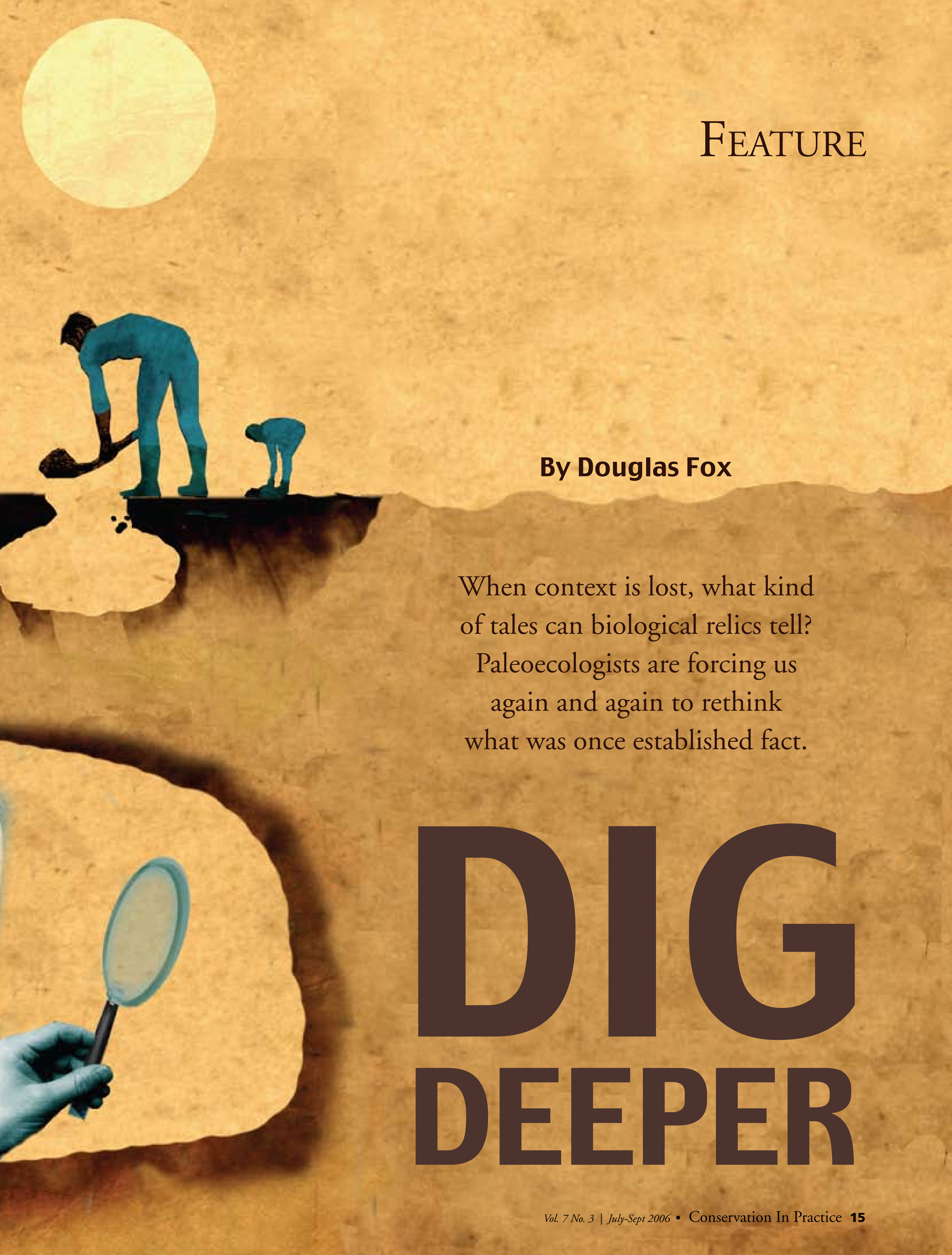

DIG DEEPER

By Douglas Fox

When context is lost, what kind of tales can biological relics tell? Paleoecologists are forcing us again and again to rethink what was once established fact.

Two trillion clam shells piled on the Colorado River Delta tell a story that no one would have believed. These shells were heaped by tides into ridges that stretch for miles across the mudflats. The vast majority belong to one species: the thin-shelled Colorado Delta clam. Yet look in the mudflats on either side of the ridges, and you won't find a single member of that species alive. Despite the 8 million tons of shells piled in ridges as far as the eye can see, only a few clams still live here today, and none of them are Delta clams.

The shells are all that remain of a vanished ecosystem, and written in their fingernail-thin clam rings are the answers for bringing that ecosystem back to life.

Conservation biologists have long operated within the cramped confines of written history. Our understanding of the ecosystems we manage is often based on published studies from the past 50 years or, if we're lucky, fishery or logging records that might extend back a century or two.

The tools of paleoecology—carbon dating, stable isotopes, fossil pollen studies, and the like—could sometimes shed light on our questions. But they were as temperamental as alchemy, requiring mazes of glass tubes and cold traps, bubbling liquid nitrogen and all.

But that's changing. Newer, off-the-shelf techniques are producing more accurate readouts from smaller samples, and at a fraction of the cost. Paleoecology is on the march, and it's forcing us again and again to rethink what was once established fact.

The shells on the Colorado Delta have shifted our whole frame of reference, revealing an entire lost ecosystem that no one expected to find and providing clues for its restoration. Excavations on tropical islands are helping rebuild forests that haven't existed for a thousand years and, along the way, overturning what had once seemed safe assumptions about how those forests looked. The study of dead stuff is even transforming our thinking about one of the most-studied ecodisasters on Earth—coastal eutrophication—and reshaping the debate over how to reverse it.

When Karl Flessa, a paleontologist with the University of Arizona, first arrived on the Colorado River Delta in 1992, he'd already spent ten years ogling shells elsewhere in the Sea of Cortez. Conservation wasn't the purpose of his visit. But here on the Delta, he was immediately surprised to see that dead clams were one species and living clams belonged almost entirely to several other species of clams. Flessa set out to learn why.

Those ridges of clam shells, called cheniers, were his only source of information. Tidal currents had mixed them so that thousand-year-old shells lay next to ten-year-old shells, with no way to distinguish them visually. For anyone used to the tidy order of sediment stratigraphy, it was a nightmare come true.

But modern radiocarbon and amino-acid racemization analyses provided Flessa and his graduate students with the crowbar they needed to pry the problem apart. Because these techniques use small samples, they could date individual shells; by analyzing a couple of hundred shells, they reconstructed a thousand-year history of the Delta's ecology.

It confirmed that the overall productivity of the Delta had plummeted since the damming of the Colorado River in 1935. For centuries, the density of clams in the mudflats had hovered around 25 to 50 per square meter; today it was just three per square meter.

Species composition had also changed radically: the thin-shelled Delta clam (*Mulinia coloradoensis*), once constituting 80 to 90 percent of

Photo courtesy of Karl Flessa, Department of Geosciences, University of Arizona

Acres of Clams (named after a traditional folk song) is located on the Colorado Delta north of San Felipe, Baja California, Mexico. Curvature of the cheniers is from the accretion of shells at the end of the spit during successive spring tides.

the clams throughout the Delta, had declined to just five percent, leaving it highly endangered. Several species of thicker-shelled Venus clams (*Chione* spp.), once minority species, now accounted for 95 percent of the clams in the area. "We were overwhelmed," says Flessa. "I realized how rich a source of information this was and that we could take this live-dead comparison study in a completely new direction—toward conservation biology and measuring environmental impact."

"It was one of those few times in your career," says Flessa, "when you go, 'Aha, here's a whole new incredibly rich direction to go.'" Like a shiny white bearing, the Delta clam had been a pivot point for the collapse of the entire ecosystem. Marks on the shells documented the existence of other animals in the Delta that had left no fossil record of their own: the Delta clam, it seems, had once supported a food web whose sheer magnitude astonished Flessa.

Thirty to fifty percent of the Delta clam shells showed signs of predation such as drilling by snails or prying open by crabs. Its thin shell—the marine equivalent to popping open a can of V8 juice—made it an ideal food source. And when those Delta clams disappeared, the thicker-shelled Venus clams left many predators effectively locked out of the fridge. Far fewer numbers of Venus shells, whether ancient or contemporary, show signs of predation. The loss of snails and crabs that once ate Delta clams would, in turn, have put the squeeze on higher-trophic-level birds and fish that fed on snails and crabs.

Based on knowledge of other clams in the same genus, Flessa guessed that the Delta clam had declined because of increased salinity resulting from the river's interrupted flow of fresh water. By analyzing the stable-oxygen isotope signatures of dead shells, Flessa could estimate the range of salinities under which Delta clams had thrived in the past (freshwater from the Colorado River contains a low level of ^{18}O compared to that ^{16}O; thus a low ^{18}O to ^{16}O ratio in a shell indicates a high ratio of freshwater to seawater once the calcium carbonate in the shell crystallizes).

Modern mass spectroscopy allowed them to use tiny samples, a few milligrams of powder

Photo courtesy of Zoological Society of San Diego

Since the arrival of Europeans in America, the **California condor** (*Gymnogyps californianus*) has relied almost exclusively on land animals for food—a source that carries the risk of lead poisoning. But for thousands of years before that, condors consumed large numbers of marine mammals—at least until seals and sea lions were depleted by the Europeans.

bored with a dental drill from individual fingernail-thin rings of a single shell. They could actually read out fortnightly salinity levels, corresponding to lunar tide cycles, throughout the life of a single clam. That kind of detail might seem fussy, but it was important, says Flessa. "If you want to reconstruct prehuman conditions," he says, "you don't want just a static baseline but rather a record of natural variation. It's this ability to sample thin layers within shells that lets us measure seasonal changes."

Seventy percent of the Delta's freshwater arrived from May to July of each year; the clams put on most of their growth during these warm months. "If we figure out the salinity tolerance of those clams farthest from the river mouth," says Flessa, "this is probably the maximum salinity this species can tolerate and still be abundant." The Delta clam seemed to grow best at salinities of 20 to 25 parts per thousand—compared to 35 parts per thousand for seawater and up to 42 parts per thousand for the present-day Delta.

While agriculture has sucked the Colorado River dry for decades now, the Delta itself lacks any legal right to a share of the river's vital fluids. But for the first time, Flessa's data open the door for dialogue on how to restore some of that flow. If even a small amount of freshwater can be negotiated for the Delta (say agricultural runoff, which at five parts per thousand, is too saline for crops), then Flessa could actually determine how much water would be needed to tip the balance in favor of the Delta clam and where to deliver it. "It's a simple mass-balance calculation," he says. "You see how much freshwater you need to add to the mouth of the river to reduce the salinity to the right amount. Water in the West is extraordinarily valuable. If you're making an argument that you should set aside some water for nature, you want to make sure you put a number on the table that's biologically right." And it might just revive a large-enough patch of habitat to support a viable population of Delta clams—and eventually the droves of other animals that once munched their thin shells like Pringles.

Researchers who toy with stable isotopes are also finding plenty of other ways to pry into the private lives of the dead. Page Chamberlain's collision with conservation biology began during a chat with an ornithologist at a backyard cocktail party. Chamberlain, a Stanford geologist, had until then focused on measuring stable isotopes to trace the emergence of mountain ranges. But in a paper published last November, he and coauthors Paul Koch and Kena Fox-Dobbs of the University of California in Santa Cruz used similar techniques to reconstruct the changing diets of California condors over the past 36,000 years.

Using isotope techniques on thirty desiccated bird skeletons, Chamberlain reconstructed the diets of condors over the past 36,000 years.

Chamberlain worked on the assumption that isotopes in condors should reflect those of their food. For example, ratios of nitrogen isotopes ^{15}N and ^{14}N vary between animals according to their position in the food web. Likewise, carbon isotope ratios of ^{13}C and ^{12}C differ between marine and land mammals and also according to the types of plants that the species consumes. So Chamberlain and his colleagues measured isotopes in the collagen of condor bones from three time windows: contemporary birds (1993-2000), museum skeletons (1904-1965), and skeletons dug from the La Brea tar pits (11,000 to 36,000 years old).

The study confirmed that, since the arrival of Europeans in America, condors had relied almost exclusively on land animals for food, a source that carries the risk of lead poisoning through ingestion of lead shot. But the study also revealed that, for thousands of years before that, condors had consumed large numbers of marine mammals—at least until seals and sea lions were depleted by Europeans.

Those results, says Chamberlain, validate the approach of releasing condors in places where they can take advantage of recovering populations of marine mammals, a food source less likely to contain the lead that has so endangered their survival.

Although that's an impressive conclusion to draw from 30 desiccated bird skeletons, other researchers have gone even further, using stable isotopes to look at the lives of dead animals that left behind not a single bone, tooth, or scale.

Bruce Finney, a paleoceanographer at the University of Alaska in Fairbanks, set out to study levels of sockeye salmon production in nursery lakes on Kodiak Island over the past 2,000 years—even though the salmon had left no visible trace.

His key insight was that salmon, unlike any other major component of the lake ecosystems, added 99 percent of their body mass while living as ocean predators before returning to the nursery lakes, spawning, and dying. That predatory lifestyle left a strong signature of ^{15}N in the fishes' bodies, and when they died, it settled into the sediments where Finney could measure it in core samples.

Years with high levels of ^{15}N in the sediment cores (meaning large numbers of returning fish) corresponded with higher primary and secondary production of diatoms and zooplankton, which in turn serve as food for newly hatched salmon fry. Finney's findings bolstered the theory that in lakes with limited nutrient inputs, rotting carcasses of returning fish provide critical nutrients for the next generation of fry.

When the dead are more plentiful, the oracles that are sought from them needn't be so specific. On Kauai, a team lead by David Burney at the National Tropical Botanical Garden is designing entire forest restorations based on the ten-thousand-year record of pollen, seeds, spores, leaves, bones, and other remains excavated from Makauwahi Cave and other sites on the island.

Around the world, efforts to rebuild island ecosystems have long obsessed over the task of restoring native species and expunging exotic species. But the excavations on Kauai are showing that our bedrock assumptions about what is native and what is not are sometimes just plain wrong.

"We're finding," says Burney, "that plants are native which we had thought were introduced by Polynesians. That's extremely important, since some of these plants are easy to grow and commercially useful."

Take for example, kou, a timber tree that Polynesians traditionally fashioned into canoes, bowls, and back scratchers. Its wide presence across the South Pacific and Indian Oceans was seen as evidence that it was introduced by Polynesians when they arrived on Kauai around 1000 AD. But the Makauwahi sediments tell a different story. The cave has coughed up ancient kou fruits pegged by accelerator mass spectrometer dating as being 5,000 to 6,000 years old—meaning the tree arrived well before humans.

The hala, or screw pine, was also considered a classic case of species introduction; its leaves are woven into baskets and mats by island peoples across Micronesia—and as with the kou, Hawaiian oral tradition even claimed that it was brought to the island by Polynesians. But now its seeds and pollen are turning up in prehuman sediments around the island and are even entombed in half-million-year-old lava.

Both kou and hala are now being planted in tracks of restored forest—a sharp reversal of the conventional wisdom that might have dictated their active uprooting from Kauaian soil.

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that eutrophication began before the modern fertilizers.

These are not the only cases where paleodata are shedding new light on a global ecological disaster. Efforts to "save the bay"—that ubiquitous battle cry against coastal eutrophication—are also feeling the shakeup.

For 30 years, foundering efforts to rescue Chesapeake Bay, the largest estuary in the U.S., from hypoxia focused on reducing the inflow of nutrients that feed its turbid throngs of phytoplankton and bacteria. But that mindset may have overlooked one critical fact: the vast reefs of eastern oysters that once filtered the entire volume of the bay's northern half—over 20 cubic kilometers of water—every three days.

The bay's plunge into summertime hypoxia during the twentieth century was blamed on the advent of modern fertilizers in the 1950s. Studies of bay sediments by Grace Brush at Johns Hopkins University in Baltimore, Maryland, provide a two-thousand-year record of the Chesapeake's ecology. The onset of hypoxia was signaled by the appearance of pyrite in sediments as well as a shift in foraminifera remains toward hypoxia-tolerant species in the sediments.

"What's interesting about the Chesapeake is that eutrophication began before the modern fertilizers," says Jeremy Jackson of Scripps Institution of Oceanography in La Jolla, California. "There are geochemical indicators of hypoxia on the bottom beginning in the 1930s."

The gush of artificial fertilizers after 1950 dealt the bay a serious body blow, but Jackson suspects that the trawling of its oysters starting around 1870 almost certainly set the stage for the disaster that followed by removing a crucial biological filter that would have devoured hundreds of tons of phytoplankton and bacteria that thrived on artificial fertilizers. By the time artificial fertilizers hit the bay, its few remaining oysters were filtering its water at a languid rate of once every 700 days or so.

The most recent insight comes from an analysis of data (published by Jackson and colleagues in *Science* this June) across 12 coastal systems around the world, including Chesapeake Bay, Pamlico Sound, San Francisco Bay, Galveston Bay, Delaware Bay, Moreton Bay in Australia, and the Baltic, Wadden, and Adriatic Seas in Europe. (1) That review pulled together paleo sediment data, archeological data, and fishery and historical records. The advance of

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Photo courtesy of Angela I. Correa, Virginia Tech

Eastern oysters (*Crassostrea virginica*) once filtered the entire volume of Chesapeake Bay's northern half every three days. By the time artificial fertilizers hit the bay, its few remaining oysters were filtering the water only once every 700 or so days.

eutrophication and hypoxia—as well as the changing abundance of up to 60 species of fish, birds, mammals, plants, and invertebrates—was reconstructed in each system.

"The big discovery," says Jackson, "is that even though the details vary from place to place, you can still see the same basic themes." The dates of industrialization differ by centuries, but in each case the widespread destruction of biological filters—oysters, mussels, scallops, sponges, sea grasses, or wetlands—shortly preceded the onset of hypoxia, which then worsened with modern fertilizers.

One minor exception that reinforces the point is San Francisco Bay, which is now populated by an invasive green mussel. "These invasive mussels took over the filter function that was lost," says Heike Lotze, a marine ecologist at Dalhousie University in Nova Scotia and lead author of the study in *Science*. "You still find increased primary production, but just not the really nasty signs of anoxia and eutrophication that you see in other estuaries."

In the Chesapeake, the relative importance of nutrients versus filter feeders remains controversial—made more so by the significant barriers to restoring oysters: poor water quality, disease, and absence of hard growth substrate. Plans for the recovery of the Chesapeake Bay already included restoration of wetlands, but the Chesapeake 2000 Agreement also aims to increase the bay's oyster population ten-fold as well as increase sea grass coverage. The Oyster Recovery Partnership has planted farm-raised oysters at 37 sites within the bay, in some cases using concrete blocks to provide a solid growth substrate where the original one was lost to trawling or sediments.

The hundreds of millions of dollars already spent to restore the Chesapeake Bay may create inertia when it comes to adopting new approaches such as large-scale oyster seeding. But the growing tab is also increasing the urgency for the types of answers that perhaps only paleo data can provide. ❧

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