MARINE BIOGEOCHEMISTRY

The Invisible Hand Behind A Vast Carbon Reservoir

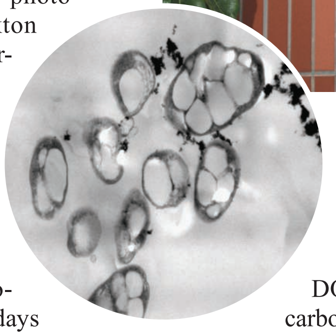
A key element of the carbon cycle is the microbial conversion of dissolved organic carbon into inedible forms. Can it also serve to sequester CO_2?

XIAMEN, CHINA—For simple sea creatures, dissolved organic carbon (DOC) is the staff of life. Much of it, however, is as unpalatable as chaff and accumulates in the water column. Scientists are unraveling how organic matter in the marine food chain is converted into forms that less readily relinquish carbon in the form of carbon dioxide (CO_2). "The existence of this 'inedible' organic carbon in the ocean has been known for quite some time. But its role in the global carbon cycle has been recognized only recently," says Michal Koblizek, a microbiologist at the Institute of Microbiology in Trebon, Czech Republic.

New findings are unmasking the invisible processes that suspend immense amounts of carbon just below the ocean waves. "It's really huge. It's comparable to all the carbon dioxide in the air," says Jiao Nianzhi, a microbial ecologist here at Xiamen University. He and others are exploring the tantalizing prospect of sequestering CO_2 in this reservoir. It's too early to say whether the vast pool will respond to geoengineering, says Dennis Hansell, a marine biogeochemist at the University of Miami in Florida. However, he says, "I expect the light to come on over heads and we'll experience an 'ah ha!' moment."

Data from several research cruises have yielded a broad-brush view of what Jiao has dubbed the microbial carbon pump (MCP): the microbe-driven conversion of bioavailable organic carbon into difficult-to-digest forms known as refractory DOC. This summer, the European Project on Ocean Acidification is carrying out a slate of experiments in Arctic waters that includes probing the MCP. Then in October, Jiao's team heads to the opposite thermal extreme: They will explore the mechanisms of the MCP and CO_2 sequestration in the equatorial Indo-Pacific Warm Pool, the warmest marine waters in the world. The MCP will also be featured next month at a Gordon Research Conference on marine microbes, and it is outlined in a paper in press at *Nature Reviews Microbiology*. The concept "could revolutionize our view of carbon sequestration," says Markus Weinbauer, a microbial oceanographer at Laboratoire d'Océanographie de Villefranche in France.

The ocean surface is like a planet-sized set of lungs that inhale and exhale CO_2. As a global average, the oceans take up about 2% more of the gas than they release. Some CO_2 dissolves into the water column, forming carbonic acid. As atmospheric CO_2 levels rise, ocean pH decreases, a phenomenon called acidification that could endanger corals and other creatures by slowing the growth of carbonate skeletons (see p. 1500). Carbon also enters the seas through the food web: During photosynthesis, phytoplankton fixes CO_2 to organic carbon—as much as 60 gigatons of carbon per year, roughly the same amount fixed on land. "The carbon is not captured for long," says Koblizek. Most new marine biomass is consumed in days and returned to the air as CO_2. Some, however, ends up in the deep ocean sink, when remains of dead organisms fall to the sea floor. Each year, this biological pump deposits roughly 300 million tons of carbon in the seabed.



Even more massive amounts of carbon are suspended in the water column as DOC. The oceans hold an estimated 700 billion tons of carbon as DOC—more than all land biomass put together (600 billion tons of carbon) and nearly as much as all the CO_2 in the air (750 billion tons of carbon). About 95% of organic carbon is bound up as refractory DOC: "the largest pool of organic matter in the ocean," says Farooq Azam, a microbiologist at Scripps Institution of Oceanography in San Diego, California. In the December 2009 issue of *Oceanography*, a team led by Hansell and Craig Carlson of the University of California, Santa Barbara, compiled the first global map of DOC distribution. Carbon-14 studies suggest that refractory compounds swirl in this microbial eddy for more than 6000 years, several times the circulation time of the ocean.

DOC doc. Jiao Nianzhi formulated the MCP concept based on his studies of AAPB, an unusual kind of photosynthetic bacteria (*left*).

The realization that refractory DOC is a key element in the global carbon cycle has lit a fire under efforts to figure out what the stuff is and where it comes from. Researchers now know that refractory DOC consists of thousands of compounds, such as complex polysaccharides and humic acids. A team led by Xosé Antón Álvarez Salgado of the Instituto de Investigaciones Marinas in Vigo, Spain, has tracked the conversion of some forms of bioavailable carbon to refractory carbon by observing changes in their optical properties: Humic substances absorb UV light and re-emit it as blue fluorescence at specific wavelengths.

The origins of most refractory DOC are a black box. Some is produced when light degrades organic matter near the ocean surface. Oil seeps contribute to the pool. "The oil spill in the Gulf of Mexico is just one drastic example of how this material is released into the ocean," says Meinhard Simon, a microbial oceanographer at the University of Oldenburg in Germany. Other compounds are likely forged in underwater vents or in wildfires and swept into the sea. For the most part, however, says Azam, "we lack understanding of the mechanisms of its formation or variations in its magnitude and composition."

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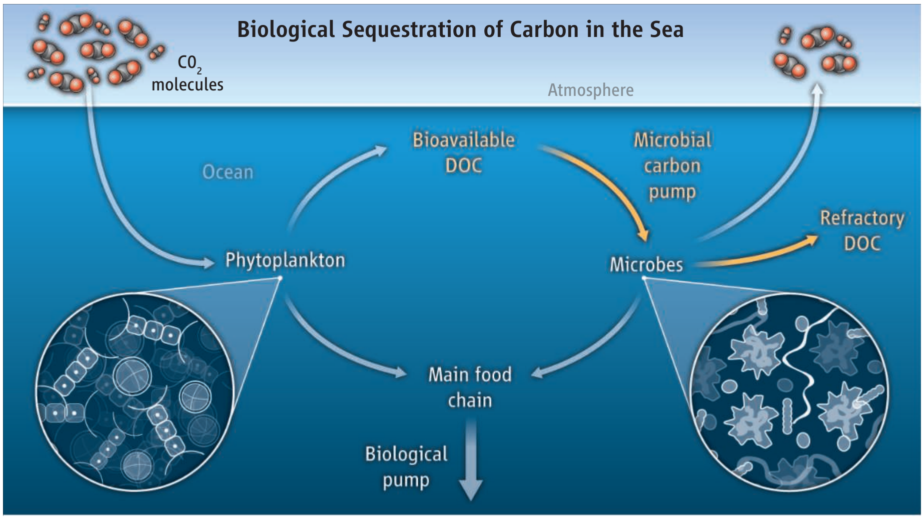
Published by AAAS

Azam and others credit Jiao with a key insight: the recognition that microbes play a dominant role in "pumping" bioavailable carbon into a pool of relatively inert compounds. Some refractory DOC hangs in the upper water column, while some gets shunted to the deep ocean interior via the biological pump. The MCP "may act as one of the conveyor belts that transport and store carbon in the deep oceans," says Chen-Tung "Arthur" Chen, an ocean carbonate chemist at National Sun Yat-sen University in Kaohsiung, Taiwan. The MCP also appears to function in deep waters, where bacteria adapted to the high-pressure environment may have "a special capacity" to degrade refractory DOC, says Christian Tamburini, a microbiologist at the Centre d'Océanologie de Marseille in France.

It took sharp sleuthing to uncover the microbial connection with refractory DOC. In a landmark paper in 2001, Hiroshi Ogawa of the University of Tokyo and colleagues showed that marine microbes are able to convert bioavailable DOC to refractory DOC (*Science*, 4 May 2001, p. 917). Then a month later, Zbigniew Kolber, now at the Monterey Bay Aquarium Research Institute in Moss Landing, California, and colleagues reported that in the upper open ocean, an unusual class of photosynthetic bacteria called AAPB accounts for 11% of the total microbial community (*Science*, 29 June 2001, p. 2492). AAPBs seemed to be plentiful everywhere, according to measurements of infrared fluorescence from the microbe's light-absorbing pigments.

It turned out, though, that other organisms were throwing the AAPB estimates way off the mark. Using a new technique, Jiao's group determined that the fluorescent glow of phytoplankton was masking the glow of the target microbes. "Just like when the moon is bright, less stars are visible," Jiao says. He put the new approach through its paces in 2005, when China's *Ocean 1* research vessel conducted campaigns to mark the 600th anniversary of Admiral He Zheng's historic voyages. The observations "turned things upside down," Jiao says. His group found that AAPBs are more abundant in nutrient-rich waters than in the open ocean, indicating that AAPB population levels are linked with DOC, not light.

Next, Jiao found that AAPBs are prone to viral infection, and he isolated the first phage that's specific for these bacteria. Phages rip apart their hosts, spilling their guts, including organic carbon, into the water. This viral shunt acting on many marine bacteria "may be a significant player in the accumulation of refractory DOC compounds" in the water column, says Steven Wilhelm, a microbiologist at the University of Tennessee, Knoxville. Pulling together several strands—the ubiquity of AAPBs, their low abundance but high turnover rate, the tight link to DOC, and their susceptibility to infection—Jiao proposed that AAPBs and other microbes are a key mechanism for the conversion of bioavailable DOC to refractory DOC. That may seem counterintuitive, as microbes do not set out to produce refractory DOC; rather, the compounds are a byproduct of their demise. "This process is not beneficial to the cell," says Simon.



Double-barrel pump. Each year, the biological pump deposits some 300 million tons of carbon in the deep ocean sink. Even more massive amounts are suspended in the water column as dissolved organic carbon, much of which is converted into refractory forms by the microbial carbon pump.

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Because the buildup of refractory DOC in the water column is accidental, it will be a challenge to coax microbes to sequester more carbon. For decades, researchers have been tinkering with the biological pump to store more carbon in the deep ocean by seeding seas with iron fertilizer. The iron triggers phytoplankton blooms that suck more CO_2 from the air. That should also drive more carbon into the refractory pool, Koblizek says.

Even tweaking the MCP could have a profound effect. The water column holds on average 35 to 40 micromoles of carbon from refractory DOC per liter. An increase of a mere 2 to 3 micromoles per liter would sock away several billion tons of carbon, says Nagappa Ramaiah, a marine microbial ecologist at the National Institute of Oceanography in Goa, India. "We have to investigate any and all means to help sink the excess carbon," he says.

Two billion years ago, when bacteria ruled Earth, the oceans held 500 times as much DOC as today, most likely generated by the MCP, Jiao says. Ecosystem dynamics have changed immensely since then, but the microbial sequestration potential could still be huge, he argues. No chemical equilibrium would limit conversion of bioavailable DOC to refractory DOC, which in turn would not exacerbate ocean acidification, says Jiao, who is planning pilot experiments this summer. Ramaiah, meanwhile, says he is looking for enhanced sequestration potential in select marine bacteria strains.

There's no simple recipe—and some scientists are not convinced that it's feasible or even safe. "I do not think it is possible to enhance carbon sequestration by the MCP. We have no handle on any controls" of how refractory DOC is generated, says Simon. With the present knowledge, any sequestration effort, argues Weinbauer, "could come back like a boomerang and worsen the problem." At the same time, humans may already be "inadvertently stimulating the MCP," says Salgado. Global warming is increasing stratification, reducing deep convection, and stimulating microbial respiration—all of which favor the MCP, he says.

The MCP concept should help address critical issues, such as whether ocean acidification and warming will significantly alter carbon flux into refractory DOC, says Azam, who with Jiao chairs the Scientific Committee on Oceanic Research's new working group on the role of MCP in carbon biogeochemistry. The upcoming research cruises should fill in more details of how the MCP governs carbon cycling and how it may respond to climate change. As Wilhelm notes, "We are just at the dawn of developing this understanding."

–RICHARD STONE