Clues to Long COVID | Milk-Drinking Amphibians

Science News

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Catching Carbon

Will stashing more CO_2 in the ocean help slow climate change?

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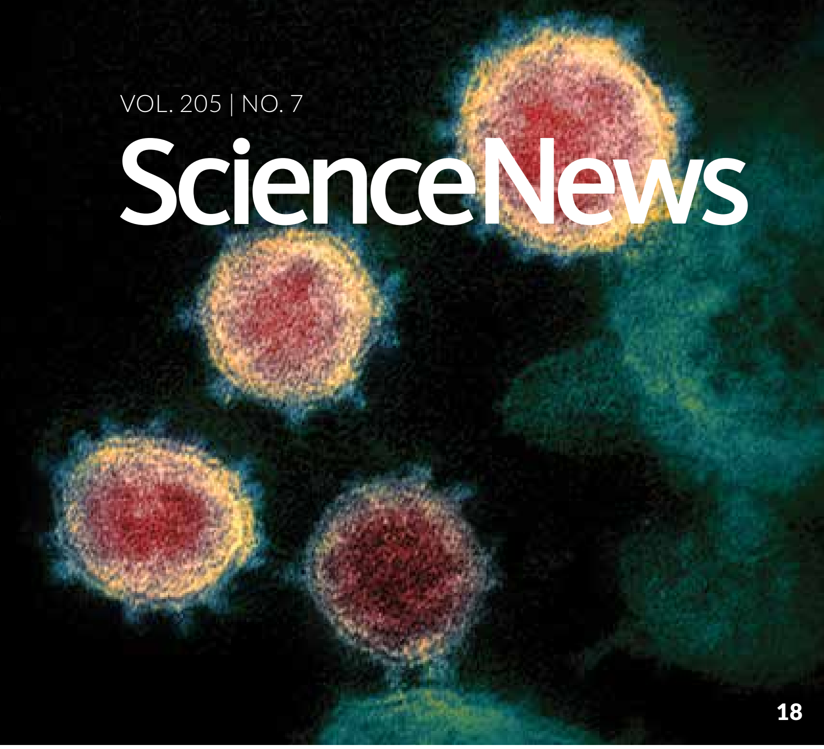

Features

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COVER The ocean absorbs a lot of humans' carbon dioxide emissions and has the capacity to take up even more. *Deb JJ Lee*

FROM TOP: NIAID (CC BY 2.0 DEED); J. DOREY PHOTOGRAPHY; IBENK.88/ISTOCK/GETTY IMAGES PLUS

Finally, scientists are making progress on long COVID

I've been thinking about the old-fashioned term "invalid." In the 19th century, popular literature was awash with characters like Beth in *Little Women*, who patiently knitted away in her sickbed until she succumbed to long-term damage from scarlet fever. Characters like Beth were a prettied-up version of reality. Many children died or were disabled by diseases that we can now fend off with antibiotics and vaccines.

My mother could have been one of those grim true-life stories. As a child in the 1930s, she almost died from an infection of the mastoid bone, which is typically caused by ear infections. In the pre-antibiotics era, it was a leading cause of childhood death. Mom remembered long, lonely weeks lying in bed, staring out the window at children playing, and then many more months of being a weak, sickly child. She recovered and grew up to become a nurse specializing in pediatrics. I still have her copy of *Little Women*.

COVID-19 may seem a long way from *Little Women*, but in an odd way we're also stuck in the part of the plot where people suffer and languish. Researchers around the world are trying to figure out how the SARS-CoV-2 virus causes lasting damage to the human body, and what treatments could restore health to those suffering from long COVID.

It's a huge challenge, in part because there's no test yet to determine if someone has long COVID. Instead, there's an unruly bundle of symptoms that can include problems thinking, exhaustion, heart issues and joint aches. These ailments are common to many diseases. That makes it difficult to get a diagnosis, let alone treatment.

But recent advances in unraveling long COVID's mysteries are exciting researchers, senior writer Meghan Rosen reports (Page 18). Immunologist Akiko Iwasaki told Rosen that it's as if there's a "picture being revealed from the fog."

That includes new findings on cognitive problems that are a persistent symptom of long COVID. In March, researchers reported that patients with what's commonly called brain fog can have a leaky blood-brain barrier, which may allow viruses, cells and other intruders into brain tissue. The brains of patients without brain fog aren't similarly affected (Page 9).

Researchers are also searching more broadly, looking for clues to how the virus plays havoc with the immune systems of long COVID patients.

Rosen, an ace journalist with a Ph.D. in biochemistry and molecular biology, had her own reasons for wanting to find out the state of long COVID research. After catching the virus, she suffered for months with exhaustion and leg pain. Her doctor tested for all sorts of illnesses, including Lyme and thyroid disease, but the tests came back negative. So, probably long COVID, but who knows? Rosen kept trying to manage work and family, only to find herself wiped out if she pushed a bit too much.

Fortunately, Rosen's now feeling much better, pretty much back to her usual energetic self. But many long COVID patients, she notes, are not so lucky. They're waiting and hoping that science will help them move on from this wretched chapter in their lives. *—Nancy Shute, Editor in Chief*

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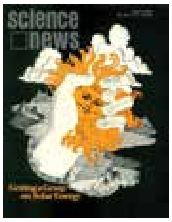


Excerpt from the April 13, 1974 issue of *Science News*

50 YEARS AGO

A world known to birds

What subtle sensory cues enable a bird to navigate ... with spectacular accuracy? [Researchers] have found that birds can sense small changes in air pressure ... and can "see" polarized light .... Meanwhile, biologists at the State University of New York at Stony Brook have found that by attaching a pair of small coils around the heads of homing pigeons and altering an applied magnetic field, they could change the orientation of the birds' flight.

UPDATE: Birds appear to navigate using a host of sensory cues — from looking at the position of the sun, stars and landmarks to smelling the air and even detecting Earth's magnetic field. Scientists are still unraveling the details of birds' magnetic sense. Iron-rich cells within the beak have long been suspected to function as internal compasses (*SN: 5/19/12, p. 8*). But recent studies have suggested that proteins in the retina called cryptochromes allow birds to "see" Earth's magnetic field (*SN: 7/23/16, p. 8*). In lab tests, cryptochromes from migratory robins were especially responsive to magnetic fields (*SN: 7/31/21, p. 9*).

This female *Hylaeus navai*, one of eight newfound masked bee species, was named after Fiji's Navai village, whose residents helped scientists collect bees.

MYSTERY SOLVED

French Polynesia's bees aren't castaways after all

In 1965, renowned bee biologist Charles Michener described a new species of masked bee from "an entirely unexpected region," the Tuamotu Archipelago of French Polynesia. Michener named the bee *Hylaeus tuamotuensis* and noted that its nearest relatives live nearly 5,000 kilometers away in New Zealand. How did a small bee make such a big journey across the Pacific Ocean?

It turns out that the answer was buzzing above scientists' heads all along. Researchers discovered eight species of *Hylaeus* bees that had never been described before. One species was found in Micronesia, another in French Polynesia and six in Fiji.

PICTURE THIS

Daddy longlegs have more eyes than they let on

A species of daddy longlegs has been hiding four extra eyes. While the newfound peepers never fully develop, the vestigial organs suggest that this arachnid lineage is about 50 million years older than previously thought, researchers report February 23 in *Current Biology*.

Unlike spiders, which can have as many as eight eyes, the roughly 6,500 species of daddy longlegs have two eyes at most. But a 2014 study described a fossilized four-eyed daddy longlegs. So developmental biologist Guilherme Gainett of Boston Children's Hospital and colleagues examined vision-related genes and proteins in *Phalangium opilio* embryos (one shown in a fluorescent microscope image). Besides the pair of front-facing eyes (magenta) that the species is born with, certain proteins suggest that embryos have two more sets (green): a front-facing one and side-set one.

Embryos of another species also have side-set vestigial eyes, hinting that all living daddy longlegs have them. An analysis of side-set eyes throughout daddy longlegs' evolutionary history suggests that the fossilized four-eyed arachnid is older than previously thought and that the group's last common ancestor lived about 537 million years ago — predating a previous estimate by 49 million years. *— McKenzie Prillaman*

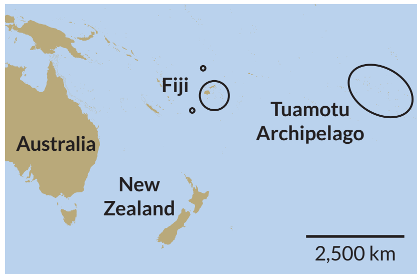
FROM TOP: J. DOREY PHOTOGRAPHY; G. GAINETT

Fiji wasn't known to have *Hylaeus* bees, which were caught by swinging insect nets high up in trees. What's more, the Fijian bees are close relatives of *H. tuamotuensis*, the scientists found.

Fiji lies between French Polynesia and Australia, where *Hylaeus* diversity is highest, so the researchers suspect that the ancestors of *H. tuamotuensis* reached their remote home by island-hopping across the Pacific. As individual bees moved from island to island, they steadily evolved into separate species, evolutionary biologist James Dorey of Wollongong University in Australia and colleagues report February 26 in *Frontiers in Ecology and Evolution*.

Most bee species live in arid regions like the southwestern United States, says bee biologist Bryan Danforth of Cornell University, who was advised by the late Michener for his Ph.D. "We don't think of bees as being terribly diverse in islands."

Bee scouts usually snag their quarry by sweeping nets low to the ground. But during a trip to Fiji in 2019, Dorey took a different approach. He knew that some bees in Australia tend to fly in the canopy of eucalypt trees and thought bees in Fiji might do the same. He equipped himself with a longer net and swung it skyward.



Masked bees island-hopped across the South Pacific, evolving into separate species on New Zealand, Australia, Fiji and the Tuamotu Archipelago among others.

"As soon as I was able to sample a flowering tree, we were catching *Hylaeus*," Dorey says. "It was clear that we had more than one [new] species from that one tree."

Searching treetops for bees is rare. But scientists are realizing that "there's a lot of bee diversity up there," Danforth says.

Dorey's team has a strong relationship with local Fijians, especially in Navai on the main island of Viti Levu, and with Fijian scientists like coauthor Marika Tuiwawa, a botanist at the University of the South Pacific. There is a lot of enthusiasm among Fijians for their native bees, Dorey says, and he hopes to train students there in bee collecting. Experts on Fiji's bees, he says, should be Fijian.

While it's clear that *H. tuamotuensis* is not alone in the South Pacific's remote islands, many mysteries remain: How did *Hylaeus* bees make it to the various islands and what paths did they take?

It's possible the bees were blown across the Pacific by storms, Danforth says, but he suspects their habit of nesting in wood may have contributed to the bees' spread. "If you nest in wood and a piece of wood falls in the ocean, and that drifts thousands of kilometers and lands on a habitable spot, that's a plausible way for these bees to disperse," he says. "We know that other wood-nesting bees have done that." — *Darren Incorvaia*

FUTUROLOGY

Forests might serve as neutrino detectors

Neutrino detectors don't grow on trees. Or do they? Trees could act as natural antennas that pick up radio waves generated by certain interactions of the elusive subatomic particles, astroparticle physicist Steven Prohira of the University of Kansas in Lawrence proposes in a paper submitted January 25 to arXiv.org.

To spot high-energy tau neutrinos that shower down on Earth from space, scientists have proposed searching for their hallmark radio waves using massive arrays of antennas. Prohira thought "it'd be cool if the antennas were already there." Previous research has shown that trees can pick up radio waves. Using forests as antennas would require wrapping trees in wire. Questions remain, including whether trees could pick up very high frequency waves that proposed tau neutrino detectors would. — *Emily Conover*

DIKOBRAZIY/ISTOCK/GETTY IMAGES PLUS

SCIENCE STATS

Global obesity rate reaches staggering milestone

~1 billion

The number of people with a BMI of 30 or above in 2022

More than a billion people worldwide — about one-eighth of the population — were living with obesity as of 2022, researchers report February 29 in the *Lancet*. For comparison, nearly 800 million people had obesity in 2016, according to the World Health Organization.

Obesity is a chronic disease that can raise the risk for heart disease, type 2 diabetes and severe COVID-19, and can limit mobility and negatively affect mental health. Global health researcher Majid Ezzati of Imperial College London and colleagues examined the health records of over 200 million people across nearly 200 countries collected over the last several decades. Dividing each person's reported weight by their height squared gave their body mass index score, or BMI. By analyzing trends in BMI, the team estimated that in 2022, almost 900 million adults worldwide had a score of 30 or above, classifying them as having obesity. In children and adolescents ages 5 to 19, nearly 160 million were estimated to have obesity. From 1990 to 2022, the prevalence of obesity doubled in women, tripled in men and quadrupled in children and adolescents. Meanwhile, global rates of those who were underweight fell.

The upsurge should raise alarms, Ezzati says. Driving factors include limited access to healthy foods and societal-level lifestyle changes, such as getting less sleep and increasing stress levels. New anti-obesity drugs show promise, but they are out of reach for most people, he says. "Governments and societies need to deal with this" through prevention and affordable medical care. — *McKenzie Prillaman*

News

EARTH

An ancient quake stirs an old debate

Did plate tectonics spark an earthquake 3 billion years ago?

The Barberton Greenstone Belt in South Africa contains remnants of ancient underwater landslides. Such landslides often result from massive earthquakes driven by plate tectonics.

BY LUCAS VAN WYK JOEL

Scientists studying rocks in eastern South Africa report evidence for the earliest known earthquake triggered by plate tectonics. The temblor struck more than 3 billion years ago.

The rocks preserve telltale signs of ancient submarine landslides that tend to occur in response to powerful earthquakes set off by some collisions of slabs of the planet's crust, geologists Cornel de Ronde and Simon Lamb report February 27 in *Geology*.

Finding evidence of a giant earthquake so early in Earth's 4.5-billion-year history throws a spotlight on a hotly debated topic in geology: When did plate tectonics, the constant movements of interlocking pieces of crust, arise (*SN: 1/16/21, p. 16*)?

Some researchers suspect that plate tectonics emerged about 2.8 billion years ago. Others argue it began much earlier (*SN: 6/6/20, p. 10*). It's hard to know for sure because very few rocks from this period of the planet's history still exist.

"I am a strong advocate … of the other argument that plate tectonics has been with us since at least as long as the oldest rocks preserved on Earth, and probably even much before," says earth scientist Timothy Kusky of the State Key Lab for Geological Processes and Mineral Resources in Wuhan, China. "This study lends strong support to this second view."

The Barberton Greenstone Belt in eastern South Africa is home to some of the oldest known rocks, ranging in age from about 3.2 billion to 3.6 billion years old. De Ronde, of GNS Science in Lower Hutt, New Zealand, had mapped the distribution of the belt's different rock types and published the results in 2021.

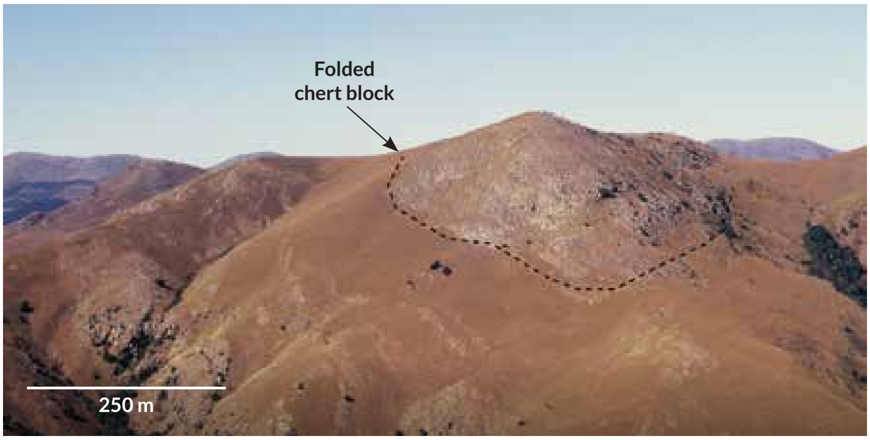
When Lamb, of the Victoria University of Wellington, saw the map, he spotted something surprising. The distribution of ancient rock layers and certain geologic features looked a lot like Lamb's map of the distribution of submarine landslides in New Zealand that were triggered by earthquakes relatively recently in geologic time.

"It's different rock, but the way the rocks were arranged was uncannily similar," Lamb says. "It unlocked the whole mystery of these early rocks."

The comparison suggests that the Barberton rocks preserve signs of being churned by giant submarine landslides. Such landslides can occur in the wake of earthquakes caused by two tectonic plates colliding and one thrusting atop the other. This process, called subduction, can be so forceful that it causes megathrust earthquakes, such as the magnitude 9.1 earthquake in Indonesia in 2004 and the magnitude 9.0 temblor in Japan in 2011.

The study offers "some of the earliest evidence for giant subduction megathrust earthquakes," Kusky says. It's the fieldwork that makes the argument convincing, he notes. The findings are based on solid, verifiable evidence in the rock record rather than on idealized models.

Geologist Richard Palin of the University of Oxford isn't entirely convinced. The initiation of plate tectonics, which today operates across the entire planet, is not a clean-cut story. "Some scientists may believe that subduction initiated everywhere all at once, hence the onset of plate tectonics is a bit like flipping a switch," he says. "This seems very unlikely to me." Palin suspects that subduction began in different places on Earth at different times. ■



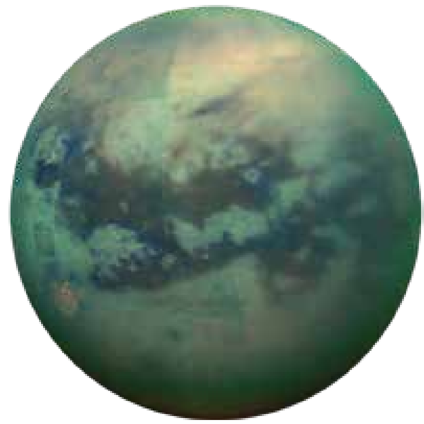
In the Barberton Greenstone Belt in South Africa, a geologic feature called a folded chert block (outlined by a dashed black line) may offer evidence that plate tectonics triggered a powerful megathrust earthquake between about 3.2 billion and 3.6 billion years ago.

FROM TOP: S. LAMB; C. DE RONDE

PLANETARY SCIENCE

Comets may have formed Titan's dunes

Simulations point to an origin for sands on Saturn's largest moon



Dune fields on Saturn's moon Titan appear as dark regions in this infrared image from NASA's Cassini spacecraft. The dunes may have formed as Saturn settled into its current location.

BY NIKK OGASA

THE WOODLANDS, TEXAS — The dark dunes of Titan, Saturn's largest moon, could have fallen from space.

More than enough cometary material may have struck Titan to have formed its vast dune fields, planetary scientist William Bottke of the Southwest Research Institute in Boulder, Colo., reported March 12 at the Lunar and Planetary Science Conference. Computer simulations suggest that the enigmatic drifts formed from objects hailing from the earliest days of the Kuiper Belt, which sits beyond the orbit of Neptune and continues to be a source of comets.

The proposed scenario could also explain the presence of similar material observed on other worlds, Bottke said.

The nature of Titan's sand has long been pondered. Beneath the moon's tangerine skies drift some 15 million square kilometers of dark dunes. These waves of sand rival the massive dunes found in the United Arab Emirates, says planetary geologist Jani Radebaugh of Brigham Young University in Provo, Utah. Those earthbound mounds are also where parts of the recent *Dune* films were shot.

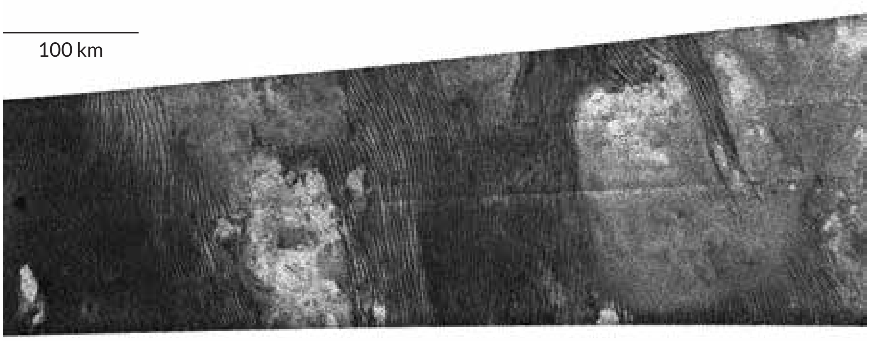
The prevailing hypothesis contends that Titan's undulating sands consist of organic particles produced by solar irradiation of the moon's hazy atmosphere (*SN: 3/2/19, p. 12*). After these micrometer-sized particles fall to the surface, they somehow grow larger into sand-sized grains that can form dunes. But it's not clear how exactly that growth would occur. And laboratory tests have suggested that the organic particles would break apart too easily to endure being buffeted into dunes, Bottke said.

Bottke and colleagues' new scenario gets around these problems and begins early in the history of the solar system, roughly 4 billion years ago.

One of the leading theories for the solar system's evolution states that the giant planets — Jupiter, Saturn, Uranus and Neptune — migrated from where they formed to their current positions, interacting with the Kuiper Belt along the way. That grand reshuffling would have led to the bombardment of Titan by comets. But many comets would have also smashed together, pulverizing them into tiny particles.

Researchers know a surprising amount about this type of debris, Bottke said, because many cometary particles have struck spacecraft and Earth. The particles are resilient enough to survive passing through our atmosphere. And they are dark in color and often about 200 micrometers wide, just the right size to build shadowy dunes on Titan.

Bottke and colleagues ran computer simulations of how Saturn, Jupiter and their moons evolved during this chaotic migratory period, tracking how much pulverized comet dust and how many large impactors fell on these planetary bodies.



NASA's Cassini spacecraft captured this radar image of dunes on Titan in 2009. The source of the dunes' sands could have been comets from a young Kuiper Belt, new simulations suggest.

FROM TOP: NASA; JPL-CALTECH/NASA

Both the dust and the impactors could have delivered more than enough material to account for Titan's dunes, the team found.

What's more, the simulations showed that much of the material also struck Saturn's moon Iapetus and Jupiter's moons Callisto and Ganymede, all of which are known to have large patches of dark material.

The material on Iapetus is thought to have arrived on the moon from somewhere else, says Radebaugh, who was not involved in the research. So it's plausible that Titan's sands could have otherworldly origins too.

But whether the material would remain on Titan's surface after falling from space is unclear. Eruptions of ice volcanoes on Titan, which have been theorized, would subsume and bury the old, fallen debris over time, Radebaugh says. "If you're resurfacing through volcanism, that would create a problem for this [story]."

NASA's Dragonfly mission to Titan, which is slated for launch in 2028, could solve the mystery. "It's a testable hypothesis," says mission scientist Melissa Trainer of NASA's Goddard Space Flight Center in Greenbelt, Md. Instruments on the rotorcraft will be able to measure the chemical compositions of the dune particles, she says, which could help determine whether they came from the Kuiper Belt.

And so one day, perhaps, a flying machine will confirm that seas of shattered comets ripple on a distant moon. ■

HEALTH & MEDICINE

Frostbite drug reduces amputation risk

The FDA has approved iloprost, which revives dying tissues

BY SAUGAT BOLAKHE

In the worst cases, frostbite kills tissues in the nose, fingers, toes and even limbs, requiring amputation. Now doctors in the United States have a new way to save patients from these life-altering effects.

In February, the U.S. Food and Drug Administration approved the country's first medication to treat severe frostbite. In a clinical trial, none of the frostbite patients who received the drug alone needed amputations compared with 60 percent of patients who received a different drug.

Frostbite affects just a few thousand people in the United States annually, but it is a major concern for those who must spend a lot of time outside in the cold, such as people without housing, construction workers and mountain climbers.

The newly approved drug, iloprost (sold as Aurlumyn in the United States), has been available as a frostbite treatment in Europe and other parts of the world for years. Developed in the 1980s, the vasodilator widens blood vessels, which improves blood flow and lowers the risk of clots. It was first used to treat Raynaud's disease, a disorder that causes narrowing of blood vessels in the fingers and toes. In 1994, scientists reported that the drug might be effective as a frostbite treatment.

Iloprost showed promise in additional studies in Europe and Nepal. In the clinical trial cited by the FDA in its approval, 47 patients rescued from high altitudes were given either iloprost, iloprost plus a blood thinner, or a different vasodilator. Of 16 patients who received iloprost alone, none had their digits amputated, scientists reported in the *New England Journal of Medicine* in 2011. In comparison, three of 16 patients in the iloprost combination group needed amputations, as did nine of 15 patients who received the vasodilator buflomedil.

Cold exposure can cause tissues in the toes and other extremities to die. A drug newly approved for use in the United States rescues frostbitten tissue, reducing amputation rates.

GOPEN RAI/AFP VIA GETTY IMAGES

Science News talked with vascular surgeon Chris Imray of University Hospitals Coventry & Warwickshire in England about what frostbite does to the body, how iloprost works and what the drug will mean for U.S. patients. The conversation has been edited for length and clarity.

What is frostbite?

Frostbite is a thermal injury that affects the hands, feet, nose, ears and occasionally external genitalia after a few hours of cold exposure. When the temperature of the tissue drops to around zero degrees Celsius, the blood flow through the tissue slows down. Then clots form within the blood vessels, which subsequently leads to loss of oxygen to the tissue. Over time, you then get gangrene and the tissue dies.

How did scientists find that blood flow is key for treating frostbite?

If a tissue that's damaged from a thermal injury has poor blood supply, you could try to treat by warming the tissue. But the problem is that if there's no blood supply, you may warm up the tissue but you won't restore the oxygen delivery to the tissue, which speeds up the deterioration.

In other situations, like stroke or acute coronary syndromes, if you can restore the blood supply quickly—within four to six hours—you can clear the clots in the small blood vessels, and then oxygen is delivered to the tissues again. One of the treatments for acute coronary syndrome is thrombolytic agents to break down the clot. But if a patient has soft tissue or bone injuries, giving them thrombolytic agents may cause more bleeding.

Iloprost works as a vasodilator rather than as a lytic agent on the clot. That's where the idea came from. It also seems to affect clotting slightly. And it changes the [ability] of the red blood cells to get through the small vessels.

How has iloprost changed frostbite treatment where it's been used?

We used to cut the sympathetic nerves to open up the blood vessels to the hands or to the feet. Once iloprost came out, it seemed to have a similar effect—it would cause the blood vessels to vasodilate. The beauty was you didn't have to cut the nerves permanently.

How is the drug administered?

The drug is given intravenously [for six hours per day for around five days]. We can do imaging tests to see if there's an improvement to the blood supply to the tissues. The overall effect is a dramatic limb and digit salvage rate, which is quite remarkable.

How soon after a frostbite injury should iloprost be administered?

We thought 24 hours was the maximum, but there have been reports of some people who have gone as long as five days [without treatment]. But the longer you go, the less impressive the effects will be.

Who will the new approval benefit?

A number of high-profile climbers have had injuries where they've been told there's nothing that can be done. And they subsequently lost tissue. So, what we're trying to do is to identify medical units [close to big mountains] where iloprost can be given, so that if you have an injury, you can be flown there as quickly as possible.

Frostbite also affects homeless people. They can have serious frostbite injuries and end up with life-changing amputations. If you look at people who would be at risk of losing limbs, [the iloprost approval] will transform that. I'm delighted [the FDA has] approved it, but they've taken quite a long time to get there. ■

HEALTH & MEDICINE

UTIs spur overzealous nerve growth

Experiments in mice hint at why pain can linger after infections

BY HELEN BRADSHAW

Urinary tract infections are painful and incredibly common. For decades, doctors haven't had any leads on why, even after several rounds of antibiotics, UTI pain can linger. Now they do.

Nerve growth from immune responses to the infection might be to blame, researchers report in the March *Science Immunology*. The findings could someday lead to new forms of treatment.

Over half of women will have a urinary tract infection during their life, and around a quarter of first-time infections return within six months. The pain from these infections can be difficult to treat, says neurological urologist Marcus Drake of Imperial College London. Persistent UTI pain is usually treated with drugs such as antihistamines, but the relief can be unsatisfactory, he says.

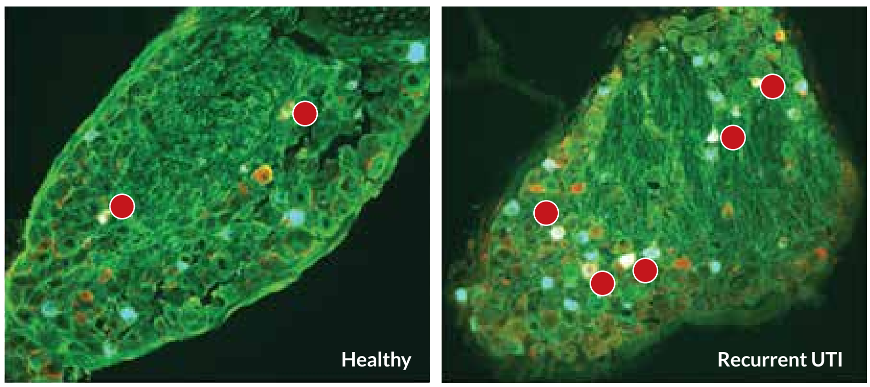
Puzzled by why UTI pain can persist after bacteria are wiped out, immunologist Soman Abraham of Duke University and colleagues collected urine samples from women with recurrent infections. Compared with those from women without recurrent UTIs, the samples showed signs of nerve activation. In an experiment, mice induced to have multiple UTIs had "a tremendous growth of nerves" compared with control mice, Abraham says.

The bladder sheds tissue during a UTI to remove bacteria. But nerves get sloughed off too, which spurs nerve-growing immune cells. A close look at the bladders of mice with repeat UTIs revealed loads of two kinds of immune cells — mast cells and monocytes — that produce a substance called nerve growth factor.

The more often the body has to fight UTIs, the better monocytes and mast cells get at their job. It becomes "an overzealous response," Abraham says. Nerve growth factor also lowers the threshold at which nerve pain receptors activate. Even after no UTI bacteria remained, mice in the study had frequent urination and lingering pain. But antihistamines and blockers of nerve growth factor provided some relief.

Understanding how UTIs influence nerve growth could lead to more effective pain management, the team says. ■

Compared with healthy mice (left), mice with recurrent UTIs (right) had more nerve cells (red dots in these microscope images of sensory cells near the spine) that transmit pain signals from the bladder.



HEALTH & MEDICINE

Brain fog tied to leaking vessels

Study hints at a biological cause for the long COVID symptom

BY MEGHAN ROSEN

Leakiness in the brain could explain the memory and concentration problems linked to long COVID.

In patients with brain fog, MRI scans of their brains revealed signs of damaged blood vessels, geneticist Matthew Campbell of Trinity College Dublin and colleagues report in the March *Nature Neuroscience*. Dye injected into the bloodstream leaked into these people's brains, pooling in the temporal lobes — regions involved in language, memory, mood and vision. It's the first time anyone's shown that long COVID patients can have leaky blood-brain barriers, Campbell says.

Tightly knit cells lining blood vessels keep riffraff out of the brain. If the barrier breaks down, viruses and other interlopers can sneak into the brain's tissues and wreak havoc, says neurologist Avindra Nath of the National Institutes of Health in Bethesda, Md. The study provides evidence that "brain fog has a biological basis," he says.

Campbell and colleagues knew that concussions and other traumatic brain injuries can disrupt the blood-brain barrier — and that people with these injuries sometimes report having brain fog. Maybe disruptions to the blood-brain barrier applies to long COVID brain fog, too, the team surmised.

Evidence for the coronavirus's damaging effects on the brain is mounting. Studies in human cells and in animals have suggested the virus crumbles parts of the blood-brain barrier. And autopsies of people who died from COVID-19 found barrier breakdowns. But no one knew if the damage persisted after the initial infection subsided (see Page 18).

The researchers scanned the brains of 32 people, 10 of whom had recovered from COVID-19 and 22 with long COVID. Half of those with long COVID reported having brain fog. Dye injected during the scans had trouble crossing the blood-brain barrier in all participants without brain fog. In 8 of 11 long COVID patients with brain fog, the dye escaped blood vessels and entered brain tissue. In one person with severe brain fog, the temporal lobes were "just flooded," Campbell recalls.

"Brain fog wasn't just a figment of [patients'] imagination," he says. The team is now exploring treatment options. ■

B.W. HAYES ET AL/*SCIENCE IMMUNOLOGY* 2024

ANIMALS

This amphibian feeds ‘milk’ to its young

Like mammals, female ringed caecilians make a nutrient-rich fluid

BY JAKE BUEHLER

In the middle of the night in a humid coastal rainforest in Brazil, a litter of pink, hairless babies snuggle with their mother. They stir and squeak for milk, mom obliges, and they are sated. But these aren’t pups or cubs. They are snake-shaped amphibians, far closer to frogs than foxes.

Ringed caecilian moms feed their hatchlings “milk” brewed in the reproductive tract, researchers report in the March 8 *Science*. The long, cylindrical creatures are the first amphibians known to feed hatchlings this way. The discovery suggests that parental care across animal life is more diverse than scientists thought.

For an animal with so few obvious external features, *Siphonops annulatus* caecilians are a fount of strange biology. The legless, nearly blind and possibly venomous amphibians are covered in poisonous slime and feed their own skin to their young (*SN: 8/1/20, p. 12*).

Herpetologist Carlos Jared of the Instituto Butantan in São Paulo and colleagues have studied ringed caecilians for years. In previous work, the team noticed that hatchlings spent much of their first two months of life near their mother’s vent, an opening on the body that’s shared by the reproductive, digestive and urinary systems. Mom would periodically expel a thick fluid from the vent, which the young would feast on. “Some even stuck their heads inside this opening,” Jared says.

Ringed caecilian females (one shown with smaller, pink young) feed their babies a fat-rich fluid similar to mammal milk that’s made in the reproductive tract.

C. JARED

Following up on those observations, the team studied 16 females and their litters in the lab, recording 36 feedings. Babies often wriggled and nibbled at their mother’s vent while making high-pitched noises. In response, mom would raise that end of her body and release the fluid. This happened up to six times per day.

The high-pitched begging is particularly fascinating, says evolutionary biologist Mark Wilkinson of the Natural History Museum in London. The adults are thought to be sensitive only to lower-frequency sounds.

Analyses of caecilian anatomy and the nutritional fluid revealed that glands in the oviduct enlarge and secrete the fluid while the female raises hatchlings. Much like mammal milk, the fluid is rich in fats. This nutritious resource may explain how hatchlings grow so fast — bulking up their mass by up to 130 percent, an additional 0.27 grams, in the first week out of the egg.

Isabella Capellini, an evolutionary biologist at Queen’s University Belfast in Northern Ireland, notes that in mammals, lactation is the most expensive stage of reproduction for the mother. “It would be useful to study whether milk production is as expensive in caecilians too.”

How the fluid evolved in these amphibians is still unclear. But the oviduct of this egg-laying species behaves similarly to those of live-bearing caecilians, which feed their young a milky substance while babies are in the womb.

Perhaps live-bearers evolved from egg-laying species that already used their oviducts to produce food, Wilkinson says. “We really have learned a lot about caecilians in the last few decades, but we are only seeing the tip of the iceberg.” ■

ANIMALS

Dragonfly coats have climate perks

Wax-wearing species persist in increasingly hot, dry habitats

BY JAKE BUEHLER

A waxy coat that keeps some dragonfly males cool while they pursue mates might also help the insects shrug off a warming climate.

In the United States, dragonfly species that produce the wax are faring better than their waxless counterparts in the face of increasingly hotter and drier conditions. This suggests the wax acts as a buffer against climate change, scientists report in the March 5 *Proceedings of the National Academy of Sciences*.

The wax gives some dragonflies a kind of “ecological superpower” that lets the insects use an expanded range of habitats, says evolutionary biologist Michael Moore of the University of Colorado Denver.

Moore and colleagues have studied how warming climates affect dragonfly coloration, and the team was itching to test a slightly different idea: whether lacking a mating-related trait might limit species from inhabiting certain climates, especially as those climates rapidly change.

So the scientists turned to dragonfly wax. In some species, mature males exude hydrocarbons that form a thick, frosty-looking layer, or pruinescence, over the exoskeleton. The team suspected that the wax, which reflects ultraviolet light, shields dragonflies from water loss and overheating — a potential boon in hot, arid climes. Lab tests confirmed this protective role, which could be a major advantage given many dragonflies’ mating behavior.

Some species use a “percher” strategy, where the males rest exposed in the sun and move only to chase away intruders or pursue females. Moore’s team tested whether pruinescence is an adaptation for dealing with brutally hot and dry conditions while chasing mates.

Using mating behavior data from 319 species in North America, the team compared perchers with fliers, which

Watch a video of baby caecilians drinking their mother’s “milk” at **bit.ly/SN_AmphibianMilk** continually fly around and take drink breaks during courtship, allowing them to stay cool and hydrated. Sure enough, perchers were more likely to have the protective wax than fliers. Computer modeling suggests that fliers largely ditched the wax when they diverged from their percher ancestors.

Wondering if pruinescence also allows the dragonflies to live in hotter and drier regions, the team analyzed nearly 400,000 geographic records for the species. Pruinescence was most common in the warmest and driest places.

The team then looked at 60 species within 385 geographic areas, comparing the insects' status — either persisting or vanishing — with temperature and precipitation trends in these areas since the 1980s. Waxless dragonflies are more likely to disappear from areas that are most rapidly warming and drying, the scientists found.

"But we're not seeing that effect in the species that have evolved pruinescence, so the species with the wax [have been] basically insensitive to climate change across the United States," Moore says.

The white wax on the abdomen of this male eight-spotted skimmer keeps the dragonfly cool and may buffer against climate change.

This finding flips a common idea in evolutionary biology on its head. Environmental factors tend to act as brakes on the evolution of mating traits. Consider deer. Large antlers may attract females, but they are costly for males to grow in a world with limited resources. The study provides an opposite view: Instead of constraining dragonflies in a warming world, the wax has kept certain habitats within reach.

The finding shows that "relationships between sexual selection and ecology are really complex and … might not be obvious at first glance," says evolutionary biologist Agata Plesnar-Bielak of Jagiellonian University in Kraków, Poland.

Species need to be able to reproduce to be successful, Moore says. He calls for a broader view of forecasting what habitats will be suitable for species in the future, considering whether the species will be able to mate as temperatures rise. ■

ANIMALS

Big caterpillars may binge on toxic sap

Milkweed latex is often a deathtrap for monarch butterfly larvae

BY SUSAN MILIUS

Maybe science has misunderstood the dining style of big monarch butterfly caterpillars. What insect watchers have called defense against toxic latex that a milkweed plant oozes may not be avoidance at all. Instead of dodging the plants' sticky white goo, the plump, older caterpillars could be gorging on it.

Monarch caterpillars (*Danaus plexippus*) hatch and feed on milkweeds, which bleed toxin-rich latex when bitten. Monarchs evolved their own counter-chemistry for surviving the toxins. Yet the latex can still kill by sheer gooeyness, says Georg Petschenka, an ecologist at the University of Hohenheim in Stuttgart, Germany. Tiny, recently hatched larvae can get stuck and their mouthparts fatally clogged.

Caterpillars can get around milkweed traps by nipping leaf stalks and then waiting for the latex to bleed out. For older caterpillars strong enough to risk glue, Petschenka argues, those cuts can do more than disarm a leaf. By this stage, the caterpillars feast on the latex itself. Offering them a latex-loaded pipette to suckle showed that they readily drink the sap and build up their own defensive toxin reserves, he and Hohenheim entomologists Anja Betz and Robert Bischoff report in the Feb. 28 *Proceedings of the Royal Society B*.

The older caterpillars dip their mouthparts in latex "like a little cat drinking milk," Petschenka says.

The toxins, called cardenolides, attack an enzyme that helps balance potassium and sodium levels in animal cells. Monarch caterpillars can convert some cardenolides into less toxic forms, which build up in the body and deter predators such as birds.

Monarchs are thought to gain most of that protection from nibbling leaves. But the idea that big caterpillars might harvest latex for protection has floated around since the early 20th century. Another idea: Caterpillars will drink latex to get it out of the way as they cut leaves.

But it's not an obvious behavior. "I have never seen monarch caterpillars drinking beads of latex sap from milkweed," says ecologist Sonia Altizer of the University of Georgia in Athens. "After reading this finding, I am going to pay more attention to what they are doing."

Petschenka became curious when he noticed that there wasn't any latex left at a wound after big caterpillars ate. "We would expect this to flow out and then maybe to dry up," he says. Maybe the wound was made to find toxins instead of drain them.

In lab tests, monarch caterpillars fed on leaves without waiting for latex to drain, Petschenka's team found. That never happened with *Euploea* caterpillars, which eat milkweed but don't stash its toxins. These diners always drained latex from leaves before eating. Very young monarch caterpillars also avoided latex — until they grew older and shifted to eager drinking.

The findings got a hard look from Anurag Agrawal, an evolutionary biologist at Cornell University who had supervised Petschenka's postdoc work. For years, Agrawal dismissed latex-sipping as a "necessary evil." Now, he says, "the study changed my mind." ■

SARAH E. NALLEY

ANIMALS

Mammal size rule needs rethinking

In many species, females equal or outweigh males

BY JONATHAN LAMBERT

In most equids, such as these feral horses wading in the waters of Shackleford Banks, N.C., there's little difference in size between the sexes.

The idea that male mammals tend to be larger than females has been scientific dogma since the days of Darwin. Bigger bodies, the thinking goes, are better in the battle to win the attention of choosy females. Turns out, that dogma may need updating.

In over half of nearly 430 mammal species studied, females equal, or outweigh, their male counterparts, scientists report March 12 in *Nature Communications*. The persistence of the larger male narrative, the scientists say, reflects long-lasting biases in the scientific literature that have constrained biologists' grasp of sexual selection — the evolutionary process that favors traits that attract mates or fend off rivals for mates.

The standard story has "just been this assumption that most people have gone along with without good evidence," says evolutionary biologist Kaia Tombak of Purdue University in West Lafayette, Ind.

Males and females of the same species can differ in size, a phenomenon called sexual size dimorphism. Biologists trying to understand what drives these differences have often turned to charismatic mammals such as lions or gorillas, which often have larger males. The dogma was propped up by analyses that didn't report size variation within a species, Tombak says, an omission that makes it hard to tell for sure whether a species is dimorphic. "We tried to get at this question by being a bit more rigorous."

She and colleagues analyzed data on the masses of males and females in 429 mammal species. On average, 45 percent of species had heavier males, 16 percent had heavier females and 39 percent had no difference. The team found similar trends in data on animal length. Well-studied groups like carnivores, primates and ungulates were skewed toward heavier males. But nearly half of bats had heavier females, and in about half of rodents, males and females weighed about the same.

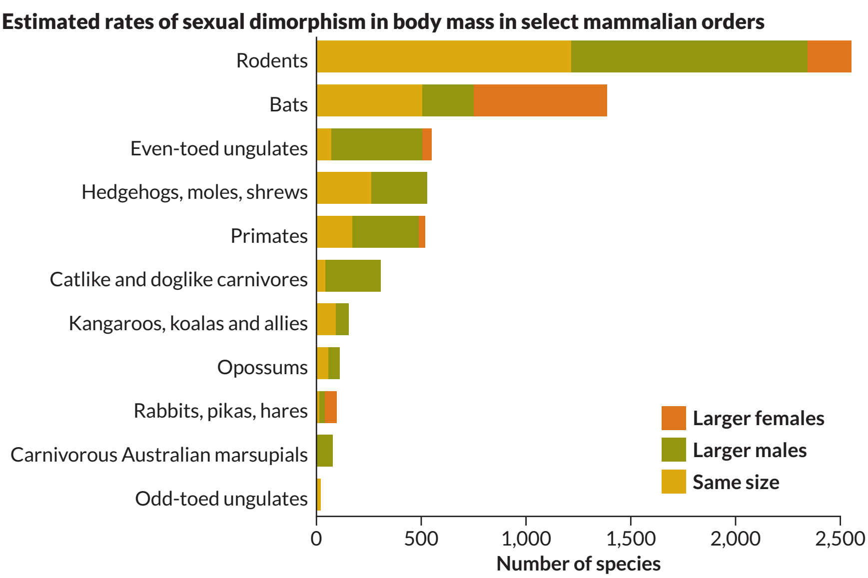
The study included about 5 percent of all mammal species. The numbers could change with more data, Tombak says, but because the team covered most of the mammalian evolutionary tree, she's confident the general picture is correct.

Previous studies have shown that larger females are quite common. But "the research has been male-centered, and equivalent evolution of females [has] often been overlooked," says evolutionary biologist Malin Ah-King of Stockholm University. As a result, the idea that males are bigger to compete for access to passive females became entrenched, she says.

Evolutionary biologist Catherine Sheard of the University of Aberdeen in Scotland says that "the real power of this study is that they were very careful and methodical." The findings underline that "there are things that people just blithely assume because they haven't thought about it since the first year of undergrad biology."

Ditching those assumptions can free biologists to ask new questions, including why females are bigger in some species or what forces keep others the same size, Sheard says. ■

Battle of the sexes The idea that male mammals are larger than females doesn't hold for many species. For instance, about half of rodent and bat species have females that weigh just as much as or more than males, scientists estimate. SOURCE: K.J. TOMBAK *ET AL/NATURE COMMUNICATIONS* 2024



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In 2021, more than 700,000 flags were planted on the National Mall in Washington, D.C., as part of Suzanne Brennan Firstenberg's art exhibition *In America: Remember*. Each flag represented one U.S. COVID-19 death at the time.

SCIENCE & SOCIETY

How do we grieve COVID-19 deaths?

The pandemic radically altered mourning for millions of people

BY AIMEE CUNNINGHAM

March 11 marked the fourth anniversary of the World Health Organization's declaration that the COVID-19 outbreak was a pandemic. COVID-19 hasn't gone away, but there have been plenty of actions that suggest otherwise.

In May 2023, WHO announced that COVID-19 was no longer a public health emergency. The United States followed suit, which meant testing and treatments were no longer free. And on March 1 of this year, the U.S. Centers for Disease Control and Prevention loosened its isolation guidelines for people with COVID-19. Now the CDC says an infected person can be around others as soon as a day after a fever subsides and symptoms are improving, even though that doesn't mean the person is no longer contagious. People with COVID-19 are contagious for an average of six to eight days.

These outward signs of leaving the pandemic behind neglect to acknowledge how many people cannot (*SN: 11/6/21, p. 18*). About 1.2 million people in the United States have died from COVID-19. Roughly 9 million adults have long COVID. Nearly 300,000 children have lost one or both parents.

There has been little official recognition in the United States of the profound grief people have experienced and continue to experience. There is no federal monument to honor the dead — mourners have constructed their own memorials. A resolution to commemorate the first Monday of March as "COVID-19 Victims Memorial Day" awaits action by Congress.

Many people are coping not just with the deaths of family and friends, but also with how pandemic restrictions robbed them of the chance to say good-bye and grieve with their family and community. Researchers are studying the extent to which these losses rippled out into society and how the pandemic interrupted the grieving process.

Demographer Emily Smith-Greenaway of the University of Southern California in Los Angeles was part of a team that estimated that for every one U.S. COVID-19 death, there are nine bereaved family members. Sarah Wagner, a social anthropologist at George Washington University in Washington, D.C., coleads Rituals in the Making. The project is examining how the pandemic disrupted rituals and the experience of mourning through interviews with mourners and death care workers, among other research methods. *Science News* spoke with Wagner and Smith-Greenaway about their work. The conversations have been edited for length and clarity.

Why is it important to estimate the number of family members affected by COVID-19 deaths?

Smith-Greenaway: We typically quantify mortality events in terms of numbers of casualties. By shedding light explicitly on the concentric circles of people surviving each of the deaths, we offer a much more experiential perspective — the burden

ANNA MONEYMAKER/GETTY IMAGES

that a large-scale mortality event imposes on those who are still alive. It also allows us to kind of rescale the true sense of the magnitude of the crisis.

[With the number of deaths today,] our model demonstrates that about 10.5 million people have lost a close relative to COVID-19. This includes grandparents, parents, siblings, spouses and children. We're not even capturing cousins, aunts, uncles. Think about how many children lost teachers or how many neighbors or friends or coworkers [died]. This is an underestimate when we're thinking about the many people who are affected by each death.

What motivated the Rituals in the Making project?

Wagner: We began in May of 2020, and this was this period of heightened pandemic restriction and confinement. We posed what we saw as a fundamental question: How do we mourn when we cannot gather? Particularly in that first year, we were focused on the rituals around funeral, burial and commemorative practice and how they would be impacted and changed by the pandemic. In the last two years, [the project] has included the ways in which misinformation also compounds individual grief and more collective mourning.

A throughline in the research is that this mourning was interrupted and constrained by the conditions of the pandemic itself, but also troubled by politicization of the deaths. And then there's this expectation that we move on, we push past the pandemic, and yet we have not acknowledged the enormity of the tragedy.

Why are rituals and memorials important to grieving?

Wagner: We think about rituals as providing a means to respond to rupture. We are able to come together, gathering to stand before a coffin to say good-bye, or to have a wake, to sit down and have a meal with the bereaved. They are about providing an opportunity to remember and honor that loved one. But they are also about the living — a way of supporting the surviving family members, a way of helping them out of the chasm of that grief.

Memorials [such as a day of remembrance or a monument] are a nation saying, "We recognize these lives, and we anoint them with a particular meaning." We think about memorials as forms of acknowledgement and a way of making sense of major tragedies or major sacrifices.

In the context of the pandemic, the rituals that are broken and [the lack of] memorials at that national level help us see that the mourners have been left in many ways to take memory matters into their own hands. The responsibility has been pushed onto them at these acute moments of their own grief.

How has the pandemic impacted survivors and the grieving process?

Smith-Greenaway: There is a generational effect any time we have a mortality crisis. A war or any large-scale mortality event lingers in the population, in the lives and memories of those who survived it.

This pandemic will stay with us for a very long time. [There are] young people who remember losing their grandma, but they couldn't go see her in the hospital, or remember losing a parent in this sudden way because they brought COVID-19 home from school. So many lives were imprinted at such an early stage of life.

1.2 million

Estimated number of U.S. deaths from COVID-19

10.5 million

Estimated number of people in the United States who lost a close relative to COVID-19

Wagner: Whether we are talking to the bereaved, members of the clergy, health care workers or staff from funeral homes, people describe the isolation. It is incredibly painful for families because they weren't able to be with their loved one, to be able to touch someone, to hold their hand, to caress a cheek. People were left to wonder, "Was my loved one aware? Were they confused? Were they in pain?" [After the death], not being able to have people into one's home, not being able to go out. That sort of joy of having other people around you in your depths of grief — that was gone.

As the study progressed, [we learned about] the impact political divisiveness had on people's grief. [Families were asked,] "Did the person have underlying health issues? What was the person's vaccination status?" It was as if the blame was getting shifted onto the deceased. Then to be confronted with, "This is all just a hoax," or "[COVID-19 is] nothing worse than a bad cold." Their loved ones' death and memory is not just dismissed, but in a way feels denied.

How can society better support the need to grieve?

Smith-Greenaway: Bereavement policies are not very generous, as we would expect in America. Sometimes it's one, two or three days. They're also very restrictive, where it has to be a particular relation.

Think about kids. I'm a professor at a university. There's this callous joke that college students just tell you their grandmother died because they don't want to turn something in. This reflects how we treat bereavement as a society, especially for young people. Kids' grief can often be misunderstood. It's perceived to be bad behavior, that they're acting out. I think we need comprehensive school policies that take better care to recognize how many kids are suffering losses in their lives.

Wagner: We're enveloped in this silence around pandemic death. I think there's a willingness to talk about the pandemic losses in other realms, the economic losses or the loss of social connection. Why is there this silence around 1.2 million deaths — the enormity of the tragedy?

If you know someone who has lost a loved one to COVID-19, talk to them about it. Ask them about that loved one. Just being an active part of conversations around memory can be a beautiful act. It can be a restorative act. ■

SCIENCE & SOCIETY

Timbre shapes harmonic taste

Finding hints at why musical scales differ across cultures

BY MARIA TEMMING

The mathematical rules for creating musical harmony may be more malleable than previously thought.

Western music theory holds that chords sound most pleasant when they contain notes separated by certain intervals. Namely, intervals where the notes' frequencies have simple ratios — like 2:1 (an octave) or 3:2 (a fifth).

But people's actual preferred harmonies depend on the timbre of the notes, a new study suggests. Timbre is the distinct flavor of sound produced by specific instruments — the reason that the same note played at the same volume sounds different on the piano, guitar or gong.

The findings, reported February 19 in *Nature Communications*, show that the recipe for a beautiful harmony is more nuanced than a simple set of mathematical relationships. The results may also help explain why different cultures — whose instruments yield different timbres — have developed diverse musical scales.

Culture plays a role in people's tastes for different blends of notes, says Tuomas Eerola, who studies music cognition at Durham University in England. "This study really nicely shows that it's not just any arbitrary [cultural influence]. It might come from the type of instruments being used in certain cultures."

Over 4,000 participants in the United States completed a battery of harmony perception tests online, listening to computer-generated notes with different timbres. In one test, people were asked to rate the pleasantness of chords containing realistic-sounding notes similar to those produced by Western instruments. Surprisingly, people seemed to prefer intervals slightly different from those tuned to simple, "ideal" frequency ratios.

People might prefer the slightly off intervals because they cause the sound to slowly pulsate, giving a chord some added texture. "Not too much, but a little bit of deviation from the integer ratio that creates a little bit of roughness," says coauthor Nori Jacoby, a cognitive scientist at the Max Planck Institute for Empirical Aesthetics in Frankfurt. "When you have that, you feel it's more pleasant."

The bonang is a Javanese array of gongs. In a test, people in the United States preferred bonanglike chords that diverged from Western music theory.

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In another test, people listened to chords that contained synthetic notes modeled after a non-Western instrument: the bonang. This collection of gongs is played in the Javanese version of an Indonesian musical ensemble called a gamelan. When study participants listened to chords with bonanglike timbres, they preferred intervals with different frequency ratios than Western "ideal" ratios.

Those chord preferences mapped onto a musical scale used by Javanese gamelans called the slendro scale. This scale has five notes per octave — compared with Westerners' 12, including sharps and flats — with frequency ratios that are not even close to simple integer ratios. (The slendro scale cannot be played on Western instruments like the piano, because some of its notes would fall between the keys.)

Even though participants probably had little or no prior exposure to Javanese gamelan music, they seemed to intuitively prefer chords at home in that musical style while listening to an artificial bonang. The finding suggests that musical scales "can be strongly influenced by the kind of instrument they're used for," Jacoby says.

The idea that timbre influences people's preference for "perfect" versus "imperfect" ratios in musical intervals fits with how gamelan instruments are tuned and played, says gamelan music expert Ki Midiyanto of the University of California, Berkeley.

The tuning of bronze gamelan instruments such as the bonang "is done by feel, and significant differences between sets of instruments is the norm," Midiyanto says. "This variation is both desirable aesthetically, and to some degree inevitable, as instrument tuning does not remain completely stable over time."

In fact, it's common to manipulate the interval of an octave in bronze instruments to create a nicer combined timbre when the gamelan ensemble plays, Midiyanto says. But that's never done with stringed instruments, such as the siter and celempung.

Jacoby's team carried out further tests that showed tampering with timbre influenced the harmonic preferences of 68 people from South Korea — offering preliminary evidence that Westerners are not the only ones whose harmony preferences are shaped by timbre.

Eerola would like to see similar investigations with people from other parts of the world who may not have as much exposure to Western music as those in South Korea. ■

Watch videos of the musical experiments at **bit.ly/SN_Timbre**

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SEARCHING FOR LONG COVID CLUES

Telltale signs in the blood could lead to tests and treatments **By Meghan Rosen**

RACHEL BARRETT/GALLERY STOCK

When I talk to immunologist Paul Morgan, he's on the hunt for potentially life-altering drugs.

He's got a call with a pharmaceutical company planned in the next half hour. His goal: Persuade the company to supply his lab with a drug that might — maybe, hopefully, someday — ease some of the unrelenting symptoms of long COVID.

Morgan's lab at Cardiff University in Wales has been studying people with the disease, including the first waves of patients, some of whom have been living with long COVID for years (SN: 9/23/23, p. 9). The "very long haulers," he calls them. Their symptoms can include brain fog, fatigue, breathlessness, and joint and muscle pain.

Morgan and his colleagues have pinpointed an immune system anomaly in the blood of some of these long haulers. A drug that targets that quirk might be one way to treat the disease. He's quick to tell me that this research is in its early days. First, his team needs to get its hands on a drug. Then, there needs to be a clinical trial — at this stage, it's still proof of concept. "Actual treatments are still some way off," he says.

But the work is part of a surge of studies mining the blood for long COVID clues. A growing cadre of labs are starting to sketch out some of the shrouded figures at play in the once-seemingly inscrutable disease. It's as if there's a "picture that's being revealed from the fog," says Akiko Iwasaki, an immunologist and Howard Hughes Medical Institute investigator at Yale University.

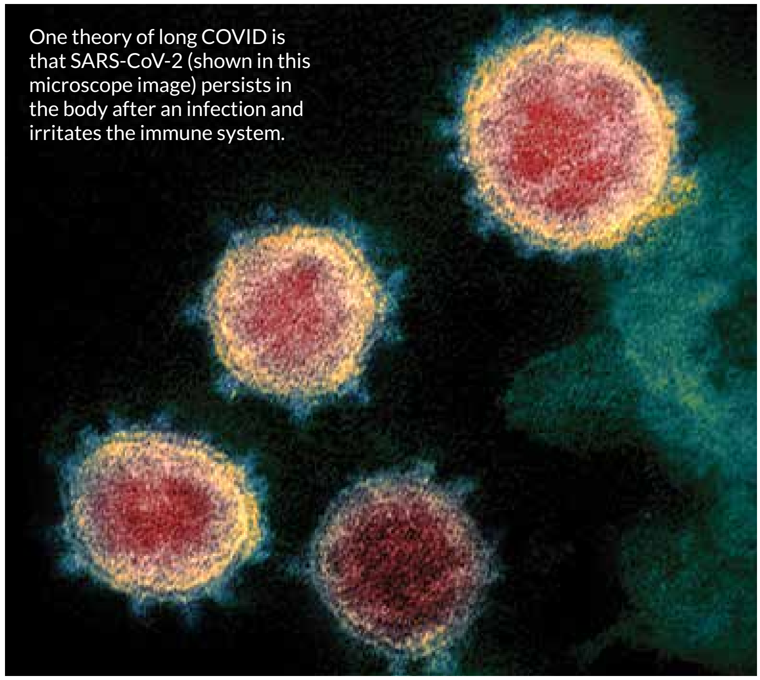
That picture features a motley cast of molecular and cellular characters that could point scientists toward potential tests and treatments — both are currently lacking. Still, the full long COVID landscape is unquestionably complicated. Assorted actors tangle together in an immunological thicket that can make the disease seem impenetrable.

But Iwasaki thinks researchers can crack long COVID's mysteries. In fact, recent work in the field has her feeling excited. Yes, investigating long COVID is complex, she says. "But it's definitely worth doing because many people are suffering."

Studying these long haulers might be key to illuminate the disease — and to getting clarity on the less severe but still vexing symptoms that stuck around for months after my own COVID-19 infection.

Many diseases in one

Some 5 to 20 percent of COVID-19 cases develop into long COVID, though the exact number is hard to pin down. One formidable challenge is diagnosis. Does a person with bone-deep exhaustion and trouble concentrating have the disease? There's no test or nasal swab doctors can use to provide a definitive answer.



One theory of long COVID is that SARS-CoV-2 (shown in this microscope image) persists in the body after an infection and irritates the immune system.

For diseases like diabetes and prostate cancer, scientists look for biomarkers in the blood — molecules that can serve as telltale signs of illness. But "we are not likely to come up with one biomarker or even one set of biomarkers to distinguish everyone with long COVID," Iwasaki says.

The difficulty is that long COVID is not just one disease. It's likely a collection of many diseases, she says, with varying sets of symptoms and triggers. Even defining long COVID is complicated. Last spring, researchers developed a long COVID scoring system that factors in a dozen signature symptoms. But more than 200 symptoms have been tied to the disease, and cases can vary greatly from person to person (SN: 11/5/22, p. 22).

"Perhaps there's SARS-CoV-2 somewhere in the body that can't be cleared."

NADIA ROAN

Today, in many doctors' offices and clinics, homing in on a diagnosis means first ruling out other conditions. For example, after months of feeling wrung out and faded, with unexpected pain in my legs following a COVID-19 infection last year, my doctor ordered a slew of blood tests. She was looking for signs of rheumatoid arthritis, Lyme disease, thyroid hormone abnormalities and a handful of other conditions. Everything was negative.

It's a "diagnosis of exclusion," Morgan says. "You test for everything else, and when nothing comes back positive, you say, 'Well, it must be [long COVID], then.'" He compares it to myalgic encephalomyelitis/chronic fatigue syndrome, or ME/CFS, another debilitating condition that also lacks clear diagnostic tests. "Many physicians don't take it very seriously at all because of that." That concern is even listed on the U.S. Centers for Disease Control and Prevention's ME/CFS Web page.

And it's true of long COVID, too, says Wolfram Ruf, an immunologist at University Medical Center Mainz in Germany. "There's still some misconception that this is just a psychological disease." A 2022 survey found that a third of long COVID patients felt as if medical professionals dismissed their illness. And stories from frustrated long haulers continue to appear in the news.

Better diagnostics mean people suffering from long COVID's myriad symptoms could put a firm label on their condition. That's important, Morgan says. But tests that spot long COVID biomarkers in the blood could also do far more. "If those tests actually lead you to a mechanism and to a treatment," he says, "then that's transformational."

34 percent
Long COVID patients who reported in a survey that their illness had been dismissed by medical professionals

A complicated cast of characters

Morgan's lab and others have zeroed in on immune proteins that defend us from bacteria and viruses. These proteins, part of a defense called complement, circulate in the blood and get chopped up during an infection. The resulting fragments sound a "we're under attack" alarm and help form a molecular machine that busts pathogens.

Once the infection clears, the fragments fade away. But in some people with long COVID, the alarm-raising fragments can linger in the blood, Morgan's team reported in the March 8 *Med*. That's a sign that the defense system is still whipping up inflammation — in some cases, even years after a person's initial COVID-19 infection. In January, a different group reported something similar in *Science* from a study of 113 COVID-19 patients.

Not everyone with long COVID will have complement abnormalities. Even in the patients Morgan studies, "there will be some people who have no changes in their complement markers at all."

But for those who do, it can be a double-edged sword, he says. Turning complement on briefly can knock out some bugs, but keeping it on chronically can damage your cells.

There's an ever-growing list of other blood anomalies, too. A protein abundant in the brain can leak out into the blood in people with brain fog, scientists have found (see Page 9). And long COVID patients can have low levels of the stress hormone cortisol, Iwasaki's team reported in *Nature* in September. In some patients, she and others have also spotted other suspicious signs, like long-slumbering herpesviruses that reawaken and start infecting cells again. "Whether this is a cause or effect [of long COVID]," Iwasaki says, "we don't know." Usually, the immune system keeps these viruses under control.

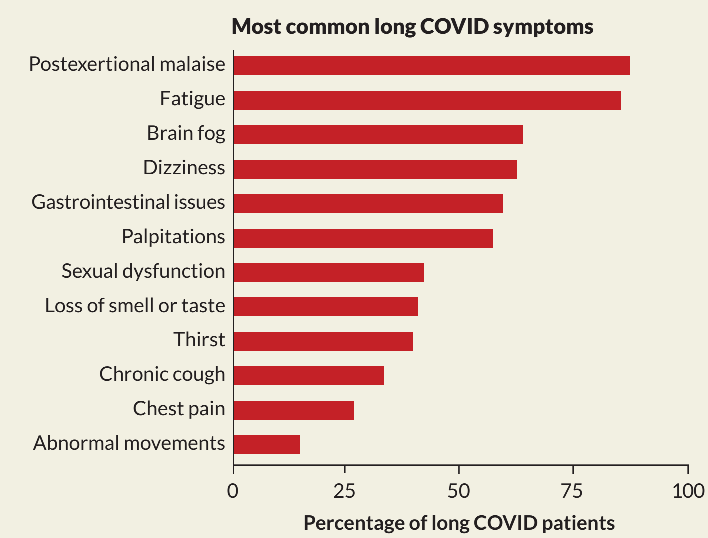
In some people with long COVID, powerful immune players called T cells also seem to go out of whack. Scientists in England analyzing the blood of long COVID patients found T cells that release high levels of an alarm signal called interferon-gamma. That signal could serve as a potential biomarker in some patients, the researchers suggest.

At the University of California, San Francisco, virologist and immunologist Nadia Roan's team is also taking a look at T cells. In some long COVID patients, T cells that recognize SARS-CoV-2, the virus that causes COVID-19, can become exhausted, her team reported in *Nature Immunology* in January. Tired T cells can have trouble wiping out infection.

"Perhaps there's SARS-CoV-2 somewhere in the body that can't be cleared," Roan says. If a hidden reservoir of virus lurks in people's tissues long-term, certain T cells might gather there for continued attack, eventually wearing the cells down. Last summer, a different team found viral traces in some people's guts nearly two years after infection. Scientists have also spotted signs of SARS-CoV-2 in other tissues, including brain, lung and liver. These traces may be enough to irritate the immune system long term.

Residual virus isn't likely to explain everything. "Different mechanisms may drive different forms

Symptom checker More than 200 symptoms have been tied to long COVID, part of what makes the condition difficult to diagnose and treat. In a recent study of patients, feelings of malaise after exertion, fatigue and 10 other symptoms occurred most frequently. SOURCE: T. THAWEETHAI *ET AL*/*JAMA* 2023



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of the disease," Roan says. But together, work from her lab and others paints a portrait of an immune system under enduring duress. And as the picture comes into focus, scientists are starting to explore new experiments, trials and treatments.

Seeking relief

Iwasaki and colleagues are nearly done recruiting 100 people with long COVID for a randomized clinical trial of the antiviral drug Paxlovid. A similar trial by the National Institutes of Health is also in the works. That study aims to enroll 900 people and should conclude testing by this summer.

An idea targeted by both trials is that SARS-CoV-2 persists in the body, triggering symptoms. Scientists will follow participants as they take Paxlovid for 15 or 25 days. (For a COVID-19 infection, the typical treatment length is five days.)

Iwasaki's team also plans to scan participants' blood for molecules that might predict a person's response to Paxlovid. Suppose participants who improve after Paxlovid had high levels of certain blood molecules before treatment. Scientists could then measure those molecules in other people with long COVID to see if they might be good candidates for the drug. "There's not one drug cure-all," Iwasaki says, "but even knowing who might benefit is a huge thing."

And though Morgan's complement work is still at an early stage, he considers it a "strong lead to a potential therapy." One bright spot is the number of complement-targeting drugs that already exist. Doctors use the drugs to treat certain blood disorders and other rare conditions. Morgan and other scientists have tried using some of these drugs to treat severe cases of acute COVID-19 infection, but large-scale trials didn't pan out.

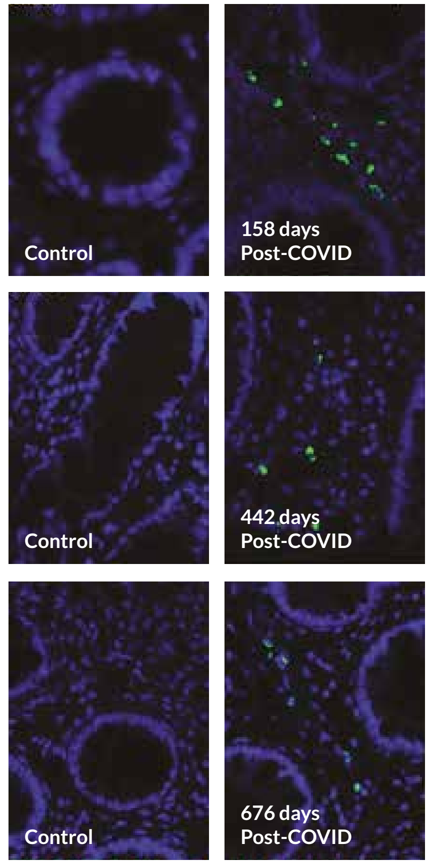
Now, Morgan wants to repurpose those drugs for long COVID patients whose complement system has gone out of control. Dialing down those defenses might help quench the fire of chronic inflammation.

So far, he hasn't seen much interest from pharmaceutical companies. Repurposing generic drugs isn't a big money maker. And Morgan's team doesn't envision long COVID patients needing to use the drugs long term — another financial disincentive for companies. But when I email him later, Morgan says his call after our interview went well. He's not naming the company yet, but he knows that patients are standing by, waiting day after day for anything that will offer some relief.

For me, lingering symptoms turned the once-easy tasks of everyday life into energy-sucking feats performed while my body's battery blinked down to zero. If I miscalculated and walked too fast or moved too much, I'd pay for it later and crash on the couch or in bed, sometimes taking days to recover. That symptom is known as postexertional malaise, and it's common for people with long COVID.

But I was never officially diagnosed with the disease. Keeping up with doctors' appointments felt daunting, and I wasn't sure how much my doctor would be able to help. There may be many people who fall into this category, Morgan says — people who have long-term symptoms but lack clear-cut answers on a diagnosis.

Though white women (like myself) are most likely to be diagnosed with the disease, in a survey from the U.S. Census Bureau, Hispanic and Black people were more likely to report long-lasting symptoms. Access to care could be one factor in the diagnosis discrepancy. Previous data have shown that people from these groups are less likely than their white counterparts to have health insurance. Another factor may be the changeling nature of the disease itself. Long COVID can show up differently in different groups of people, scientists have found.



Traces of SARS-CoV-2 (green) have been found in the gut tissue of long COVID patients well after symptoms of the initial infection began, in some cases almost two years later (bottom right). Control samples were collected from other people before the pandemic.

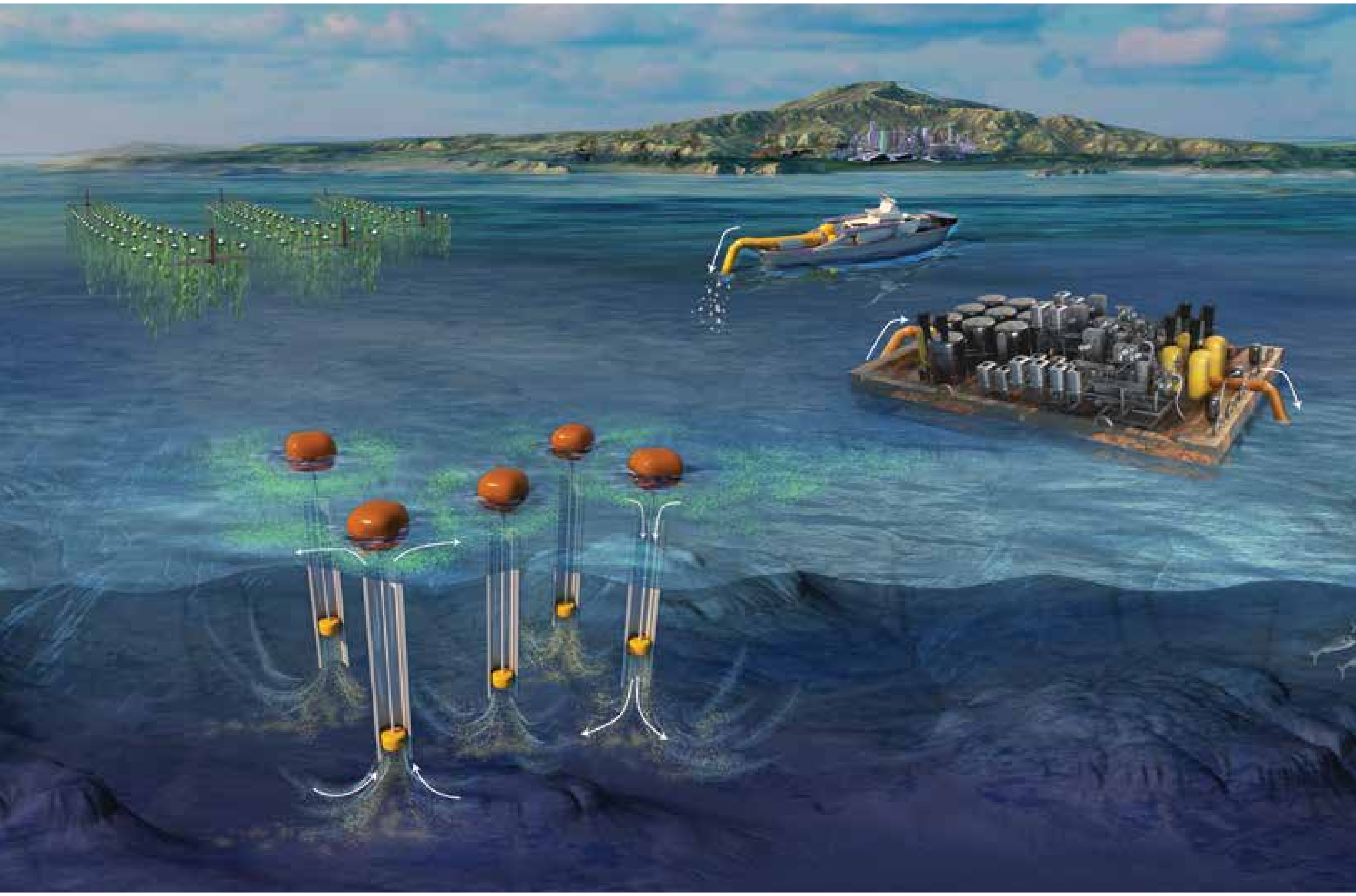
I'm lucky because my symptoms started improving after about six months. I knew I was mostly recovered the first time I went grocery shopping and carried my bags into the house by myself, without crashing afterward. But so many others continue to struggle.

Morgan sees that firsthand. Since his paper came out, "I've been absolutely deluged by letters from patients," he says. They ask to be tested and if he has drugs that can treat them. For Morgan, those letters show the depth of the problem.

"I reply to them all." ■

Explore more

- Kirsten Baillie *et al*. "Complement dysregulation is a prevalent and therapeutically amenable feature of long COVID." *Med*. March 8, 2024.



Ocean to the rescue

Drawing carbon dioxide out of the air and into the sea could help us slow climate change

By Carolyn Gramling

Several ocean-based methods of removing carbon dioxide from the atmosphere have been proposed, including seaweed farming, artificial upwelling and downwelling, enhanced rock weathering, direct ocean capture and ocean iron fertilization (illustrated above from left to right).

The ocean is Earth's climate hero.

For decades, ocean waters have helped hold back the juggernaut of global warming, absorbing at least a third of the carbon dioxide emitted by human activities since the Industrial Revolution began.

Now, the world may ask the ocean to do even more. That would require tinkering with the chemistry and biology of the ocean to increase how much carbon it takes up.

Such an approach is worth considering because the window for limiting warming by reducing carbon emissions alone is closing fast, climate simulations suggest. Forestalling the worst impacts of climate change by 2100 will require actively pulling carbon back out of the atmosphere — at a scale possible only with the ocean's help, some scientists say.

Earth is on track to warm by about 3.2 degrees Celsius by the end of the century, relative to preindustrial times, according to the Intergovernmental Panel on Climate Change. Even if all nations meet

ALL ILLUSTRATIONS: SAYOSTUDIO

their current emission-reduction pledges, the world would still warm by about 2.7 degrees.

That's higher than the target of 1.5 to 2 degrees set by the 2015 Paris Agreement, an international climate treaty signed by 195 parties (*SN: 1/9/16, p. 6*). In fact, Earth's average temperature is likely to surpass the 1.5-degree benchmark as soon as the mid-2030s. Each uptick in the thermostat increases the risk of devastating consequences, including deadly heat waves, more intense storms and inundations of coastal cities due to melting ice and rising seas.

Technologies that remove carbon from the atmosphere could help turn the thermostat back down by the end of the century. "The latest IPCC report notes that to meet the [Paris Agreement] climate goals, we have to employ carbon dioxide removal technologies," says geochemist Gabriella Kitch of the U.S. National Oceanic and Atmospheric Administration in Silver Spring, Md.

Carbon dioxide removal, or CDR, is in its infancy, currently drawing only about 2 billion metric tons of CO_2 per year out of the atmosphere. That's a small fraction of the 37 billion tons of CO_2 emitted each year by humans' energy consumption. Most of that CDR comes from forests, whether via planting new trees, regrowing old forests or better managing existing growth.

To stay on track with Paris Agreement goals, the world needs to ramp it up, removing 10 billion to 15 billion tons of CO_2 annually by 2050, Kitch says. By the end of the century, that would need to add up to a grand total of 400 billion to 1,000 billion tons of atmospheric CO_2, a range that depends on how quickly we also reduce carbon emissions.

Land-based CDR, including planting trees, restoring coastal ecosystems and building facilities that directly capture CO_2 from the air, can get us part of the way there, Kitch says. But all of the carbon uptake from land-based approaches would add up to only about 10 billion tons annually, Kitch says. Such calculations need to ensure sufficient land area for food, water and biodiversity preservation, she adds. "That gets us to 2050, but what about beyond that?"

That's where the ocean comes in. "The big advantage of the ocean is its capacity," Kitch says. "The ocean can store about 19 times the amount of carbon that can be stored on land."

There are a few basic ways to enhance the ocean's current carbon uptake: Increase the ocean's abundance of photosynthesizing organisms, increase the water's alkalinity so it can absorb more acidic CO_2 and build huge facilities at sea that suck carbon directly out of the water.

But CDR in the big blue is largely untested — and in that sense, the ocean's vastness is both a feature and a bug. Ocean waters are complex and always in motion, making shifts in chemistry fiendishly difficult to monitor. And there's little baseline data on large swaths of the ocean, which will make it hard to evaluate how well CDR is working. And current observational technologies, such as sensors, may not be up to the challenge.

On top of that, there are also long-standing concerns about environmental impacts, of which there's very little data. Changes to regional water properties might create ripple effects through ecosystems, critics note. Fostering phytoplankton blooms, for instance, could shift local food webs or even produce greenhouse gases. Treating large parcels of seawater to remove carbon could pose risks to local wildlife.

But the biggest challenge of all is time. Researchers are racing to explore these uncharted waters before the climate crisis worsens.

THE CLIMATE FIX

This article is part of a series of stories on climate change solutions and how people around the world are tackling the biggest challenge of our time.

Data sources
The charts in this story compile data from NOAA and the National Academies of Sciences, Engineering and Medicine.

Turning back the carbon clock

Carbon dioxide can linger in the atmosphere for centuries before it's taken up by plants or incorporated into the molecular structure of rocks. Those natural carbon "sinks" are too slow to match the pace of emissions from fossil fuel burning and other human activities, however.

CDR can be thought of like "a time machine," David Ho, an oceanographer at the University of Hawaii at Manoa, wrote last year in *Nature*. Stripping some of the CO_2 out of the atmosphere would be like returning to an earlier time with lower concentrations.

For example, the world's largest direct air capture plant, Climeworks' Iceland-based Orca plant, can remove up to 4,000 tons of CO_2 each year. That might set the clock back by perhaps three seconds annually, Ho estimated.

Planting 100 million trees around the globe buys back about 33 minutes annually, says paleoclimatologist Peter de Menocal, president and director of the Woods Hole Oceanographic Institution in Massachusetts (SN: 7/3/21 & 7/17/21, p. 19).

Today, the ocean naturally absorbs about a quarter of the world's carbon emissions annually. That's equivalent to setting the clock back by about three months each year.

The ocean's carbon storage capacity is vast. For example, from 10,000 years ago until the dawn of the Industrial Revolution, the atmospheric CO_2 concentration was about 280 parts per million. But at the height of the last ice age, about 20,000 years ago, that concentration was just 180 ppm. The "missing" 100 ppm of CO_2 during the ice age was all stored in the ocean, in part due to decreased ocean circulation at this time.

"Sixty years ago, atmospheric carbon dioxide levels were [also] 100 parts per million lower than they are today," de Menocal says. In other words, natural ocean uptake has the ability to set the clock back by as much as 60 years. With ocean-based CDR, the clock could be pushed back even further.

But potential is not proof. "Almost all [CDR strategies] are in the early days," says Jessica Cross, a carbon biogeochemist at the Pacific Northwest National Laboratory in Seattle.

Highlighting the urgent need for more research, the U.S. National Academies of Sciences, Engineering and Medicine suggested in 2021 that nearly $2.5 billion in research funding over the next decade is needed to really drive the field forward.

An influx of funds arrived last September, when the U.S. National Oceanographic Partnership Program, a funding alliance that bridges federal agencies, academia and industry, awarded over $24 million to fund 17 ocean CDR research projects. In October, the Department of Energy announced $36 million in funding for 11 other projects.

The snapshots below feature the most-discussed types of ocean CDR, revealing the pros and cons of each strategy, plus the key questions that researchers must answer before society moves forward.

Seaweed farming	
How much CO_2 could it remove?	0.1 to 1 billion metric tons per year
How long could it store CO_2?	10 to 100 years
Estimated cost	$25 to $125 per metric ton of CO_2 removed
Technological readiness	Moderate
Field experiments	A variety of small-scale pilot projects

Seaweed farming

Red, green and brown seaweed — or in scientific circles, macroalgae — are speedy growers, with some species shooting up by tens of centimeters per day. To fuel that growth, these photosynthesizers rapidly absorb CO_2 from the ocean. When the algae die, they sink down to the depths, where the carbon may cycle through deep-sea food webs or be buried in sediments, lingering for decades to centuries.

Seaweed farming speeds up this natural biological pump by growing algae on offshore floating platforms and then sinking the platforms to deep water once the algae are fully grown. Natural macroalgae populations in coastal waters around the world sequester somewhere around 0.17 billion tons of carbon each year, researchers reported in 2016 in *Nature Geoscience*. Cultivating seaweed could increase that to about 1 billion tons annually, according to a 2022 report by the National Academies of Sciences, Engineering and Medicine.

That's if the seaweed is allowed to sink rather than be consumed. Although seaweed has been suggested as a climate-friendly food, feedstock or biofuel, consuming it would return the carbon to the atmosphere (SN: 5/7/22 & 5/21/22, p. 34).

Macroalgae alone probably wouldn't make a huge dent in the amount of carbon the world needs to sequester and wouldn't store it for very long. Climate simulations of the impact of seaweed farming also suggest that the algae might end up competing for nutrients with phytoplankton — floating microscopic "plants" also being looked to for climate assistance.

Ocean iron fertilization

Although the Amazon rainforest is often called the lungs of the world, ocean phytoplankton also deserve the moniker. These photosynthesizing organisms produce at least half of the oxygen in the atmosphere, while pulling out carbon dioxide.

Like land plants, phytoplankton need sunlight, CO_2 and nutrients such as nitrate and phosphate to live. And to really thrive, they also need smaller infusions of certain micronutrients, particularly iron, which can be in short supply in many parts of the ocean.

Observing how iron-laden dust blowing from continents to the ocean leads to large blooms of phytoplankton, American oceanographer John Martin proposed in the 1980s artificially adding the nutrient. The iron could kick-start additional blooms that would soak up more carbon — thereby lowering global temperatures. "Give me a half tanker of iron, and I will give you an ice age," he famously once said.

Scientists tested the concept of ocean iron fertilization 13 times from 1993 to 2009, dumping iron sulfate into patches of the eastern equatorial Pacific, northern Pacific and Southern oceans. These experiments confirmed that adding iron makes the ocean bloom. But they were too small and too brief to address how much CO_2 was removed from the atmosphere and how long it was sequestered in the deep ocean, says Ken Buesseler, a marine chemist at Woods Hole.

The experiments also produced a bloom of environmental backlash. Critics worried that seeding the ocean might lead to toxic algal blooms or even ocean dead zones, as the eventual decomposition of dead phytoplankton might remove too much oxygen from the water and release methane, itself a greenhouse gas. In 2008, the United Nations Convention on Biological Diversity stepped in, calling for a moratorium on these experiments "until there is an adequate scientific basis on which to justify such activities" and there are regulatory mechanisms in place. After that, ocean iron fertilization experiments were dead in the water. "The pushback was so strong," Buesseler says, "we just couldn't find any funding."

But things are very different now as a result of the climate crisis, he says. "There's absolutely a big change, working in this area, from 15 to 20 years ago." In 2022, he and colleagues formed the Exploring Ocean Iron Solutions consortium, identifying key research questions for the field and proposing best practices for studying them. This time, societal acceptance and citizen participation are highlighted as core features of any ocean fertilization project.

In September, Buesseler and colleagues were among the National Oceanographic Partnership Program's awardees, receiving almost \$2 million to fund a three-year research project to investigate the long-term effects of using iron fertilization in different regions of the ocean.

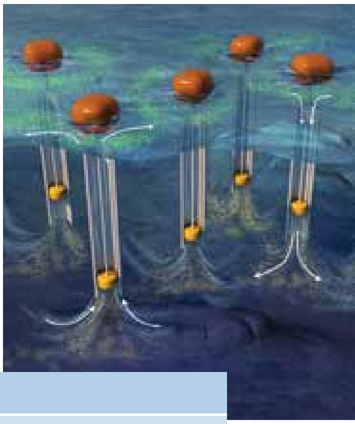
Ocean iron fertilization	
How much CO_2 could it remove?	0.1 to 1+ billion metric tons per year
How long could it store CO_2?	10 to 100 years
Estimated cost	\$50 to \$125 per metric ton of CO_2 removed
Technological readiness	Moderate
Field experiments	13 small-scale tests in the eastern equatorial Pacific, northern Pacific and Southern oceans

In some ways, ocean iron fertilization is among the further-along CDR technologies — but it's far from ready for prime time. "We have to come up with a way to scale this up that would be acceptable and reproducible," and address the long-standing environmental concerns, Buesseler says.

One challenge is developing a way to assess the amount of carbon captured from the blooms and the duration of storage as phytoplankton sink toward the ocean bottom. Other outstanding questions include what form of iron offers the most bang for the buck. It could be a liquid solution of iron sulfate, dry dust, iron nanoparticles or even floating, iron-coated rice husks.

Artificial upwelling and downwelling

Some of the best fishing grounds in the world are off the western coast of Peru, the result of a complicated dance between Earth's rotation and prevailing winds blowing along the shore. Redirected by the Coriolis effect, the winds push nutrient-depleted surface waters away from the shoreline, and then cooler, deep, nutrient-rich water surges up to replace the surface waters, juicing the regional food web.

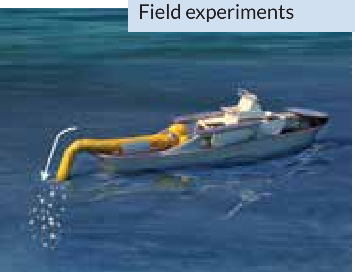


Artificially re-creating this upwelling effect by pumping nutrient-rich waters from the deep ocean toward the surface could be another way, theoretically, to give phytoplankton a boost. Similarly, carbon-laden surface waters might be sent downward to be sequestered. That could be achieved through pumping or by altering the density of the water, either by increasing the water's salinity or decreasing its temperature.

That artificial upwelling could also increase the

Artificial upwelling and downwelling	
How much CO_2 could it remove?	0.1 to 1 billion metric tons per year
How long could it store CO_2?	10 to 100 years
Estimated cost	\$100 to \$150 per metric ton of CO_2 removed
Technological readiness	Low
Field experiments	None

Enhanced rock weathering	
How much CO_2 could it remove?	1 to 15+ billion metric tons per year
How long could it store CO_2?	20,000+ years
Estimated cost	\$25 to \$160 per metric ton of CO_2 removed
Technological readiness	Low to moderate
Field experiments	3 tests in Florida, England and Canada



effectiveness of seaweed farming or ocean iron fertilization, computer modeling studies suggest. But there are a lot of caveats: Deep water can contain a lot of carbon that, if pumped toward the surface, might escape to the atmosphere. And the long-term impacts of artificial upwelling and downwelling, both on carbon sequestration and on the denizens of the deep, are unknown. Pumping would also require a lot of energy, which could lead to a release of carbon into the atmosphere if the energy source is based on fossil fuels.

Enhanced rock weathering

It takes thousands to millions of years for wind and rain to erode rocks on land, for those rocky grains to then disintegrate and drift into rivers, lakes and groundwater, and ultimately find their way into the sea. The dissolved remnants of those rocks give the ocean its acid-buffering ability, known as alkalinity. Thanks to that alkalinity, as carbon dioxide enters the ocean from the atmosphere, the gas reacts and transforms into dissolved carbonate molecules, particularly bicarbonate. Ultimately, the carbon ends up in carbonate sediments on the seafloor, where it can stay sequestered for as long as 100,000 years.

Enhancing the ocean's alkalinity could allow the ocean to take in even more carbon. Boosting the alkalinity would also counter ocean acidification, which threatens to erode the carbonate shells of many sea creatures (SN: 5/27/17, *p. 11*).

One way to enhance alkalinity is to simulate rock weathering by dumping large amounts of finely ground alkaline minerals, such as sodium hydroxide, magnesium hydroxide or calcium hydroxide, into the water. Researchers have done just that in a few pilot projects, including in Florida's Apalachicola Bay in 2022 and in Canada's Halifax Harbor in 2023. These tests demonstrated the ability to neutralize acid and draw some CO_2 out of the atmosphere. But there's not much real-world data yet on how by-products of the minerals, such as trace metals, or changing the ocean's pH might impact sea life.

Planetary Technologies, a Canadian company that won a \$1 million XPRIZE for climate change solutions in 2022, faced local protests to its plan to deploy magnesium hydroxide through a waste pipe into St. Ives Bay, England, in September 2023. Protestors called for much more scientific study of how the test might impact the bay's wildlife, including the region's prized gray seals.

"We're here today for our children's futures. We want them to be able to enjoy the bay for years to come," a protestor told the *Guardian* last year. "We don't know what the outcome will be if they dump these chemicals into the sea."

Some critics also cite other environmental costs, such as the mining and transporting of the minerals.

Electrochemical alkalinity enhancement	
How much CO_2 could it remove?	0.1 to 1 billion metric tons per year
How long could it store CO_2?	100+ years
Estimated cost	\$150 to \$700 per metric ton of CO_2 removed
Technological readiness	Low to moderate
Field experiments	1 ongoing test in Washington State

Electrochemical alkalinity enhancement

Electrochemically removing acid from ocean water is another way to increase alkalinity. This method proposes to pump seawater through an ocean-based electrochemical system. The electricity would rearrange the molecules of water and salt, splitting them into two solutions, one acidic and one alkaline.

The alkaline solution would be mixed with seawater and returned to the surface ocean, increasing the water's alkalinity so the water can pull more carbon dioxide out of the atmosphere. The acidic portion, meanwhile, might be neutralized, diverted to industrial markets or perhaps stored in deep ocean waters or the seabed.

Numerous unknowns surround the environmental impacts of this approach, including how pumping large volumes of seawater and changing water chemistry might impact marine life and local ecosystems.

Existing electrochemical systems are expensive. Pumping the seawater and splitting the molecules requires a lot of electricity, which could result in a large carbon footprint if not from renewable sources. Building the infrastructure for such a system could also be costly, though repurposing the acidic solution might help recoup the costs. Combining the technique with offshore energy generation, such as wind turbines, could help offset both the carbon footprint and costs.

The concept has remained largely lab-based, but in August, the American start-up Ebb Carbon unveiled a prototype electrochemical CDR facility at Sequim Bay in Washington. The pilot project, a partnership with the Pacific Northwest National Laboratory, aims to demonstrate that it can capture 100 tons of CO_2 per year.

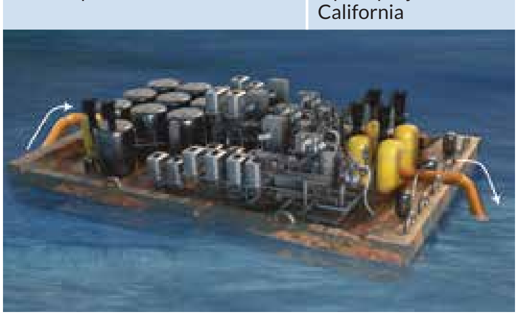
Direct ocean capture

Another option is to directly strip carbon dioxide out of large parcels of water and then bury it in the deep ocean. Ocean-based direct capture is also an electrochemical method that shunts seawater through a large membrane. The membrane then mediates a reaction between the seawater and another solution, such as a sodium hydroxide solution, that strips out dissolved carbon dioxide. This process ultimately increases the surface water's pH, allowing it to absorb more atmospheric carbon dioxide. It's a technology that can be fully offshore, so it doesn't require valuable land area. And, theoretically, it could be powered by renewable energy.

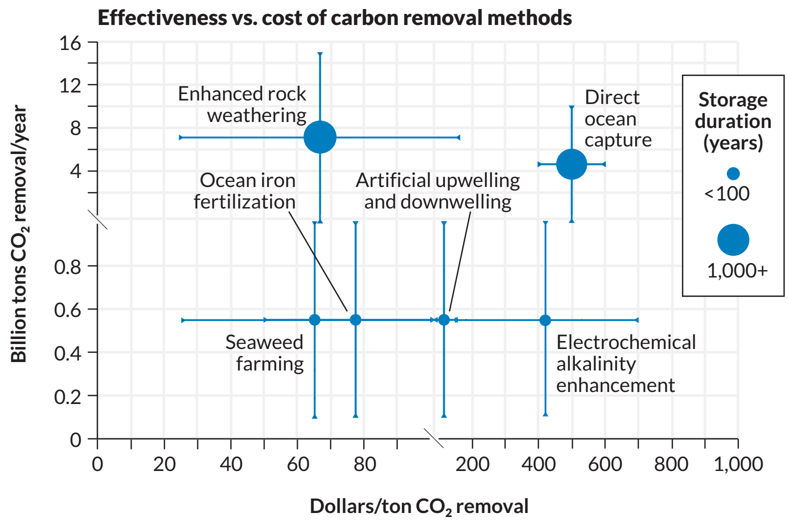
One big disadvantage is the cost due to the massive amounts of water that have to be circulated through the facility, as well as the expense of the large membranes needed to treat the seawater. Drawing in large amounts of seawater to the facility could also pose risks to marine organisms. And little is known about how changing the properties of the seawater could affect nearby marine life.

Direct ocean capture technology has only recently moved out of the laboratory. In 2022 and 2023, the start-up company Captura, founded by Caltech researchers, conducted ocean field trials of the technology at Newport Beach and the Port of Los Angeles. The group is planning two pilot projects this year in Canada and Norway.

Direct ocean capture	
How much CO_2 could it remove?	1 to 10 billion metric tons per year
How long could it store CO_2?	1,000+ years
Estimated cost	\$400 to \$600 per metric ton of CO_2 removed
Technological readiness	Low to moderate
Field experiments	2 pilot projects in California



GRAPH: C. CHANG



Sizing up solutions

In evaluating ocean CDR methods, effectiveness and cost are two big considerations. In this graph, the lines show the estimated range of carbon removal and cost for each method; the circle represents the midpoint. The circle's size corresponds to how long the carbon might be stored. SOURCES: NOAA, NAS

A sea shift

If CDR becomes a success, it will likely require several approaches working in tandem. Cross, the biogeochemist at the Pacific Northwest National Laboratory, points to one study, published in *Nature Climate Change* last year, that "lives rent-free in my brain." The paper suggests that "the more different methods of CDR that you have, the fewer challenges from each different method you may be incurring all at once," she says, such as competition for land and water, or the massive energy costs associated with crushing rock for enhanced weathering or pumping large volumes of seawater. "That way you avoid the cascading problems," she says.

The ocean research community is now awash in discussions of how best to create a responsible research agenda.

The intense societal pushback to some early field tests of ocean CDR highlights "how challenging it's going to be to do this kind of work," and how crucial it will be to have communities on board every step of the way, Cross says.

"Emotions tend to run high when we're talking about our coasts," she adds. "The ocean is a cultural asset, an economic asset, a real estate asset, a sport asset. These concerns are there for all forms of ocean CDR. Is this going to change the look and feel of *my* ocean in *my* backyard?" ■

Explore more

- Jessica N. Cross *et al.* "Strategy for NOAA carbon dioxide removal research." NOAA, May 2023.
- National Academies of Sciences, Engineering and Medicine. "A research strategy for ocean-based carbon dioxide removal and sequestration." 2022.

Jennifer Lashley
Executive Director of SoLA Robotics and member of Regeneron ISEF's Los Angeles Local Arrangements Committee

WHY I VOLUNTEER AT REGENERON ISEF

Volunteering at the Regeneron International Science and Engineering Fair (ISEF) is an enlightening experience. There's something special about being surrounded by so much youth potential, especially as an educator who wants a bright future for all my students.

My favorite memory from last year's fair was speaking to several finalists as they prepared to meet with local middle and high school students on Education Outreach Day. I learned more about each finalist's research and gained an understanding of what it takes for a high school student to earn the opportunity to compete at Regeneron ISEF.

At Regeneron ISEF in Los Angeles this May, I look forward to seeing the interactions and smiling faces of young scholars from around the world. I especially look forward to talking with them, allowing them to share their areas of expertise and letting them know how much I appreciate their research.

I highly recommend volunteering at Regeneron ISEF. It is unique among all the other science fairs I've seen. I consider it a privilege to assist these intelligent young minds who will be our STEM leaders, innovators and game changers someday soon.

Volunteer at Regeneron ISEF in Los Angeles this May!
www.societyforscience.org/volunteer

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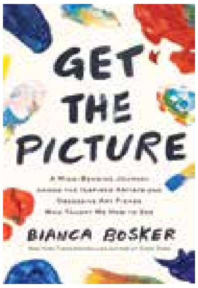


Get the Picture
Bianca Bosker
VIKING, $29

BOOKSHELF

Science helps find the meaning of art

If you're like me, perhaps you've visited a contemporary art installation, seen a painting of a single plain square or a giant sculpture of a fork, and wondered, how on Earth is this art? I'll bet you didn't dare ask this out loud, for fear of looking gauche. Luckily for us, journalist Bianca Bosker is willing to ask the age-old question — What is art? — and go to great lengths, fish-out-of-water style, to find the answer. The result is her latest book, *Get the Picture*, a participatory dive into the art world and the spiritual sustenance that art itself provides.

A review of an art book probably isn't what you'd expect in the pages of a science magazine. But Bosker wields many tools, including scientific research, to understand humankind's primal desire for art.

She sets out to develop what art disciples call an "Eye," a discerning ability to separate the "good" art from the "bad." The only way to do that, she decides, is to embed herself among members of the trade. This is no easy task; the art world is secretive, closed and judgmental. Acolytes are as obsessed about art as they are about maintaining an aura of exclusivity. When Bosker finally penetrates fine art circles, what she finds isn't pretty. The art world often excludes those who can't afford to go to art school or the luxury of creating vanity projects. Practitioners often take on multiple jobs to make ends meet; many eventually quit from burnout. On top of that, there's a culture of top-down bullying.

But as much as Bosker's experiences might destroy your faith in art, she relentlessly digs deeper until she redeems it, by discovering the fundamental joy that art can bring to both those who create it and view it.

Bosker works as a gallery assistant, art-fair seller, studio helper and museum security guard to examine art from different angles. Each role provides a fascinating vignette into how the art machine operates, and you can't help but admire Bosker's willingness to suffer fools. Her can-do attitude puts her in bizarre situations — she lets a performance artist sit on her face in the name of art — making for a hilarious exposé about the art industry.

While entertaining, the recounting of her exploits means it takes a while for the book to get to the meaning of art. But once it does, science provides several clues. Some experts theorize that prehistoric humans were compelled to paint on cave walls because it showed off the artist's skills and potential fitness as a mate. One anthropologist has argued that art bound communities together toward common survival.

In today's world, art's utility has expanded. Here too, science can help us understand how. Bosker introduces readers to the growing field of neuroaesthetics, the application of

Just as beauty is in the eye of the beholder, so too is art. Here, visitors at London's Serpentine North Gallery watch a projection of AI-generated work by Turkey-born artist Refik Anadol.

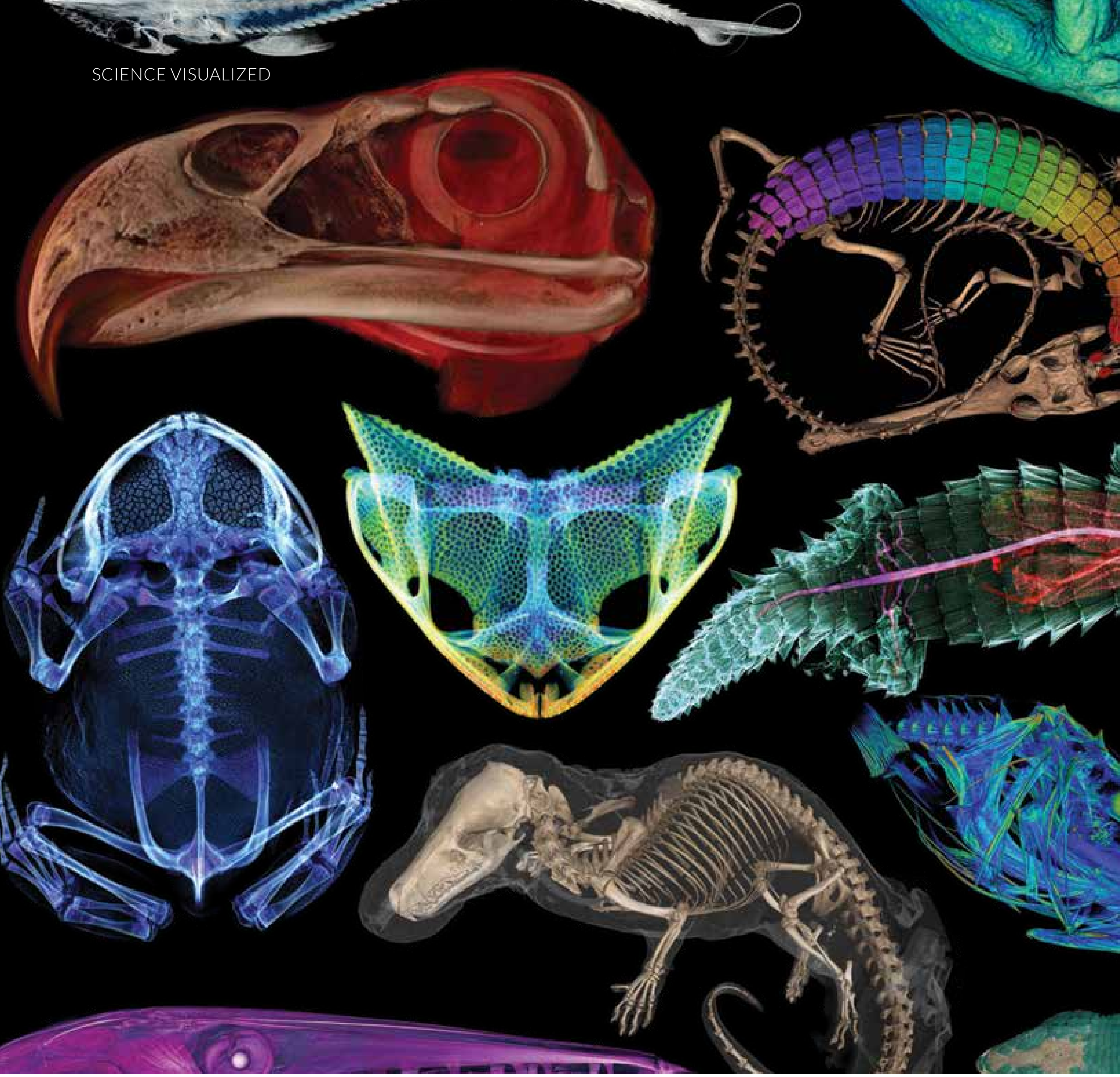
DAN KITWOOD/GETTY IMAGES

neuroscience to study the perception of art. Researchers have demonstrated that seeing is often secondary to believing — a "filter of expectation" in our brains distorts the raw data stream of light that hits our eyes. This filter allows us to take mental shortcuts and dismiss certain visual details to rapidly process our chaotic environment. This is why we know a white vase next to the window is still white, even as natural light transforms its exact hue to sunset golden or moonlight gray throughout the day.

One function of art, Bosker writes, is to yank off this filter to reexamine the world with renewed wonder. Art has a therapeutic quality, a fact that's seized upon by doctors who prescribe patients visits to art museums and the pleasure of hanging wall art. Removing that filter can also help doctors themselves. Over two dozen medical schools require students to study paintings to avert the habit of snap judgment. Studies have shown that trainees who take an art-based visual literacy course perform more holistic physical examinations and read human facial expressions better than those who don't.

The most scintillating aspect of the book is Bosker herself — the narrator, the why-person, the self-acknowledged philistine and, most importantly, the reader's friend. Instead of lecturing from an authoritative vantage point, Bosker lets readers witness at eye level her growing clarity of art's function. She's also witty, self-deprecating and isn't afraid to call out snobbery. In her trips to galleries, she writes, "pretension hung in the air like an unacknowledged fart."

In the end, readers don't get a complete answer for humankind's compulsion toward art. Bosker instead offers her own interpretation: Art is a way to find beauty and heighten our appreciation for life. In debunking the infallibility of an "Eye," Bosker argues that art is everywhere and can be anything, as long as we're open to letting what we see move us. By the last page, you'll be compelled to revisit that fork sculpture and behold the artwork with fresh eyes. — *Shi En Kim*



A digital gallery of vertebrate specimens

Frog entrails, lizard scales and mouse tails, oh my. These body parts are from more than 13,000 museum specimens that had their innards CT scanned as part of a six-year mission to create 3-D digital reconstructions. The effort, called openVertebrate, or oVert, aims to make vertebrate specimens freely available online, researchers report March 6 in *BioScience*.

Museum specimens are typically kept in storage until put on display for the public or pulled for examination by a specialist. The oVert replicas make museum collections accessible to more individuals, and also give people a peek inside animals without the need for scalpels or other equipment.

"The best part of that is the weird, wonderful things that you weren't expecting to see that jump out," says evolutionary biologist Edward Stanley of the Florida Museum of Natural History at the University of Florida in Gainesville.

Those things include parasitic infections, last meals and new insights into anatomy. Scans of pumpkin toadlets' inner ears, for instance, revealed that the amphibians crash-land

OPENVERTEBRATE

their hops due to misshapen ear tubes (SN: 7/16/22, *p.* 5). And images that Stanley and colleagues took of spiny mice showed that the animals' tails are covered in bony armor like an armadillo.

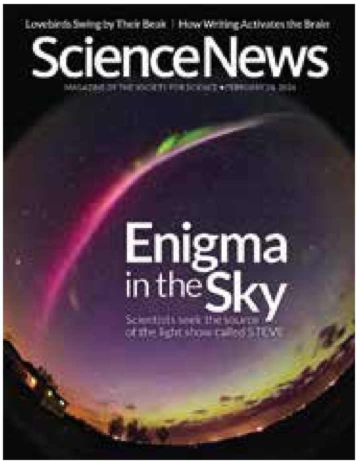
As part of oVert, Stanley and researchers across 25 institutions took CT scans of fluid-preserved specimens from thousands of vertebrate genera, lighting up the skeletons of chameleons, frogs, bats, lizards, snakes, eagles and more (some reconstructions shown above). Some animals were soaked in iodine so that internal organs and muscle were visible.

To make the scans, the researchers mounted each specimen inside a tube. The tube then rotated around a fixed X-ray scanner that captured a complete picture of the animal's body. But few vertebrates are tube-shaped, so the team had to pack the cylinder with materials that could hold the specimen in place without interfering with the scan.

"It turns out bubble wrap, packing peanuts, plastic Coke bottles, that sort of thing, that's the magic," Stanley says.

The technology could help digitize additional organisms tucked away in natural history collections, including invertebrates and plants, the researchers say. Some scanners may even work for living vertebrates. — *Erin Garcia de Jesús*

See more reconstructions from oVert at **bit.ly/SN_overt**



FEBRUARY 24, 2024

Under the weather

*New climate reconstructions show that periods of decreasing temperature and rainfall coincided with three plagues that struck the Roman Empire, **Bruce Bower** reported in "Did climate drive ancient plagues?"* (SN: 2/24/24, p. 13).

Bower reported that researchers are uncertain exactly how those climate shifts may have influenced the plagues' spread. Reader **Robert J. MacCoun** asked if one explanation could be that the colder conditions drove people to spend more time indoors with poor ventilation.

Cold periods do "tend to bring people indoors, closer together, increasing the chances of spreading infectious disease," says classical archaeologist **Brandon McDonald** of the University of Basel in Switzerland. But this is just one of many ways that climate shifts can impact disease spread. Identifying the pathogen behind an infectious disease is a crucial part of the puzzle, **McDonald** says. That's because some changes in temperature and precipitation are advantageous to certain pathogens and the animals that spread them but disadvantageous to others.

"For most Roman period [disease] events, we haven't yet scientifically determined the pathogenic cause," **McDonald** says. While the new findings are noteworthy, he says, researchers need to know more about the diseases and their ecology to determine how climate may have influenced their spread.

Pioneering plants

*A Panamanian tree fern is the first known plant that turns dead leaves into roots that seek out nutrient-rich soil, **Darren Incorvaia** reported in "Fern revives dead leaves"* (SN: 2/24/24, p. 5).

Reader **Douglas B. Quine** was surprised that the discovery was considered novel, given that the leaf-into-roots process seems similar to the widespread practice of propagating plants using leaf cuttings.

The root formation observed in the fern, called *Cyathea rojasiana*, is a different process from propagation through leaf cuttings, says tropical forest ecologist **James Dalling** of the University of Illinois Urbana-Champaign. In cuttings, new roots and leaves are created in the leaf or leafstalk and differentiate into completely new leaf and root tissue. "The original leaf dies," **Dalling** says. "In *C. rojasiana*, the original leaf loses its photosynthetic function and partially decomposes but continues to live for many years, functioning as a root. In this case, the vascular tissue of the leaf is repurposed."

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EMAIL feedback@sciencenews.org

MAIL Attn: Feedback
1719 N St., NW
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