Eos
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Ukrainian Scientists Race to Document Soil Fungi

Earth's First Evidence of Fresh Water

Mosquitoes Without Borders

LAND OF THE Long White Cloud AND THE Deep Blue Sea

Innovative geoscience projects are documenting Aotearoa New Zealand's deep history—and far-reaching future—on land and sea.

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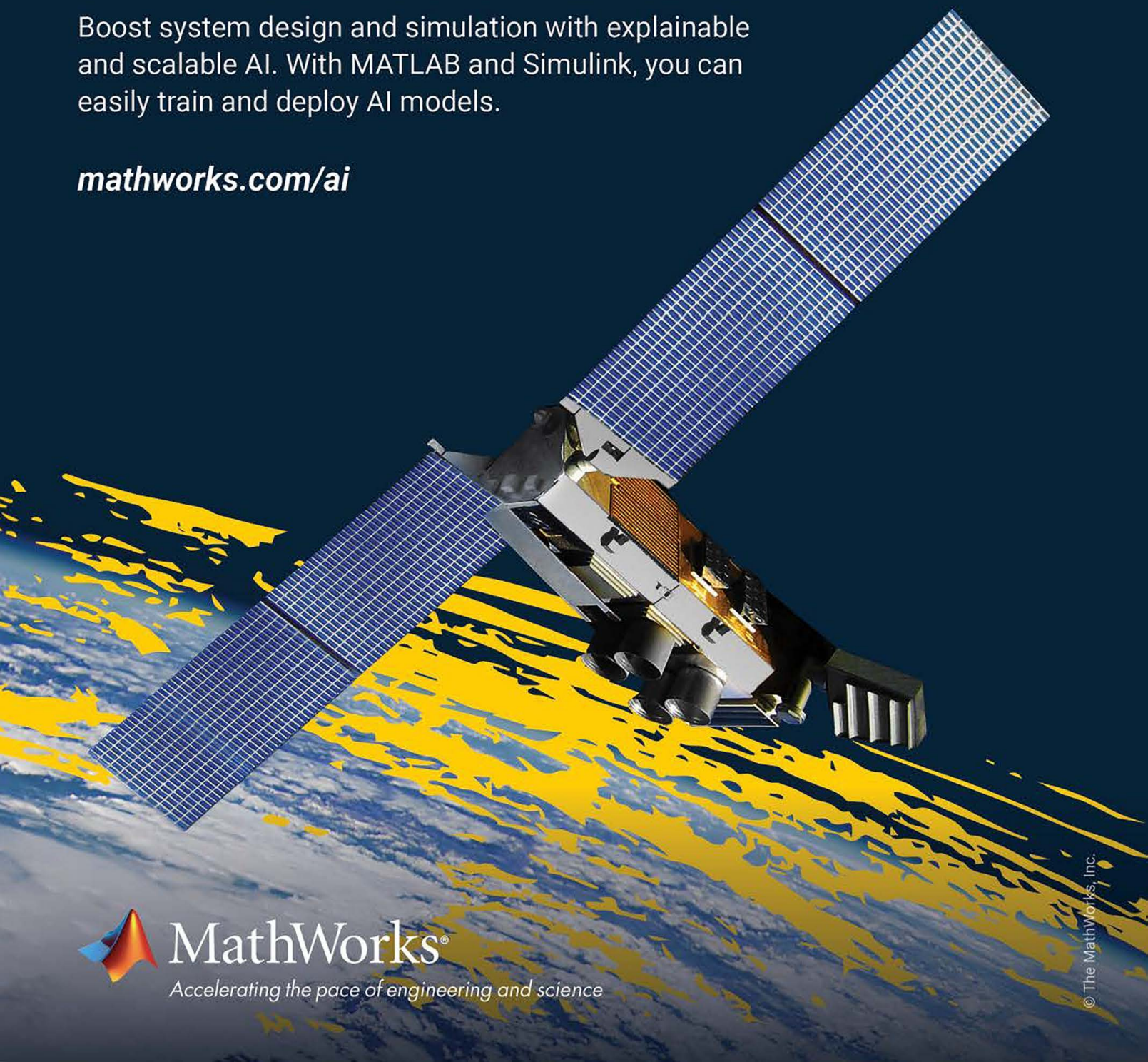

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From the Editor

Aotearoa, the Māori name for New Zealand, is usually translated as "land of the long white cloud." In this issue of *Eos*, we explore some of the dynamic Earth systems that make the country such a valuable site for white clouds, blue seas, muddy sediments, and FRED.

Dive into the country's coastal waters with scientists of the Moana Project on page 18. Using ocean temperature as a guide, the innovative project braids Māori Traditional Knowledges with Western science for a healthier, more sustainable ocean. Beneath the ocean, "Sedimentary Basins Tell Zealandia's Ancient Story" on page 11. Finally, meet FRED—Aotearoa New Zealand's Fossil Record Electronic Database—on page 9, and conclude your sojourn in "Kiwi Country" with a classic crossword from Russell Colson on page 32.

On the Cover

As part of the Moana Project, scientists and commercial fisheries are monitoring the fluctuating temperatures of the ocean around Aotearoa New Zealand, including Milford Sound. Credit: Summit Art Creations - stock.adobe.com

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Scientists Capture the First Glimpse of a Rare Polar Aurora

For nearly 28 hours, starting on Christmas night of 2022, a rare type of aurora illuminated the Arctic. A faint, greenish glow known as a polar rain aurora covered thousands of kilometers across the sky. This intriguing light show was captured on camera for the first time by a group of scientists who had been waiting for more than a decade for the opportunity.

Run-of-the-mill aurorae are caused by the solar wind, a stream of charged particles emanating from the Sun that relentlessly hit our atmosphere. Earth's magnetic field funnels these particles toward the poles, where they collide with atmospheric gases, primarily oxygen and nitrogen, making them emit light.

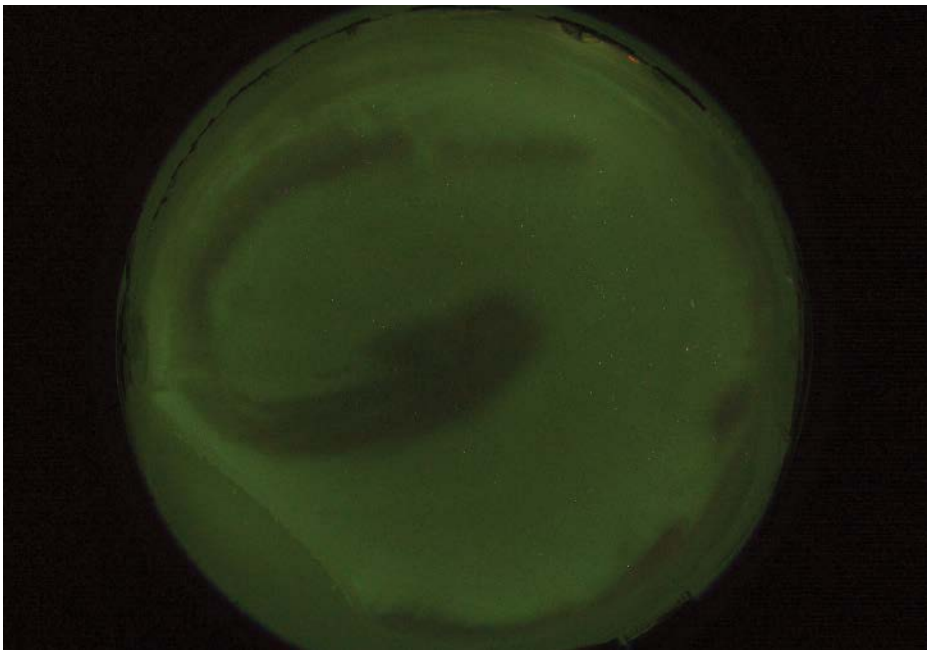
Polar rain aurorae, on the other hand, appear only during a prolonged pause in the flow of the solar wind—an unusual occurrence. When chaotic solar winds subside, energetic electrons emanating directly from the Sun's corona can travel along magnetic field lines and reach Earth's atmosphere without interference.

In December 2022 such a pause occurred, likely at the boundary between two "gusts" traveling at different speeds. Like ocean waves crashing on a beach, when a faster-moving wave is followed by a slower one, a temporary gap forms between them. The same gap also reached Mars, where it was detected from orbit by NASA's Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft.

> **"This is a very special situation."**

"This is a very special situation," said Keisuke Hosokawa, a space physicist at the University of Electro-Communications in Tokyo who led the team that captured the first ground-based images of the phenomenon. The last time a comparable event happened was in 1999, when a polar rain aurora was detected by satellite.

Hosokawa had been looking forward to this moment for years, ever since he and his colleagues installed a robotic camera with this specific goal at a dedicated facility on the Norwegian archipelago of Svalbard, very close to the North Pole.



A polar rain aurora lit up the Arctic sky on 24–25 December 2022. Credit: Keisuke Hosokawa

Typical aurorae appear at latitudes between 65° and 70°, whereas polar rain aurorae happen farther north, at 90°—right at the pole. The phenomenon also lacks the usual features of normal aurorae, such as waving streams and pillars of light.

What the researchers captured looked "very much different" from typical aurorae, Hosokawa said. His camera was especially sensitive, but he said the phenomenon was so bright that bystanders in Svalbard could have seen a homogeneous greenish glow covering the entire sky with their naked eyes.

Hosokawa and his colleagues matched their observations to ultraviolet images from U.S. military weather satellites, confirming that the greenish glow was, indeed, a polar rain aurora. They reported the findings in *Science Advances* (bit.ly/polar-rain-aurora).

Thanks to a fish-eye lens, Hosokawa's camera showed that the entire visible sky glowed, but that was just a fraction of the aurora's extent.

The images also showed that the aurora wasn't completely smooth. It had some embedded structures that looked like greenish glowing patches and occasionally took on a mushroomlike shape. The researchers speculated that this could reflect activity on the solar surface itself, with Earth's atmosphere acting like a screen.

"That's the key about this type of aurora—it's not modified by anything between the Sun and the Earth," said Allison Jaynes, a space and plasma physicist at the University of Iowa who wasn't involved in the study. "I'm sure people are going to be working on modeling this and trying to understand what all those features are."

More Than Pretty Lights

Unlike typical aurorae, which tend to appear in both hemispheres simultaneously, polar rain aurorae have been observed only in the Northern Hemisphere. This is likely because the phenomenon requires a direct magnetic connection between the Sun and Earth, and that can't happen at both poles at the same time, Hosokawa said. It is surprising, he added, that the connection seems never to have been observed at the South Pole.

Hosokawa said he thinks that studying these aurorae can help scientists understand these rare instances of a direct magnetic connection between the Sun and Earth. And what

Scientists used sensitive cameras to capture the polar rain aurora. Credit: Keisuke Hosokawa

they learn could be applicable to other planets, such as Mars and Venus.

The next step for the authors is to check whether the incoming solar electrons had any effect on Earth's atmosphere. Recent studies suggest that aurorae can influence ozone density in the polar regions below the 100-kilometer altitude in which they form (bit.ly/aurora-ozone). "I'm guessing that this special aurora can also affect the atmosphere," Hosokawa said. He and his colleagues are already looking into the ozone concentration in satellite data. "We are hoping to find a connection," he said.

"Now that we know that [polar rain aurorae] can be detected from the ground, we can actually specifically build imagers that have the right sensitivity."

"Now that we know that [polar rain aurorae] can be detected from the ground, we can actually specifically build imagers that have the right sensitivity," Jaynes said. In the meantime, the data collected by Hosokawa and his colleagues will be looked at in detail for years to come, until the next polar rain aurora comes.

By **Javier Barbuzano** (@javibarbuzano), Science Writer

Ukrainian Scientists Race to Document Soil Fungi

In 2022, shortly after Russian forces launched a full-scale invasion of his country, Oleh Prylutskyi was studying fungal communities in soil. He was assessing how such communities vary in both space and time as part of a global project conducted by the Society for the Protection of Underground Networks (SPUN). Much to his dismay, Prylutskyi realized Ukraine didn't have a single data point to feed into the analysis.

"There are a lot of fungal researchers in Ukraine with a long history, but Ukraine was a blank spot, nothing on the map," Prylutskyi said.

Documenting Fungal Biodiversity

By July 2023, Prylutskyi, an associate professor at Kharkiv National University, and his colleagues at SPUN had secured funding from the Human Frontier Science Program (HFSP), allowing small multidisciplinary teams across the country to begin gathering soil samples that could be analyzed for their environmental DNA (eDNA). The aim was to reveal the country's fungal species diversity, which is important because more than 90% of fungal species remain unknown to science. Preserving this fungal biodiversity is critical because once they are gone, any economic, health, or ecosystem benefits these species might have provided are lost, too.

Kateryna Lavrinenko collects a soil sample in Ukraine's Buzkiy Gard National Nature Park in September 2023. Lavrinenko was part of a team working across Ukraine to document the fungal diversity of its soils. Credit: Dariia Borovyk

The project involved 34 contributors in 17 teams, yielding 225 soil samples from 21 of Ukraine's 24 oblasts, or administrative regions, including areas close to the front lines.

"Ukrainian scientists are determined to fully utilize every opportunity to study the astonishing diversity and complexity of life, from the mighty ancient trees to microscopic soil fungi."

Prylutskyi and his wife, biologist and founder of the Ukrainian Bat Rehabilitation Center Alona Prylutska, conducted soil sampling and bat surveys throughout central and western Ukraine, at one point collecting soil samples by lamplight.

"It was challenging to measure the study plot correctly and identify plants around [it], but we did it successfully, listening to the owl calls above our heads," Prylutska said.

Another team, comprising botanists Dariia Borovyk at the M. G. Kholodny Institute of Botany and Kateryna Lavrinenko at Bohdan Khmelnytsky National University, visited the steppe slopes, floodplain meadows, and forests of the ancient Ukrainian Crystalline Shield formation.

"We tried to choose locations farthest from settlements with minimal anthropogenic impact on the soil microflora," Lavrinenko said, and as a result, the only large animals they "noticed along the way were wild birds or startled roe deer."

"Ukrainian scientists," Lavrinenko said, "are determined to fully utilize every opportunity to study the astonishing diversity and

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Dariia Borovyk samples the alluvial sandy grasslands of Khortytsia, an island in the Dnieper River, in September 2023. Credit: Volodymyr Shyriaiev

complexity of life, from the mighty ancient trees to microscopic soil fungi."

Prylutskyi explained that the project's most dangerous sampling point was the bottom of Kakhovka Reservoir, which had been drained when its dam was destroyed in the conflict; the sample point was just 4 kilometers from Russian-controlled firing positions.

"All [researchers] returned safe and sound, though Russian drones were flying around," he said, adding that the project never encouraged any of its collaborators to take unnecessary risks.

"Staying in Ukraine is a risk on a daily basis. Thousands have died for no particular reason—sleeping at home or being in public places—so I doubt any Ukrainian would say that pushing the scientific frontier is not worth taking a slightly higher risk than average."

DNA Sleuthing

At each sampling site, the teams mapped out a 30-meter by 30-meter quadrant and took nine soil samples. "From several kilograms of soil, we got 20–50 grams of soil; then in the lab, we mixed it again very carefully and took 200 nanograms (0.2 gram of soil)," Prylutskyi said. "We are hoping that this careful mixing ensures a representative sample."

Most fungi are microscopic and do not produce mushrooms, noted Mark Anthony, an assistant professor of fungal ecology at the University of Vienna who isn't involved in the project.

To identify these microscopic organisms, the scientists use DNA metabarcoding, a technique that uses genetic sequencing techniques to determine which fungi species are present in a sample and their relative abundance.

"It is currently the best tool available to study fungal biodiversity when people do it right," Anthony said. "This [project's] data is also good for the international community because earlier research shows that Ukraine is an area where we know very little about fungal biodiversity."

The sequences from the soil samples are now being analyzed in labs in the United States, and results are expected by the end of the year.

"These Organisms Are a Black Box"

"These organisms are a black box: We don't know where they are distributed, or what environmental conditions they can tolerate—Oleh Prylutskyi is closing this gap," said Michael Van Nuland, lead data scientist at SPUN.

Julia Köninger, a soil ecologist and postdoc at the Universidade de Vigo in Spain who isn't involved in the project, explained that documenting soil health was important because war itself introduces pollutants to soils. Human activity at battle sites can leave behind oil and heavy metals; heavy tanks compact soils, and craters from missiles may erode topsoil.

"Understanding the diversity and health of soil fungi before the conflict provides a reference point to assess the damage caused by the war," Köninger said. "This knowledge is vital for documenting environmental war atrocities and understanding the long-term ecological impact."

"I have read about scientists that lived during World War II...and I used to wonder why they didn't just go running and screaming. Now I understand them: Today is the perfect time to try to make the most brave ideas happen."

Meanwhile, Prylutskyi has kept working. "I have read about scientists that lived during World War II in Poland and Ukraine, and I used to wonder why they didn't just go running and screaming. Why were they describing fungi species in the middle of a war?" he said. "Now I understand them: Today is the perfect time to try to make the most brave ideas happen."

By **Andrew J. Wight,** Science Writer

More Than Half of Contiguous U.S. River Water Comes from Ephemeral Streams

Of the roughly 600,000 cubic feet (17,000 cubic meters) of water that flows each second from the Mississippi River into the Gulf of Mexico, half comes from streams that don't even exist for part of the year.

So-called ephemeral streams, which sit above the water table, supply 51% of the Mississippi's water. That's on par with the average for U.S. rivers, according to a new study published in *Science* (bit.ly/ephemeral-streams). This is one of the first times the contribution of ephemeral streams to downstream flows has been quantified, and the analysis comes at a pivotal moment for regulations around these kinds of less obvious waterways.

Following a 2023 U.S. Supreme Court decision, EPA and other federal bodies lost their authority to regulate some kinds of waters within the United States, including most ephemeral streams. Critics of the ruling have said this could leave even still-regulated rivers and lakes vulnerable, as smaller bodies of water feed into them. But hard numbers on what those contributions are have often been lacking. This new study helps to change that.

"There are exponentially more headwaters and ephemeral streams than there are large rivers," said Adam Ward, a hydrologist at Oregon State University who wasn't affiliated with the research. "By demonstrating how much of the water comes from those, it gives us a context for how important they will be to regulation of environmental quality."

Only Sometimes a Stream

Ephemeral streams sit above the water table, meaning they are fed only by precipitation. That means most sit dry for stretches of time—some in the arid southwestern United States flow only a few days each year, on average.

To find these on-again, off-again waterways, the study's authors took an existing map of stream channels in the contiguous United States and laid it over a groundwater model. By excluding streams that dipped below the modeled average level of groundwater, they were able to pick out most ephemeral streams. Then they validated a portion of those streams with existing site assessment data to make sure their model was accurate.

Showing how much of the water comes from headwaters and ephemeral streams, "gives us a context for how important they will be to regulation of environmental quality."

Their data showed that 55% of the water coming from rivers in the contiguous United States begins in ephemeral streams, though large regional variations exist. The percentage of river flow derived from ephemeral streams is much higher in the West than the East, for example, and very low overall in the upper Midwest, where the water table is shallow.

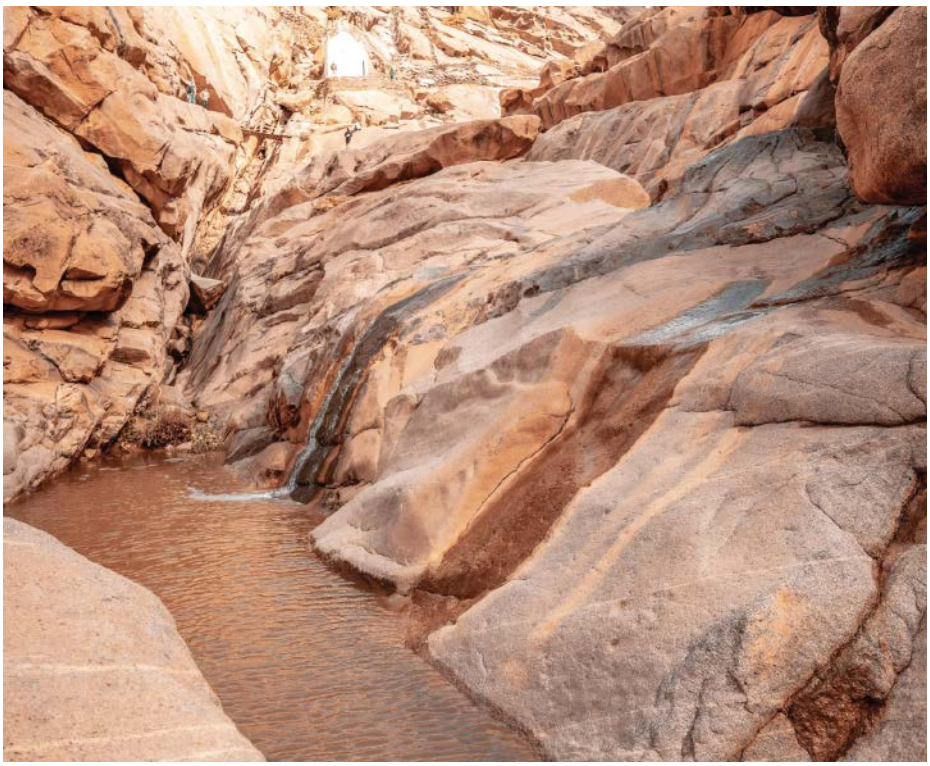
The results underline the fact that ephemeral streams are an important factor in water flow across the country, said Craig Brinkerhoff, a hydrologist at Yale University and the study's first author.

"We usually think ephemeral streams are characteristic of the desert," he said. But trace river headwaters back far enough in many places, and you'll find seasonally dry gullies that become streams only when rain falls.

How Far Does the Clean Water Act Extend?

This new quantification of where the water in major waterways originates has implications for a long-standing debate about which waters federal agencies such as EPA and the Army Corps of Engineers (which issues permits for development work near bodies of water) can regulate.

The Clean Water Act, passed in 1972, is the primary federal law governing water qual-



Ephemeral streams sit above the water table and flow only in response to precipitation. They contribute more than half the flow of U.S. rivers. Credit: Janosch Diggelmann, Unsplash

ity in the United States. But which bodies of water the law covers has long been a subject of debate. Part of that confusion stems from a 2006 Supreme Court case that said it applied only to "relatively permanent, standing or flowing bodies of water" and wetlands with a "continuous surface connection" to them. A concurring opinion from Justice Anthony Kennedy left the door open to waters with a "significant nexus" to those covered waters, an imprecise definition that allowed federal agencies to extend protections more broadly.

In 2023, the Supreme Court revisited the matter in *Sackett v. Environmental Protection Agency*, this time removing the "significant nexus" language and narrowing the law's scope to just relatively permanent bodies of water such as rivers and lakes, as well as those with a continuous surface connection to them. That means that ephemeral streams, which are not, by definition, "relatively permanent," don't count.

Brinkerhoff argued that the new research shows we may need that more expansive definition, however. With half the water in rivers coming from ephemeral steams, significant amounts of pollution resulting from underregulation could come with it.

"All of the systems are connected," he said. "If you turn regulation on and off, you can still end up with water in nominally regulated water bodies that might have come from an unregulated place."

"All of the systems are connected."

The research doesn't alter the definition of an ephemeral stream, but by quantifying how much water these streams contribute to protected bodies, it does highlight their significance in a way that could cause lawmakers to take note, Ward said.

"They can see very clearly now [that] more than half of the water in the rivers they intended to protect originates in ephemeral streams and headwaters," he said. "It seems a logical outcome of that would be to explicitly say, Protect the ephemeral streams and headwaters."

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

Extreme Wildfires Are Getting More Extreme and Occurring More Often

Canada's 2023 wildfire season was the most destructive ever recorded, burning an area twice the size of Portugal. This photo shows an experimental forest fire in northwestern Canada, ignited to increase understanding of wildfire behavior. Credit: Stefan Doerr/Imaggeo, CC BY-ND 3.0 (bit.ly/ccbyncsa3-0)

With near-constant reports of wildfire catastrophes in the media, it may seem like extreme fires are occurring more regularly. And a recent study in *Nature Ecology and Evolution* confirms it—showing that intense wildfires are now twice as common as they were 2 decades ago (bit.ly/wildfire-rise).

Many scientists had suspected that extreme fires were getting worse, said Calum Cunningham, a pyrogeographer from the University of Tasmania who led the study. "But we've not had the evidence to prove this at a global scale before," he said.

Periodic, small wildfires can help maintain healthy ecosystems by clearing dead vegetation. But extreme blazes burn hotter and more uncontrollably, causing significant damage to the environment, people's health, and economies. Large wildfires also emit vast stores of carbon, exacerbating global warming—in turn fueling conditions for more wildfires.

"We focused on the energetically extreme fires," Cunningham said. Global wildfire patterns are usually established by counting pixels of burned land on satellite images. But the traditional approach overlooks the most dangerous fires, he said. "The intensity of fires, particularly the extreme ones, also matters."

Cunningham and his colleagues mapped the intensity of more than 30 million wildfire events (made up of clusters and individual fires) detected by NASA's MODIS (Moderate Resolution Imaging Spectroradiometer) satellites between 2003 and 2023, homing in on the most intense burns.

Using infrared sensors, MODIS satellites can see the heat released by wildfires. "That heat energy directly relates to the amount of biomass burned and the emissions released," explained Cunningham. "It's essentially a measure of environmental damage."

The researchers took daily snapshots of wildfires around the world by summing the heat energy measured within 20- × 20-kilometer (12- × 12-mile) blocks across Earth's surface. Then they isolated which of these blocks contained the top 0.01% of

wildfires according to their radiative power (about 2,900 fire events, made up of clusters and individual fires).

"The analysis is impressive," said Virginia Iglesias, a wildfire ecologist from the University of Colorado Boulder who was not involved in the study. With long-term satellite records now available, handling the abundance of data poses a challenge, she added. "Pinpointing the extreme events meant they could tease out an important trend."

"Pinpointing the extreme events meant they could tease out an important trend."

An Exponential Rise

Cunningham said that during the study period, the greatest number of extreme fires occurred in 6 of the past 7 years. Last year saw the most extreme fires and was also the hottest year on record.

That uptick in extreme fires fits with existing observations of worsening fire activity in specific regions, Iglesias said. In a 2022 study, Iglesias showed that wildfires had become larger and more frequent across the United States since the early 2000s (bit.ly/US-fires-2000s).

However, the global picture of wildfire had been less clear because records that were long enough were not available. Scientists have previously shown a long-term reduction in the acreage burned by wildfires around the world. That pattern reflects changing agricultural practices (and a decline in the use of fire to clear land) in the savanna grasslands of Africa, where around 70% of the world's burning by land area occurs.

Savanna fires typically burn at lower intensity, Cunningham said, and once those fires were filtered from the global data set, the steep rise in extreme wildfires was clear.

Cunningham and his colleagues found that the global trend was driven by a dramatic worsening of extreme wildfires in the western United States, Canada, and Russia. They noted an elevenfold increase in extreme fires in the coniferous forests of North America since 2003. High-latitude boreal forests experienced a sevenfold increase over the same period.

Fanning the Flames

"Climate change is unambiguously making the conditions required for an extreme fire more common," said Cunningham. The study didn't try to make the link to climate change, but, he said, scientists have a wealth of evidence to show that hotter, drier conditions are turning landscapes into tinderboxes, making wildfires more likely and more energetic.

Iglesias said that legacies of land management are likely compounding the effects of climate change. Particularly in North America, aggressive fire suppression policies during the 20th century have allowed dead vegetation to pile up. "All that excess fuel, coupled with a drying climate, stacks the odds in favor of intense fires," she said.

"Climate change is unambiguously making the conditions required for an extreme fire more common."

As climate change accelerates and wildfires burn with more intensity, our relationship with fire needs to change too, Cunningham said. "We've moved beyond a period where suppressing all fire was the objective. It's now time to learn to live in fire-prone landscapes." Using frequent, low-intensity fires as a tool to reduce fuel loads and mitigate the effects of larger fires, just as Indigenous peoples have for millennia, could be one way forward.

By **Erin Martin-Jones,** Science Writer

Four-Billion-Year-Old Zircons May Contain Our Earliest Evidence of Fresh Water

Earth may have contained fresh water 500 million years earlier than previously thought, according to a new study of tiny grains of Australia zircon that were dated to about 4 billion years ago. The minerals contain evidence of rain falling on land, according to scientists, providing new evidence that early Earth had continental crust in addition to oceans.

It's a new glimpse into the Hadean eon, which ended about 3.8 billion years ago—a time when our young planet held little more than rock, magma, and water. Data on this ancient period are sparse, making this new analysis a welcome addition to scientists' understanding of how our planet formed.

The discovery, published in *Nature Geoscience*, could also help researchers better pinpoint when life emerged on Earth (bit.ly/fresh-water-onset). Fresh water and exposed continental crust are two ingredients some scientists posit were necessary for life to begin.

Currently, the earliest evidence of life may be 3.5-billion-year-old stromatolites from Australia. The new work shows "we have the same conditions around 4 billion years ago," said study coauthor Hamed Gamaleldien, a geochemist at Khalifa University in the United Arab Emirates. "So we pushed back the line 500 million years."

Earth may have contained fresh water and continents protruding above the ocean surface 4 billion years ago. Credit: Thom Holmes, Unsplash

"We pushed back the line 500 million years."

Looking at Young Earth

Little remains of Hadean Earth. Most rocks from that time have been worn away or subducted deep under the crust. Some of the only remaining minerals from the Hadean are crystals of zircon embedded in younger rocks.

Zircon is tough and resistant to chemical alteration, and it contains small bits of uranium, which allow scientists to date it. Zircon also contains oxygen, which was the key to the new discovery.

Oxygen has three stable isotopes: oxygen-16, oxygen-17, and oxygen-18. The ratio of light oxygen (^{16}O) to heavy oxygen (^{18}O) is influenced by Earth processes such as evaporation and condensation. Deviations from the standard ratio have long been used by paleoclimatologists as a proxy for temperature. The deviation has its own measure: $\delta^{18}O$.

The $\delta^{18}O$ in some Australian zircons has been used in new research (bit.ly/Hadean-zircons). Earth likely had a solid crust at that time, as well as liquid water oceans, as opposed to the globe-spanning magma oceans previously imagined.

In the new study, Gamaleldien and his colleagues took samples from Australia's Jack Hills, a region known to contain the oldest zircon grains on Earth. They dated some of the grains they collected to 3.4 billion years ago and others to around 4 billion years ago, before the end of the Hadean.

The researchers then determined $\delta^{18}O$ in the zircons and found that samples from both time periods contained a higher ratio of ^{16}O relative to ^{18}O.

That's a strong signal that these zircons formed by interacting with fresh water, Gamaleldien said. Fresh water, which forms as vapor as seawater evaporates, is more enriched with ^{16}O and retains that ratio as it falls to land. The $\delta^{18}O$ in the zircons studied by Gamaleldien follows this pattern and is therefore closer to what researchers would expect to find in rocks that had interacted with fresh water, not seawater. And if rocks were interacting with fresh water, it must mean there was dry land sticking up above the ocean, hinting that Earth had continental crust 4 billion years ago.

The indication of a continental crust is not the only implication of their research, Gamaleldien said. One theory of life's origins suggests it began in shallow pools of water on land, where prebiotic ingredients could col-

lect. The presence of continental crust and an evaporation–precipitation cycle 4 billion years ago means the stage could have been set for life to form just 500 million years after Earth's formation.

The study does not weigh in on whether life was, in fact, present at that time. "We do not know if the conditions for the origin of life on the Earth were optimal for its emergence or just good enough for it to happen," said Stephen Mojzsis, a geologist at the Hungarian Academy of Sciences not affiliated with the new research. This research "pushes us a little bit more towards the optimal side."

"We do not know if the conditions for the origin of life on the Earth were optimal for its emergence or just good enough for it to happen."

The Elusive Emergence of Fresh Water

The case for fresh water 4 billion years ago isn't closed, however. There are other ways to get the oxygen ratios found by the researchers, according to Ilya Bindeman, a geochemist at the University of Oregon who wasn't affiliated with the study.

One assumption the researchers make is that the background oxygen isotopic ratio of seawater hasn't changed over Earth's history. A number of studies suggest that's the case, but still, said Bindeman, it's not settled (bit.ly/early-ocean-isotopes). Finding other isotopic ratios could alter scientists' interpretations of zircon crystals such as these. Alternatively, zircons with similarly light oxygen isotopic ratios could also form from seawater interacting with high-temperature rocks, he said.

In any case, both Bindeman and Mojzsis welcomed the new samples of 4-billion-year-old zircon grains the authors found and analyzed. These fragments from Earth's early days are not easy to come by and represent some of the only remnants of a rapidly evolving planet.

By **Nathaniel Scharping** (@nathanielscharp), Science Writer

Aotearoa New Zealand Has a Unique Fossil Record Named FRED

Fossils in the FRED database span species and time. Credit: GNS Science

Aotearoa New Zealand is the only country in the world that has an essentially complete, open-access database of its known fossil record.

It's existed for almost 80 years, beginning in 1946 as a filing cabinet stuffed with paper forms at the New Zealand Geological Survey. The project was the initiative of Harold Wellman—the pioneering geologist who famously discovered Aotearoa New Zealand's 370-mile-long Alpine Fault—and a few others working on the first geological mapping of the country.

"They wanted ready access to all this information in a standardized, accessible way," said James Crampton, a paleontologist at Te Herenga Waka–Victoria University of Wellington. "It was a brilliant idea."

The forms assigned a map reference and a serial number to locations. They also recorded the fossils seen or collected there, as well as notes on stratigraphy and the rocks' grain size, weathering, and color.

Because it began so early in Aotearoa New Zealand's scientific history, pulling the few existing records into the database "was doable in a way that wasn't doable anywhere else in the world," Crampton said.

Roughly similar databases do exist in other countries, and some, like the global Paleobiology Database, contain more records. But none has such dense coverage of an entire region, said GNS Science's Chris Clowes, current custodian of the Fossil Record Electronic Database—dubbed FRED.

The fossil record is only a partial chronicle of life on Earth, he's careful to point out. But Aotearoa New Zealand has an extremely rich trove of fossils, especially from the Late Cretaceous and later periods, and the database represents "a very complete coverage of the incomplete record that we have. Of the fossils we have, a huge proportion of them have been captured," Clowes said.

Over the decades, the records moved from physical to digital and the maps were recalibrated from imperial to metric. FRED now contains more than 100,000 location entries, mainly from Aotearoa New Zealand, but also from the southeastern Pacific islands and the Ross Sea region of Antarctica.

The database is considered "an icon of New Zealand geological literature," according to an article published in 2020 by Clowes and others.

The file is a way of "passing on information from one scientific generation to the next."

Open to All

Anyone can sign up to access FRED's online portal and make an entry. Four curators from different universities review the entries and fix obvious errors. "We have all sorts of people contributing data, from rank amateurs to professional paleontologists," Clowes said.

In the years since its inception, the database and the spirit of trust and collaboration it embodies have become an important part of Aotearoa New Zealand's geological and paleontological culture—and the envy of international colleagues, said Daphne Lee, a paleontologist at the University of Otago who has been using the database for many decades.

It's long been an expectation—even a requirement—that any newly discovered Aotearoa New Zealand fossil site will be entered into the file, she said. "For scientific papers to pass peer review or students' theses to be accepted, they must have the FRED serial number included."

She admitted that scientists aren't always prompt at submitting a record for every single fossil they find. But overall, the file is a way of "passing on information from one scientific generation to the next," she said. "You might find a place you thought was new, but you'll find, my goodness, in 1957 someone already found a fossil there, and you didn't know about it." Many more detailed data are preserved than tend to make it into scientific papers, she added, meaning knowledge paleontologists amass over their lifetimes doesn't die with them.

And now, other scientists around the world can analyze those decades of data to make new discoveries. In 2018, for instance, researchers based in the United States delved into FRED's fossil records to calculate mollusk extinction rates, and found that Aotearoa New Zealand (alongside the Caribbean) is a present-day extinction hot spot for bivalves.

Some scientists fear that FRED's heyday may be behind us. Aotearoa New Zealand's science funding has been slashed, and job losses are rife in both universities and government-funded institutions.

When it comes to paleontology, "we're struggling to keep critical mass in several of our universities, and we've lost it entirely in a couple," said Clowes. "I think that probably we're going to enter a phase where there's not an awful lot of new data being entered [into the database]. I'm hoping that at some point, the pendulum will swing back, and we'll start doing more fundamental research again."

"It's a remarkable data set, and it's served New Zealand incredibly well."

Crampton said he hopes FRED will be around for at least another 80 years. "It's a remarkable data set, and it's served New Zealand incredibly well," he said. "It allows us to interrogate what we know of New Zealand's fossil history in a way that no one else can."

By **Kate Evans** (@kate_g_evans), Science Writer

Sedimentary Basins Tell Zealandia's Ancient Story

Seven years ago, Zealandia was confirmed as Earth's eighth continent—a slab of continental crust stretching from Aotearoa New Zealand to New Caledonia, 95% of it underwater. In 2023, it was fully mapped for the first time.

Now, scientists have pulled together decades of work by hundreds of researchers to consistently characterize and map all of Aotearoa New Zealand's offshore sedimentary basins—offering clues about Zealandia's evolution.

"A sedimentary basin is any hollow on the surface of the Earth," explained Lorna Strachan, a geologist from the University of Auckland. "This can be anything from a puddle in your driveway to the Pacific Ocean."

These basins accumulate sediments over time. Layer upon layer of sand, mud, rocks, shells, pollen, and bones tell myriad stories of past climates, ocean currents, plate tectonics, the birth of mountain ranges, ecology, and evolution.

A new study analyzed sediment cores from 25 major offshore basins around Aotearoa New Zealand. Credit: Kyle Bland

"I'm biased—I'm a sedimentologist. But to me, [sedimentary basins] are a really rich archive of past history—I'd argue the most important."

"I'm biased—I'm a sedimentologist," said Strachan. "But to me, they're a really rich archive of past history—I'd argue the most important."

In a new paper, researchers from GNS Science Te Pū Ao (the Institute of Geological and Nuclear Sciences Limited, an Aotearoa New Zealand Crown Research Institute) compiled decades of data to define the distribution, extent, and sediment thickness of 25 major offshore basins around Aotearoa New Zealand (bit.ly/NZ-basins). The work is part of a much larger, likely decades-long project to unravel Zealandia's geologic history.

First author Kyle Bland likened the endeavor to the Māori concept of whakapapa—tracing Zealandia's ancestry or genealogy. "Why does it have the shape it does? When did it break away from Gondwana? Why do we have these central North Island volcanoes? Why do we have the Southern Alps? If you understand how everything came to be, you can explain—at least at a high level—why we have the structure of New Zealand that we do."

Fragments and Forams

One key data source for the researchers was a collection of rocks drilled from the deep seafloor. The sediment cores were collected by prospecting petroleum companies as well as by scientists participating in the International Ocean Discovery Program.

Inside these 10-centimeter-diameter cylinders are millions of years of history, Bland said. Most of Zealandia's basins formed during the mid- to Late Cretaceous (about 100 million to 66 million years ago), although younger basins date to as recently as 3 million years ago.

He held up a 3D printed seashell-shaped object, a model of a type of foraminifera (foram), a family of single-celled ocean-dwelling organisms. It wasn't to scale: "This thing would be about the size of a human hair in terms of thickness," Bland said. Small, yes, but mighty: Researchers are "reconstructing a continent, how we think it looked over 100 million years…mostly using these little things."

Because forams evolved quite rapidly, diversifying into new species that are relatively easy to identify, their fossils can help geologists date the sedimentary rocks in which they're found. "We have scientists here who sit at a microscope with a really fine little brush, picking and picking," Bland said. "And by looking at the species we find, we can say,

'Aha, this rock must be 50 million years old.'"

By applying the same dating methodology consistently to samples from all 25 basins, Bland's team was able to identify when Zealandia began to break away from the rest of Gondwana—about 105 million years ago. "Across the basins…the number's the same. You have to stand back and look at everything together to get that sense of a pattern."

The sediments reveal what was happening above the waves, too. Researchers were able to identify when Aotearoa New Zealand's Southern Alps started to rise from the South Island's backbone 10–12 million years ago, for example, as a result of the collision of the Australian tectonic plate with the Pacific plate.

The cores reveal "incredible volumes of sediment being deposited in the areas surrounding the South Island and as far north as Taranaki," Bland explained, referencing a western region on the North Island.

Similarly, around 100 million years ago, the sediments in basins across Zealandia were full of coarse riverbed conglomerates, he said. The pattern is suggestive of high fault activity, the growth of hills, and a landscape type called horst and graben.

In addition to the cores themselves, Bland's team compiled seismic reflection imagery to compare sediment thicknesses across Zealandia's basins. The deepest—reaching up to 11 kilometers thick—were the Taranaki, Raukumara, East Coast, and Pegasus basins, those nearest the modern Australian–Pacific plate boundary. Knowing the depth to the harder basement rocks beneath will be crucial for future work to calculate seismic hazard risks in different places, Bland said.

"New Zealand's been this little climatic dipstick sitting in glorious isolation in the southwest Pacific, just recording it all for us—and that record is in the sedimentary basins."

A Little Climatic Dipstick

In a separate but related paper published in 2022, Bland and other colleagues, including James Crampton, a paleontologist from Te Herenga Waka–Victoria University of Wellington, used analyses of the same sedimentary basins data to underpin and test a computer model (bit.ly/NZ-basins-model). They then used the model to produce a series of paleogeographic maps showing our best current understanding of Zealandia's evolution from the mid-Cretaceous to the present.

Inorganic sediments found in the cores helped confirm these interpretations. Fragments of volcanic rock and ash, for example, contain particles of iron, which align themselves with magnetic north. This alignment can help identify where on Earth's surface the rock was formed, informing the maps. "They're like little ancient compasses," said Bland.

Together the papers provide a great baseline and a springboard for future work, said Strachan, who was not involved in either study. Big questions remain about the tectonic evolution of Zealandia, she said, especially over the past 30 million years.

The deep-sea sediment cores we have are largely clustered around areas thought to have oil-drilling potential, leaving huge areas of the undersea continent essentially unexplored. "We're trying to reconstruct an area the size of Wales or Switzerland based on one 10-centimeter hole," acknowledged Bland.

"I'm not a jigsaw puzzle enthusiast," said Strachan. "But I liken it to having a 10,000-piece jigsaw puzzle, and all you've got is five pieces—and the pictures have rubbed off. It's difficult. There are lots of things missing. And so you put together the most logical interpretation based on what you've got."

What scientists do have is a site that sheds light on an important corner of Earth's surface. "We sit right across all these latitudinal, oceanographic, climate, and atmospheric boundaries. New Zealand's been this little climatic dipstick sitting in glorious isolation in the southwest Pacific, just recording it all for us—and that record is in the sedimentary basins," Bland said.

By **Kate Evans,** Science Writer

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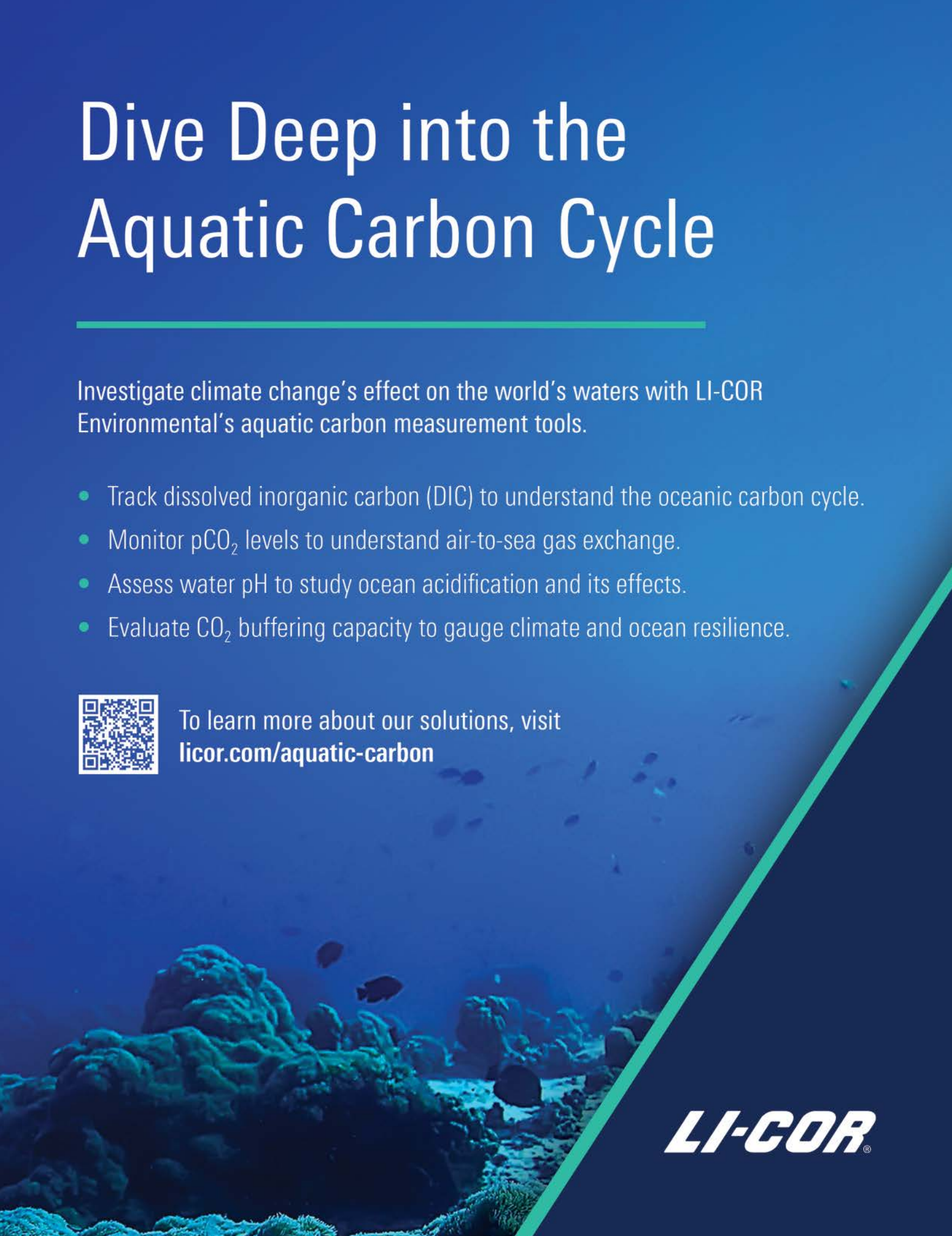

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Global Change Research for a More Secure World

A fleet of small fishing boats floats in Lampung Province, Sumatra, Indonesia. Globally, humanitarian crises are often tied to environmental disruptions, such as the collapse of fisheries, which can erode food security and undermine livelihoods. Credit: J. Lubchenco

Intensifying global changes, caused by human activity, are dramatically affecting human and ecological communities around the world. The individual and collective impacts of worsening floods, wildfires, and deforestation; melting glacial ice and rising seas; and emerging infectious diseases all exacerbate biodiversity loss and threaten human health, economic development, and poverty alleviation, especially for already vulnerable populations [*The White House*, 2022].

In recent decades in the United States, researchers, policymakers, and the public have further recognized that national security and the stability of civil society are tightly tied to the planet's health. As the implications of global change for national security are better understood, they are increasingly being acknowledged in government policy and guidance.

In January 2021, for example, President Joe Biden's Executive Order on Tackling the Climate Crisis at Home and Abroad instructed the Department of Defense (DOD), the Department of Homeland Security (DHS), and the Office of the Director of National Intelligence to explore the implications of climate change for their respective missions. This policy action recognized how climate change exacerbates existing security challenges, impedes efforts to manage them, and requires dedicated, urgent action and sustained investment to build resilience [*North Atlantic Treaty Organization*, 2022].

The United Nations recognizes a triple planetary crisis that includes biodiversity loss and pollution in addition to climate change.

Climate change is not the only environmental threat to national security. For example, the United Nations recognizes a triple planetary crisis that includes biodiversity loss and pollution in addition to climate change. Moreover, the 2022 U.S. National Security Strategy states explicitly that national security cannot be isolated from its environmental context, emphasizing the need to support environmental protection and noting that biodiversity is "vital to food security, clean air and water, a stable climate, and health and wellbeing."

The global science enterprise has a central role to play in supporting efforts to manage the national security risks posed by global change. Only recently have security practitioners and global change researchers started breaking out of their silos to work together, in part because of the growing evidence of the environmental basis of diverse security challenges.

We contend that these groups must give greater priority to understanding the pathways by which global change adversely affects social, economic, political, and ecological systems.

Expanding the role of Earth system science in characterizing the risk landscape, through efforts of both scientific and

national security experts, should also be a high priority. Insights gained from this approach will help identify opportunities to mitigate emerging security risks before they manifest. These opportunities may include improving preparedness for hazards and protecting natural resources that support sustainable livelihoods [*National Science Foundation*, 2021].

Appropriations by Congress in the fiscal year 2023 budget for DOD and DHS accounted for more than half of the federal government's $1.7 trillion in discretionary spending. This amount underscores the high priority the United States places on security. Interventions developed through coordination between security practitioners and global change researchers have the potential to build long-term resilience and minimize financial risks by reducing the demands placed on defense and national security infrastructure.

Below, we identify five research endeavors to bolster national security and promote planetary and human well-being.

Science, defense, and intelligence agencies can better coordinate their efforts to capitalize on space-based remote sensing and generate a more integrated understanding of security-relevant global change processes.

Enhance Earth Monitoring Systems

The proliferation of space-based sensors and the expansion of remote sensing are augmenting opportunities to collect information about global change processes and the behaviors of human populations. However, science, defense, and intelligence agencies can better coordinate their efforts to capitalize on these capabilities and generate a more integrated, systems-level understanding of security-relevant global change processes.

A few programs are already monitoring rapidly changing Arctic conditions, with far-reaching security implications. For example, the Global Terrestrial Network for Permafrost has tracked changes in permafrost for more than 20 years, providing insights into risks to infrastructure and human mobility as the layer thaws. NOAA and DOD's Defense Meteorological Satellite Program monitors Arctic sea ice, offering crucial views of previously unnavigable waters that the security community can use to anticipate changes in maritime traffic and resource extraction and develop contingencies.

However, monitoring gaps remain for many aspects of global change. Enhancing surveillance of biophysical changes in the Arctic, such as the retreat of winter sea ice, could warn of security threats in other parts of the world. For example, changes in the Arctic are a leading indicator of the pace of global climate change. They also have the potential to affect global shipping routes.

Looking beyond the Arctic, disruptions related to water (e.g., drought and floods), soils, fisheries, and other critical natural resources can influence people's behavior, leading to involuntary displacements or damaging resource use practices. The risk of negative outcomes is higher for vulnerable populations, where elevated resource dependency, political marginalization, and social inequities exacerbate the impacts of environmental change and raise the potential for conflict [*Ide et al.*, 2020].

For example, the resource competition and depressed economic opportunities have fueled maritime piracy in the Gulf of Guinea, which interferes with subsistence fishers' ability to secure food and livelihoods and has further destabilized the region [*Broohm*, 2021]. Remote sensing can be used to track the movements of pirate vessels and large distant-water fleets that overexploit the region's fish stocks. Still, social marginalization, inequality, and other aspects of human behavior are not currently observed in ways that can inform security decisions.

In this and other cases, Earth observations should be enhanced to better meet security needs by advancing the capacity to observe human-environment interactions at the population level while maintaining the privacy of individuals.

For example, observations of poaching and illicit logging activities in areas with limited health care capacity would help target management actions. These actions would not only help reduce environmental harms but also lower the risks of emergent diseases that can destabilize communities and contribute to migration.

Regularly observing these and other human-environment connections on larger scales, including in areas prioritized by the U.S. Department of State, would yield vital information for security priorities.

Siloing among research disciplines and practitioners is a persistent limitation in applying science to security challenges.

Develop Holistic Knowledge Systems

Siloing among research disciplines and practitioners—especially in physical, biological, health, social, security, and political sciences—is a persistent limitation in applying science to security challenges. It hinders opportunities for discovery afforded by integrating knowledge and often excludes practitioners with relevant expertise and lived experience.

Border security, migration, and human trafficking are a few issues that would benefit from transdisciplinary approaches. Although these challenges are high priorities for many nations, their underlying environmental drivers are usually overlooked. For example, migration from Africa to the European Union has been linked to the decline of African coastal fisheries due to overfishing, climate change, and pollution [*Belhabib et al.*, 2019]. Similarly, pressure from migrants arriving at the U.S. southern border has been partly linked to climate-fueled agricultural losses in Central America that have eroded rural livelihoods [*de San Miguel et al.*, 2021]. These issues are exacerbated by other drivers of human vulnerability, such as poverty, corruption, conflict, and weak governance institutions [*Alpízar et al.*, 2020].

Diagnosing the multidimensional causes of such security challenges requires collaboration among diverse fields of knowledge and ways of knowing. Understanding ecosystem health and changes in the physical environment is crucial, as is understanding the social dynamics and political and geopolitical dimensions governing human responses.

Experts across public policy, Earth science, and other disciplines have called for developing holistic and inclusive knowledge systems with respect to sustainability. These systems serve as mechanisms "to motivate and harness relevant research and development work in support of problem-solving and decision-making activities" [*Cash et al.*, 2003, p. 8,090].

In 2022, the White House released guidance to federal agencies recognizing Indigenous Knowledges as knowledge systems that contribute to the "scientific, technical, social, and economic advancements of the United States," including the understanding of climate change, sustainability, and natural resource management. And the global health and environment communities have advanced the One Health and planetary health frameworks, which emphasize the interconnectedness of human, animal, and environmental health and advocate for integrated and holistic approaches to promote both human and ecological well-being.

We can build on the examples of such models to benefit national security by enhancing the incentives for collaboration across knowledge systems and by developing ambitious, diverse knowledge networks capable of capturing the inherent complexity in monitoring, experimentation, modeling, and other aspects of needed global change and security research.

Humanitarian crises are often tied to environmental disruptions.

Improve Reporting of Nature-Security Links

Humanitarian crises are often tied to environmental disruptions. For example, drought- or pollution-induced water shortages or the collapse of fisheries can erode food security and undermine livelihoods, and coastal wetland degradation can leave communities vulnerable to storms. Maintaining Earth's ecosystems and the benefits they provide offers dividends for human well-being and security.

Strengthening and communicating the evidence base for how nature undergirds security are important in designing and implementing interventions, such as nature-based solutions that sustain ecosystems and enhance social and economic benefits.

Regular reports on how nature contributes to the economy and society and on how changes in this connection are relevant for security are highly valuable. Such reporting systems are currently in development. For example, many countries are establishing natural capital accounts to track changes in how nature supports food systems, water provision, property values, storm risk reduction, and other areas relevant to both the economy and national security.

In 2023, the United States published a strategy to expand natural capital accounting in the federal government, accompanied by a commitment to undertake its first National Nature Assessment (NNA). The NNA aims to complement both the U.S. National Climate Assessment and international assessments conducted under the auspices of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. The report will synthesize the status and trends of U.S. lands, waters, and wildlife and their connections to national security and other societal benefits.

The success of this critical national assessment, expected for release in 2026, will depend on collaboration between the scientific and security communities beyond traditional silos. Efforts on this front, particularly over the next few years, could significantly improve our ability to diagnose relationships between the environment and security and to prioritize effective interventions where needed.

Enhance Strategic Foresight Capacity

Understanding how strategically important aspects of the Earth system, such as biological diversity, nutrient cycling, and the hydrologic cycle, evolve over time and how they may be affected by policy actions is crucial for successfully managing environmentally influenced security challenges. To this end, researchers and decisionmakers are increasingly applying strategic foresight—a toolbox for exploring alternative possible futures—to anticipate likely outcomes and develop appropriate responses.

For example, the Earth system modeling community has long developed scenarios to project future environmental change and explore alternative pathways through which global demographic, economic, technological, and policy shifts could unfold. These scenarios can also enable a more focused exploration of specific risks or opportunities, such as how major failures in the world's agricultural breadbaskets could sharply affect global food prices and security [*Lunt et al.*, 2016].

Meanwhile, techniques such as vulnerability analysis, which is used to explore the conditions under which systems like water, food, and energy could fail, can help identify potential national security threats for intervention.

Rapid advancements in machine learning, artificial intelligence, and other data analytic techniques are enhancing strategic foresight capabilities.

Rapid advancements in machine learning, artificial intelligence, and other data analysis techniques are enhancing strategic foresight capabilities. Such methods can improve understanding of local disaster impacts, refine climate change projections, and improve pattern recognition, such as in land use change and animal identification and movement. To capitalize fully on these data analysis techniques, researchers and security analysts must be able to access high-quality data and models that skillfully integrate information on environmental, social, economic, and cultural factors relevant to security.

Here again, though, we confront the persistent challenges of siloed research, because most existing tools for strategic foresight fail to integrate all aspects of future conditions at the environment-security nexus. Documenting the lived experiences of populations exposed to global change is critical for building more comprehensive and culturally relevant data models. For example, although agent-based models are widely used in both sustainability and security studies, adding parameters to such models to simulate the dynamics of human responses to global change requires an understanding of the social, economic, cultural, and behavioral characteristics of the populations being simulated [*Natalini et al.*, 2019].

Increase Science Coproduction and Translation

Information alone does not necessarily lead to actionable security insights. In fact, data and analyses that are poorly aligned to decisionmakers' needs can undermine the effectiveness of interventions they develop. Scientists and security decisionmakers working together to coproduce research and translate findings is critical for converting scientific discovery into actions that bolster security.

Scientists and security decisionmakers working together to coproduce research and translate findings is critical for converting scientific discovery into actions that bolster security.

This coproduction should involve developing research questions with the security community and accelerating the pace at which scientific innovation is translated into usable products and decision support tools. Federal investments can facilitate coproduction by creating programs, grants, or other avenues by which the scientific and security communities have incentives to collaborate. Such efforts would enable greater and more immediate scrutiny of security-relevant scientific findings, as well as more robust evidence-based policy interventions.

Translating science for security requires ensuring that data collection and analysis are responsive to the needs of decisionmakers and practitioners. The U.S. Agency for International Development's Famine Early Warning Systems Network, for example, not only provides access to a range of relevant data sources for understanding famine risk [*McNally et al.*, 2017] but also analyzes those data for users to identify priority regions of concern and underlying drivers of food insecurity. This prioritization is instrumental in helping policymakers triage interventions through parallel and compounding global crises.

The growing power of computing and data analytics is accelerating the deployment of such tools. However, the quality and robustness of the information they provide must be carefully managed.

Establishing a set of best practices for the development and dissemination of knowledge, data, and tools in the interest of national security could aid in creating decision-ready science, improving the accessibility of information, avoiding duplication of efforts, and addressing the information needs of the security community. For example, establishing criteria for identifying high-priority environmental data for specific security challenges and increasing interoperability among disparate data types could enhance data stewardship and knowledge discovery for national security applications.

Toward Unity Among the Earth System and Security Sciences

Continuing human impacts on the planet will almost certainly tighten the relationship between Earth system stress and human and national security. In the meantime, critical pathways can strengthen security and peace building through enhanced environmental stewardship.

As outlined here, many opportunities exist for innovative, and transdisciplinary research that can inform actions to promote human and ecological well-being. In the United States, these opportunities should engage a range of federal agencies involved in intelligence, defense, homeland security, and global change science, as well as academic institutions and organizations in the nonprofit and private sectors.

This breadth reflects the need for diverse, collaborative knowledge networks to effect change.

Continuing human impacts on the planet will almost certainly tighten the relationship between Earth system stress and human and national security.

Building such networks requires substantial coordination and investment to integrate physical and social sciences, connect the scientific community with security practitioners and policymakers, and maximize the impact and benefits of research efforts. The payoff will be more robust security science and the evidence base needed for policy interventions that influence people's lives and livelihoods for the better.

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The Moana Project

Braids Tradition and Science for a More Sustainable Ocean

By João Marcos Azevedo Correia de Souza, Julie Jakoboski, Jonathan Gardner, Maui Hudson, and Malene Felsing

Scientists and Māori communities in Aotearoa New Zealand are gathering knowledge on marine conditions and ecosystems to protect livelihoods and help ensure a sustainable future for the blue economy.

The Moana Project and a "nation of oceanographers" deployed networks of Mangōpare ocean temperature sensors to monitor the waters around Aotearoa New Zealand. Credit: Amanda Rudkin/Moana Project

Aotearoa New Zealand has been inhabited since settlers arrived in voyaging canoes between 1250 and 1300 CE. Wayfinding based on Traditional Knowledge of navigation guided them, and the prevailing winds and currents propelled them.

These settlers, the ancestors of the Māori people, found food in abundance around the coast and built kaitiakitanga (guardianship and protection) practices rooted in the deep identification of the Māori with the ocean. They established traditional management of marine resources using rāhui (bans) and tapu (restrictions). These bans and restrictions control when fish and shellfish species may be harvested, for example, to avoid overfishing and damaging or polluting fishing areas with human waste.

Today, Aotearoa New Zealand leans on the ocean as a major source of wealth and well-being while also honoring traditional and cultural practices. Members of the Māori community own about half of the country's seafood sector, which includes the fishing and aquaculture industries and brings in NZ$5.2 billion each year. However, the ocean is changing, and its resources are threatened by warming waters and other environmental shifts driven by global climate change.

Aotearoa New Zealand leans on the ocean as a major source of wealth and well-being while also honoring traditional and cultural practices.

Although Mātauranga Māori (Māori Traditional Knowledge) is constantly evolving to adapt to new environmental conditions, a braided rivers approach helps us find solutions to the complex problems posed by the changing ocean. Similar to the North American Mi'kmaq concept of "two-eyed seeing," which involves interweaving traditional and scientific knowledge systems, braided rivers communicate and intersect on their journey to the sea.

The Moana Project, named for the Māori word for "ocean" and launched in 2018, is a pioneering endeavor in ocean stewardship that combines Traditional Knowledges, cutting-edge technology, and collaborative partnerships with Aotearoa New Zealand's fishing and aquaculture industries to bolster the blue economy, enhance societal well-being, and safeguard ocean health. These goals are achieved by providing tools and information that help improve water safety and forecasts of extreme events, monitor marine reserves and ocean climate change at a national level, inform preservation efforts, and make fishing more efficient and sustainable, among many other benefits.

The project represents an inclusive, multicultural approach to ocean science and management that is necessary for ensuring a sustainable future for Aotearoa New Zealand communities—one that could provide a template for other countries or regions to follow. In fact, the results from the project have already inspired similar systems in such places as Antarctica, Australia, and Ghana.

Monitoring the Ocean

Thermal stress is one of the greatest threats to Aotearoa New Zealand's aquaculture and fisheries. Extreme climate events, especially marine heat waves, have become more frequent in recent years, with devastating impacts on ocean ecosystems.

For example, the deepwater hoki (*Macruronus novaezelandiae*) fishery, which generates roughly NZ$205 million in exports annually, suffered a NZ$13 million loss in 2017 alone, likely due in part to elevated ocean temperatures.

Our capacity to observe and predict ocean conditions has been historically limited, which in turn limits our ability to anticipate and prepare for negative effects of environmental change. Furthermore, sizes and distributions of key source populations of taonga (treasure) species—those of particular economic and cultural importance, such as pāua (abalone) and kuku (native greenshell mussels)—at a national level have been unknown, hampering our understanding of the overall health of these populations.

Integrating various knowledge sources and priorities into ocean monitoring is critical for enhancing marine ecosystem management. Such integration must account for the valuable insights of coastal Indigenous communities that stem from generations of using and managing marine ecosystems through their local and traditional environmental knowledge.

In the Moana Project, our approach for successful collaboration between scientists and affected communities involves two-way knowledge sharing, joint development of funding proposals and project plans, agreements about ecosystem monitoring, and ongoing data sharing following FAIR (findable, accessible, interoperable, and reusable) and CARE (collective benefit, authority to control, responsibility, ethics) principles. The project was conceived with the Whakatōhea Māori Trust Board, which represents an iwi (tribe) whose traditional homeland is on Aotearoa New Zealand's North Island along a stretch of the Bay of Plenty coast, and with iwi aquaculture and fishing interests at heart.

Early in the project, scientists developed an innovative temperature sensor system that iwi project partners named Mangōpare (hammerhead shark; Figure 1). The system is deployed in collaboration with the commercial fishing industry, local communities, crew aboard educational and research vessels, amateur scientists, and others. More than 250 vessels participate in collecting near-real-time observations while performing their normal at-sea activities.

The sensor technology provides cost-effective, near-real-time ocean temperature monitoring at a national scale in coastal regions, filling a recognized gap and complementing existing global observing systems. The resulting subsurface temperature observations offer profound insights into oceanic conditions and provide early warnings of extreme events.

The system's huge success played a key role in the establishment of an international group focused on promoting fishing vessels as ocean observing platforms: the Fishing Vessel Ocean Observing Network. This initiative was recently endorsed by the United Nations Decade of Ocean Science for Sustainable Development under the CoastPredict program, and it is now included in the Global Ocean Observing System as an emerging network.

Predicting the Future

When oceanographic observations are assimilated into ocean models, they enhance the accuracy of coastal and shelf sea simulations and improve forecasts of future conditions (Figure 2). These models can provide insight into causes of extreme heating events, reveal local dynamics influencing important traditional aquaculture sites, and explore connectivity among different populations of marine species.

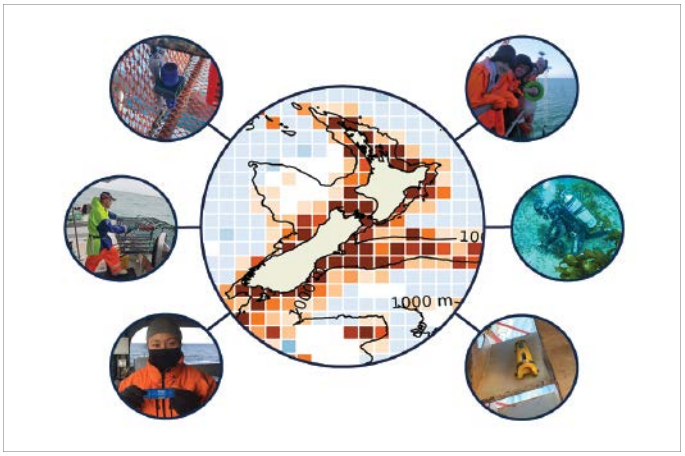


Fig. 1. The Moana Project captures cost-effective, high-quality ocean temperature measurements through a "nation of oceanographers" approach, that is, by partnering with commercial fishers and amateur scientists from coastal regions around Aotearoa New Zealand. The map shows average 2020–2023 coverage of the ocean around the country by temperature sensors in the Argo (blue) and Mangōpare (orange) networks, highlighting how Mangōpare sensors can complement Argo measurements. (Darker shades represent higher numbers of temperature profiles collected.) The surrounding photos show sensor deployments and some of the individuals involved. Credit: left middle, Willie Maclardy; left bottom, Peter McComb; right middle, Tom McCowan; all others, Moana Project

Fig. 2. The life cycle of ocean observations collected in partnership with the fishers. The observations are eventually fed into models that help provide forecasts of ocean conditions, which contain valuable information for fishers and other users.

Short-range ocean temperature forecasts are a useful tool for preparing for and responding to emergencies, such as extreme weather and rapid, heat wave–induced declines in fisheries. However, industry and government stakeholders in Aotearoa New Zealand have highlighted an additional

The Moana Project team is invited into the Omarumutu Marae in Ōpōtiki for the final hui (meeting) with the Whakatōhea Māori Trust Board (top). Members of the project team and the Whakatōhea Māori Trust Board pose for a group photo outside the marae (bottom). Credit: Whakatōhea Maori Trust Board

urgent need to understand upcoming mid- to long-term (i.e., the middle to the end of the century) changes in the marine environment. Such changes may have long-lasting effects on population sizes and distributions—and possibly the survival—of many species, including taonga species.

Understanding the potential impacts of warming water and other environmental changes is usually limited by a lack of knowledge of animal physiological responses to increasing temperatures. In the Moana Project, new knowledge of physiologies and distributions of multiple species gleaned from studies conducted outside the project is integrated with ocean forecasting of the impacts of future climate scenarios on Aotearoa New Zealand's coastal waters. This holistic approach enables informed decisionmaking and the development of effective adaptation strategies.

The Origins of Seafood Species

Connectivity among different populations of a given species is critical to maintaining the health and robust numbers of that species' populations. Identifying source populations that—through breeding or migration—provide many new recruits to fishery or aquaculture populations is particularly important in conserving those valuable societal resources, which face the possibility of depletion because of ongoing extraction.

The Moana Project has focused on understanding and quantifying population connectivity at regional and national spatial

The Moana Project brings together biology, Traditional Knowledges, ocean observations, and numerical modeling, as represented by images of (left to right) a pāua shell and seaweed, traditional Māori sailing vessels called waka, the Mangōpare ocean temperature sensor developed during the project, and modeled ocean temperatures in the Bay of Plenty. Credit: Moana Project

scales for key seafood species, including kuku, pāua, and kōura (rock lobsters). We use different approaches: Mātauranga Māori, modeling of larvae trajectories, analyses of genetic variation, and shell microchemistry.

We highlight two examples of this work related to mussels below.

In the Bay of Plenty, Whakatōhea and neighboring iwi provided information about important sites at which mussels are present and have been harvested for many generations. With permission from local iwi, project scientists collected mussels along approximately 110 kilometers of coastline. In addition, newly settled mussels on the Whakatōhea offshore mussel farm were collected to see whether it was possible to determine where they originated.

Analysis revealed small but important genetic differentiation on a regional scale, suggesting that recruitment to the mussel farm is mostly local. Confirming this finding, a modeling study identified a recirculation current in the eastern part of the bay that retains local larvae. Shell microchemistry analysis of newly settled mussels collected from shallow offshore settlement sites further supported the importance of local populations as sources for new recruits to the mussel farm.

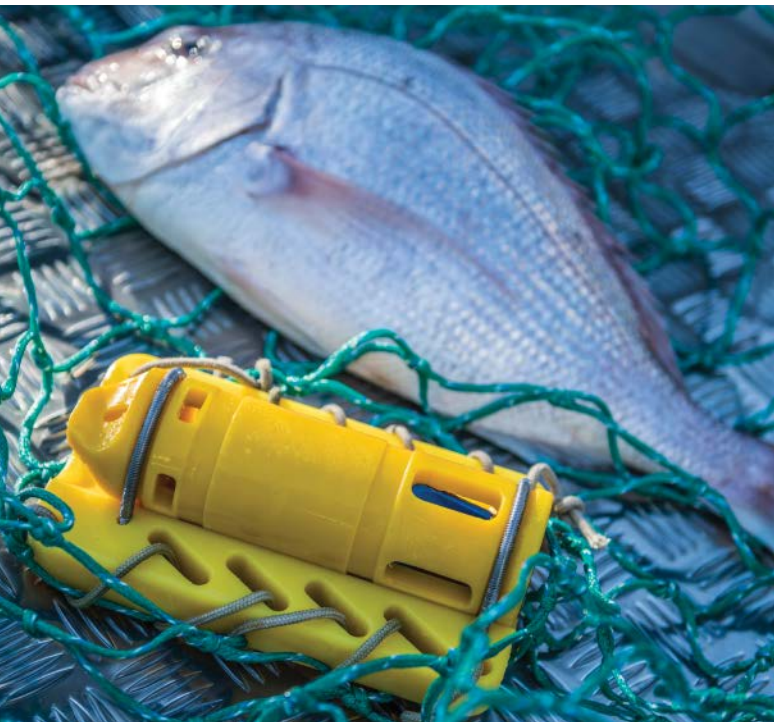
This transdisciplinary work highlights how Mātauranga Māori and western science can be intertwined to improve coastal management (e.g., through protection of existing key sites) and spatial planning (e.g., through identification of new mussel farm sites in the coastal areas of the local iwi).

In another example, large numbers of wild spat (small mussels roughly 5–10 millimeters long) wash up naturally along Ninety Mile Beach on the west coast of the Northland Peninsula in the extreme north of Aotearoa New Zealand. Eighty percent of Aotearoa New Zealand's greenshell mussel aquaculture relies on spat collected in this region. Understanding where these mussels come from and the oceanic mechanisms that carry them to this beach is critical for the growth of the country's mussel aquaculture industry.

We worked with multiple iwi in the far north to collect mussels from sites that iwi identified as culturally important. Genetic analysis revealed no significant genetic differentiation among mussels collected from this region, confirming long-held Māori knowledge that the mussel spat that wash up at Ninety Mile Beach are locally derived. However, we found pronounced differentiation between these northern mussels and those from farther south. Physical oceanographic modeling corroborated this finding, helping to reveal that this genetic distinction derives from the absence of suitable mussel habitat along Ripiro Beach, Aotearoa New Zealand's longest sandy beach. The 107-kilometer-long beach acts as a divider that keeps the northern and southern populations from intermingling.

Integrating various knowledge sources and priorities into ocean monitoring is critical for enhancing marine ecosystem management.

This work provides important information that will help iwi better understand mussel population dynamics. Iwi may also use these results to support their calls to the government for better protection of the



Scientists developed ocean temperature sensors that were deployed in collaboration with the commercial fishing industry, local communities, crew aboard educational and research vessels, amateur scientists, and others to help monitor ocean conditions around Aotearoa New Zealand. Credit: Moana Project

We worked with multiple iwi in the far north of Aotearoa New Zealand to collect mussels from sites that iwi identified as culturally important.

critically important mussel beds in shallow offshore and intertidal regions of the rohe moana (traditional marine areas) in the region.

Completing the Coproduction Cycle

The two examples above demonstrate the key role of Māori in identifying important sites for sample collection and in providing leadership and networking among iwi to ensure that research efforts develop with input from all interested parties and science collaborators as early as possible in the process. The results provide iwi with the best available scientific knowledge, enabling them to better protect existing resources and make more informed decisions about where to locate potential new aquaculture initiatives (e.g., farms and spat-catching operations). Such decisions ultimately involve major economic investments by iwi and provide employment opportunities for local people in the region.

To complete the cycle of coproduced research in the Moana Project, scientific results must not only be shared with the communities and stakeholders involved but also be transformed into useful products and services developed with their input. Information from the project has, for example, been integrated into the Whakatōhea Moana Plan, which outlines Whakatōhea values, goals, and aspirations for its coastal and marine territory.

Project members have also created a publicly available marine heat wave forecast tool to provide warnings up to 10 days in advance of an extreme event. Looking back at ocean temperatures in previous years, another approach used by the project, can shed light on how marine heat wave events affected—and may affect in the future—catch and productivity fluctuations registered by our fishing industry partners.

By providing information and tools tailored to specific community and industry users, the Moana Project empowers them to develop and apply information-based management practices. And by uniting modern science with time-honored wisdom, the Moana Project is paving the way—and providing a model—for responsible ocean stewardship and the prosperity of marine environments nationwide and beyond.

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Mosquitoes Without Borders

Researchers say there may be more power in using ecological regions instead of geopolitically defined regions to analyze the spread of mosquito-borne illnesses. Credit: James Gathany via the CDC Public Health Image Library, Public Domain

Scientists often use forecasting models to predict the spread of infectious diseases. The data informing these models are usually framed by geopolitical boundaries such as states or counties.

Moser et al. argue that using boundaries based on human activity and physical geography rather than climatic or ecologic factors may limit the accuracy of forecasts by obscuring relationships between disease and environment. Mosquitoes carrying pathogens such as West Nile virus, for instance, pay no mind to the geopolitical boundaries along which health data are divided.

Regional U.S. disease forecasts often use the nine climate regions defined by NOAA. These regions consider climate factors but are still grouped along state lines.

In this study, the researchers instead used 10 level I ecoregions—or areas with similar ecosystems and comparable environmental resources—defined by the EPA.

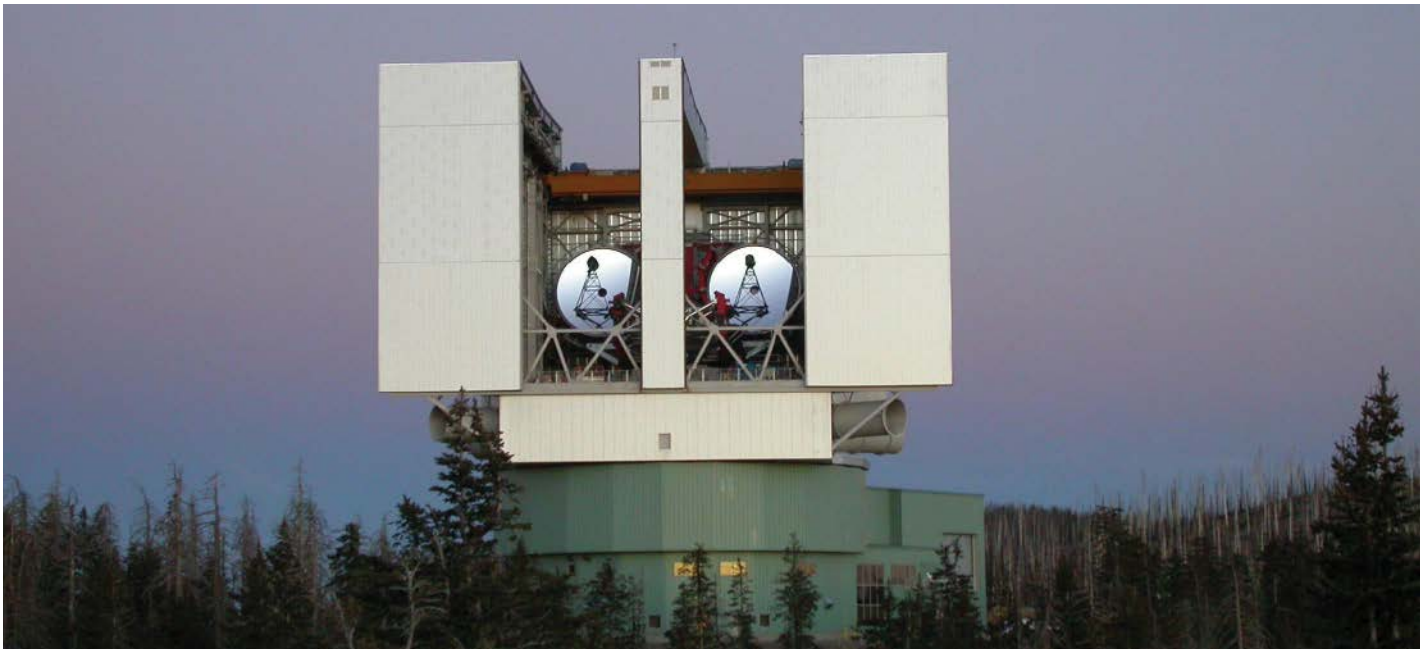
The researchers studied Centers for Disease Control and Prevention (CDC) data on West Nile virus from 2005 to 2019 to examine correlations between temperature, precipitation, and West Nile cases both in NOAA climate regions and in EPA ecoregions.

In some areas, the correlation between climate variables and virus incidence levels changed depending on which regional breakdowns were used in the analyses. For example, the Southern Semi-Arid Highlands EPA ecoregion is within the Southwest NOAA climate region, but the former showed a negative correlation between temperature and virus incidence levels, whereas the latter showed a positive correlation.

The correlations found within EPA ecoregions more often agreed with established knowledge about how environmental dynamics and mosquito biology affect the spread of disease. For instance, virus rates tend to increase with anomalously high temperatures, but extremely high temperatures can have the reverse affect by causing mosquitoes to die off. (Because NOAA-defined regions tend to include more than one type of ecology, trends calculated for the entire region might be less accurate for specific locations within that region.)

The authors' results suggest that using regions partitioned by ecology (such as EPA ecoregions) instead of geopolitical regions could enhance future disease forecasts. (*GeoHealth*, https://doi.org/10.1029/2024GH001024, 2024) **—Sarah Derouin,** *Science Writer*

Supersharp Images Reveal Scars of Major Eruption on Io



A new instrument installed at the Large Binocular Telescope in Arizona enables researchers to observe worlds in our solar system in exquisite detail. Credit: Large Binocular Telescope Observatory

Of all known volcanically active worlds in our solar system—including Earth and some moons of Jupiter, Saturn, and Neptune—the Jovian moon Io is the most restless. Its surface boasts active lava flows, bubbling lakes of molten lava, and more than 400 volcanoes.

SHARK-VIS captured this image of Jupiter's moon Io—the highest-resolution image of Io ever obtained by an Earth-based telescope—on 10 January 2024. Credit: INAF/Large Binocular Telescope Observatory/Georgia State University; IRV-band observations by SHARK-VIS/F. Pedichini; processing by D. Hope, S. Jefferies, G. Li Causi

Now, *Conrad et al.* present the highest-resolution images of Io ever captured by an Earth-based instrument. These visible-wavelength snapshots reveal surface features that hint at a recent powerful eruption on the moon and demonstrate the capability of new technology to dramatically enhance monitoring of Io and other worlds in the solar system.

The technology in question, SHARK-VIS, is a new high-contrast optical imaging instrument installed last year on the Large Binocular Telescope (LBT) on Mount Graham in Arizona. SHARK-VIS (System for High Contrast and Coronography from R to K at Visual Bands) mitigates the blurring caused by Earth's atmospheric turbulence, yielding images that, after postprocessing with the image restoration software Kraken, exhibit resolution 3 times that of visible light images obtained by the Hubble Space Telescope. Previously, only spacecraft or Hubble could capture visible light images of Io. But the LBT can now capture features on Io's surface smaller than about 80 kilometers across—comparable to taking a picture of a dime-sized object from 100 miles away.

After SHARK-VIS was installed, researchers used the telescope to observe Io in November 2023 and January 2024. Looking closely at the images, they noticed something curious: A well-known, red-hued, annular ring of deposits from a continuously erupting volcano called Pele appeared to have been partially covered by other multicolored deposits.

By cross-referencing this information with data previously captured by other instruments, the researchers concluded that they were most likely looking at the aftermath of a large 2021 eruption of a nearby volcano called Pillan Patera.

Similar resurfacing events might be commonplace on Io. But with spacecraft visits to the moon being few and far between and only low-resolution images previously offered by Earth-based telescopes, researchers have had scant opportunities to detect them.

SHARK-VIS will help scientists closely monitor Io's surface for years to come, allowing a deeper understanding of the moon's dynamic volcanism. The technology should also enable high-resolution images of bodies throughout the solar system, including other moons, planets, and asteroids. (*Geophysical Research Letters,* https://doi.org/10.1029/2024GL108609, 2024) **—Sarah Stanley,** *Science Writer*

Mantle Upwelling May Have Triggered Morocco Earthquake

The High Atlas Mountains in western Morocco, seen here from the road between Midett and Fez, were struck by a magnitude 6.8 earthquake in September 2023. New research suggests that the quake may have been caused by mantle upwelling. Credit: Ralf Steinberger/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

On 8 September 2023, a magnitude 6.8 earthquake struck western Morocco, causing damage and destruction that claimed thousands of lives in rural communities in the High Atlas Mountains. Prior to this event, the last powerful earthquake to affect Morocco occurred in 1960. The long stretch of quiescence may have contributed to the region and its infrastructure being underprepared for major shaking and associated damage.

Most of Morocco's seismic activity occurs north of the 2023 epicenter, near the Rif Mountains, which are formed by convergence of the African and Eurasian plates. To the south, closer to the High Atlas Mountains—the tallest in North Africa, with peaks rising to more than 4,000 meters—the plates are converging at a rate of only about 1 millimeter per year. It's thought that mantle upwelling beneath the High Atlas, more so than the slow convergence, is a main reason these peaks reach as high as they do.

By examining geodetic and seismic data, *Huang et al.* found that the 2023 Morocco quake originated in the Tizi n'Test fault system on a fault plane centered about 26 kilometers below the surface and that the rupture's strongest effects occurred at a depth of 12–36 kilometers. The event caused displacement of the Moho, the boundary about 32 kilometers beneath Earth's surface, where the crust meets the mantle.

Because of the unusual origination depth of the earthquake and its occurrence far from plate boundaries, the researchers suggest that the quake may have been triggered by the same mantle upwelling that helps lift the High Atlas Mountains, rather than by faulting activity closer to the surface.

The findings suggest that seismic hazard models should incorporate more data about deeper dynamics in intraplate regions, which are often overlooked in favor of plate boundary dynamics, according to the authors. They also highlight the importance of seismic monitoring for regions, such as this one, where slow deformation rates and complex fault structures cause infrequent but devastating earthquakes. (*Geophysical Research Letters*, https://doi.org/10.1029/2024GL109052, 2024) **—Rebecca Owen,** *Science Writer*

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The Secret to Mimicking Natural Faults? Plexiglass and Teflon

Scientists have discovered that coating some sections of plexiglass laboratory samples with Teflon can create confined ruptures that are similar to the way earthquakes occur on faults in nature. Here, Ph.D. student Jun Young Song prepares such an experiment. Credit: Gregory McLaskey

When a fault ruptures, some sections slip suddenly and generate earthquakes. In these patches, the faster a fault slips, the weaker the fault zone, and the easier it becomes for a rupture to propagate. Other fault sections, by virtue of their minimal friction, creep slowly and generate little to no seismicity. There, the faster a fault slips, the stronger the fault surface becomes. Ruptures that propagate into these "velocity-strengthening" sections are generally halted. Therefore, the relative locations of these different sections affect the size and nature of seismic activity along the entire fault.

Scientists use multiple techniques, including modeling and laboratory experiments, to re-create and better understand faulting behavior. In laboratory experiments, researchers build small-scale models of faults using materials such as rock and plastic to see how they respond to ruptures. But this approach has had various pitfalls. For instance, most experiments use samples that have uniform, velocity-weakening properties. Others have used powders of various composition to simulate the velocity-weakening and velocity-strengthening properties of fault gouge. But these can compact inconsistently and complicate the results.

In a new study, *Song and McLaskey* created a technique to more easily represent natural fault ruptures in a laboratory setting. They built an entire model fault out of plexiglass, or acrylic, which is known to be velocity weakening. Rather than using a different material entirely, they coated sections of the fault interface with famously low-friction Teflon to mimic a velocity-strengthening area that surrounds a velocity-weakening area. This created a heterogeneous fault with conditions similar to those found in nature.

The researchers found that when they increased the amount of normal stress on the plexiglass and Teflon fault or increased the size of the velocity-weakening area, the slip behavior changed from stable slip movement to more irregular stick-slip events—similar to how numerous faults move in nature. Further, they noted that when there was no velocity-strengthening material confining the fault rupture, seismic waves were radiated less efficiently than in nature. These findings could be helpful for understanding the relationship between the rupture lengths of faults and earthquake behavior. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2023JB028509, 2024)

—Sarah Derouin, *Science Writer*

Fifty-Three Experts Weigh In on the Global Methane Budget

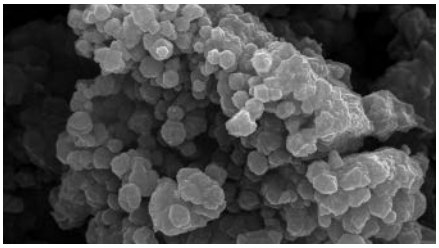
Accurate estimates of atmospheric greenhouse gas levels are needed to understand and address the drivers of climate change. Of particular interest is atmospheric methane, which has increased in concentration by 160% since preindustrial times and accounted for 35% of warming from greenhouse gases from 2010 to 2019.

The Global Methane Budget (GMB; bit.ly/global-methane-budget) debuted in 2016 to track trends and estimates of both anthropogenic and natural methane emissions. Updated in 2020, it integrates research from top-down studies, which provide broad, regional-level pictures of methane sources and sinks, and bottom-up studies, which provide more detailed views of specific emissions sources. But uncertainties (quantitative estimations of error) in the data behind the GMB vary from sector to sector.

Rosentreter et al. surveyed 53 methane experts, including both modelers and empiricists, to learn about the magnitude, distribution, and types of uncertainties in measurements of global methane sources and sinks. The experts were asked to rate uncertainty levels related to various methane sources and sinks, such as wetlands, fossil fuels, and wildfires. They were also asked to share their personal confidence levels (a subjective measure ranging from "very low confidence" to "very high confidence," not referring to statistical confidence) for a range of both top-down and bottom-up methane emissions estimates from sectors such as fossil fuels, soil uptake, and agriculture and waste.

The experts ranked the GMB's "other natural sources" category as having both the highest uncertainty and lowest confidence, reflecting uncertainty in methane emissions data from sources such as fresh water, vegetation, and coastal and ocean areas, as well as in parameters for wetland models. Confidence was particularly low in bottom-up estimates of these other sources. In addition to those results, about 67% of the experts surveyed felt that atmospheric methane will play a larger role in global warming by 2050.

The authors suggest that rather than labeling methane emissions as either natural or anthropogenic, emissions should be categorized along a gradient between the two. Using this method, they calculated that more than 76% of global methane emissions are either fully human caused or related to human influences—about 26% higher than suggested by the 2020 GMB.



Researchers took this scanning electron microscope image of magnetite particles from methanic marine sediments found in the northern South China Sea. Credit: Zhiyong Lin

They also propose ways to reduce uncertainty in the GMB, including further researching the role of permafrost thaw and extending methane observation networks to poorly monitored regions. (*Earth's Future*, https://doi.org/10.1029/2023EF004234, 2024) **—Aaron Sidder,** *Science Writer*

Microbes Likely Form Magnetite in the South China Sea

Magnetite, one of the most magnetic minerals on Earth, is increasingly being found in seafloor environments that are rich in iron and have high methane flux. But how it forms in such settings—whether by microbes that thrive near methane seeps or by processes that don't require life—is not entirely clear.

Knowing the source of seafloor magnetic signals helps scientists interpret magnetic records of the ancient sea, which can hold clues about tectonic activity, the timing of Earth's pole reversals, and other environmental changes through geologic time.

In 2014, *Lin et al.* took two sediment cores from an area of the northern South China Sea where methane seepage from underwater formations such as mud volcanoes and gas chimneys is common. They looked at magnetic, mineralogical, geochemical, and genomic properties of the cores to determine the source of magnetite formation in the region.

The researchers observed layers with abundant fine-grained magnetite crystals, which they say probably formed in an iron-rich environment because these layers also had high levels of iron overall. Gene sequencing confirmed the presence of methane-producing microbes such as *Methanosarcina* and *Methanocella* in these sediment layers as well.

The team suspects that these microbes can reduce iron for energy, which triggers the formation of magnetite. In contrast, sediment layers in the cores that were richer in pyrite but low in magnetite and iron overall suggested past activity of methane-oxidizing microbes.

From their findings, the researchers conclude that magnetite found in the floor of the South China Sea likely formed by microbial iron reduction, rather than by an abiotic process. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2023JB028312, 2024) **—Rachel Fritts,** *Science Writer*

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HARVARD UNIVERSITY

POSTDOCTORAL FELLOW POSITION IN GEOPHYSICS/EARTHQUAKE SCIENCE AT HARVARD UNIVERSITY

JOB DESCRIPTION:
Professor Brendan Meade invites applications for a **Postdoctoral Fellow** position. We have an open position for a postdoctoral fellow with a background in geophysics, earthquake science, or other similarly quantitative fields. Research projects will be focused on imaging earthquake cycle kinematics, statistical earthquake cycle models, large-scale data (geologic and geodetic) integration, and novel dynamical systems modeling. The appointment is initially for one year with the possibility of an extension two more years for a total of a three-year appointment.

QUALIFICATIONS:
A Ph.D. in Geophysics, Earthquake Science, or other similarly quantitative fields is required at the time of appointment.

APPLICATION PROCESS:
Interested candidates should submit a cover letter, CV, a one-page research summary, and three references' names and contact information. Applications are due **December 1st, 2024**. Applications should be submitted through ARIES Harvard's university-wide system for administering academic searches.

Harvard is an equal opportunity employer, and all qualified applicants will receive consideration for employment without regard to race, color, sex, gender identity, sexual orientation, religion, creed, national origin, ancestry, age, protected veteran status, disability, genetic information, military service, pregnancy and pregnancy-related conditions, or other protected status.

Contact **Brendan Meade** with questions regarding the position or the application process.

SENIOR STAFF SCIENTIST, PLANETARY SCIENCE

The Universities Space Research Association's Lunar and Planetary Institute (LPI) in Houston, TX, invites applications for **one or more full-time staff scientists**. We seek mid-career, self-motivated scientists with a strong record of outstanding research and a demonstrated record of external funding, although we will also consider applications from early-career scientists with similar research records and a history of successful research grants. We especially wish to augment and extend our expertise in astromaterials research, specifically the petrology and geochemistry of planetary materials, including extraterrestrial solid and terrestrial analog samples. The successful applicant will maintain and enhance the strong ties between the LPI and our colleagues at the Astromaterials Research and Exploration Science (ARES) Division at NASA Johnson Space Center (JSC); existing or recent collaborative projects with ARES researchers are desirable. The applicant will have access to the LPI's analytical facilities and would be able to arrange access to ARES' analytical facilities (e.g., SEM, EMP, LA-ICP-MS) and experimental laboratories (e.g., high P-T petrology, hydrothermal, impact).

At the LPI, the successful candidate will enjoy interactions with the diverse Science Staff, scientists at the nearby ARES Division (JSC), and with faculty of nearby universities such as Rice University and the University of Houston. The LPI Science Staff has expertise in many areas of planetary science, is leading a new NASA Support for Planetary Sample Science team focused on training in astromaterials sample handling and research, includes a NASA Solar System Exploration Research Virtual Institute (SSERVI) team focused on the Moon and on impact processes, and includes a growing astrobiology laboratory. The successful candidate must have a Ph.D. in Planetary Sciences, Geosciences (e.g., Geology, Geochemistry), Astrobiology, Astronomy, Physics or related relevant fields, ideally with at least 10 years of experience as a scientist. The candidate must be a U.S. Citizen or Legal Permanent Resident and must be able to pass a detailed government background investigation. The successful candidate will be expected to: design and conduct research in planetary science; maintain, propose for and receive external funding for research; support and advise post-doctoral fellows, graduate students, and/or undergraduate summer interns; maintain or seek involvement with spacecraft missions; and participate with NASA and the science community in review panels, analysis and advisory groups. Experience in managing diverse science personnel would be an asset.

Part of the role of an LPI staff scientist is to support NASA and the planetary science community. This support includes (but is not limited to) activities such as: conceiving and implementing broad, multi-year science research programs that may involve other LPI and/or ARES personnel; maintaining and managing the LPI's SEM and spectrometers; participating in LPI's summer intern programs; working with visiting scientists on NASA-funded research; supporting workshops and conferences focused on topics in planetary science; participating in the XSPACE meteorite curation facility; and involvement in public engagement activities. Experience in some of these areas is expected, along with excellent communication skills.

For more information about the position, please contact the **LPI Director, Dr. Walter Kiefer, kiefer@lpi.usra.edu**. Interested applicants should apply to the posting at USRA Careers and must submit all materials via ADP; application material submitted outside of this platform will not be considered. The required application material includes: **(1)** cover letter evidencing the qualifications of the applicant to this position, **(2)** curriculum vitae with list of publications and research grant history, **(3)** two- to three-page statement of research interests and plans describing the candidate's expected independent research program at the LPI, and **(4)** list of at least three professional references. Review of candidates will begin on **October 15, 2024**.

POSTDOCTORAL SCHOLARSHIPS

Applications accepted from current or recent Ph.D. recipients who wish to broaden their background and training while advancing the knowledge of the ocean and its connection with the Earth system. Applicants in all areas of mathematics, engineering and science, economics and policy, including doctorates in the physical and biological sciences and engineering who wish to pursue their own research interests in association with a member of the resident research staff are encouraged to apply. Interdisciplinary research interests are encouraged.

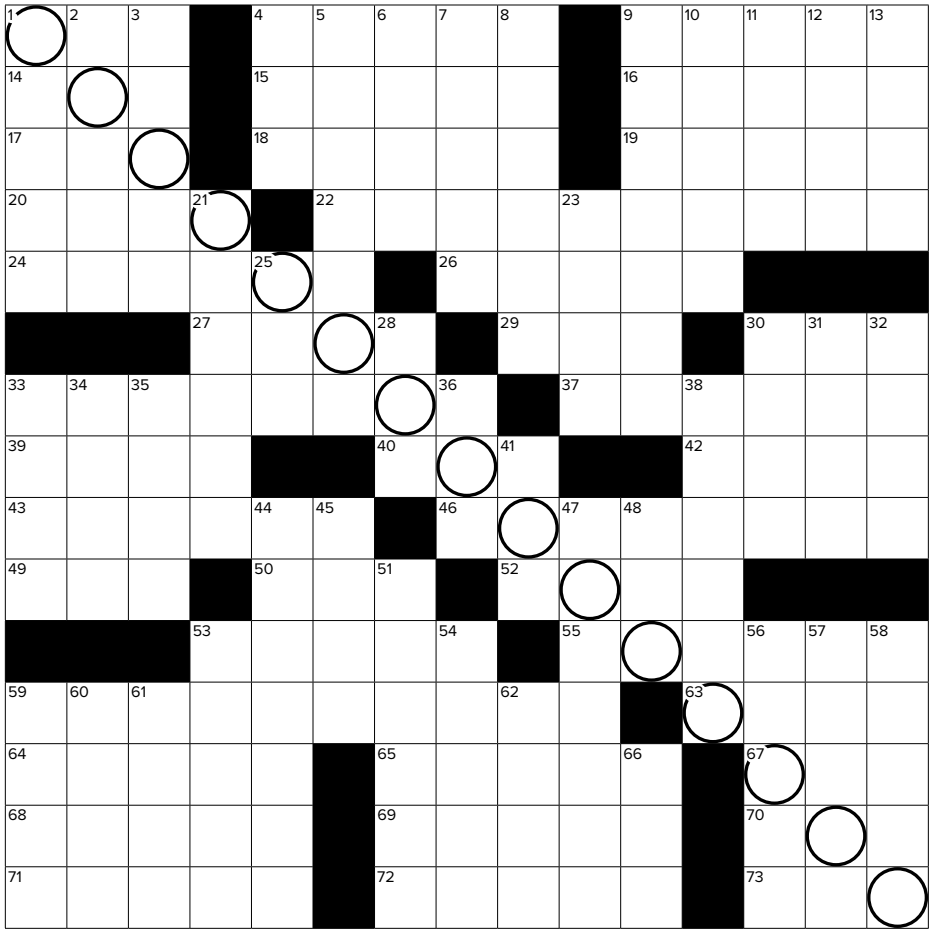
In addition to awards in these general areas, the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) will award a fellowship in radiocarbon research and/or the development or improvement of analytical techniques or instrumentation; and a USGS/ WHOI award in areas of common interest between USGS and WHOI Scientific Staff will be given.

Criteria for awards include demonstrated research independence, productivity and novelty, and community service. Scholarships are awarded for 18-month appointments ($71,000 annual stipend; health and welfare and travel allowances; and a research budget). Communication with potential WHOI advisors prior to applying is strongly encouraged. **Applications must be received by October 15, 2024, to start any time after January 1 and before December 1, 2025**. All qualified applicants will receive consideration for employment without regard to race, color, religion, gender, gender identity or expression, sexual orientation, national origin, genetics, disability, age, or veteran status.

For further information: **go.whoi.edu/pdscholarship**

Kiwi Country

By Russ Colson, Minnesota State University Moorhead



ACROSS

1. No fs, _____, or uts
4. Feature on a fish, dragon, or bathroom floor
9. Pascal or Almodóvar
14. _____ though I walk through the valley of the shadow of death
15. Monstrous and ghostly creature, like kehua and taniwha
16. Egg-shaped
17. Kitten's cry
18. A good _____ of humor—when things go well after the joke?
19. *New Zealand's geology has helped us _____ the beginning, at least the breakup of Gondwana, in a way
20. Like Joe, Donald, or W, casually
22. Bloomers native to China grown in Georgia and California
24. They can be tragic, epic, or super
26. Thought-full action
27. Cool, hot, swell
29. It optimizes web traffic (abbr.)
30. Keep it simple
33. "The best way to get a bad law repealed is to enforce it _____."
37. *Dollars and _____, the smell of money?
39. New Zealand has little of this ore in rocks but plenty of it on the North Island's beaches
40. Egyptian airport code
42. "No _____ to be anybody but oneself." —Virginia Woolf
43. A trilogy famously filmed in New Zealand features the One _____ _____ a signature plot element
46. Teeth, or those who grind them
49. Ambulances and paramedics, e.g.
50. Ball up
52. Synthetic copy of genetic material
53. Painter of *Le Déjeuner sur l'herbe*
55. Profit _____ _____
59. Takes down the tent
63. It's either you _____ _____
64. New Zealand is not a small country but a _____ village. —Peter Jackson
65. Crochets, darns, _____
67. Scam
68. Its belt, Tautoru, rises due east in any season
69. Heron relative
70. NZX trades in New Zealand's stk _____
71. *Financially, an illogical decision makes no _____
72. Milk, cheese, butter, etc.
73. Great publication!

DOWN

1. Immature insect
2. Tractor maker
3. Cutter
4. Swiss inspection company, formerly Société Générale de Surveillance
5. Incrementally cuts away or diminishes (2 words)
6. Steak sauce brand
7. Filmmaker George or actor Josh
8. Votes in
9. Position after a Ph.D.
10. "God bless us, _____ one"
11. Finished
12. New Zealand's Southern Alps have been on the _____ for about 5 million years
13. Poems that praise
21. Paying no attention (with "out")
23. Tints
25. Precursor to the EU
28. Pampering acronym
30. Connects the shin bone to the thigh bone
31. Repeat (abbr.)
32. Data strg devs
33. Papa stallion
34. Prune
35. Rugby player Ackland and *Willow* director Howard
36. Yttrium garnet used in lasers
38. Encircle with light
41. LLC alternative
44. What good art does for thought and emotion
45. "Without" in French, as in "_____ serif"
47. Early buyer of new technology, e.g.
48. Not Jnr.
51. Floored with a punch
53. Algerian macaque or a Chinese figurine named for it
54. Island group in Papua New Guinea
56. Solar events might include a flare _____ _____ (abbr.)
57. Break from work in Kiwi slang
58. *I have an eerie feeling that I have six _____ in my outbox
59. Group (of nations)
60. _____ or endangered birds in New Zealand include the kākāpō, the fairy tern, and the kiwi.
61. Emerald Isle
62. Instrument on the Webb or a Malaysia port
66. Ending for pig, hone, and mode

See p. 29 for the answer key.

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Book housing by **12 November.**

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